Developing a Foundation for Space-Based Two-Phase Thermal Control Systems

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Presented By
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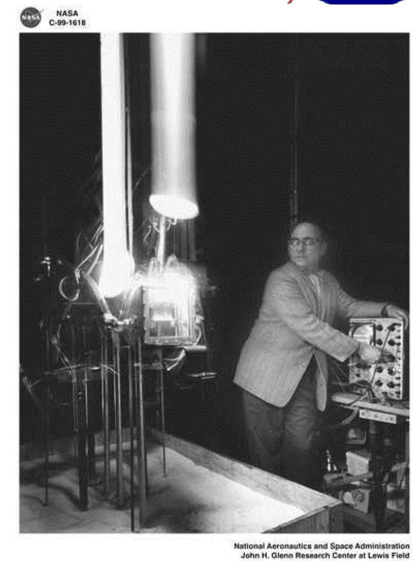
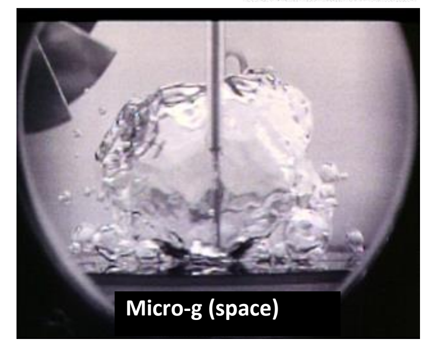
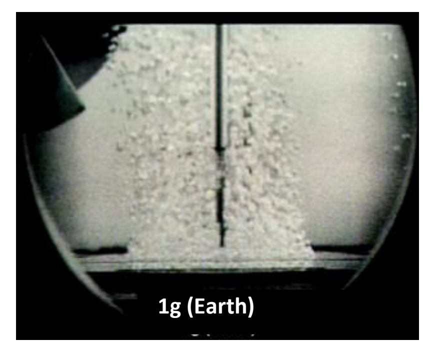
Introduction

Since the beginning of Space Flight, the effects of low gravity on fluids have been of an important topic of research.

- In 1957 (same year that Sputnik-1 orbited the planet – Robert Siegel (NASA Lewis) conceived a drop tower experiment to study fluids.
- This led to the first "fluids experiment in space in 1962 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).
- In the early 1990's Herman Merte (U. of Michigan) flew as series of Pool Boiling Experiments (5 total) on Shuttle Get-Away-Specials (GAS).
- During the 1990s, others used aircraft parabolic trajectories & sounding rockets to continue to advance our understanding – mostly pool boiling-type (Straub, Vogel, Lee, Hasan, Nagashima, Abe, Oka, etc.)
- Transitioning into the ISS era, NASA developed a specific sub-discipline under what is now the SLPS-funded Fluid Physics Discipline – <u>specifically to advance a fundamental understanding of fluid behavior in low gravity</u>.







Why is this needed?

- If we want to make two-phase heat transfer a useable option for low gravity environments we need to advance CFD modeling capabilities – similar to 1-g.
- There are a number of codes (commercial, open source, proprietary) that model <u>some</u> aspects well.
  - Difficulties still exist in mass/heat transfer across interface, determining onset of nucleation, predicting phase distribution in 0-g, etc.
- Reasonably good (useful) models in two-phase flow have been developed for terrestrial applications such as for the nuclear power industry.
- Regardless of the particular situation, multiphase flows are generally complicated and to a large extent models are <u>empirically</u> based.
- There is very little “good” data available in 0-g to validate new/existing models.
- Experimental 0-g data is critical to:
  - Validation of CFD models
  - Closure Laws (e.g., Re stresses, turbulence)
  - Empirical Correlations

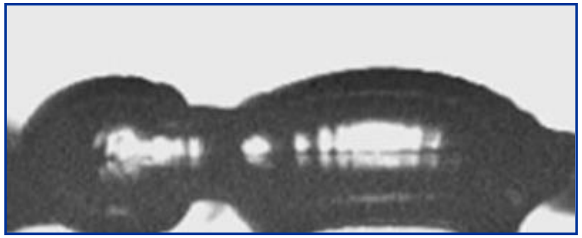
Recent Experiments

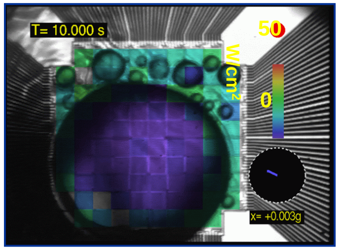
PI: Prof. Vijay K. Dhir, University of California, LA
PI: Prof. Jungho Kim, University of Maryland

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

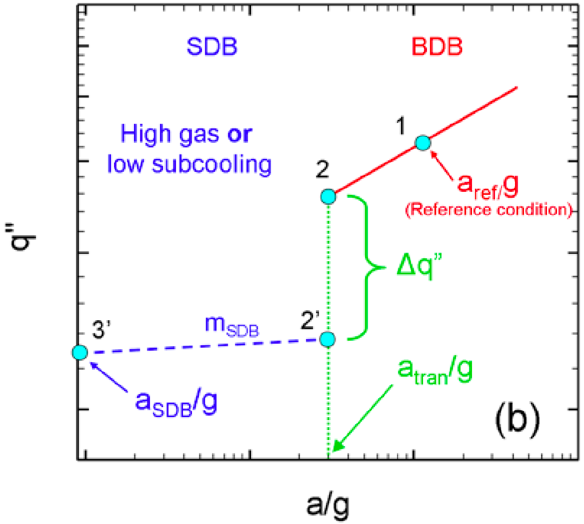
Paulo Nespoli installing BXF in MSG.





(Left) *Coalescence of vapor bubbles on NPBX wafer.*

(Right) *Subcooled nucleate boiling in μg. The MABE microheater array is colorized with actual heat flux data.*

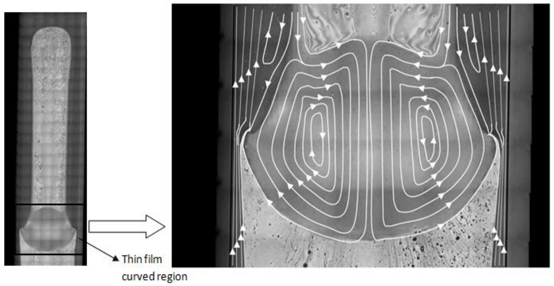


Transition of boiling Heat Flux as a function of acceleration.

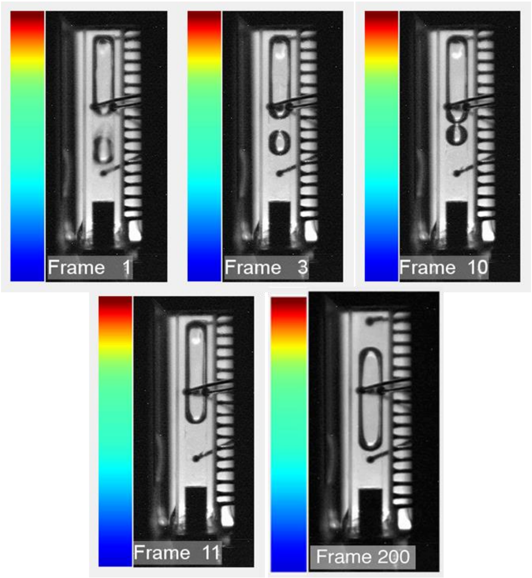
Recent Experiments

Constrained Vapor Bubble (CVB) Experiment – 2009 & 2013

- Highly instrumented 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).



Marangoni limit and flooding of heater end with flow streamlines.



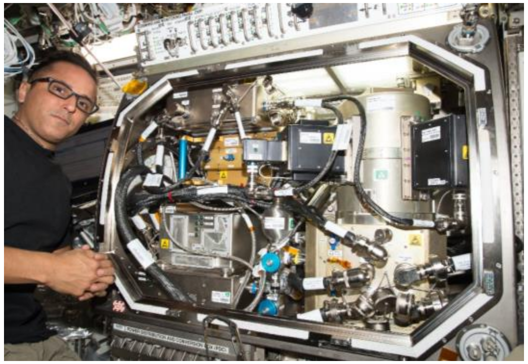
Unexpected Explosive Nucleation in 0-g.

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

Recent Experiments

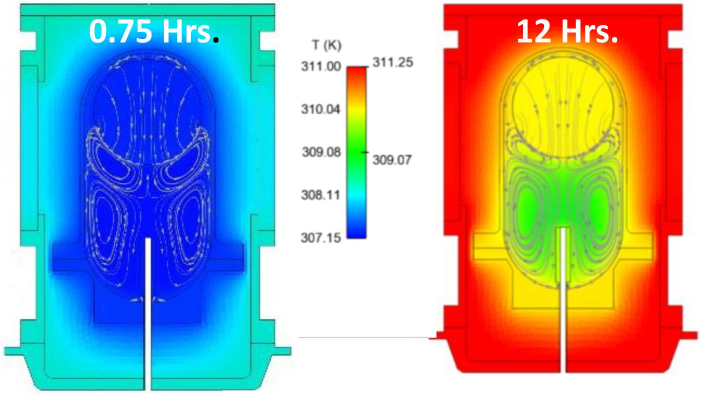
Zero Boil-Off Tank Experiment- (ZBOT) - 2017

- Small-scale simulant-fluid experiment to study storage tank pressurization & pressure reduction through fluid mixing.
- Obtained high fidelity 0-g data under controlled conditions for verification and validation of storage tank CFD models.
- Used to formulate 0-g empirical correlations for thermal stratification, pressurization, liquid mixing, pressure reduction, and interfacial heat and mass transfer.
- Assess the engineering feasibility of dynamic pressure control.

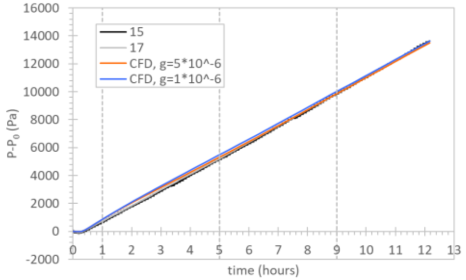


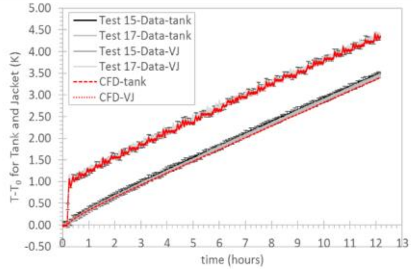
ZBOT Installed in the MSG aboard the ISS

Two-Phase CFD Model Validation: Microgravity Vacuum Jacket Self-Pressurization



Simulation showing evaporation at top and condensation at the bottom of the Ullage inducing a counter-clockwise vortex squeezed against the ullage by a lower residual gravity driven natural convection vortex





Comparison of CFD model prediction of tank pressure and average Tank temperature to microgravity data for the vacuum jacket heating case indication excellent agreement with in 3%.

PI: Dr. Mohammad Kassemi, CWRU/GRC

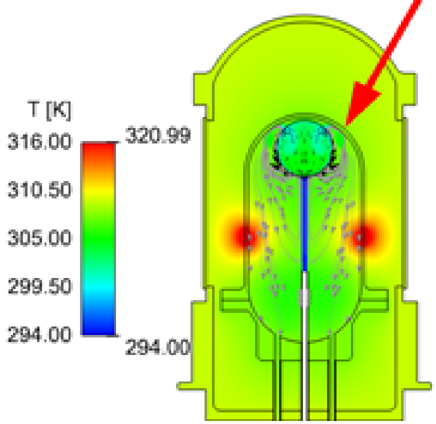
Future Experiments

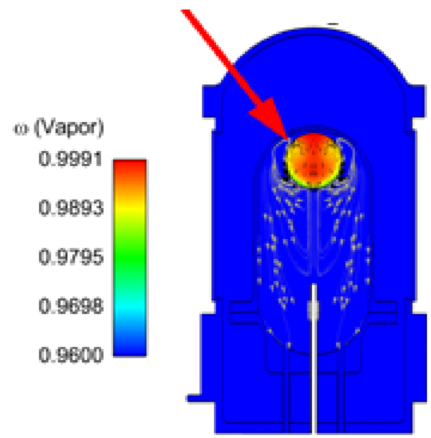
Zero Boil-Off Tank Experiment- NonCondensibles (ZBOT-NC) - 2022

Investigate three important effects of noncondensables on the transport and phase change phenomena that control tank pressure in microgravity:

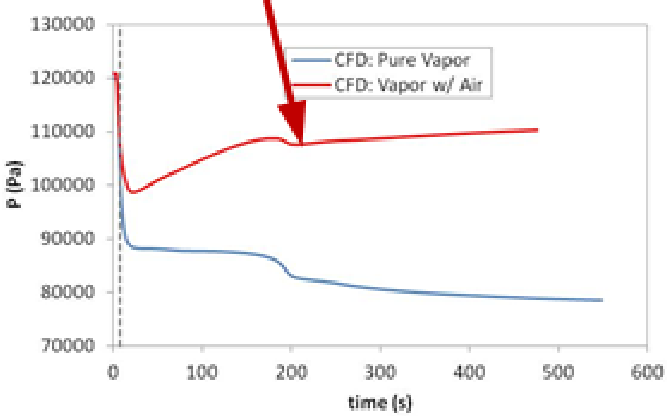
1. The effect of noncondensable gas on microgravity vapor transport in the ullage during pressurization
2. The creation of thermocapillary convection induced by noncondensable gas and its effect on mixing, stratification and destratification in the liquid.
3. The penetration of noncondensbles into the Knudsen layer and its impact on condensation during microgravity pressure control

Residual noncondensable forms transport barrier for vapor condensation in μg





Non-Condensable gas mitigates pressure reduction in space



PI: Dr. Mohammad Kassemi, CWRU/GRC

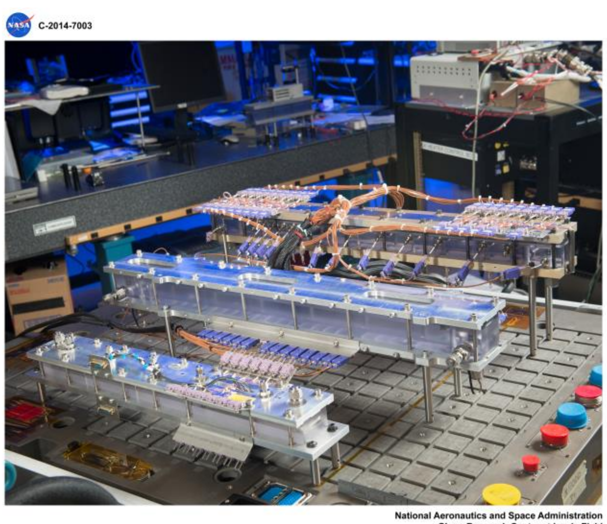
Future Experiments

0-g Flow Boiling

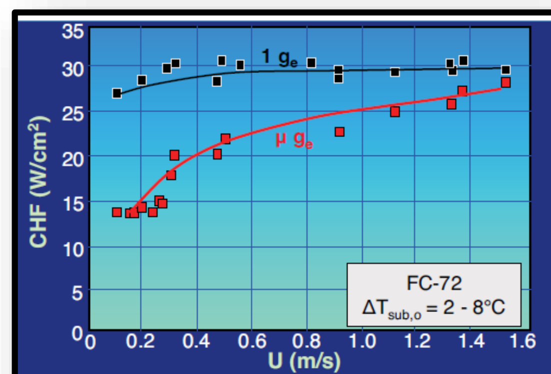
Flow Boiling and Condensation Experiment (FBCE) – 2019

- Provides the first integrated two-phase flow boiling/condensation facility in microgravity.
- Develop experimentally validated, mechanistic model for microgravity flow boiling critical heat flux (CHF) and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent CHF.
- Develop experimentally validated, 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.

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



FBCE Test Module

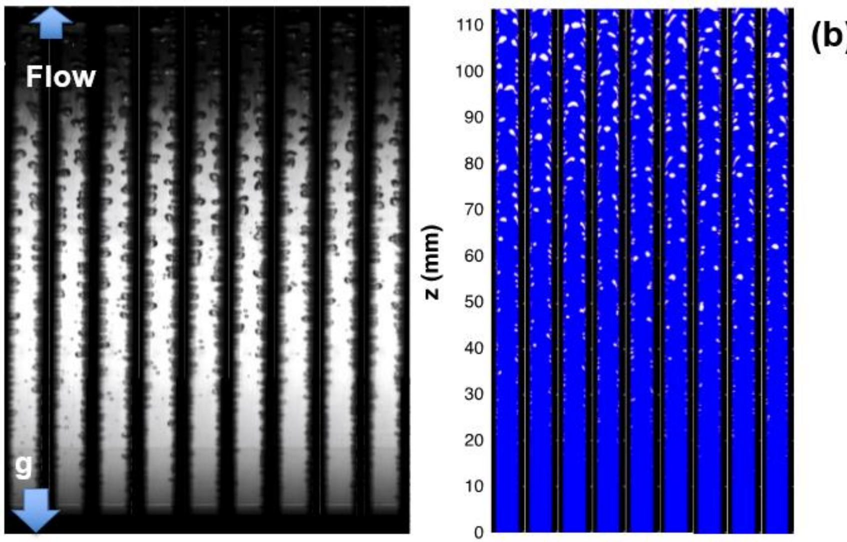


Critical Heat Flux (CHF) data and model predictions for 0-g and 1-g as a function of velocity.

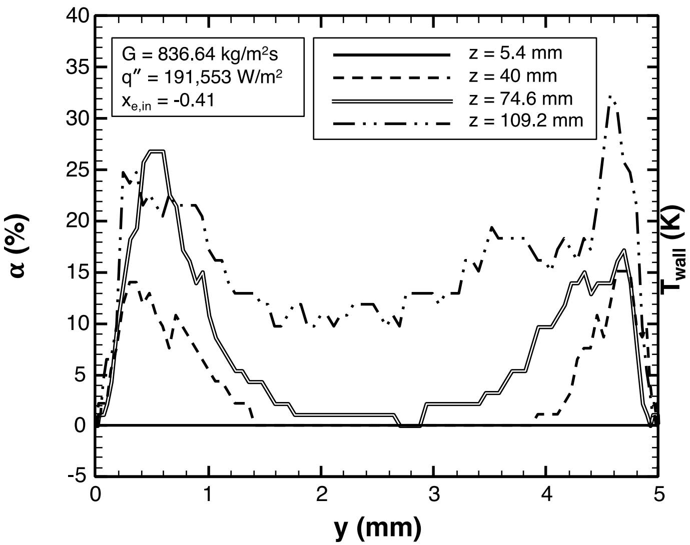
Future Experiments

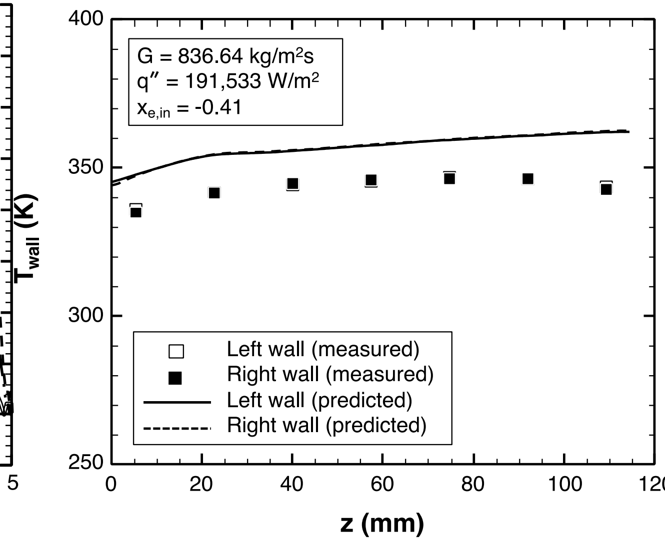
Flow Boiling and Condensation Experiment (FBCE) – continued

- Developed new 2D computational model of interfacial behavior and heat transfer performance of FBM.
- Experimental results, including wall temperatures, heat transfer coefficients, and flow visualization images, are used to verify the computational scheme.



Profiles of transverse void fraction, all for *G* = 834.64 kg/m^{2}s and $x_{e,in}$ = -0.41.





Experimentally and computationally obtained (a) wall temperatures and (b) sequential flow visualization images and void fraction contours of entire heated portion of channel, both for *G* = 836.64 kg/m^{2}s, $x_{e,in}$=-0.41

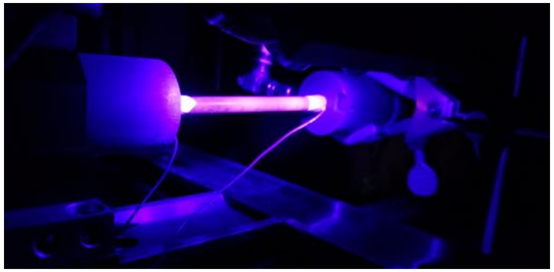
Future Experiments

PI: Prof. Jungho Kim, University of Maryland
ESA Science Team PI: Catherine Colin, Institut de Mécanique des Fluides de Toulouse

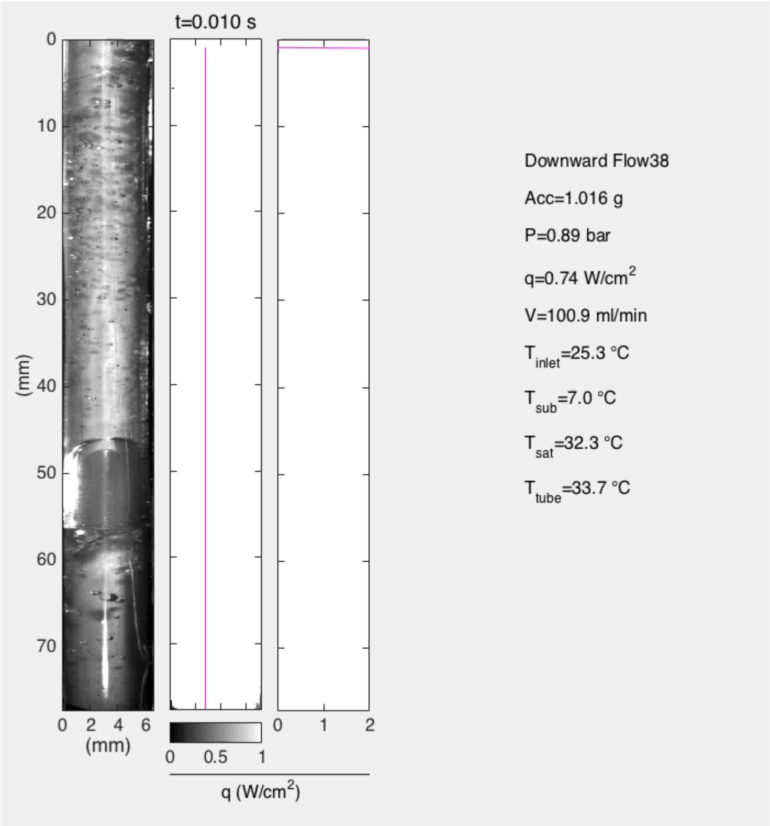
Multiphase Flow and Heat Transfer Experiment (MFHT) – 2021

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 high resolution local measurements of the wall heat transfer coefficient utilizing temperature sensitive paints.
- Fluid Science Laboratory (FSL) Thermal Platform.



MFHT Flow Loop Assembly – Test Section



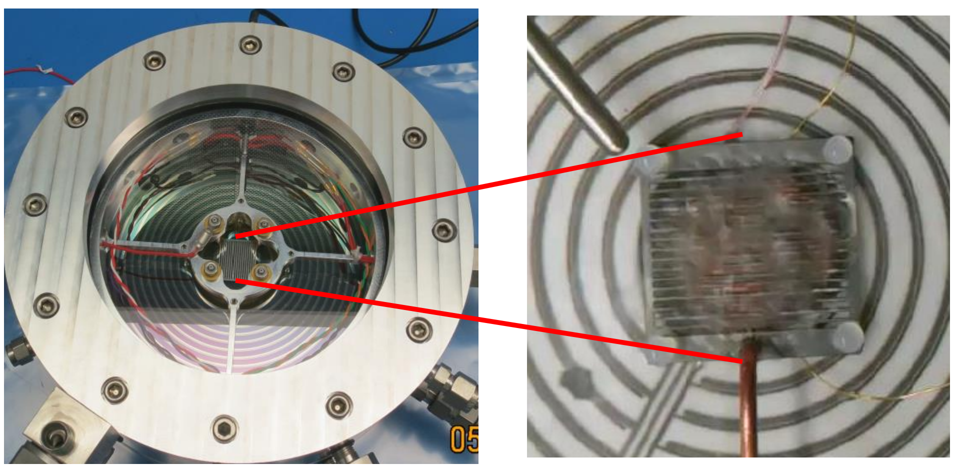
The heat flux in movie was only 0.74 W/cm2 resulting in some noise in the data since the temperature variations are much smaller.

Future Experiments

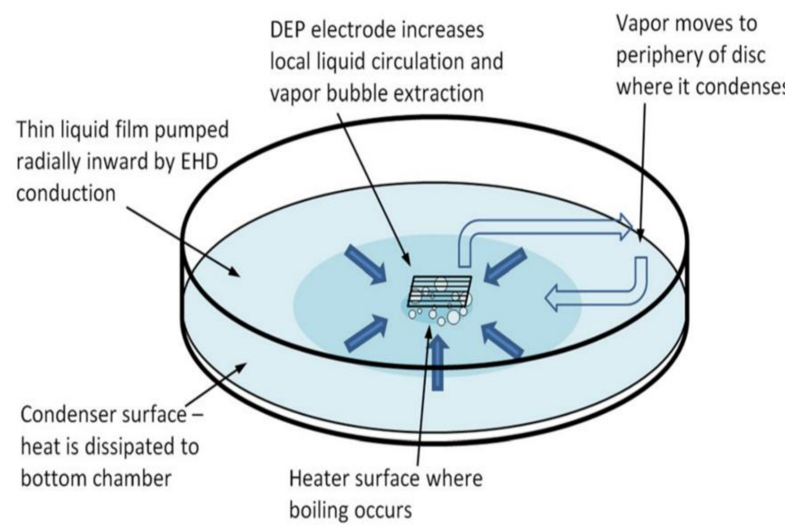
Electro-Hydrodynamic (EHD) Experiment – 2021

Characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change specifically pertaining to:

- The effects of microgravity on the EHD generated two-phase flow.
- The effects of microgravity on the EHD driven liquid film flow boiling and di-electro-phoretically extracting bubbles from heating surface
- Phenomenological foundation for the development of EHD based two phase thermal management systems.
- Development of intelligent two-phase heat transport device with no moving parts, light weight, and easy to control..
- Potential applications range from micro-g to high-g and from micro-scale to macro-scale.



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



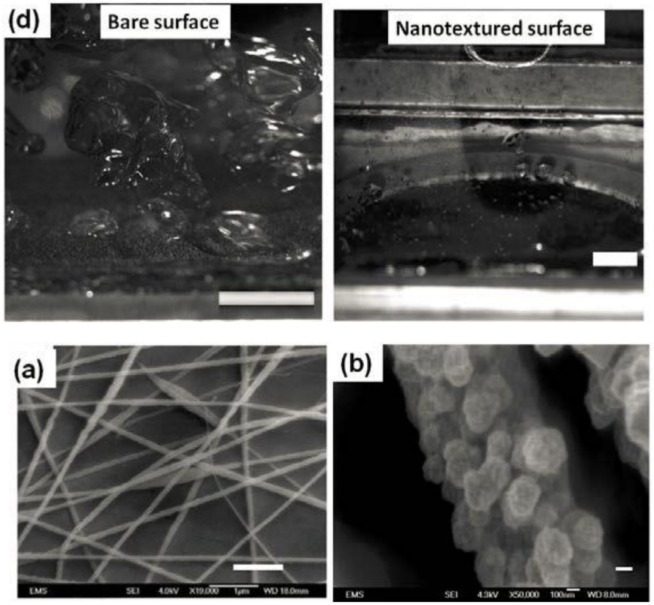
EHD Test Chamber with heater and DEP electrode with fluid movement

Future Experiments

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

Dynamics of Liquid Film/ Complex Wall Interaction (DOLFIN II) - 2019

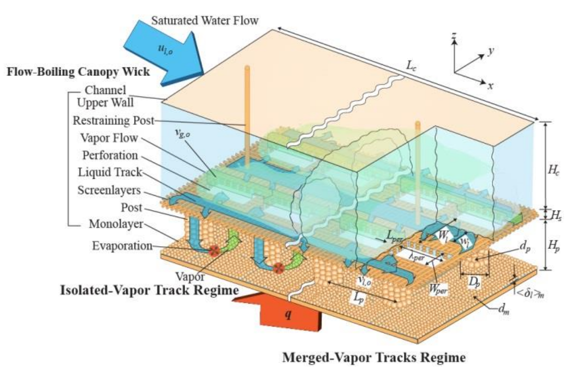
- ESA led experiment to develop continuum models to describe interactions between spreading fluids and chemically and/or morphologically complex surfaces in 0-g.
- Ability to manipulate surface flows in microgravity is a key to thermal management solutions in space exploration.
- US PI (Yarin) will perform experiments on spray cooling over specially patterned surfaces.
- Recently developed numerical model to detail physical mechanisms of pool-boiling.
- Boiling curves measured on nano-textured surfaces revealed heat fluxes 2-7 times higher than those on the bare surfaces, also increasing the CHF.
- Polymer nanofiber mats significantly increase heat transfer in pool boiling in channel flows (this part was conducted together with the group of the Technical University of Darmstadt, Germany).



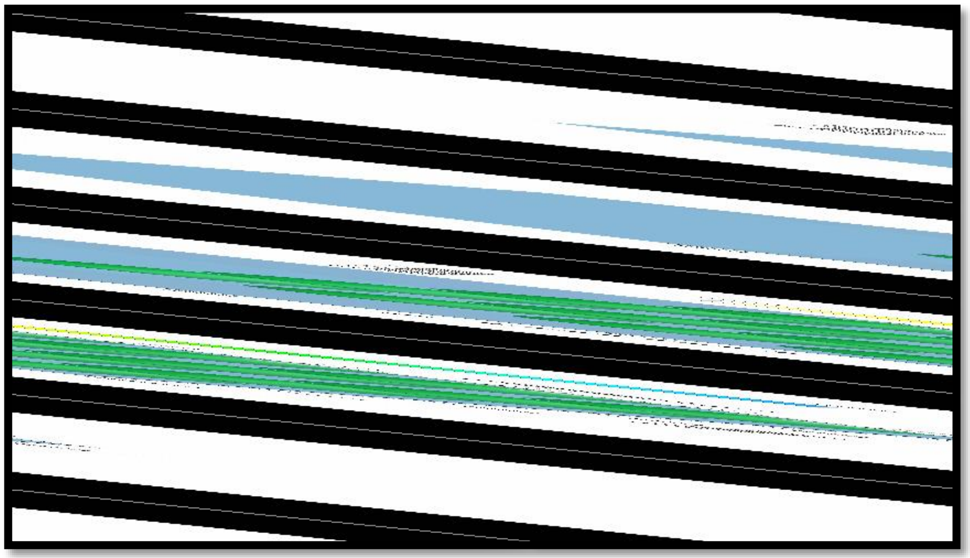
Nanofibers (a) are plated with copper (b) to form a mat that greatly alters nucleation patterns leading to much higher heat flux (d)

Conclusion

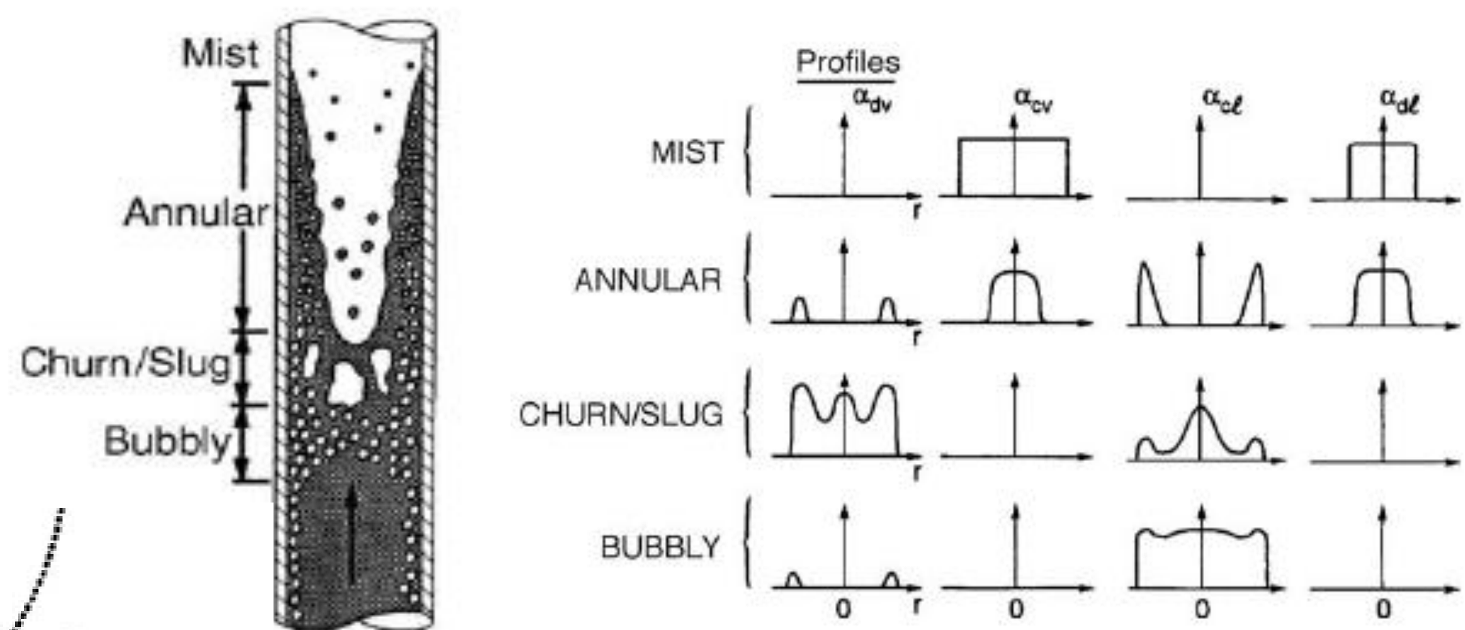
- Coordinated work continues to advance our fundamental understanding of two-phase heat transfer in low gravity.
- Key goals:
    - Understand the conditions required for gravity independent systems.
    - Develop methods to enhance Critical Heat Flux.
    - Understand how to prevent boiling (cryogen storage).
    - Develop a quality database to establish a basis (closure laws) for CFD models as well as provide model validation.
    - Most importantly, this must lead to models and design guidelines that become the foundation for technology development.
- Data from completed experiments is upload to a NASA's Physical Science Informatics System (PSI) - typically 1-2 years after flight: https://psi.nasa.gov/index.html

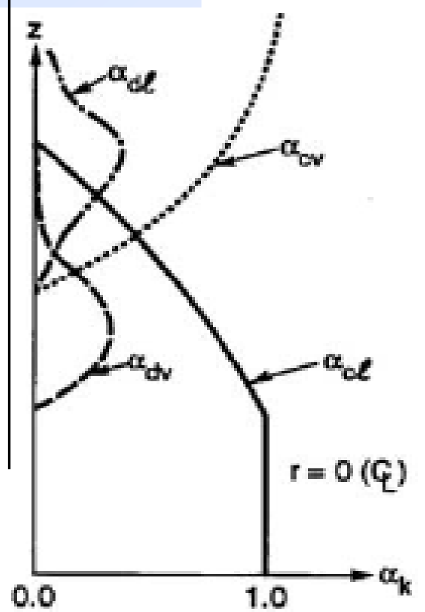


Canopy wick liquid-vapor control for enhanced microgravity flow boiling



Backup

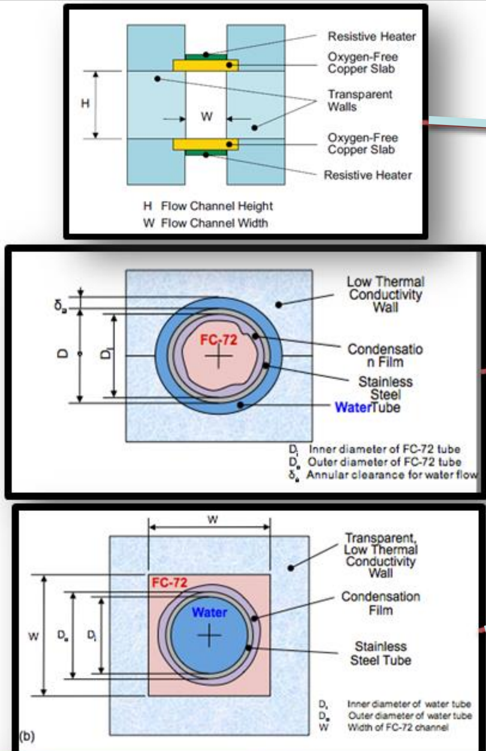




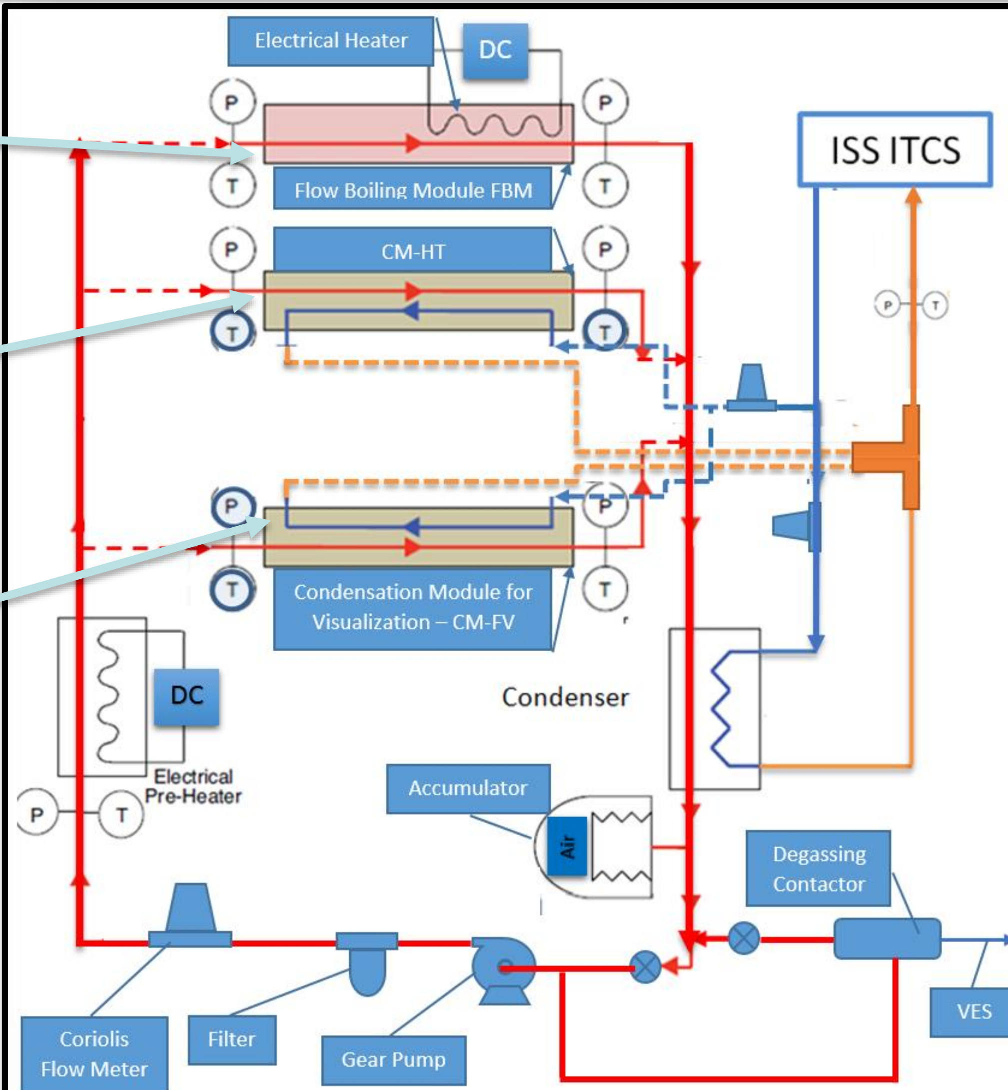
Typical results of a 2-fluid, 4-field CMFD model [Lahey, 2005]

Flow Boiling and Condensation Experiment

Flow Boiling and Condensation Fluid Systems

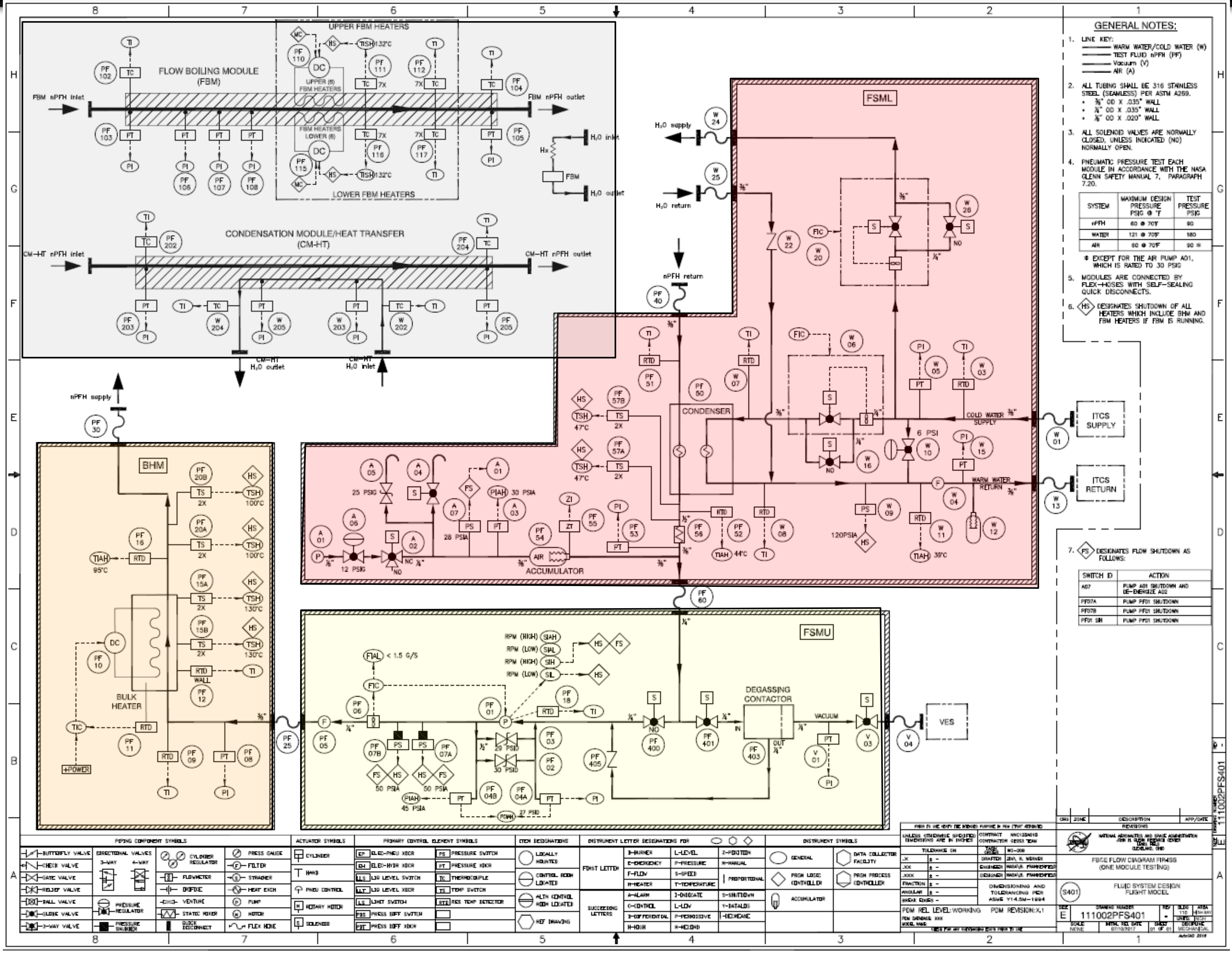


	Flow Meter		Heater
	Relief Valve		Three Way Valve
	Gear Pump		Accumulator
	Pressure and Temperature Measurements		Hot Water
	Flow Control Valve		Cold Water
	On-Off Valve		Test Fluid
	Condenser		Cold Water Return to ISS or Lytron



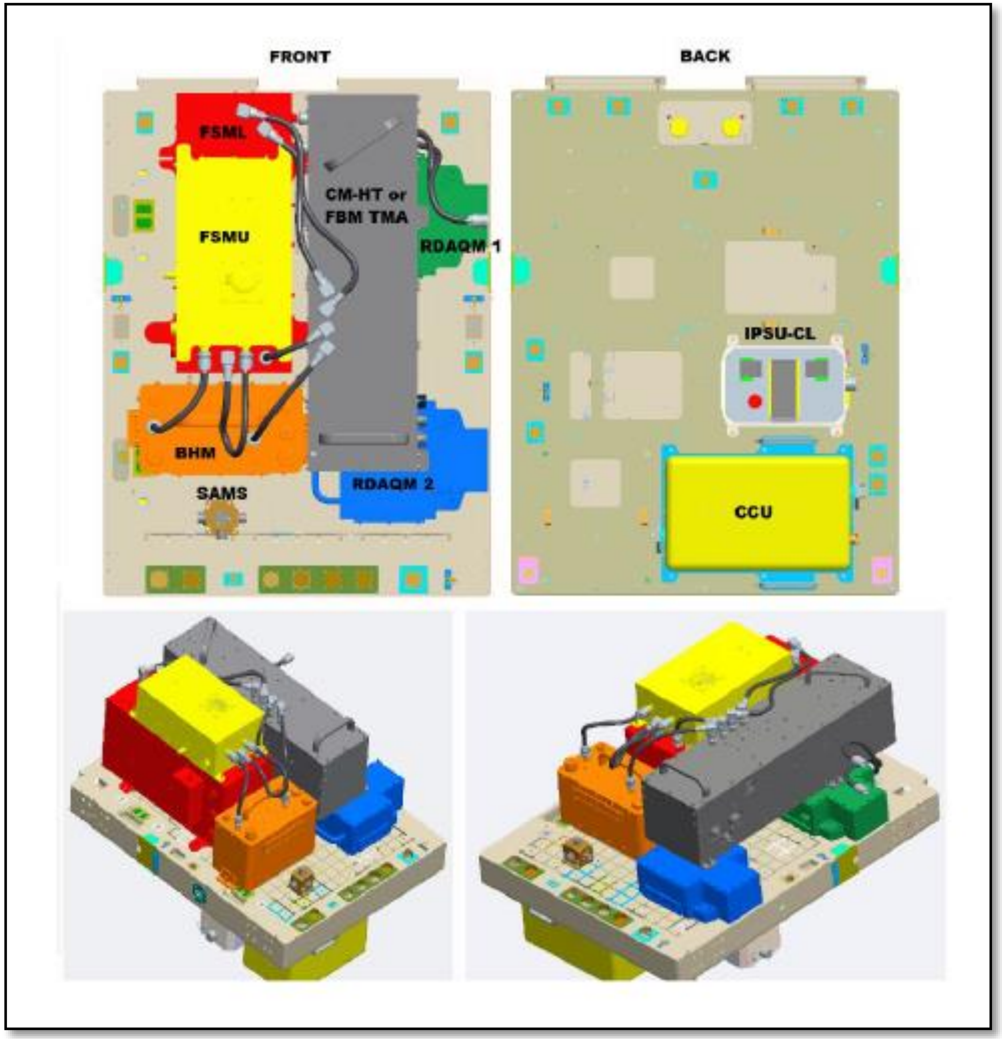
Flow Boiling and Condensation Experiment

FBCE Fluid System Schematic



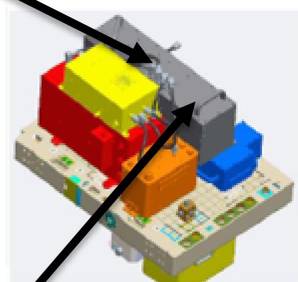
Flow Boiling and Condensation Experiment

FBCE Hardware



FBCE Hardware-Test Modules

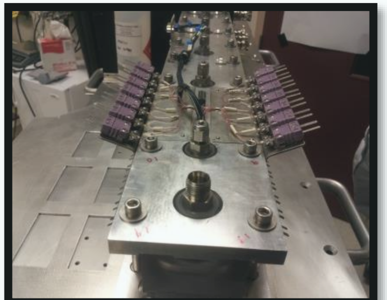
Flow Boiling Module for flow boiling heat transfer and critical heat flux measurements



Condensation Module for heat transfer measurements

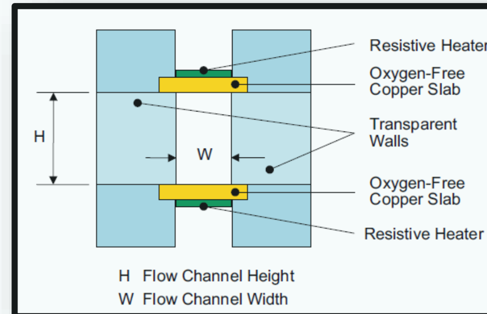
Flow Boiling and Condensation Experiment

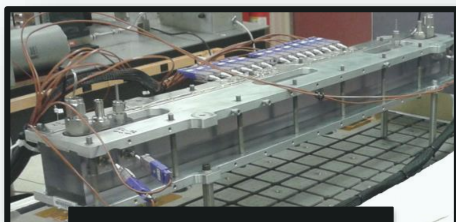
Flow Boiling and Condensation Test Modules



Flow Boiling Module Assembled

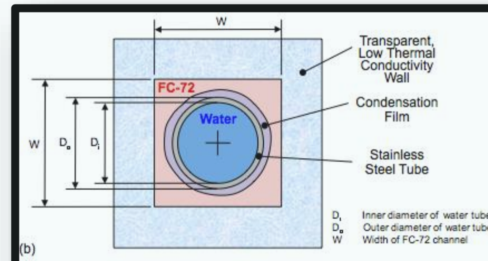
- **Flow Boiling Module**
  - Subcooled, saturated and 2-phase Inlet condition at:
    - Mass Flow Rate 2.5 to 40 g/s
    - Heat Flux < 60 W/cm^2





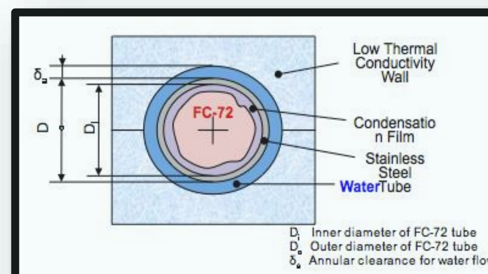
CM-FV Test Module

- **Condensation Module –Flow Visualization**
  - Saturated vapor Inlet condition
    - Mass Flow Rate 2 to 14 g/s



CM-HT Test Module

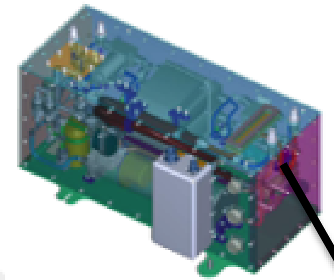
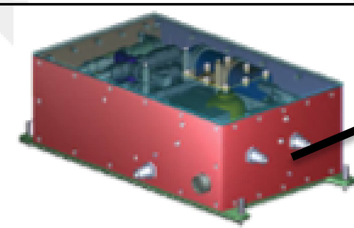
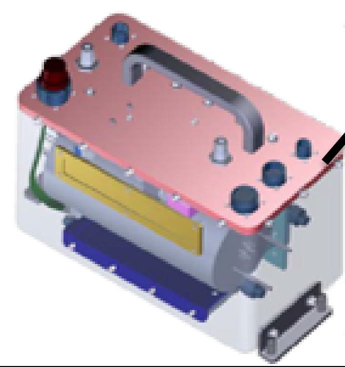
- **Condensation Module –Heat Transfer**
  - Saturated vapor Inlet condition
    - Mass Flow Rate 2 to 14 g/s

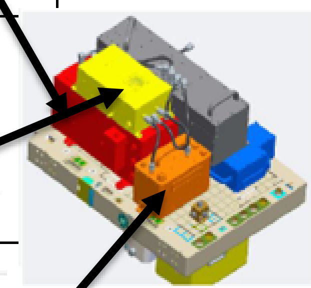


•Science Requirements Document for FBCE, March, 2013
•Science Concept Review Presentation, December 2011

Flow Boiling and Condensation Experiment

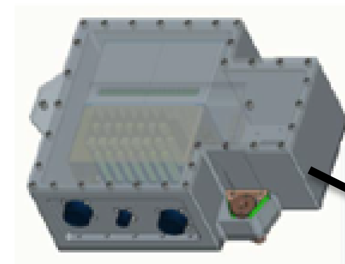
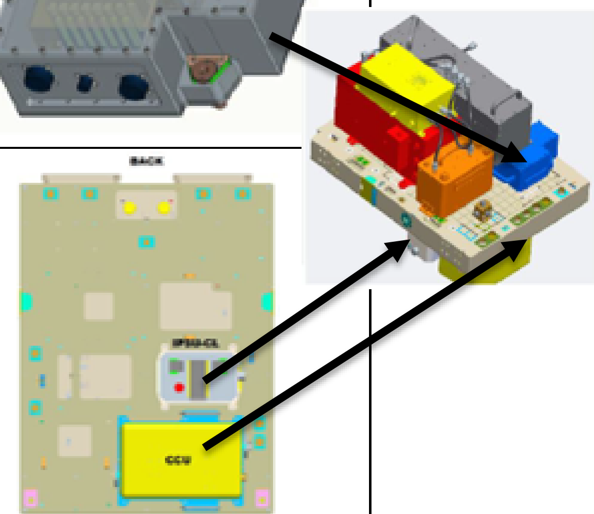
FBCE Hardware-Fluid System Modules

Fluid System Module	Description	
FSM-L	Fluid System Module-Lower sets the system pressure, provides the cooling for the test fluid	
FSM-U	Fluid System Module-Upper provides the pumping of the test fluid throughout the nPFH loop	
BHM	Bulk Heater Module provides heating of the test fluid to reach thermodynamic conditions required by the SRD	



Flow Boiling and Condensation Experiment

FBCE Two-Phase Flow Avionics

Avionics Modules	Description	
RDAQM 1 and 2	Remote Data Acquisition Module1 acquires the thermocouple data from test modules whereas RDAQM 2 acquires data from the fluid system	
CCU and IPSU-CL	Provided by ZIN Technologies. The CCU is the computer and the IPSU-CL is the data and video storage media.	

Flow Boiling and Condensation Experiment

Top Level Science Requirements and Constraints

- Fluid System Capability
  - Delivers flow rates between 2 and 14 g/s of nPFH for Condensation Experiments and 2 to 40 g/s for Flow Boiling Experiments
  - Delivers up to 1440 W to the fluid from the bulk heater and 340 W from the FBM heater
  - Delivers a system pressure of 130 to 160 kPa
  - Volume increase is accommodated with an accumulator
  - Delivers the required thermodynamic conditions of the fluid at the entrance of the test modules (subcooled, saturated and two-phase mixture)
  - Provides the fluid cooling function via ISS ITCS cooling water
  - Provides degassing function for the test fluid
- Constraints
  - Limitation on the available power
  - ITCS cooling water flow rate up ~50 g/s to and returning stream temperature requirement of 40-49 ^{o}C
  - Volume constraint 91.44x121.92x48.28 cm^3 (36x48x19 in^3)