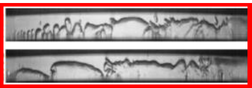

PERFORMANCE EVALUATION OF THE INTERNATIONAL SPACE STATION FLOW BOILING AND CONDENSATION EXPERIMENT (FBCE) TEST FACILITY

ASGSR 2016
Cleveland OH

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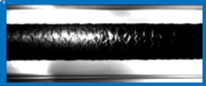
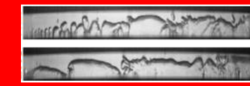


Flow Boiling and Condensation Experiment



FBCE Science Objectives

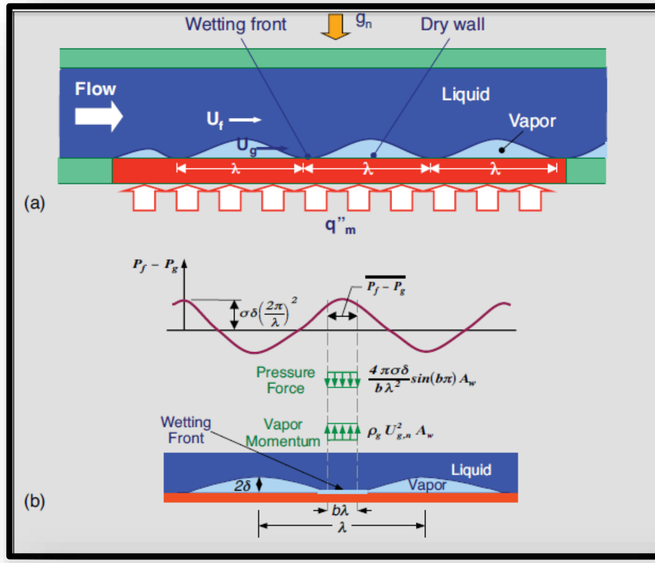
The proposed research aims to develop an **integrated two-phase flow boiling/condensation facility for the International Space Station (ISS)** to serve as primary platform for obtaining two-phase flow and heat transfer data in microgravity.

Key objectives are:

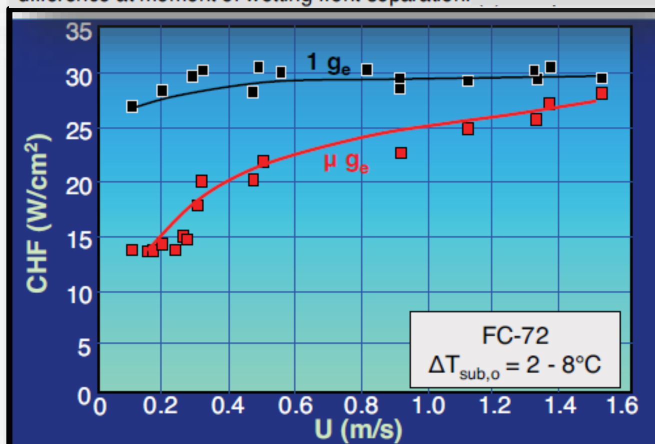
1) Obtain **flow boiling database** in long-duration microgravity environment
2) Obtain **flow condensation database** in long-duration microgravity environment
3) Develop experimentally validated, **mechanistic model** for microgravity flow boiling **Critical Heat Flux (CHF)** and **dimensionless criteria** to predict **minimum flow velocity** required to ensure **gravity-independent CHF**
4) 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

Applications include:

1) Rankine Cycle Power Conversion System for Space
2) Two Phase Flow Thermal Control Systems and Advanced Life Support Systems
3) Gravity Insensitive Vapor Compression Heat Pump for Future Space Vehicles and Planetary Bases
4) Cryogenic Liquid Storage and Transfer

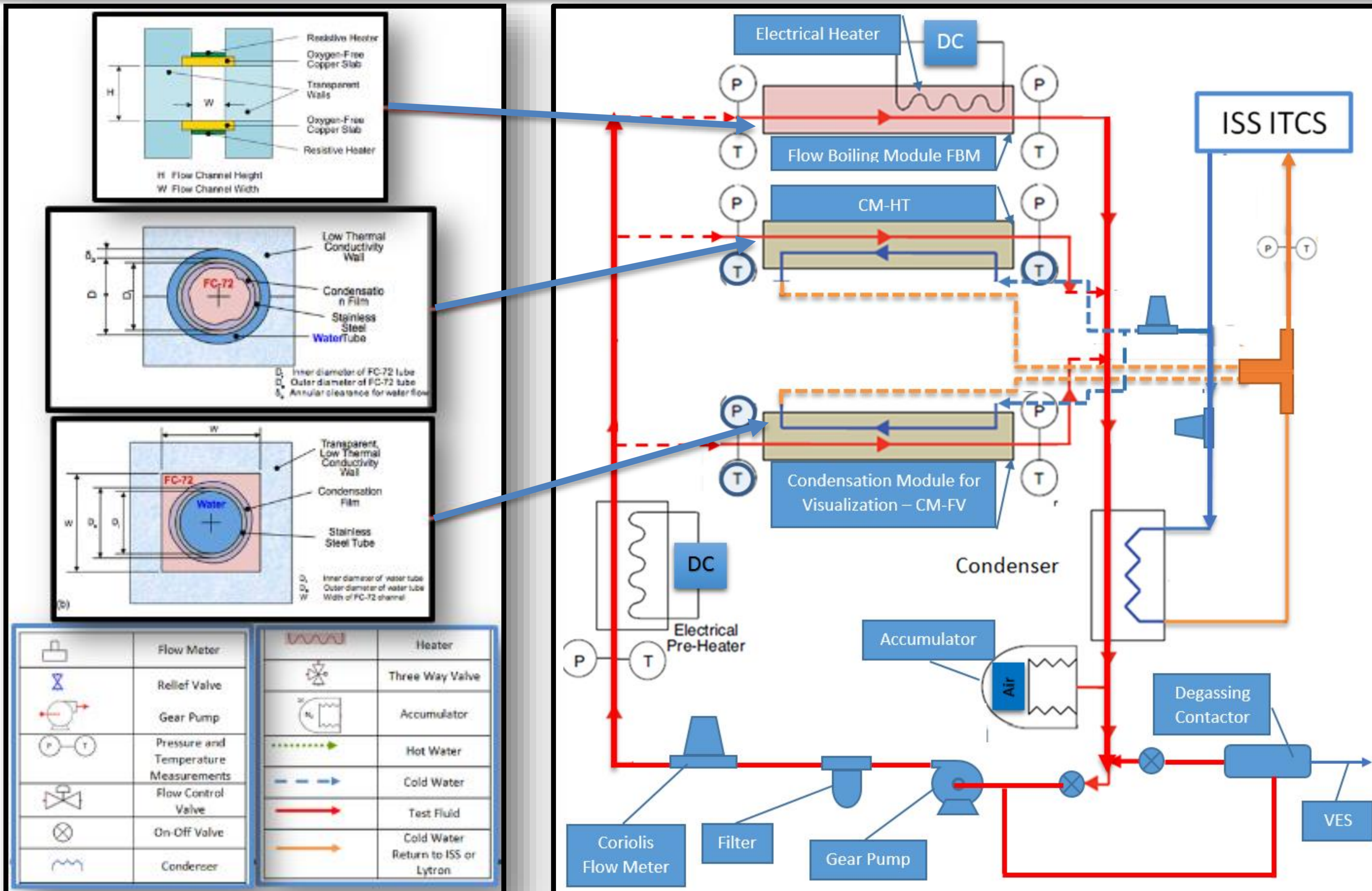


Interfacial Lift-off Model: (a) schematic representation of wavy vapor layer. (b) Balance of vapor momentum and interfacial pressure difference at moment of wetting front separation.



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

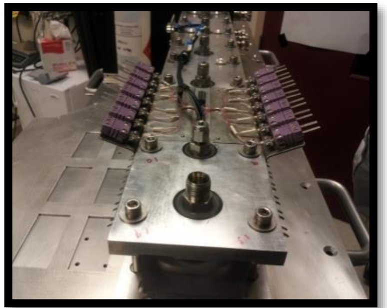
Flow Boiling and Condensation Fluid Systems



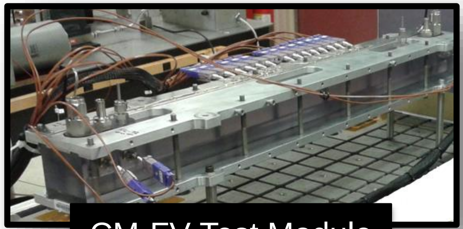
Top Level Science Requirements and Constraints

- Requirements-Fluid System
  - Deliver flow rates between 2 and 14 g/s of nPFH for Condensation Experiments and 2 to 40 g/s for Flow Boiling Experiments
  - Deliver the required power up to 1550 W to the fluid
  - Deliver the required system pressure between 110 and 170 kPa
  - Volume increase is accommodated with an accumulator
  - Accumulator is used to set the system's pressure
  - Deliver the required thermodynamic conditions of the fluid at the entrance of the test modules (subcooled, saturated and two-phase mixture)
  - Provide the fluid cooling function
- Constraints
  - Limitation on the available power (1550 W total available for heating)
  - ITCS cooling water flow rate up ~50 g/s to and returning stream temperature requirement of 40-49 °C
  - Volume constraint 91.44x121.92x48.28 cm^3 (36x48x19 in^3)
  - Mass constraint (~200 kg max)

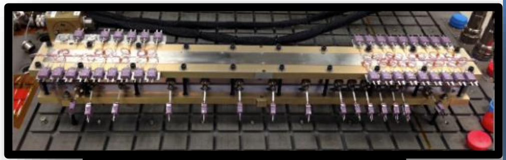
Flow Boiling and Condensation Test Modules



Flow Boiling Module Assembled

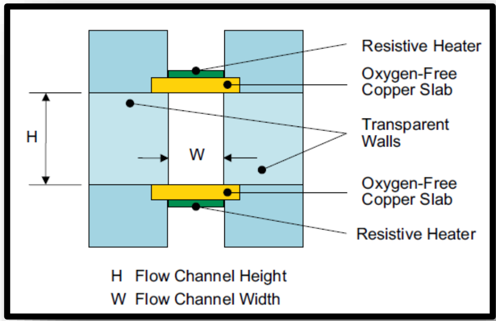


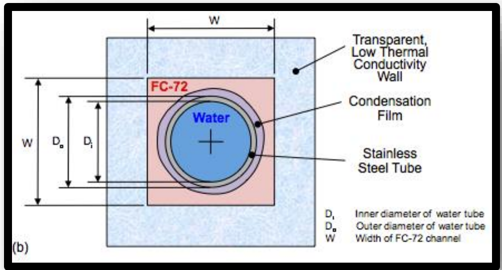
CM-FV Test Module

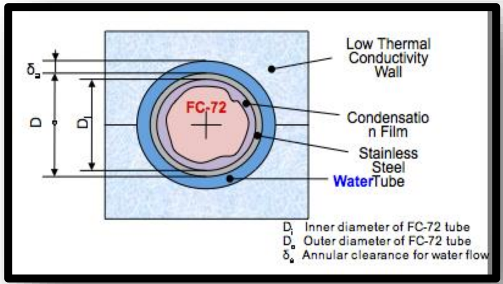


CM-HT Test Module

- ❑ Flow Boiling Module
  - o Subcooled, saturated and 2-phase Inlet condition at:
    - • Mass Flow Rate 2.5 to 40 g/s
    - • Heat Flux < 60 W/cm^2
- ❑ Condensation Module –Flow Visualization
  - o Saturated vapor and two-phase Inlet condition
    - • Mass Flow Rate 2 to 14 g/s
- ❑ Condensation Module –Heat Transfer
  - o Saturated vapor and two-phase Inlet condition
    - • Mass Flow Rate 2 to 14 g/s





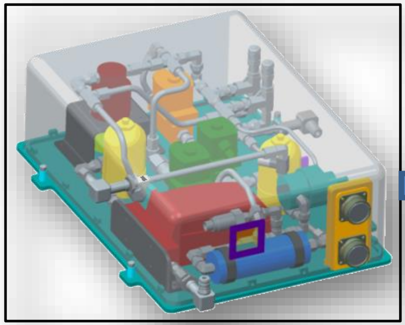


•Science Requirements Document for FBCE, March, 2013
•Science Concept Review Presentation, December 2011

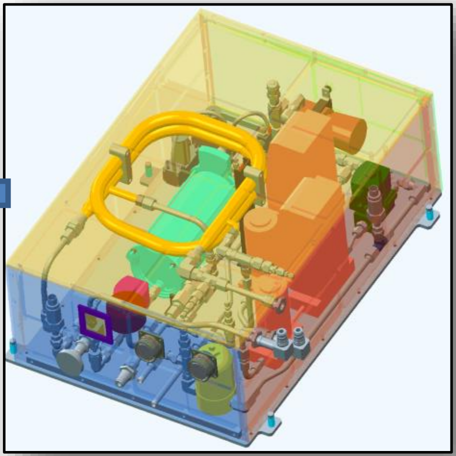
FBCE Fluid System (FS) Modules

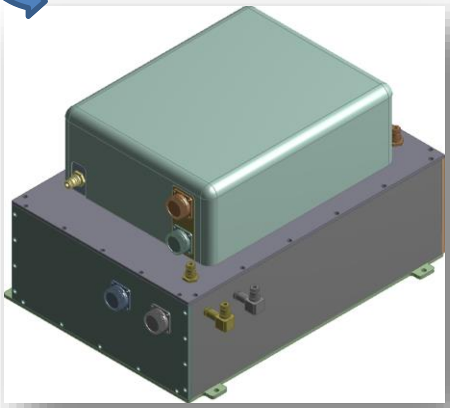
- ❑ Fluid System Module
  - o Consists of:
    - Pump
    - Filter
    - Coriolis flow meter
    - Degassing membrane contactor
    - Condenser
    - Accumulator
- ❑ Bulk Heater Module
  - o Consists of:
    - Bulk Heater
    - Electronics and Control

FS nPFH Module

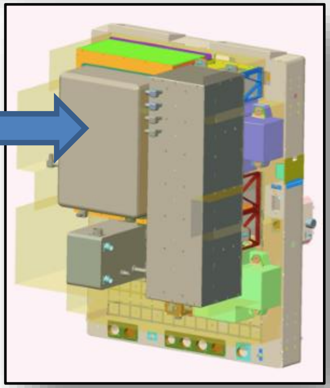


FS Cooling Module

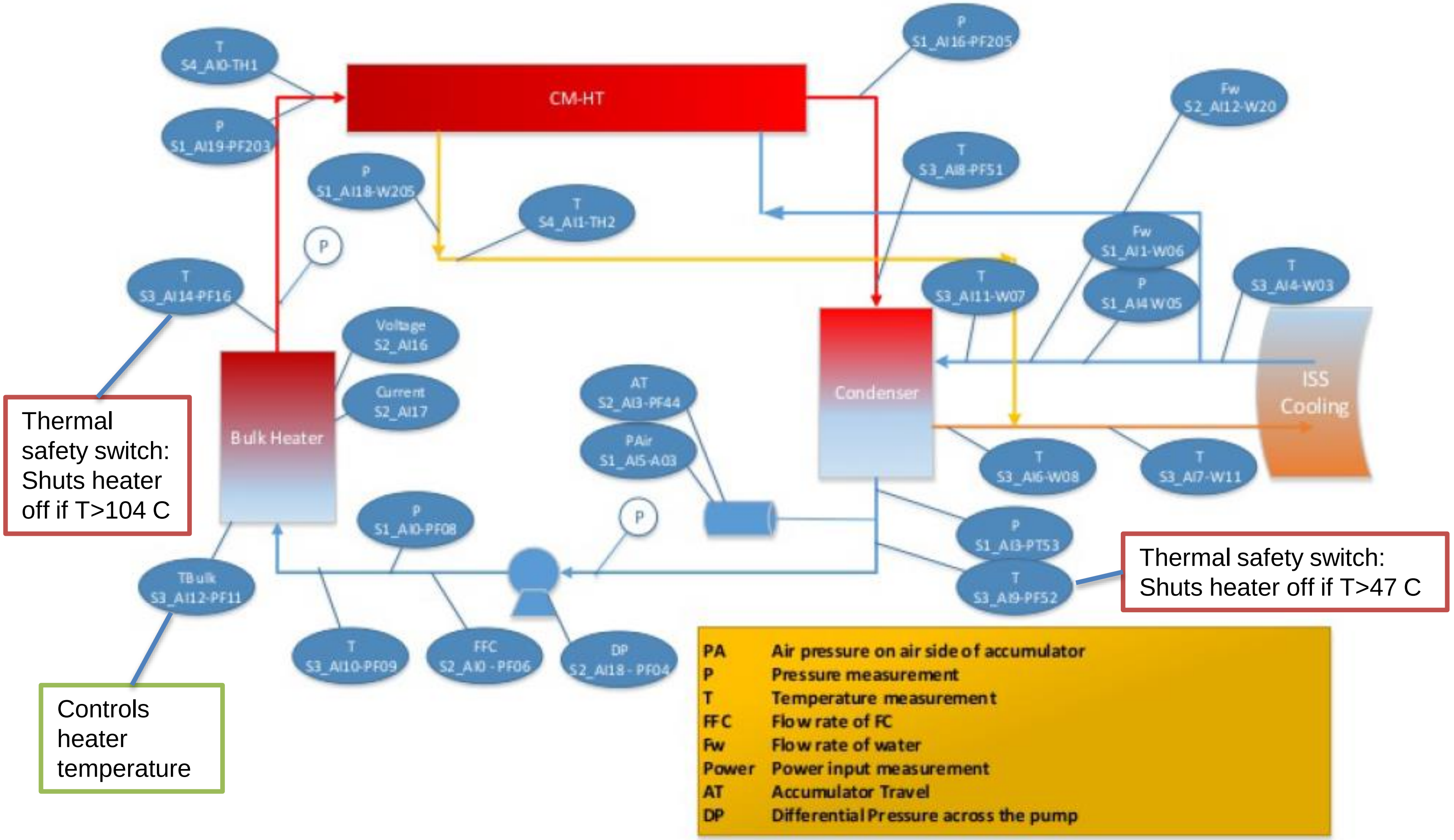


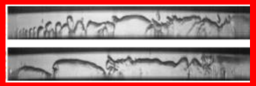


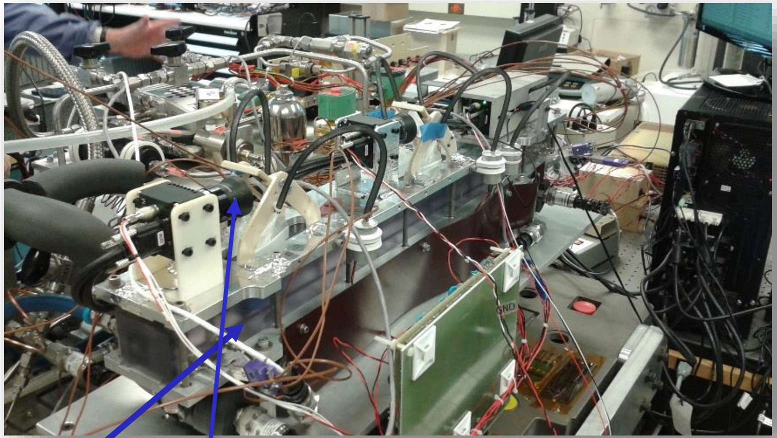
FSM



FBCE Brassboard Flow Loop and Instrumentation

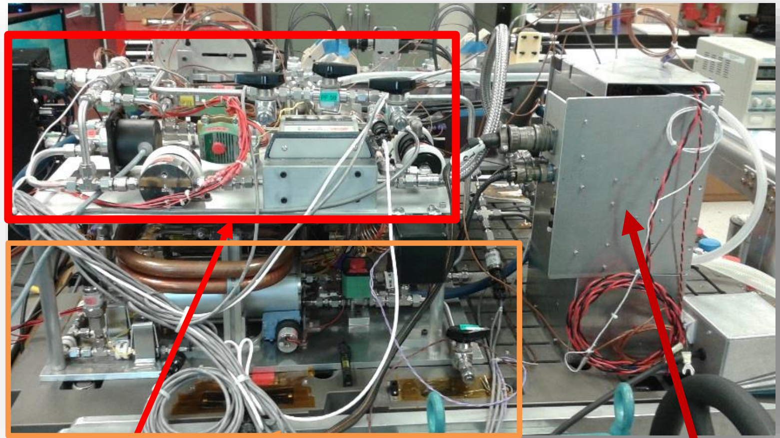






CM-FV

High Speed Cameras

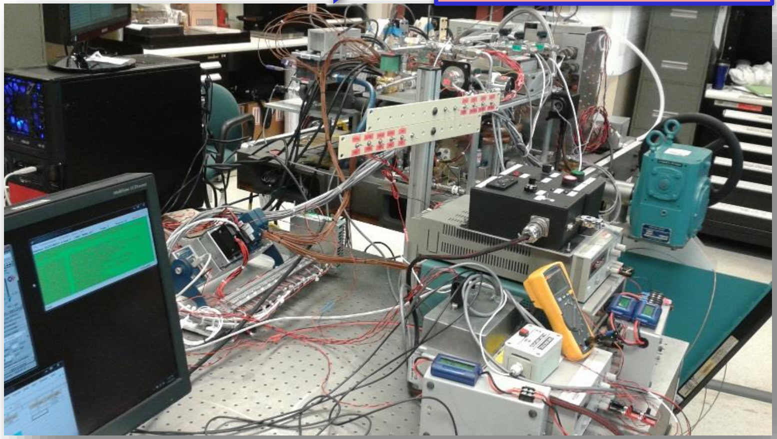


nPFH Module

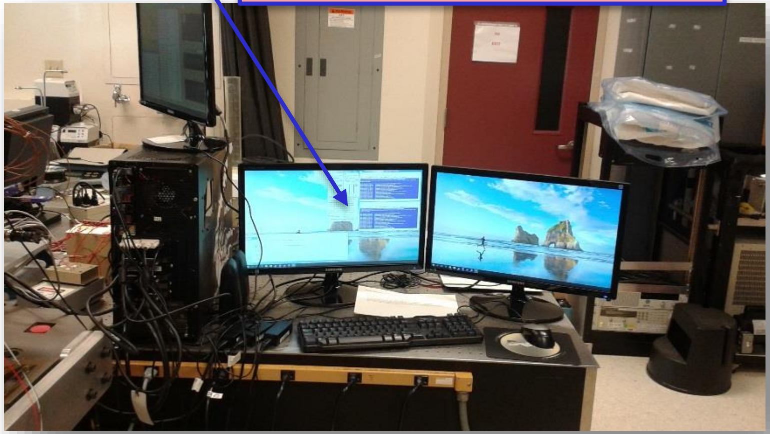
Cooling Module

Bulk Heater Module

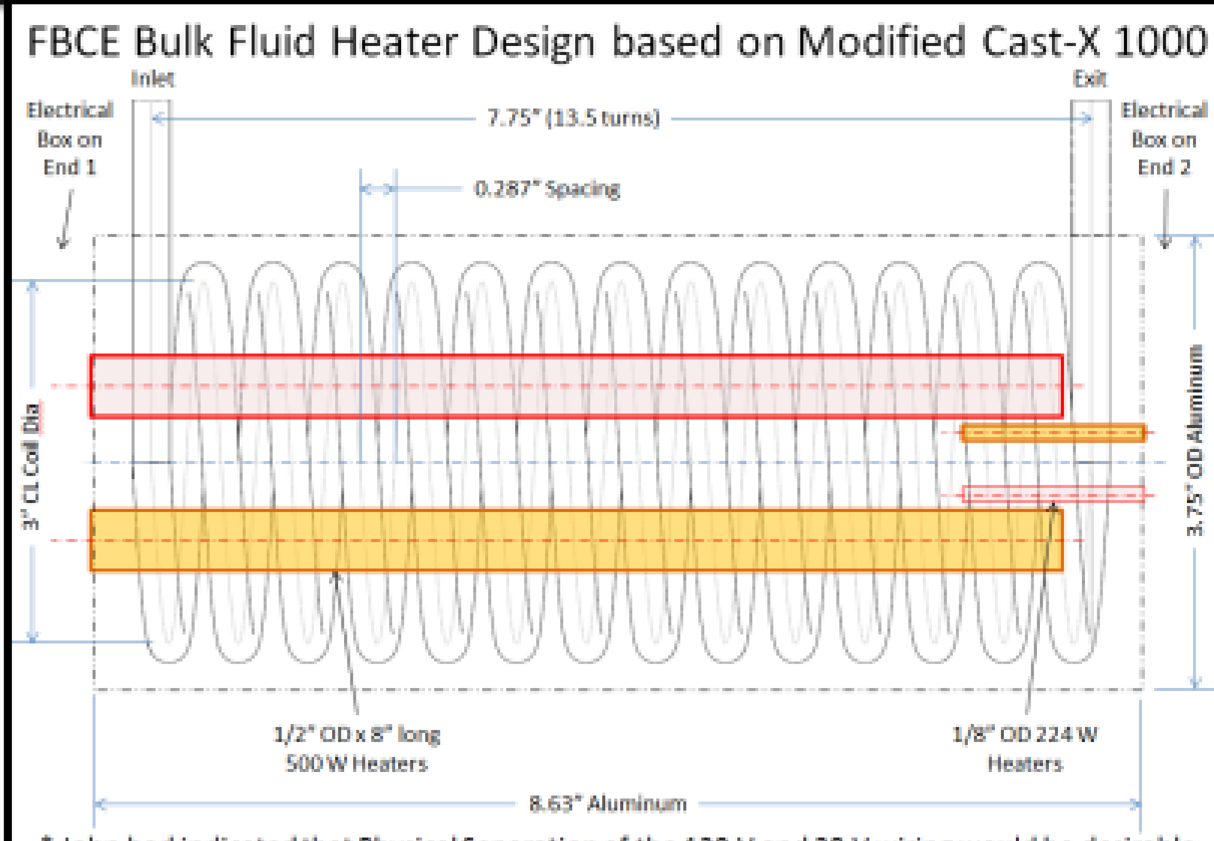
Data Acquisition and Control



High Speed Video Recording and Observation

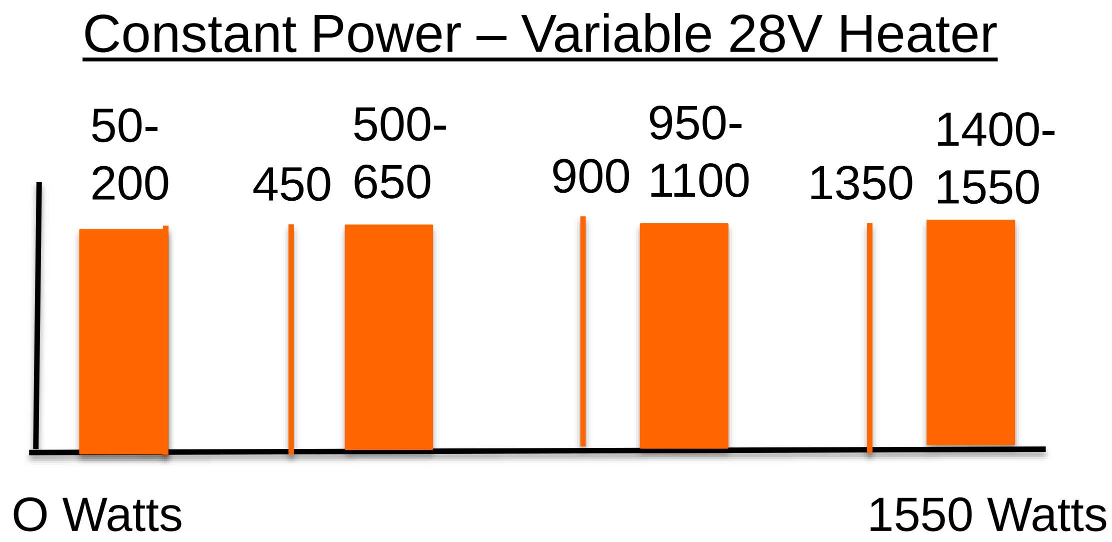


Bulk Heater Cross Section

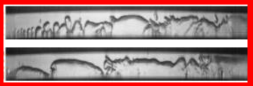


- ❑ Brassboard Bulk Heater can operate at constant or cyclic power mode for the entire power range (0-1550 W)

- Flight Bulk Heater can operate at constant power only for selected power ranges



- For cyclic heater operation mode and two phase inlet conditions into the test modules (FBM, CM-HT, CM-FV), we need to know the average power input to the bulk heater
  - Needed for accurate calculation of the thermodynamic quality



Bulk Heater Performance Study

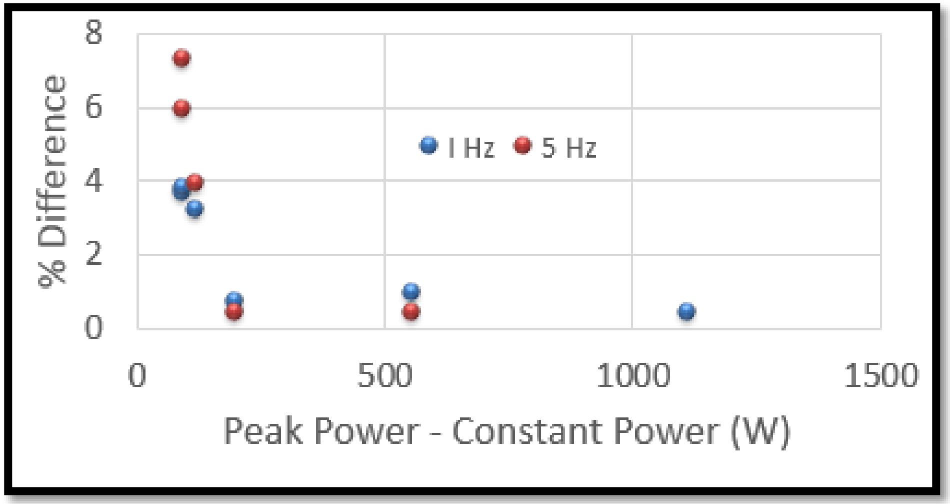
- Heater Power Operation Modes
  - Constant power mode operation
  - Switching power mode operation and set point control
  - Experiments have been performed to assess the calculated average power as a function of sampling frequency
  - Average power is compared with the constant power corresponding to the same experimental condition (flow rates, pressure, heater temperature)

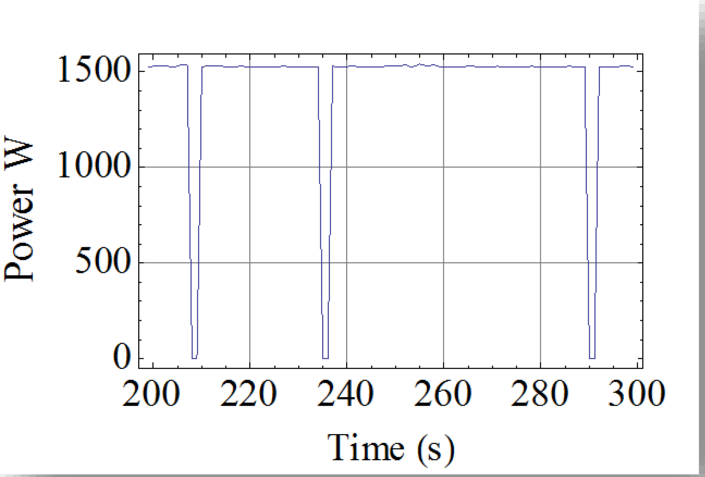
1. Set the FC-72 flow rate, water flow rate (test module) and water flow rate (condenser)
2. Set the bulk heater at a specified power
3. Determine steady state bulk heater metal temperature
4. Set the bulk heater set point temperature 1 C above the metal temperature determined above
5. Set the bulk heater at the maximum power, record data at specified sample rates (HZ)
6. Determine average power by integrating on-off power profile

Bulk Heater Performance Study

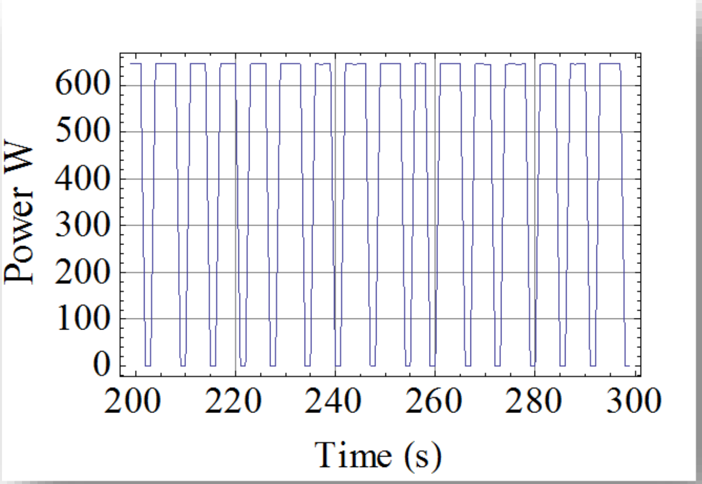
Date	Case #	Power (W)	Peak Power (W)	BHT Set Point .(C)	BHT Metal Temperature .(C)	Frequency (Hz)	Integrated Power (W)	% Deviation from Constant Power
9/14/2016	3	448			69.3	1	447.6	
	5		648	70	69.9	1	444.5	0.69
	6		648	70	69.9	5	445.7	0.42
	7		648	70	69.9	10	451.3	0.83
9/15/2016	3		648	70	69.9	25	454.3	1.50
	4		648	70	69.9	50	455.8	1.83
	6	1002			76	1	1003	
	9		1095	77	76.3	1	1039.7	3.66
	10		1095	77	76.2	5	1076	7.28
	11		1095	77	76.3	10	1083	7.98
	12		1095	77	76.3	25	1087.2	8.39
	13		1095	77	76.3	50	1067.2	6.40
	15	1435			86	1	1436	
	17		1528	87.5	86	1	1490.1	3.77
	18		1528	87.5	86	5	1520.9	5.91
	19		1528	87.5	86	10	1513.9	5.42
	20		1528	87.5	86	25	1517.2	5.65
	21		1528	87.5	86	50	1517	5.64

Bulk Heater Performance Study



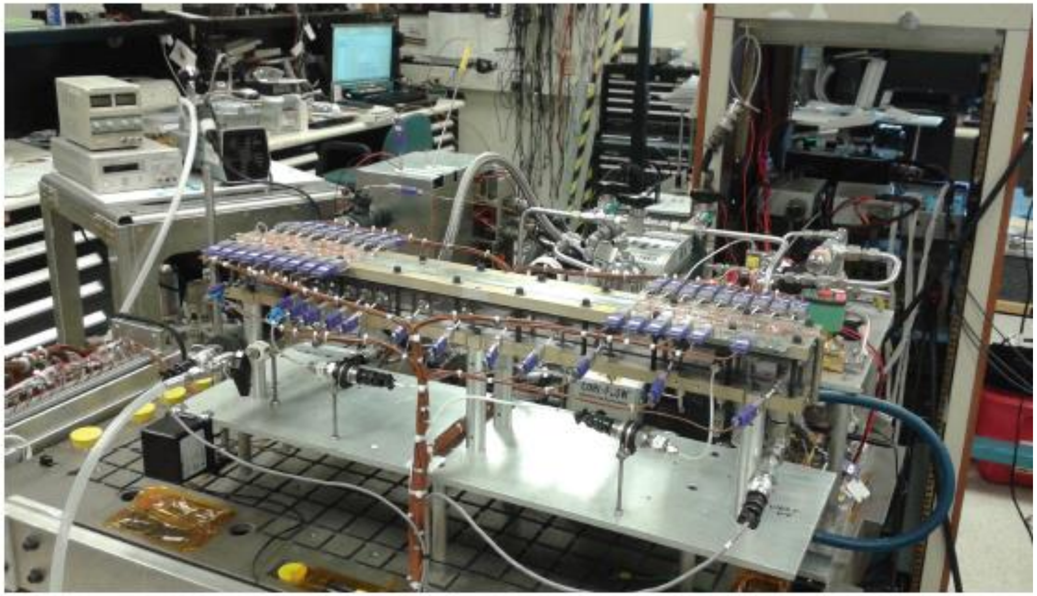


- The larger the difference between the peak set power and the constant power, the smaller the error in power integration.
- Attributed to high periodicity in power cycling exhibited in large amplitude power oscillations

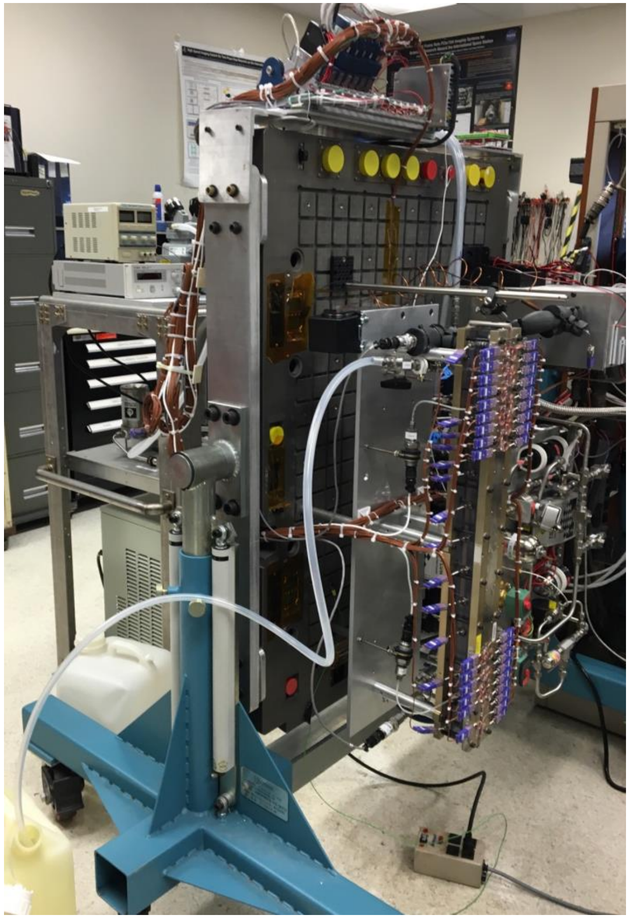


Condensation Module-Heat Transfer (CM-HT) Testing

- CM-HT was tested in both horizontal and vertical orientations for FC-72 flow rates from 2 to 12 g/s and cooling water flow rate from 10 to 30 g/s
- Saturated to slightly superheated vapor at the inlet to the test module (All vapor inlet condition was determined by comparing vapor inlet temperature with the saturation temperature and was verified by visual observation)



CM-HT Horizontal Orientation



CM-HT Vertical Orientation

CM-HT Module Inlet Pressure

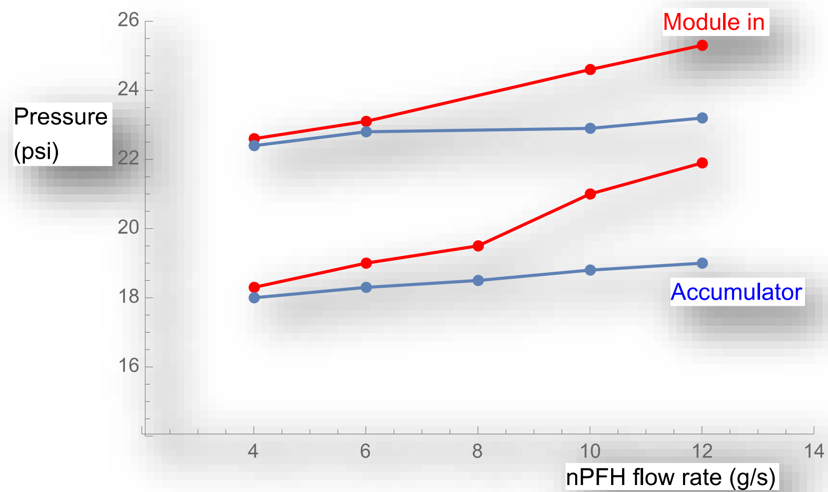
Tests were conducted in the following two ways

- Accumulator pressure set to a desired value at isothermal conditions and the gas-side vent valve closed. CM-HT module inlet pressure varies with FC-72 flow rate.
- Accumulator pressure adjusted during the tests to maintain a constant inlet pressure to the CM-HT module for all flow rates.

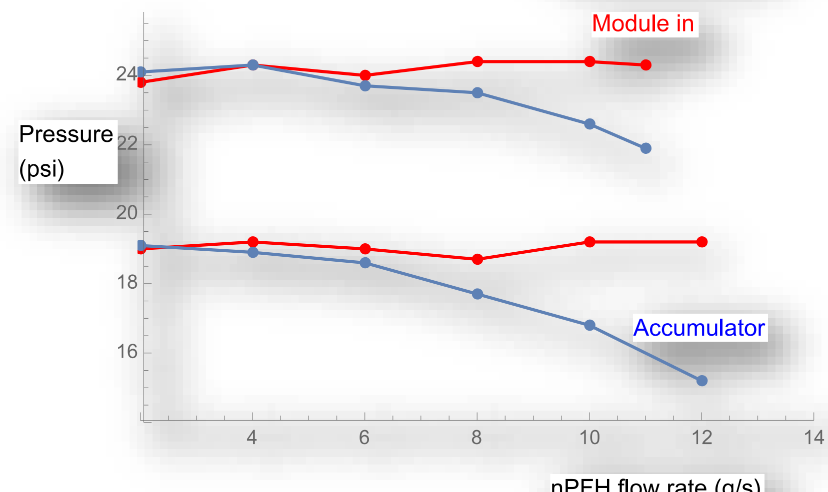
Vertical down-flow –Vapor at Module Inlet

We conducted the tests with FC-72 flow rate varied from 2 to 12 g/s.

- Accumulator pressure set to 14.5 psia and vent valve closed. The module inlet pressure varied from 18.3 to 21.9 psia.
- Accumulator pressure set to 18.2 psia and vent valve closed. Module inlet pressure varied from 22.6 to 25.3 psia.

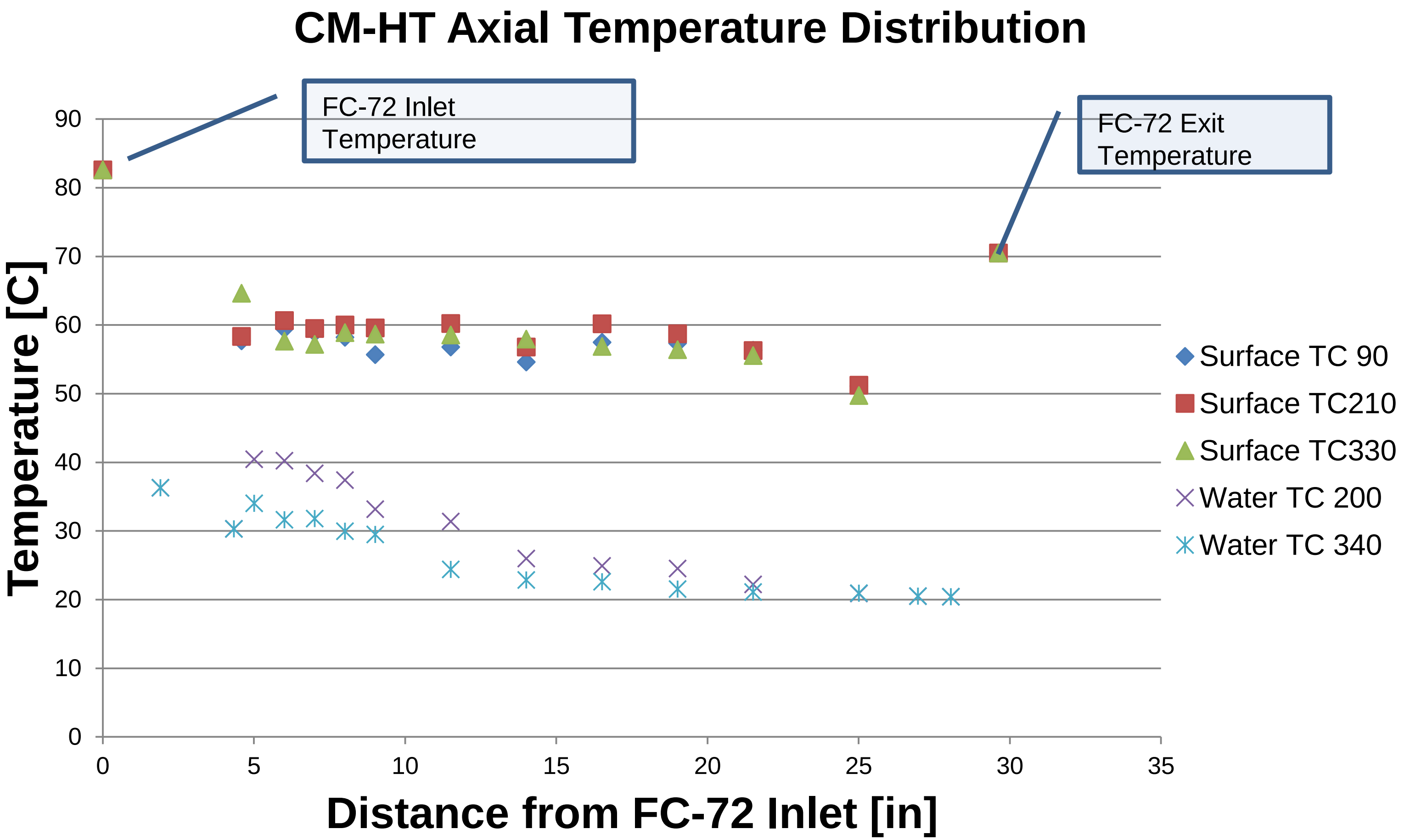


- Accumulator pressure adjusted by venting or pumping air.
- Module inlet pressure maintained at 19 psia. The accumulator pressure adjusted from 19.1 to 15.2 psia (lowest accumulator pressure slightly above ambient).
- Module inlet pressure maintained at 24 psia. The accumulator pressure adjusted from 24.1 to 21.9 psia (max accumulator pressure limited by relief valve pressure)



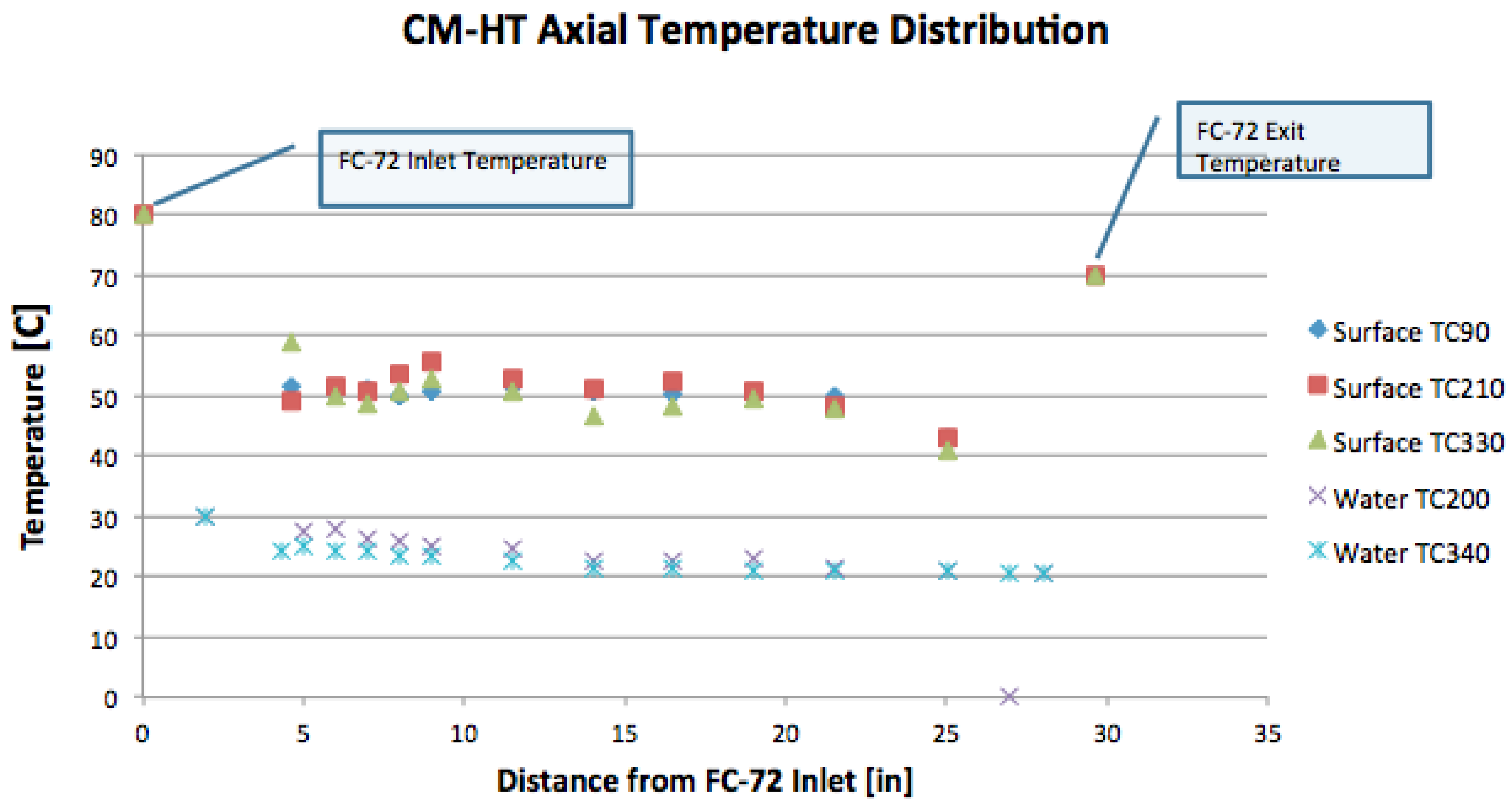
Glenn Research Center

CM-HT Testing



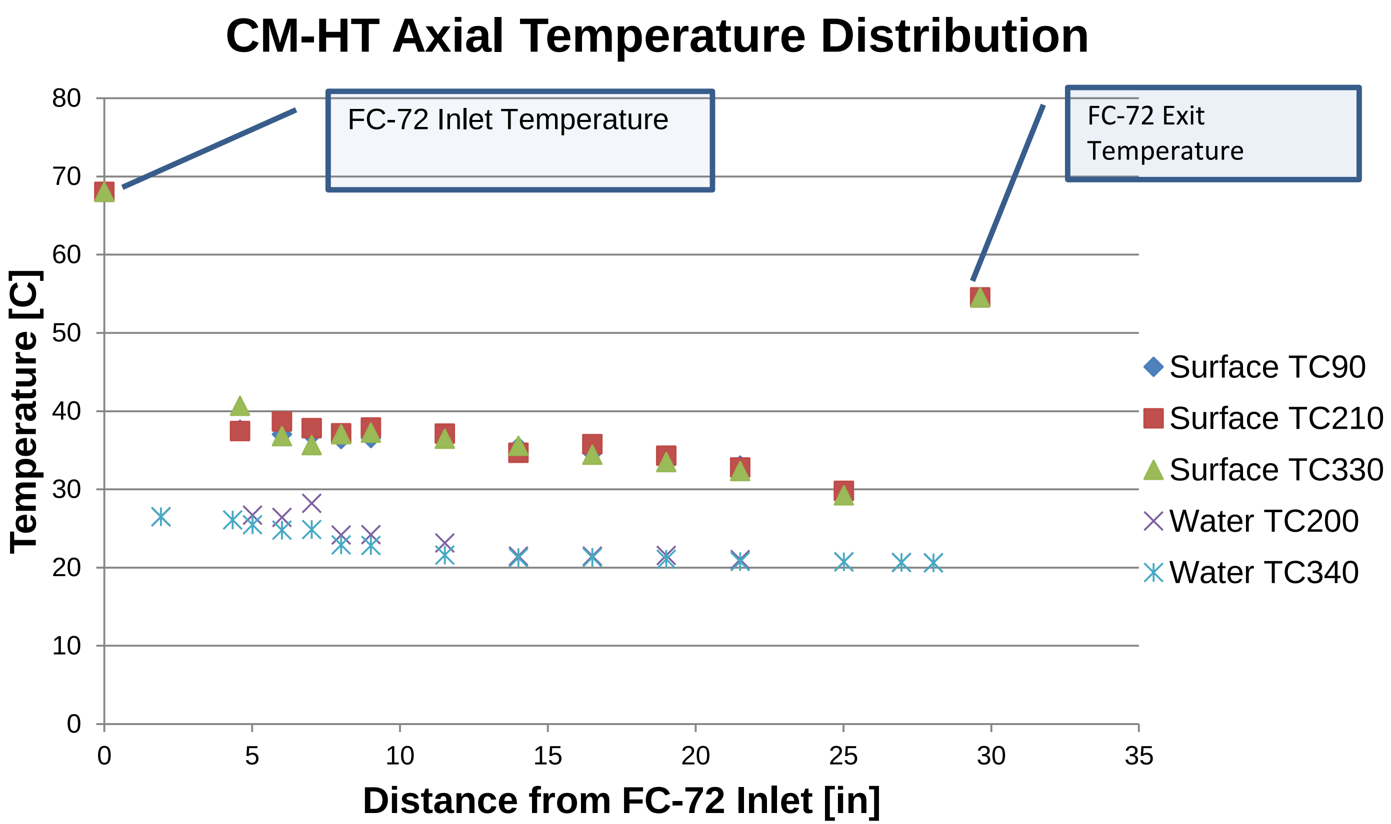
Vertical orientation: FC-72 flow rate = 10 g/s,
Module water flow rate = 10 g/s, Condenser water flow rate = 10 g/s
Module inlet pressure = 24.4 psia

CM-HT Testing



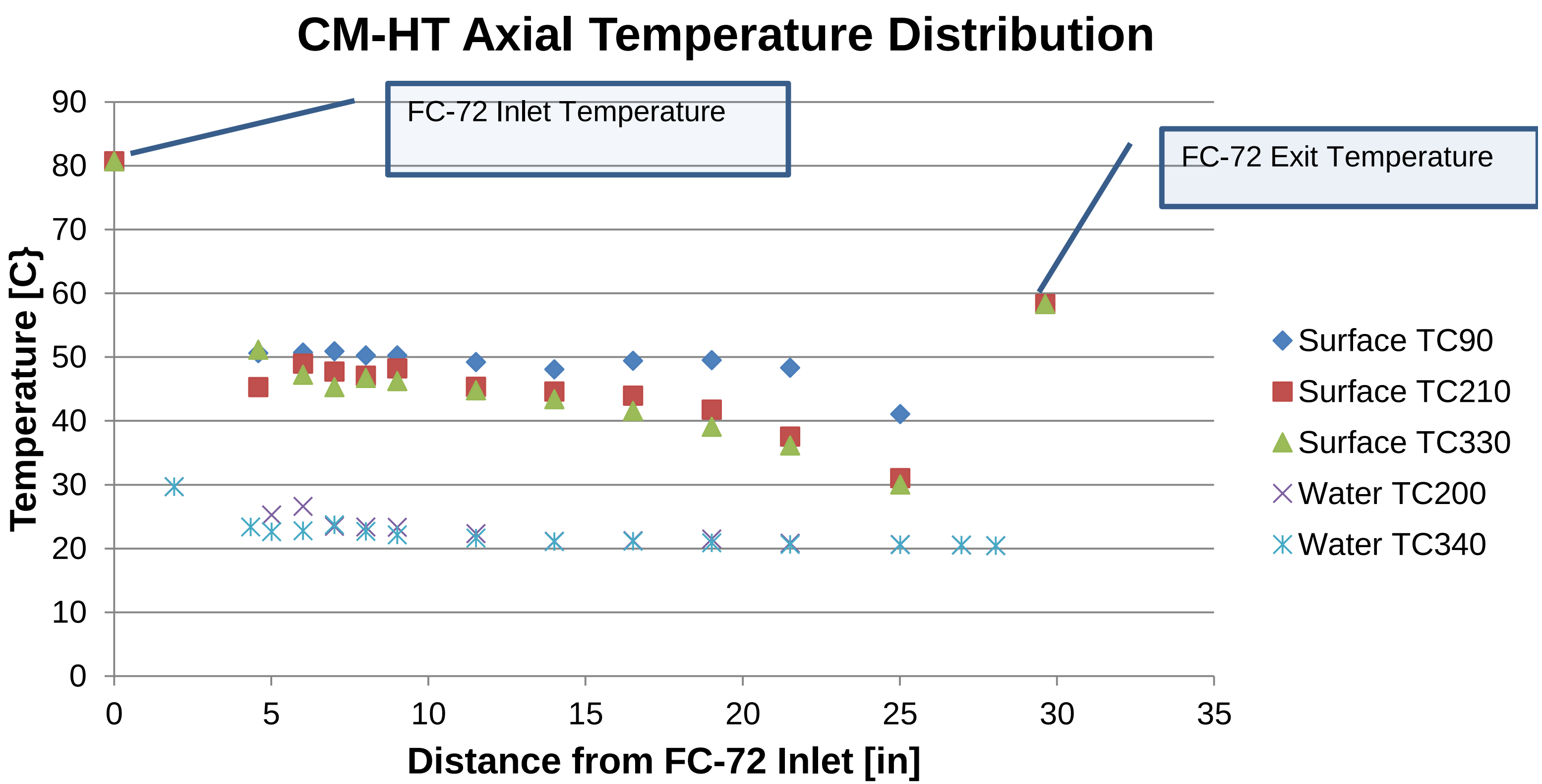
Horizontal orientation: FC-72 flow rate =10 g/s,
Module water flow rate = 10 g/s, Condenser water flow rate = 20 g/s
Module inlet pressure = 24 psia

CM-HT Testing



Vertical orientation: FC-72 flow rate = 4 g/s,
Module water flow rate = 10 g/s, Condenser water flow rate = 20 g/s
Module inlet pressure = 22.6 psia

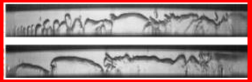
CM-HT Testing



Horizontal orientation: FC-72 flow rate = 4 g/s,
Module water flow rate = 10 g/s, Condenser water flow rate = 20 g/s
Module inlet pressure = 21.3 psia

Preliminary CM-HT Test Summary

- For 4 g/s FC flow rate, vertical downflow tests exhibited axi-symmetric surface temperatures compared to horizontal flow tests
- For 10 g/s FC flow rate, vertical downflow and horizontal flow tests exhibited axi-symmetric surface temperatures
- Water temperature at 200 degrees circumferential location consistently higher than water temperature at 340 degrees for the selected cases
  - Need to evaluate whether this might be due to differences in radial location of thermocouple.



Concluding Remarks

- Heater was demonstrated to operate in vertical and horizontal orientations and deliver the required test module inlet thermodynamic conditions
- Heater performance testing resulted in an optimum hybrid constant/cyclic power operation for ISS operation
- Average power for cyclic heater operation compared favorably (<2%) with corresponding constant power
- Constant inlet pressure to CM-HT module for all FC-72 flow rates was demonstrated by adjusting the accumulator air-side pressure
- CM-HT module axial and circumferential temperature distribution was assessed in both horizontal and vertical orientations for FC-72 flow rates from 2 to 12 g/s and cooling water flow rate from 10 to 30 g/s
  - Temperature distributions appear to be physically reasonable