

Proposed Space Flight Experiment Hardware

The primary thrust for this plan is to develop design tools and fundamental understanding that are timely and consistent with the goal of the various exploration initiatives. The plan will utilize ISS facilities, such as the Fluids Integrated Rack (FIR) and the Microgravity Science Glovebox (MSG). A preliminary flow schematic of Two-Phase Flow Facility (T ϕ FFy) which would utilize FIR is shown in Figure 3. MSG can be utilized to use the Boiling eXperiment Facility (BXF) and Contact Line Dynamics Experiment (CLiDE) Facility (see Figure 4).

The T ϕ FFy system would have multiple test sections whereby different configurations of heat exchangers could be used to study boiling and condensation phenomena. The test

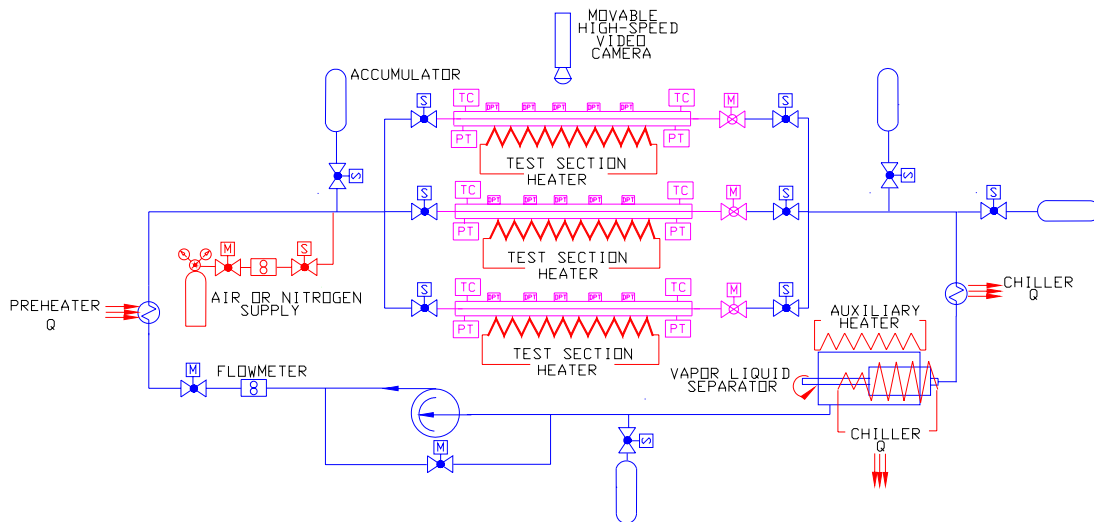


Figure 3: Proposed Flow Schematic for ISS Two-Phase Flow Experiment

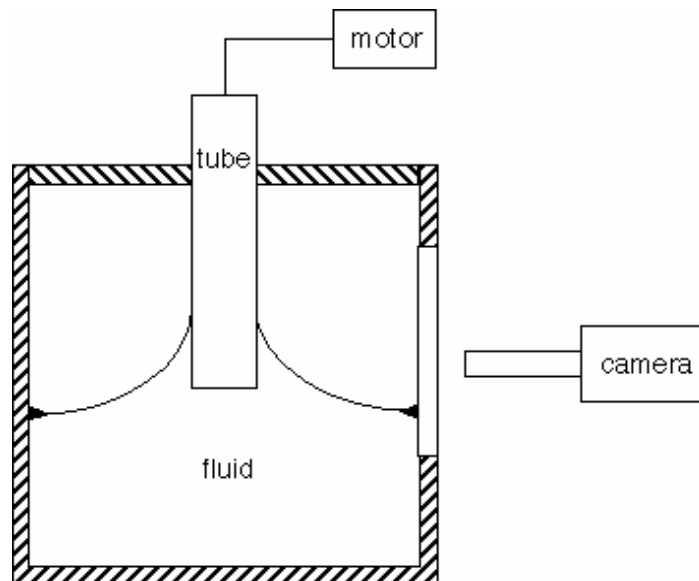


Figure 4: Schematic of Contact Line Dynamics Experiment (CLiDE) Facility

sections would be instrumented for pressure drop, void fraction, heat fluxes, temperatures, high-speed imaging and other diagnostics. Besides a high-speed data acquisition system with a large data storage capability, telemetry could be used to update control and test parameters and download limited amounts of data. In addition, there would be multiple accumulators that could be used to investigate system stability and fluid management issues. The system could accommodate adiabatic tests through either the space station nitrogen supply or have an experiment-specific compressor to pressurize a sufficient amount of air or other non-condensable gas for reuse as the supply bottle is depleted.

The general purpose CLiDE facility would allow for studies of effects of contact line dynamics on real systems of strategic importance. It would consist of a square cell with viewing windows. An axisymmetric fluid interface will form between a central cylinder (with a surface finish appropriate to the application) and a circular pin lip fitted to the walls. The cylinder may move into or out of the fluid to provide limited controlled dynamics. Temperature control of both the fluid and central tube will permit examination of evaporative and condensation effects on moving contact lines. A video camera (with microscope if needed) will capture the interface dynamics. Possible candidate systems include (but are not limited to) unsteady contact lines with significant inertia.(see Figure 4). This hardware requires minimal controls besides indexing the cylinder to the appropriate position in the fluid and filling the cell with the test liquid.

The following limitations would be imposed upon any space station experiment:

- ISS power availability is ~ 3kW, 2kW for rack system support and 1kW for pumping, separating and heating fluid.
- ISS heat rejection availability is about 3 kW for the rack, is single phase, with an inlet coolant temperature of about 20 deg C
- ISS volume constraints are about 1 x 1 x 0.5 m.
- Acceleration and vibration levels range from the micro (10^{-6}) to milligravity(10^{-3}) range.
- Fluid needs to be non-toxic
- Fluid needs to be triple-contained. Flow loop would count as only the first level of containment.
- ISS manifesting opportunities.

At least two flow loops would be constructed. One flow loop would be for testing aboard ISS. The second flow loop would be “similar” to the ISS experiment loop in terms of test sections and components but would have special modifications that would enable normal gravity and ground-based low-g testing, perhaps with either components, or the entire loop, at a variety of different orientations relative to gravity. This feature would allow for the development of normal gravity testing techniques that would build limited confidence in determining how the system and components might behave in reduced gravity.

Similarly, a ground-based CLiDE Facility of appropriate dimensions should be available for drop tower tests of limited scope.

Because of the limitations listed above, namely the volume and power constraints and the manifesting opportunities, the ground-based facilities can also provide answers to some of the previously-identified issues. These facilities can also provide a short-term intermediate low gravity environment (from 0.01 to 1.0 g's).

Since these exploration missions will be to planetary bodies other than earth, or normal, gravity, it will be necessary to conduct tests in long-duration partial gravity facilities. Other than the 2.5 m research centrifuge planned primarily for life science research aboard the ISS, there are no current plans for such a facility.

While modeling and scaled-down experiments can provide sufficient insight into the performance of space power and propulsion systems, it is necessary to conduct larger-scale and full-scale tests with the actual working fluids in order to boost the confidence in the predictive tools that have been developed. For example, a full-scale experiment on fluid management principles in reduced gravity using liquid cryogenes needs to be conducted in tanks of at 1 m³ of volume. Because of safety considerations, some of these experiments will require an expendable launch vehicle.

ROADMAP

Timeframe 2003-2008

Space Flight

- Design and build multi-user two-phase test facility for ISS to conduct experiments on:
 - Phase Change
 - Boiling-related research would focus on measuring the two phase heat transfer coefficients, and Critical Heat Flux (CHF), not only in the steady state flow and heating conditions, but also during transients. As part of the CHF research, study quenching/rewetting of dried out surfaces. Spray-cooling research for high heat flux applications should also be conducted.
 - Condensation-related research should be on the drainage of the liquid condensate, especially in low vapor-shear applications.
 - Two-phase instability phenomena
 - Experiments on parallel flow channels would focus on flow through multiple evaporating channels. The primary objective of these tests would be to study two-phase flow through some splitting manifold into the parallel channels. The “preheater” in Figure 2 would be expected to have sufficient capability to generate boiling, into at least the slug flow regime. The parallel channels could focus on different aspects of boiling.
 - Density wave oscillations (DWO) experiments would utilize control valves placed within the flow loop in order to induce and

respond to the passage of vapor and liquid slugs through the system.

- Phase accumulation experiments with regards to the behavior of accumulator with regards to its orientation to tees and other components.
- Long duration experiments on two-phase flow through components and porous media.
- Phase distribution, separation and control to assess the effectiveness vs. the design and operating parameters for both active and passive separation techniques. One type of experiments would include an assessment of the effect of slugging phenomena on at least one active separation device
- Begin scoping experiments aimed at determining suitability of surface modifications for optimizing damping in interface oscillations.
- Design and build multi-user facility to conduct experiments on contact line dynamics.
- Conduct the Microheater Array Boiling Experiment (MABE) and the Nucleate Pool Boiling Experiment (NPBX) in the Boiling eXperiment Facility (BXF)
- Conduct flight experiments to investigate pressure control in vented or unvented storage tanks..

Ground based

- Conduct ground-based low-g testing of a variety of components. These should include splitting and mixing tees and manifolds to determine their effects on phase distribution and in support of space-flight experiment on parallel channels.
- For phase change related phenomena:
 - Conduct appropriate ground based testing for rewetting/quenching of hot surfaces
 - Investigate the effects of wetting characteristics of a condensing surface on its heat transfer performance and determine how control of wetting properties can lead to enhanced heat transfer
 - Investigate the effectiveness of techniques to enhance heat transfer performance (heat transfer coefficient and CHF) using acoustic, electric field, surfactants and surface enhancement for 1-g and low-g
- For passive two-phase flow separation techniques:
 - Drainage of condensate with refrigerators from their "cold plates. "
 - Drainage of waste water, including urine from rat cages
 - Continue current investigation of bubble removal schemes for the tissue-growth bioreactor and other bubble/drop positioning techniques.
- Conduct ground-based 1-g and low-g hydro-dynamic and mass transfer experiments to provide flow characteristics of two-phase liquid-gas flow in Packed Bed Reactors over an extended range of conditions.

Other

- Modeling and scaling in the development of a two phase design and operator's manual

- Develop 3-D CFD predictive capabilities and verify the accuracy against existing reduced gravity data.
- Extend the 3-D CFD model to other flow regimes of interest in low gravity based on appropriate direct numerical simulations. Results will be used for the development of suitable closure laws for the CFD model.
- Develop predictive and mechanistic models for nucleate pool and flow boiling in low-g for the realistic parameter space of proposed space power systems (e.g., Rankine Cycle).
 - Including contributions of nucleation, bubble growth, bubble departure and rewetting in low-g
 - Use data from “designed” heater experiments on ISS using the Boiling eXperiment Facility (BXF) in MSG to validate the mechanistic models for boiling and heat transfer at the single bubble level
 - Evaluate the effectiveness of selected strategies (additives) in enhancing boiling and capillary performance to attain significant enhancement in heat transfer performance
- Evaluate current two-phase system designs for known and appropriate normal gravity instability mechanisms
- Extend predictive modeling capability for dynamic contact angle.
- Extend predictive models for tracking phase fronts and phase distributions and for interface and phase management through application of external fields.
- Develop rational correlations or models of contact line motion at higher Suratman, Reynolds and Capillary numbers with steady or unsteady motion (e.g., interface reorientation in large tanks)
- Implement proper dynamic contact line boundary conditions in conventional CFD formulations, and validate with experiments.
- Normal gravity testing
 - Design a suitably scaled test loop and characterize it during parametric experiments on earth in conjunction with ISS test loop.
 - Use the test loop to verify two-phase elements of the Rankine cycle with scalability to liquid metal conditions.
- Design and build a suitably scaled cell to study systematically interface reorientation upon a sudden g-change, in drop tower. Begin the experimental program..
- Develop passive capillary controlled low-mass tank configuration to control liquid-vapor interface position and maintain continuous liquid supply at the outlet (without gas ingestion) in low-g environments.
- Conduct ground-based experiments to determine wetting characteristics of solid-liquid combinations and strategies (additives) to modify/control the wetting and spreading
- Develop techniques for mass gauging (inventory management) for low-g

Timeframe 2009-2015

Space Flight

- Conduct experiments and test predictive tools on multi-user two-phase test facility on ISS for:
 - Parallel channel instability tests with parallel test sections that would be designed for a wide range of differences in flow rates.
 - Phase change experiments for various heater surfaces and configurations
 - CHF
 - Quenching
 - Spray cooling
 - Phase change experiments on condensation to determine condensation heat transfer coefficient in microgravity
 - Liquid-gas flows through porous media.
- Conduct research on liquid handling techniques and pressure control within accumulators and tanks to validate predictive models of contact line motion for higher Reynolds (Re) and Capillary (Ca) Numbers coupled with unsteady motion (sloshing in tanks), See next item.
- Acquire data for microscale motion near a contact line in low gravity to validate predictive models for parametric regimes of practical importance.
- Conduct a full scale experiment to test fluid management principles using liquid cryogenics in tanks of at 1 m³ of volume. This experiment will utilize an expendable launch vehicle.
- Define flight experiments for advanced phase separators concepts

Ground based

- Conduct advanced phase separator tests for a wide variety of concepts, including passive methods.
- Conduct scaled experiments using “exotic” materials and fluids such as those required for cryogenic and nuclear power applications.
- Electrical and electroacoustic manipulation of interfaces and fluids
- Conduct further low-g experiments to expand the applicable range and refine predictive models for boiling heat transfer and CHF validated over expected operating range to support the design of
 - Rankine cycle based power system for Nuclear Electric Propulsion.
 - Two-phase advanced thermal management technologies.
- Use bubble level analyses to develop a comprehensive analytical foundation for
 - positioning bubbles in normal and low-g and conduct microgravity experiments to validate the model
 - designing two phase separators and conduct microgravity tests to validate the model
- Conduct experiments for pool and flow boiling and CHF from surfaces of specified characteristics for low-g and normal-g to examine the effect of boiling enhancement techniques.

- Conduct experiments and extend predictive model capabilities to determine the effect of free surface turbulence and presence of noncondensable gases on phase change (evaporation and condensation).

Other

- Modeling and scaling in the development of a two phase design and operator's manual
 - Perform pretest predictions using the 3-D CFD code for experiments to be performed on the ISS.
 - Extend predictive models for pool and flow boiling and CHF from surfaces of specified characteristics for low-g and normal-g
 - Develop predictive models for contact line behavior in the presence of evaporation and condensation
 - Modify the 3-D CFD code, as required, to produce a combined comprehensive modeling effort for multiphase heat transfer and flow leading to user design code.
 - Perform a detailed verification and validation of the user design code.
 - Complete development of generalized models for design of propellant and liquid storage tanks for low-g operation
- Provide results from ISS experiments on liquid-gas flows in packed beds to closed loop ECLSS and ISRU designers
- Perform trade study of requirements vs. hardware design and performance for phase separation.
- Complete development of accurate fluid quantity gauging and liquid inventory management techniques/sensors for low-g operation

Timeframe 2016+

Space Flight

- Conduct large scale system technology demonstrations at relevant pressures, temperatures, and complex geometries to verify robustness of predictive techniques, tools, and scaling.

Ground based

- Conduct experiments for advanced phase separator operations concepts in a wide range of gravity levels including “microgravity,” lunar, Martian, normal and transitional that would be associated either the start of thrusting operations or the end of thrusting operations.

Other

- Thoroughly verify comprehensive computational techniques and incorporate them into either existing or new software packages.
- Use the new predictive framework for pool and flow boiling heat transfer coefficient and CHF and condensation heat transfer to design more efficient heat transfer equipment for terrestrial and space applications

- Provide rational design rules for systems control by wetting
- Provide validated dynamic contact line boundary conditions for higher Re and Ca , steady and unsteady flows, for use in computational modeling of realistic industrial and space-based processes
- Assemble results into two-phase design and operations manuals for space exploration and look into potential for software package development, either as a standalone package or as tools for existing packages.

PROGRAMMATIC RECOMMENDATIONS

Several participants were very concerned about the selection process for strategic research. While the scientific peer-review process has worked well in advancing the fundamental understanding of interfacial phenomena and multiphase flow, these participants felt that the focus of strategic research should be on development and specific technology needs rather than more general phenomenological topics. The research selection processes instituted by the Office of Naval Research Lab was mentioned as an example of outcome or technology-driven proposal selection.