



Flow Boiling and Condensation Experiment (FBCE)

Capabilities and System Description

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Abstract

This document provides a description of the Flow Boiling and Condensation Experiment (FBCE) and the facility that accommodates three different test modules; the flow boiling and two flow condensation test modules. In this document, the overall system-level architecture of the fluid system is described with interfaces, followed by descriptions of the various modules of the FBCE including the avionics modules, the fluid system modules, and the test modules. The FBCE system capabilities and constraints are also expressed in terms of a table showing all the FBCE subsystems capabilities and limitations.

1.0 Introduction

The Flow Boiling and Condensation Experiment (FBCE) is a flight experiment that aims to understand flow boiling and flow condensation in microgravity and is planned to run onboard of the International Space Station (ISS). A high-level description of the FBCE system capabilities, design and interface characteristics is presented. Each of the eight FBCE modules are discussed as well as the mechanical, electrical, and software interfaces with the Fluid Combustion Facility's (FCF) Fluid Integration Rack (FIR), where the experiment will be installed for International Space Station (ISS) operations.

1.1 Background

The FBCE will serve as a primary platform for obtaining two-phase flow boiling and condensation heat transfer data in microgravity. By comparing the microgravity data against data obtained in Earth's gravity, it will be possible to ascertain the influence of body forces on two-phase transport phenomena in pursuit of mechanistic models as well as correlations, and to help determine the minimum flow criteria to ensure gravity independent flow boiling and condensation. Key areas of impact include the Rankine cycle-based power systems and two-phase thermal control systems. Rankine cycle power systems are considered one of the most viable options for space application due to their high power output per unit mass and volume. Similarly, two-phase thermal control systems can yield significant advancement in thermal performance for spaceflight applications compared to current single-phase thermal control loops.

1.2 FBCE Objectives

The four primary objectives for FBCE are:

1. 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.
2. 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.
3. Obtain flow boiling data (heat flux, void fraction, the wall temperature difference) in long duration microgravity environments for a well-characterized heating surface as functions of liquid inlet mass velocity and subcooling.
4. Obtain flow condensation data (heat flux, void fraction, the wall temperature difference) in long duration microgravity environments for a well-characterized condensing surface as functions of inlet quality and flow rate of condensing vapor.

1.3 Test Fluid Properties

The test fluid for FBCE is normal-perfluorohexane (nPFH-C₆F₁₄) which is a coolant used in engineering applications. The properties of the fluid are given in the following Table 1 at saturation pressures of 100 and 160 kPa.

TABLE 1.—THERMOPHYSICAL PROPERTIES OF NORMAL-PERFLUOROHEXANE

Saturated properties of nPFH	$P_{sat} = 1.0 \times 10^5 \text{ N/m}^2$, 100 kPa	$P_{sat} = 1.6 \times 10^5 \text{ N/m}^2$, 160 kPa
Saturation temperature, T_{sat} (°C)	56.52	71.07
Liquid density, ρ_f (kg/m ³)	1622.04	1584.98
Vapor density, ρ_g (kg/m ³)	13.32	21.00
Latent heat of vaporization, h_{fg} (J/kg)	83.67×10^3	79.40×10^3
Liquid specific heat, $c_{p,f}$ (J/kg.K)	1.10×10^3	1.14×10^3
Liquid viscosity, μ_f (kg/m)	415.58×10^{-6}	342.03×10^{-6}
Vapor viscosity, μ_g (kg/m.s)	11.85×10^{-6}	12.51×10^{-6}
Liquid thermal conductivity, k_f (W/m.K)	54.21×10^{-3}	52.52×10^{-3}
Liquid Prandtl number, Pr_f	8.48	7.40
Surface tension, σ (N/m)	8.47×10^{-3}	7.19×10^{-3}

2.0 FBCE Common Systems

Figure 1 shows the main elements of the FBCE experiment mounted on the FIR Optics Bench (see Section 2.1.1). Within the view area on the front of the FIR optics bench are the modules that are provided by FBCE. In this document, the Operational Nomenclature (OpNom) for FBCE is used. This is the nomenclature that will be used during the experiment operation by the astronauts. However, FBCE adopted names for its components that do differ slightly from OpNom and a cross reference between the OpNom and the nomenclature used is given in Table 2. The purpose of this Table 2 is to provide a reference to the hardware described in open literature papers using the engineering nomenclature.

A simplified version of the Fluid Schematic with only the primary elements required for operation is shown in Figure 2.

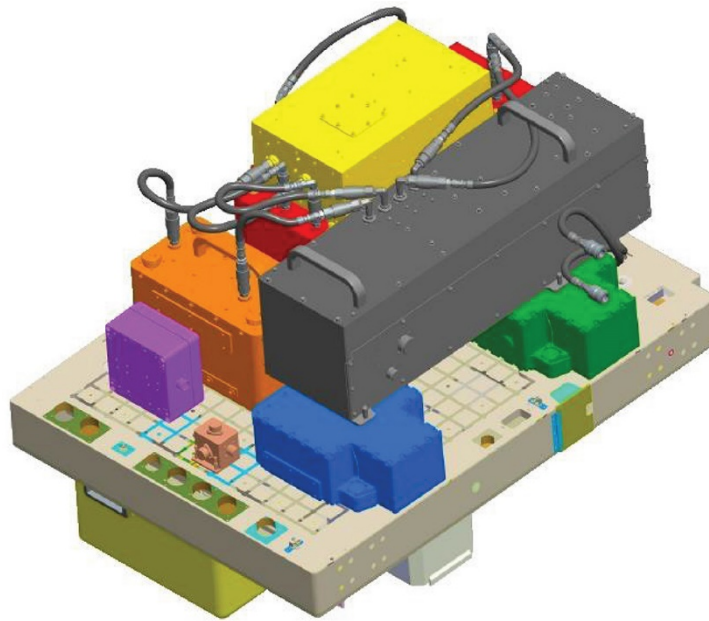


Figure 1.—FBCE hardware mounted on the FIR Optics Bench in the flight configuration. Gray: Current Test Module (Either the FBCE Flow Boiling Test Module or the FBCE Condensation Test Modules 1 and 2, depending on the test configuration needed for operations), Yellow: FBCE Fluid Module 2, Red: FBCE Fluid Module 1, Orange: FBCE Heater, Green: FBCE Avionics 1, Blue: FBCE Avionics 2, Purple: FBCE Power Filter.

TABLE 2.—OPERATIONAL NOMENCLATURE AND ENGINEERING NOMENCLATURE CROSS REFERENCE

Operational Nomenclature	Engineering Nomenclature
Flow Boiling Test Module	Flow Boiling Module (FBM)
Condensation Test Module 1	Condensation Module—Heat Transfer (CM-HT)
Condensation Test Module 2	Condensation Module—Flow Visualization (CM-FV)
FBCE Fluid Module 1	Fluid System Module—Lower (FSML)
FBCE Fluid Module 2	Fluid System Module—Upper (FSMU)
FBCE Heater	Bulk Heater Module (BHM)
FBCE Avionics 1	Remote Data Acquisition Module 1 (RDAQM1)
FBCE Avionics 2	RDAQM 2
FBCE Power Filter	FBCE Power Filter

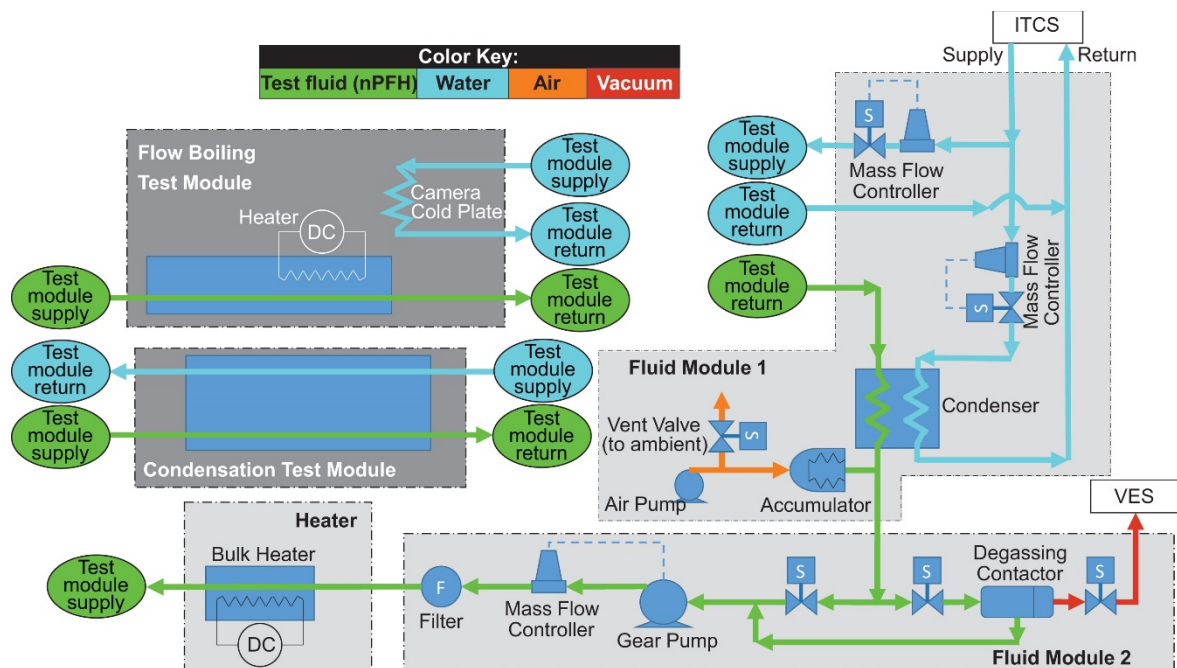


Figure 2.—Simplified fluid system schematic for FBCE.

2.1 FBCE System-Level Layout on Fluids Integration Rack

The FIR is a modular multi-user fluid science experiment facility located in the ISS U.S. Lab Module (Destiny) that will accommodate FBCE. Because the FIR has area and volume constraints, FBCE will be configured for one test module at a time. The FBCE system is designed to allow a test module to be removed following the completion of its specific science objectives and replaced with a new test module that supports new science objectives. Removal and replacement of the test modules is supported by using the Quick Disconnects (QDs), removable wire harnesses, and common structural supports and fasteners. Operation of the system will be controlled from the ground. Astronaut support will not be required during ground commanded operations but will be required during initial system installation, test module removal and replacement, and system removal.

Three additional elements will be provided by FIR. One of these units, the Space Acceleration Measurement System (SAMS) Tri-axial Sensor Head (TSH), is shown on the front of the optics bench as the small tan cube in Figure 1. The back of the optics plate includes the other two units, the Image Processing Storage Unit-Camera Link (IPSU-CL) and the Confocal Control Unit (CCU).

2.1.1 Fluid Integration Rack (FIR) Interfaces

To operate as designed, the FBCE hardware will have to interface with five ISS systems for specific services: the Input/Output Processor (IOP) via the CCU; the Vacuum Exhaust System (VES); the Internal Thermal Control System (ITCS) via the Water Interface Panel (WIP); the Electrical Power Control Unit (EPCU); and the FIR Rack 120 VDC Power Interface. The EPCU will supply 28 V power to the experiment, while the FIR Rack 120 VDC Power Interface will provide 120 V power. Heaters in the system are directly powered by the EPCU and the FIR 120 VDC Power Interface, while other systems will be powered through connections on the Optics Bench itself.

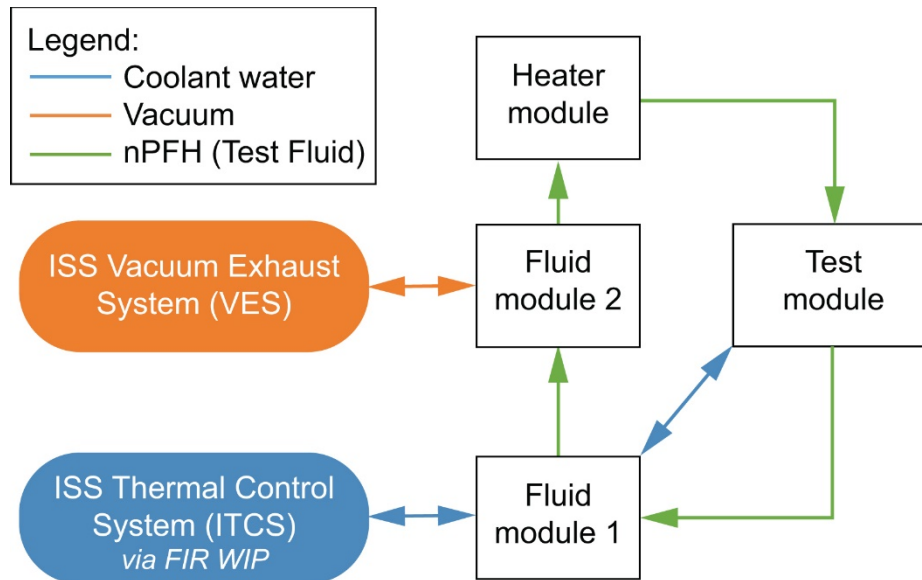


Figure 3.—Fluidic interfaces for the FBCE modules and FIR.

The FIR rack provides air-cooling by drawing air from the inside of the Optics Bench through the UML Air-Cooling Port into an air/liquid heat exchanger, then into the experiment working volume. Fluid Modules 1 and 2, Avionics 1, and Avionics 2 have ports to receive cooling air internally. The other modules will not have internal air-cooling. External airflow provided by the FIR rack will provide additional cooling of the FBCE hardware.

FBCE will also require fluidic interface connections with the FIR facility, as shown in Figure 3. Fluid Module 1 will receive ITCS cooling water from the WIP using a flex hose and quick disconnect (QD) fluid connection. The cooling water will be used to cool the test fluid within the Fluid Module 1 and one of the Test Modules. For operations with the Condensation Test Modules 1 and 2, cooling water will be used to condense the test fluid for completion of science objectives. For the Flow Boiling Test Module, cooling water will be used to provide cooling of the camera. Fluid Module 2 will connect to the VES with a flex hose and QD to provide a vacuum source on the membrane contactor during degassing operations. The test fluid itself will be closed-loop, with no interfaces with the FIR. All module-module fluid connections and connections with the FIR will utilize flex hoses and QDs.

2.2 Fluid System Modules

The Fluid System Modules contain the primary fluid conditioning hardware to support the inlet requirements to the Test Modules. The Fluid Module 1, also referred to as the Fluid System Module – Lower (FSML), provides cooling of the test fluid exiting the Test Module as well as an accumulator for pressure control. The Fluid Module 2, also referred to as the Fluid System Module – Upper (FSMU), provides the degassing, circulation, and flow control of the test fluid prior to entering the Heater. The Heater, also referred to as the Bulk Heater Module (BHM), holds a heater to condition the fluid to the proper phase and temperature required at the Test Module inlet.

2.2.1 FBCE Fluid Module 1

The Fluid Module 1 provides the primary cooling to the test fluid prior to entering the pump in Fluid Module 2. Additionally, it houses a bellows accumulator that can be used to set the system pressure of the flow loop by pressurizing or depressurizing the bellows with an air system. Unique elements in Fluid

Module 1 include the condenser, the mass flow controllers, and the bellows accumulator. The condenser consists of a 2.22 cm stainless steel twisted tube within an outer 2.54 cm stainless steel tube for an initial/straight length of 168 cm. That tube-within-a-tube length is then coiled to reduce its overall footprint for packaging purposes. The condenser is shown in Figure 4.

The ITCS flow controllers consist of a Coriolis Flow Meter paired with a Solenoid Valve and measures and controls flow rates between 0 to 60 g/s based upon the set point commanded by the FBCE software. The control valves fail closed, requiring the use of bypass solenoid valves that fail-open for safety reasons to ensure ITCS water is flowing through the system in the event of loss of power to the valves.

The test fluid accumulator sets the suction pressure of the pump in order to control the overall system pressure of the test fluid loop. The accumulator housing is constructed of 300 series stainless steel. The pressure vessel is made up of two end flanges bolted to a cylinder that contains a welded 347 stainless steel bellows to accommodate the change in fluid volume up to 980 ml. Two string potentiometers measure the bellows travel.

Photographs of the assembled flight hardware with some enclosure walls removed are shown in Figure 5.



Figure 4.—Conceptual drawing of the Condenser, spiral finned inner tube visualized through the outer tube.

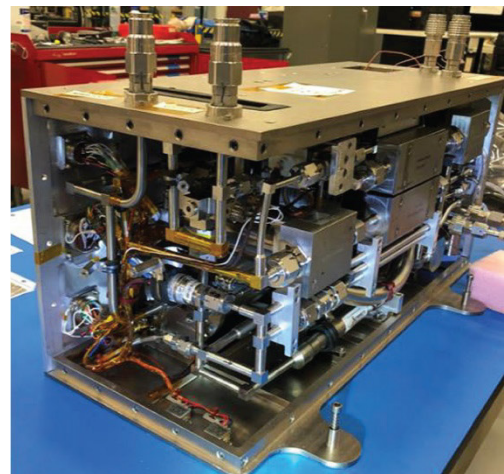
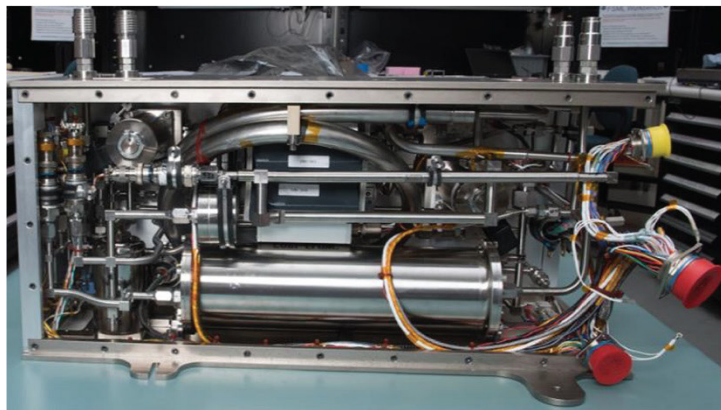


Figure 5.—Different views of assembled Fluid Module 1 with some enclosure walls removed.

2.2.2 FBCE Fluid Module 2

The Fluid Module 2 provides the primary flow control for the test fluid, including a gear pump and a Coriolis flow meter/mass flow controller. In addition, it houses the hardware required for degassing operations should the test fluid have an unacceptably high amount of entrained air.

Unique elements in Fluid Module 2 include the gear pump, mass flow meter, and membrane degasser. The gear pump is a magnetically coupled gear pump that is driven by a 24 V dc brushless motor and electronically mated to a Coriolis mass flow meter. The mass flow meter, when paired with the gear pump, acts as an integrated mass flow control assembly.

The degassing contactor, is a semi-permeable membrane that, when vacuum is drawn on one side, allows dissolved gasses in a fluid to cross the membrane and exit through the vacuum port, with minimal liquid loss across the membrane. The membrane contactor housing is polyethylene.

A photograph of the assembled flight hardware with some enclosure walls removed is shown in Figure 6.

2.2.3 FBCE Heater

The Heater provides the primary heating required to condition the test fluid to the desired thermodynamic states for science operations. The Heater contains a bulk heater subassembly, temperature switches, resistance temperature detectors (RTDs), and several custom heater control PCBs.

Photographs of the assembled flight hardware are shown in Figure 7. The primary component inside the Heater is the bulk heater, which heats the test fluid to the desired quality and temperature. The bulk heater consists of a helically coiled 316 Stainless Steel tube inside a solid cast aluminum body into which the cartridge heaters and RTDs are inserted. Based on thermal model results (as shown in Figure 8), this enables evenly distributed, indirect heating of the test fluid, and eliminates potentials for hot spots.

The system is wired so that only one set of three heaters can operate at a time, with an external jumper in place to swap which set of three heaters is functional. Three dedicated 120 V Heater Control PCBs control the 120 V heaters. The operator selects how many heaters (1, 2, or 3) are operated at a time based on the science needs.

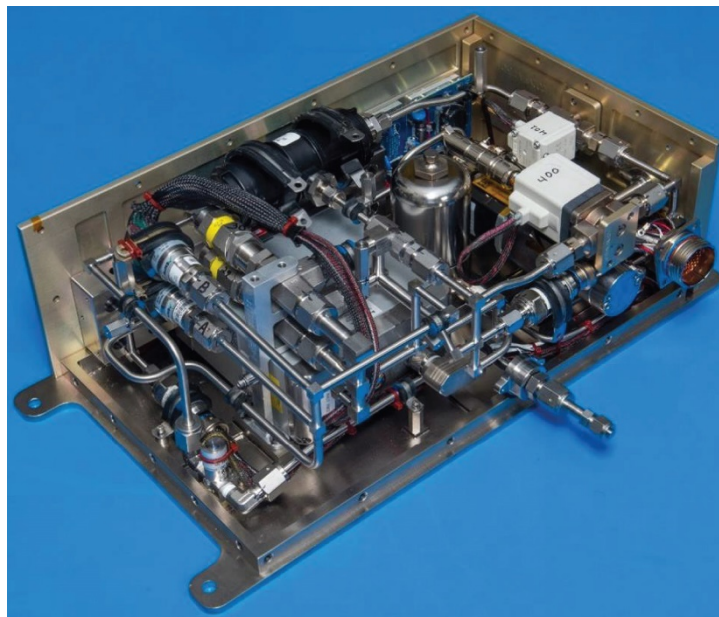
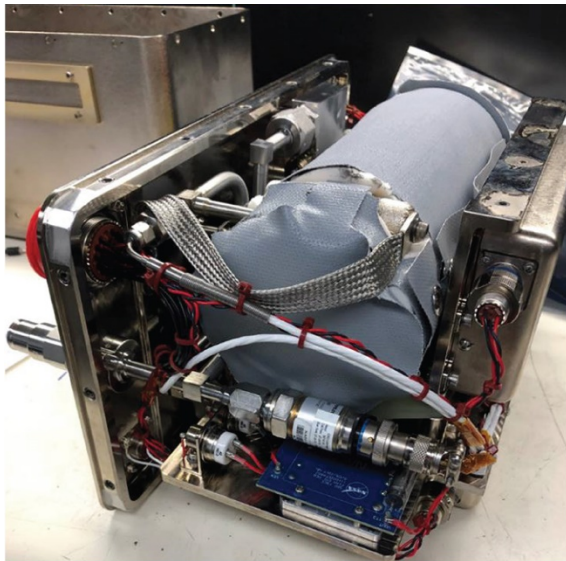


Figure 6.—Photograph of the Fluid Module 2 with the left, rear, and top plates removed.



(a)



(b)

Figure 7.—Photograph of the FBCE heater with the drawn aluminum can enclosure removed (a). Installed (b).

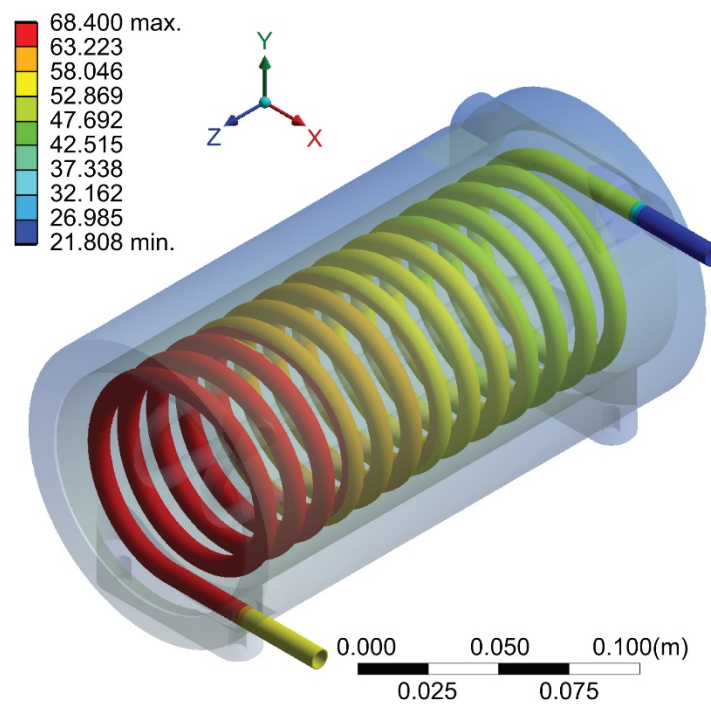


Figure 8.—Heater thermal modeling results.

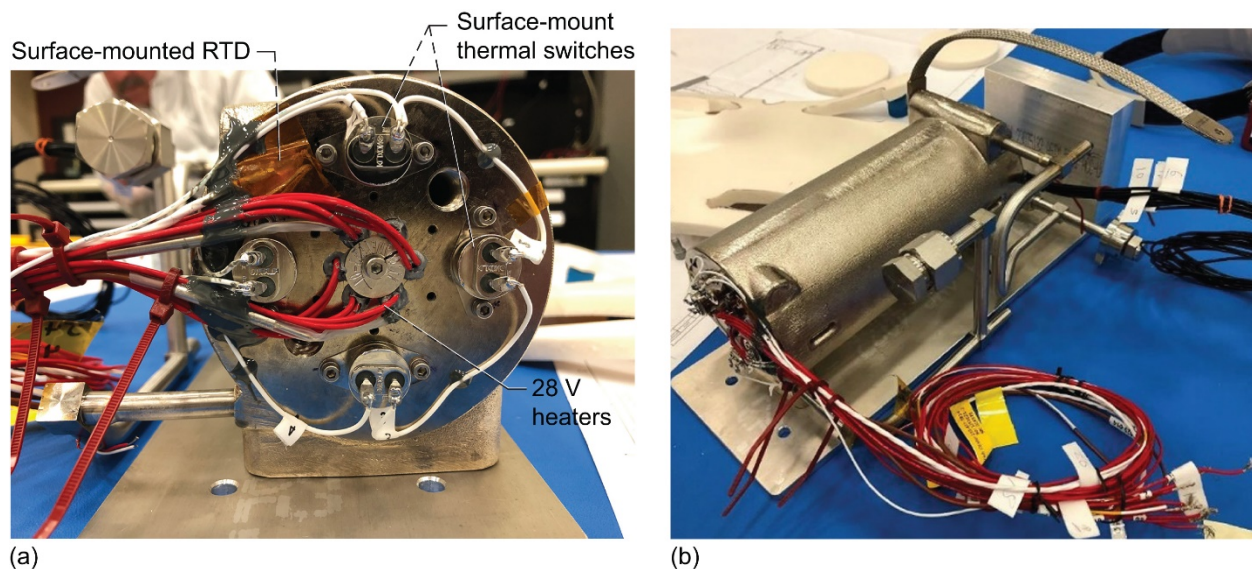


Figure 9.—Hardware installed on the 28 V end of the bulk heater (a). The bulk heater subassembly with instrumentation and heaters installed (b).

In addition, two redundant sets of three-28 V booster heaters provide up to 180 W of additional heating based on the temperature set point provided by the operator. A photograph of the 28 V heaters installed in the bulk heater is shown in Figure 9(a).

The temperature control loop for the 28 V heaters utilizes a thermocouple installed at the tip of the heaters for temperature sensing. A thermocouple provides a fast response to ensure constant temperature of the fluid is maintained. Two heaters have thermocouples mounted on their ends, one for each set of three. Also described in the Temperature Sensors specifications are two fluid inline RTDs to sense the temperature at the inlet and outlet of the bulk heater.

A pressure transducer measures the inlet pressure to the bulk heater. Also included in the heater are several safety switches to prevent overheating of the test fluid. Four surface-mounted thermal switches are attached to the cast aluminum body of the bulk heater and initiate a hardware shutdown of all heating elements in the FBCE system when a temperature greater than 130 °C is detected. In addition, four inline thermal temperature switches are located at the outlet of the bulk heater and initiate a hardware shutdown of all heating elements in the FBCE system when they detect a temperature greater than 100 °C.

2.3 Avionics Modules

Each of the FBCE Avionics Modules contains a commercial-off-the-shelf data acquisition system to collect instrument data and perform Input/Output (I/O) communications and commands. The avionics modules also serve as the mechanical mounting platform for the Test Module that is installed at any given time. Avionics 1, also referred to as Remote Data Acquisition Module 1 (RDAQM 1), captures thermocouple measurements in the Test Modules. Avionics 2, also referred to as Remote Data Acquisition Module 2 (RDAQM 2), performs the remainder of the sensor data capture as well as I/O command processing. Additionally, Avionics 2 contains the Sensor Supply Printed Circuit Board (PCB), which conditions power and distributes it to various sensors in the FBCE system.

2.3.1 FBCE Avionics 1

FBCE Avionics 1 houses a data system with several PCB cards. Each Thermocouple Input Card also includes a modified Screw Terminal Panel card extender. In total, 72 data channels are available in Avionics 1, with 61 channels allocated for thermocouple measurements when using the Condensation Test Module 1. Only 16 channels are utilized when using the Flow Boiling Test Module and 15 channels when using the condensation Test Module 2. Avionics 1 receives power and communications from Avionics 2, and its primary function is thermocouple data measurement.

2.3.2 FBCE Avionics 2

Avionics 2 consists of a data system, a custom Sensor Supply PCB, and a DC/DC Converter with an Electromagnetic Interference (EMI) filter used for power filtering on the UML 28 VDC power feed. The data system holds several cards for sensor measurement inputs and I/O command processing. The analog inputs from different data system cards are pressures, flow rates, Heater and Flow Boiling Test Module assembly sense voltages and sense currents, gear pump-motor speed, accumulator position indication, and RTD Temperature Measurements in the Fluid Modules 1 and 2 and Heater. The analog outputs consist of setpoints for the BHM and Flow Boiling Test Module. The digital inputs are Safety Circuit Shutdown Indicators, Solenoid Valves and Air Pump status, and Gear Pump-Motor Fault Lines Status, whereas the digital outputs are Turning ON/OFF Solenoid Valves and Air Pump. One data subsystem provides serial communication capability with four channel RS232 that set the flow controller and receive flow data.

2.4 FBCE Flight Software

The FBCE flight software manages the experiment and acquires data measurements from diagnostics components. The IPSU-CL assembly is used to acquire images from the FBCE high-speed camera and together constitute the FBCE imaging system. The FBCE flight software is hosted on the FIR CCU. The CCU has two hard disks of one terabyte size that will be utilized to store the operating systems, the FBCE flight software application and configuration files, and all FBCE flight software-generated data files. The hard disks are solid state and will be swapped out with the hard disks currently in use for a different experiment in the FIR on installation of the FBCE hardware into the FIR.

3.0 Test Modules

As described in Section 2.0, FBCE consists of six support modules and three test modules, with only one test module installed and operating at a given time depending on the research being conducted. Of the six support modules, three include fluid system hardware used to condition the test fluid prior to entering the test module; these are the Fluid Modules 1 and 2 as well as the Heater. The other three house electronics and avionics hardware are required for system operations.

The test modules house the hardware required to perform the specific science objectives, and receive test fluid and coolant water at the conditions required to execute the test matrix from the fluid system modules. The Flow Boiling Test Module investigates flow-boiling phenomena in microgravity. It contains temperature and pressure sensors, a heated test section, and flow visualization hardware to capture microgravity flow boiling steady-state and critical heat flux (CHF) data. Condensation Test Module 1 investigates condensation phenomena in microgravity. It includes temperature and pressure sensors and a water-cooled test section to further understanding of fundamental condensation heat transfer in microgravity. Condensation Test Module 2 also investigates the flow condensation in microgravity using high speed video cameras which image the developing condensate film on the surface of a cooled tube, which is instrumented with a limited number of surface and bulk coolant water temperature measurements.

3.1 FBCE Flow Boiling Test Module

The Flow Boiling Module test section consists of a rectangular flow channel 5.0-mm high by 2.5-mm wide, with an adiabatic developing length of 327.9 mm, a heated section of 114.6 mm with heating provided on two opposite sides, and an exit length of 60.9 mm as shown in Figure 10 which also shows a cross section of the heated section of Flow Boiling Test Module. The Flow Module Assembly solid model is illustrated in Figure 11. Flow of nPFH is introduced/pumped into the channel at different flow rates up to 40 g/s as subcooled, saturated liquid, or two-phase fluid and as the fluid passes through the heated section, flow boiling occurs. The heat flux to the heated section is increased in a prescribed manner until the critical heat flux is achieved. Two sets of seven Type-E thermocouples are inserted into shallow holes along the centerline of each copper plate between the resistors. If any of these thermocouples senses a maximum temperature of 122 °C or greater, the flight software decreases the power to the heaters in the Flow Boiling Test Module and records the heat rate imposed on the heaters that resulted in the 122 °C as the CHF as shown in in Figure 12. Pressure is also measured at five different locations along the unheated and heated section. Up to 175 W per side can be delivered to the heaters in the Flow Boiling Test Module. A high speed camera of 2000 frame/s is used in Flow Boiling Test Module to capture the flow boiling process and the state of the fluid near and at the critical heat flux point.

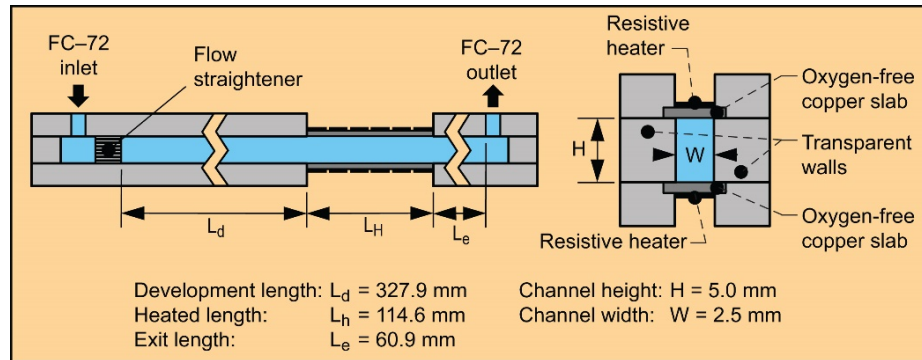


Figure 10.—Schematic of the Flow Boiling Module with basic dimensions.

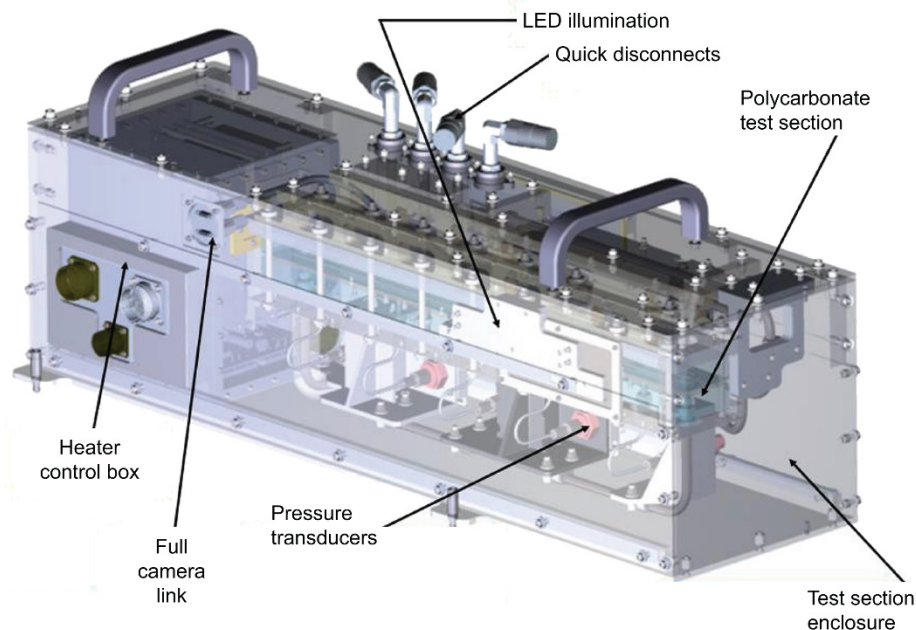


Figure 11.—Flow Boiling Test Module Assembly solid model.

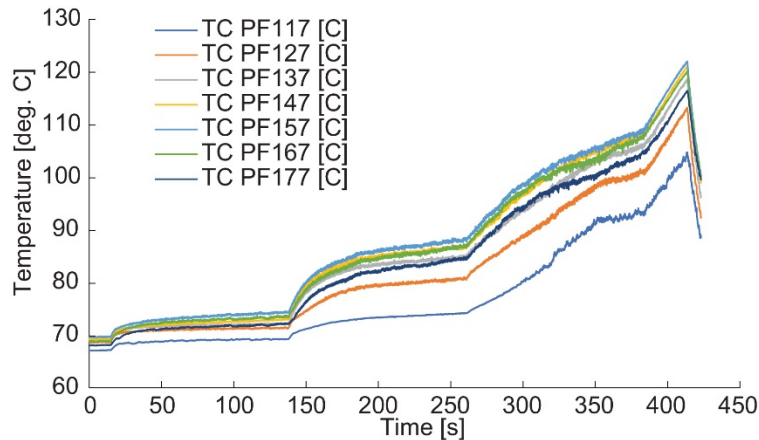


Figure 12.—Typical temperature excursion at Critical Heat Flux.

3.1.1 Flow Visualization

Two cameras are provided for flow visualization, as shown in Figure 13. The miniature analog camera, pictured in Figure 13, has a 3.5 mm/F2.6 lens to provide a qualitative view of flow status prior to test run. The high frame-rate camera with a F0.95/25 mm lens provides science imaging of the test section. The test section is backlit with an array of four blue LEDs and a light-shaping diffuser. The high intensity blue LEDs provide ample lumens for highest frame rate and fast shutter speed imaging, while the Teflon and Light Shaping Diffusers distribute uniform backlight illumination behind the flow. One camera covers the entire field of view, with one set point of 2,040 by 164 pixels at 2,000 frames per second and a shutter speed of 10 μ s.

The Flow Boiling Test Module cameras are directed towards the heated section of the polycarbonate test section, where scientific imaging and heating occurs for boiling investigation, as shown in Figure 14. The test section itself is comprised of three polycarbonate pieces aligned and held in compression by metallic clamp plates. A small, narrow, rectangular cross- section flow channel resides within the middle polycarbonate piece.

3.1.2 Resistive Heaters Subassembly

A resistive heater subassembly is located on both the top and bottom of the test section to provide heating of the fluid to the science requirements. Each subassembly consists of six resistive heater elements. Each subassembly can be operated independently for either top-only heating, bottom-only heating, or heating on both the top and bottom. The heaters were selected based on their resistances. As shown in Figure 15, a set of two thermocouples is located on either side of each heater. One of these thermocouples is designated to provide science data, while the other is wired to the safety shutdown circuit. The heaters are mounted on a copper slab as shown in Figure 15, and the test fluid flows over the reverse side to prevent direct heating of the fluid, as shown in Figure 16.

Also included in the Flow Boiling Test Module are five pressure transducers, which are used to measure the absolute pressure in the unheated segment and before and after the heated segment of the test section. The pressure transducers are depicted in Figure 17.

The Boiling Test Module enclosure consists of eight aluminum panels that encompass all of the Boiling Test Module hardware.

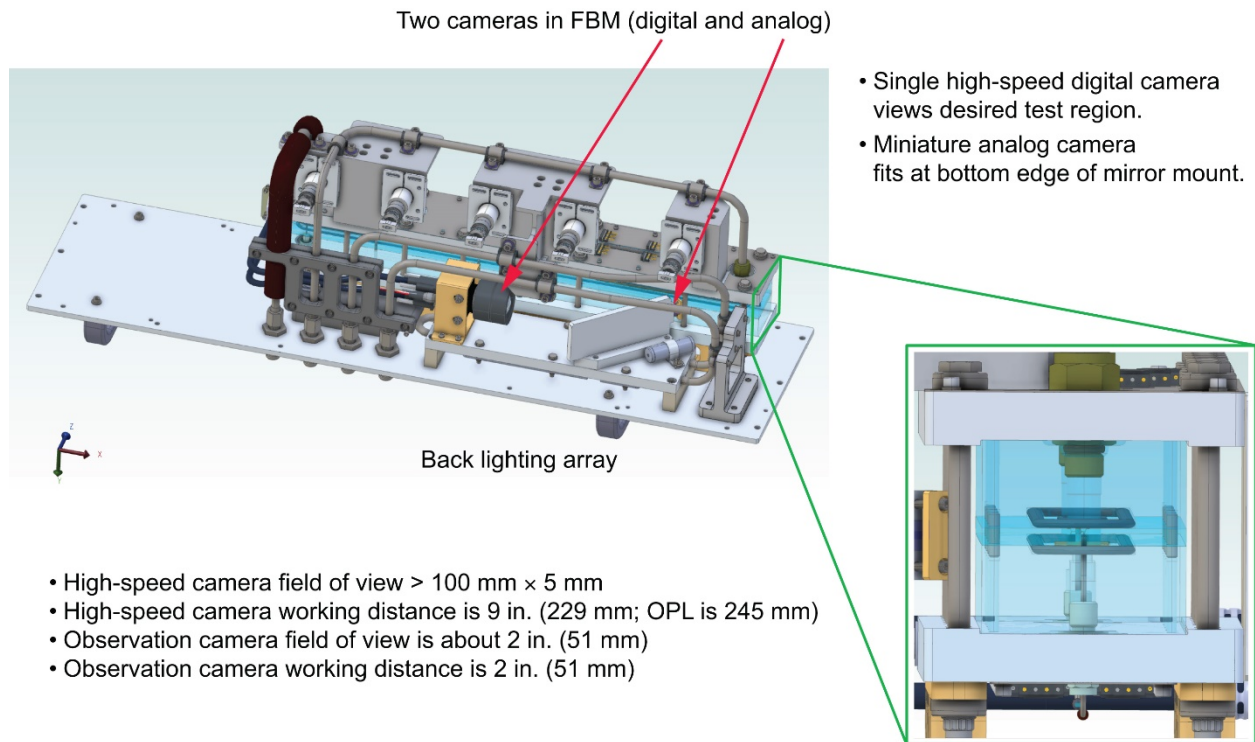


Figure 13.—Camera layout in the Flow Boiling Test Module.

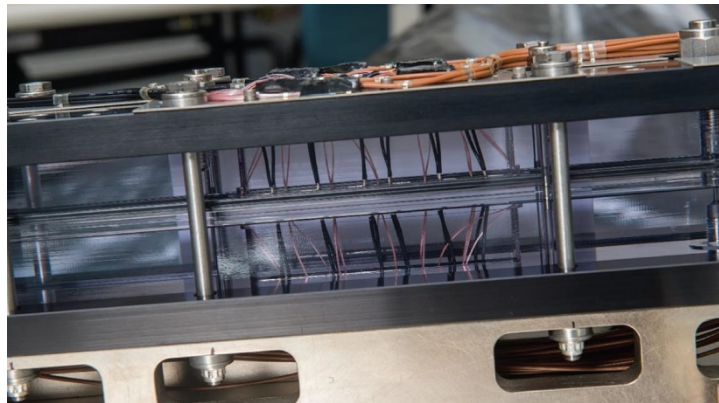


Figure 14.—Flow Boiling Test Module heated portion of the test section.

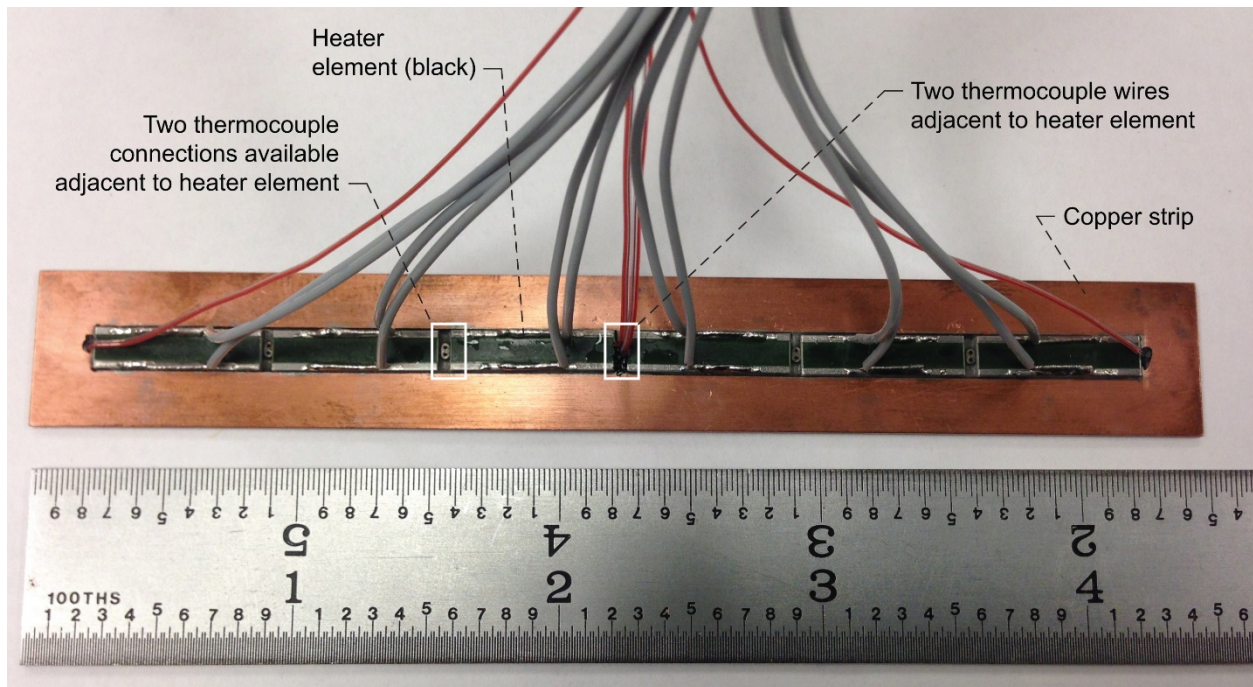


Figure 15.—Flow Boiling Test Module thermocouple and heater element locations.

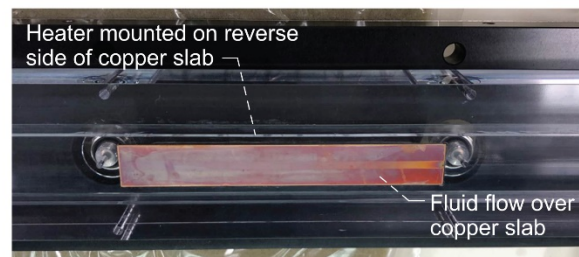
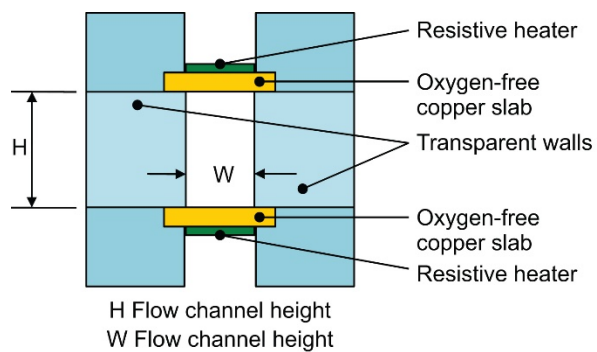


Figure 16.—Flow Boiling Test Module heater subassembly mounting with respect to test fluid flow.

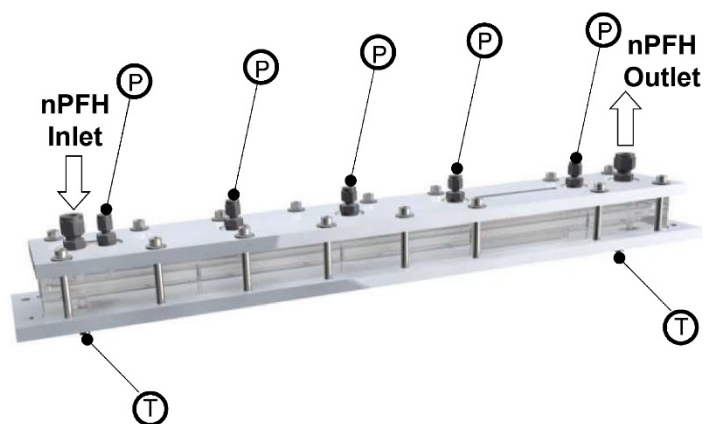


Figure 17.—Pressure Transducers in Flow Boiling Test Module.

TABLE 3.—FLOW BOILING TEST MODULE MATRIX MAP

Number of test runs	Test category	Inlet pressure, kPa	Inlet subcooling, C	nPFH mass flow rate, g/s	Test duration, min.
24	Saturated/Subcooled flow, both sides heated	130	2 to 30	2.5 to 40	~30
24	Saturated/Subcooled flow, both sides heated	160	2 to 30	2.5 to 40	~30
18	Saturated/Subcooled flow, one side heated	130	2 to 30	2.5 to 40	~30
18	Saturated/Subcooled flow, one side heated	160	2 to 30	2.5 to 40	~30
Number of test runs	Test category	Inlet pressure, kPa	Inlet quality	nPFH mass flow rate g/s	Test duration, min.
32	Two-phase inlet flow, both sides heated	130	0.05 to 0.4	2.25 to 40	~30
31	Two-phase inlet flow, both sides heated	160	0.05 to 0.4	2.25 to 30	~30
21	Two-phase inlet flow, one side heated	130	0.05 to 0.4	2.25 to 40	~30
19	Two-phase inlet flow, one side heated	160	0.05 to 0.4	2.25 to 20	~30

3.1.3 Flow Boiling Test Module Test Matrix Map

The test matrix for the Flow Boiling Test Module is summarized in Table 3.

3.2 FBCE Condensation Test Module 1

The FBCE Condensation Test Module 1 is also referred to as the Condensation Module – Heat Transfer, or CM-HT. It contains a polycarbonate test section outfitted with 61 thermocouples and four pressure transducers. The primary elements are shown in Figure 18, with the enclosure walls made transparent in the solid model to show the internal components. The Condensation Test Module 1 does not have its own electronics, but utilizes Avionics 1 for thermocouple signal conditioning.

The test section for the Condensation Test Module 1 is comprised of two polycarbonate pieces held in compression by metallic clamp plates, with circular cross section polycarbonate flow channel contained by two O-ring seals machined inside the polycarbonate. A brazed stainless steel tube is located inside the circular flow channel, creating an annular space between the outer tube wall and the inner polycarbonate wall. Test fluid is flowed inside the stainless steel tube (see Figure 19) while ITCS cooling water is flowed in the opposite direction through the annular space outside of the condensation tube.

The test section for Condensation Test Module 1 is outfitted with 61 thermocouples to measure temperature in both the cooling water and test fluid streams. Four thermocouple probes measure the test fluid and water stream temperatures at the inlet and outlet. An additional twenty-four thermocouple probes measure the water stream temperature along the test section length. Thirty-three more thermocouples are installed on the brazed tube exterior wall in eleven locations along its length, with three thermocouples spaced radially at each location, as shown in Figure 20.

Also included in the Condensation Test Module 1 are two pressure transducers to measure test fluid absolute pressure, and two pressure transducers to measure water absolute pressure.

The Condensation Test Module 1 enclosure consists of eight aluminum panels that encompass all of the Condensation Test Module hardware.

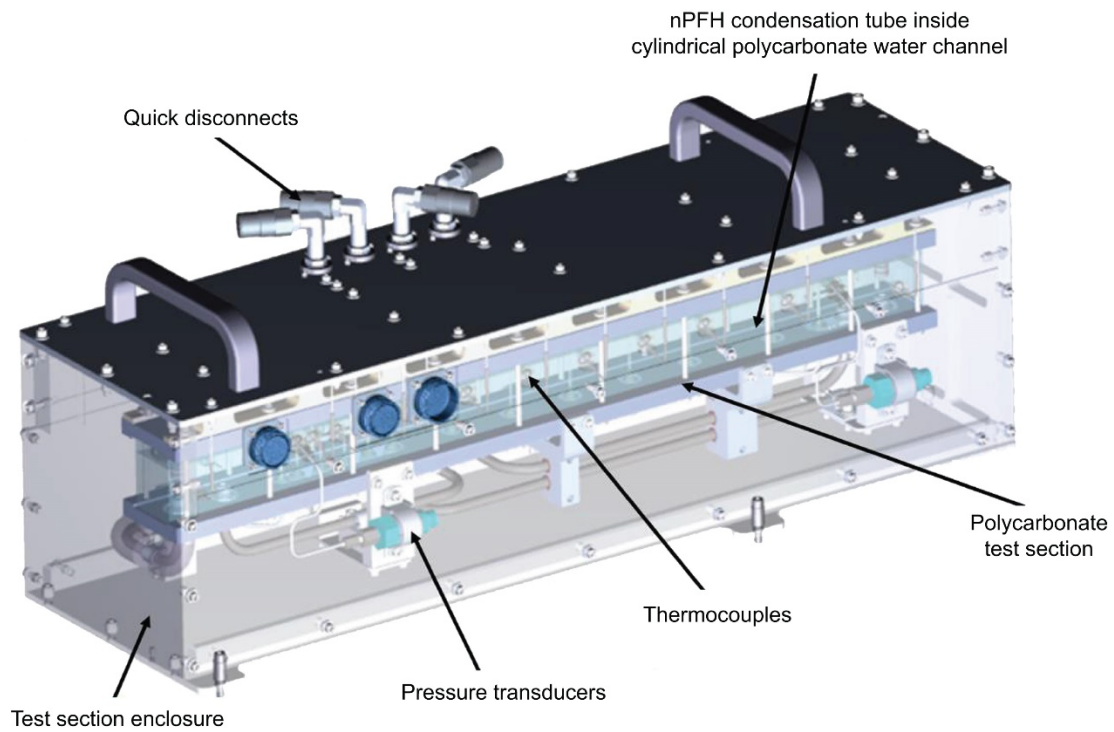


Figure 18.—Primary elements in the Condensation Test Module 1.



Figure 19.—Braided tube installed in the lower polycarbonate piece of the Condensation Test Module 1.

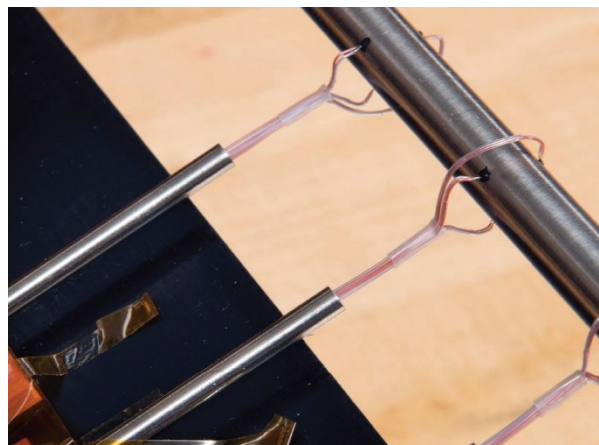


Figure 20.—Thermocouples installed on the Braided Stainless Steel Condensation Tube.

3.2.1 Condensation Test Module 1 Test Matrix Map

The test matrix for Condensation Test Module 1 is summarized in the Table 4.

3.3 FBCE Condensation Test Module 2

While Condensation Test Module 1 has the capability of direct heat transfer measurements, to achieve direct optical access to the condensing film, the nPFH vapor will be passed through a square transparent outer channel, while the cooling fluid (water) will be supplied in counter-flow through a central seamless stainless-steel tube in Condensation Test Module 2 (also referred to as the Condensation Module – Flow Visualization, or CM-FV). As shown in Figure 21, the condensing liquid film will form on the exterior of the stainless tube, which would be clearly seen through the walls of the transparent outer channel.

TABLE 4.—CONDENSATION TEST MODULE 1 TEST MATRIX MAP

Number of test runs	Inlet quality	Inlet pressure, kPa	nPFH flow rate, g/s	Water flow rate, g/s	Test duration after reaching SS, min.
21	1	130	2 to 13	10, 20, 25	5
21	1	160	2 to 13	10, 20, 25	5
12	0.4 to 0.8	130	4 to 14	25	5
12	0.4 to 0.8	160	4 to 14	25	5

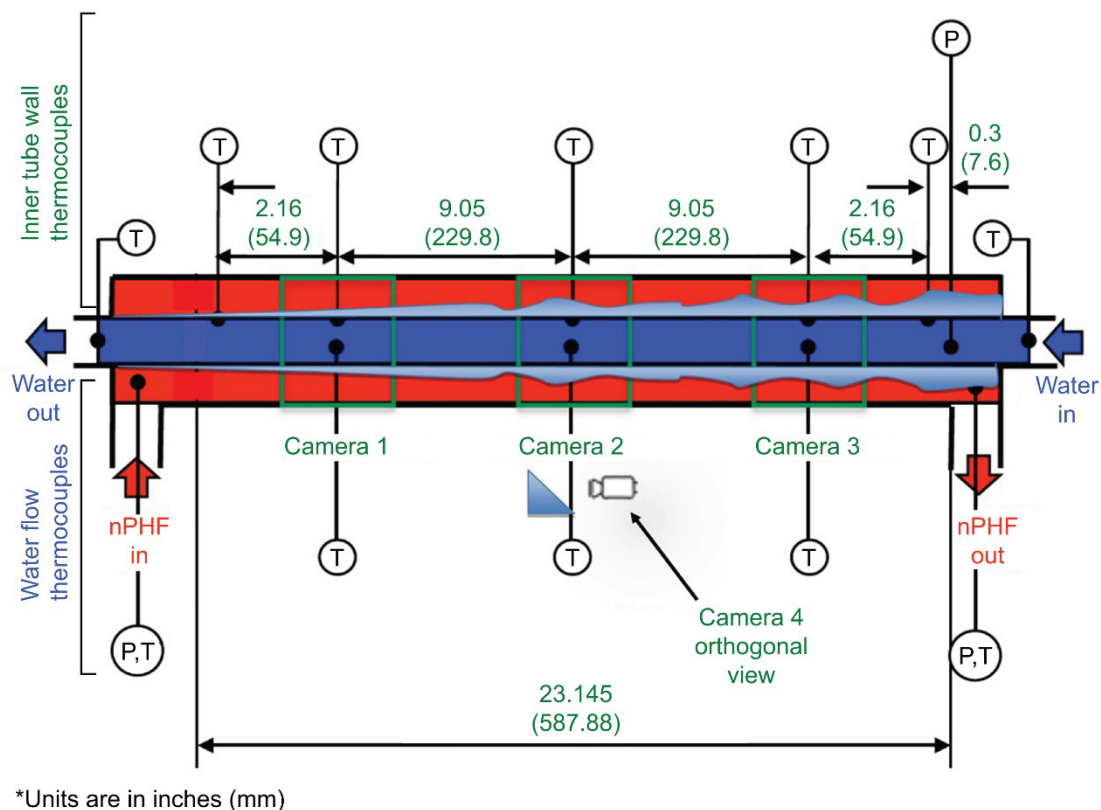


Figure 21.—Schematic of the Condensation Test Module 2.

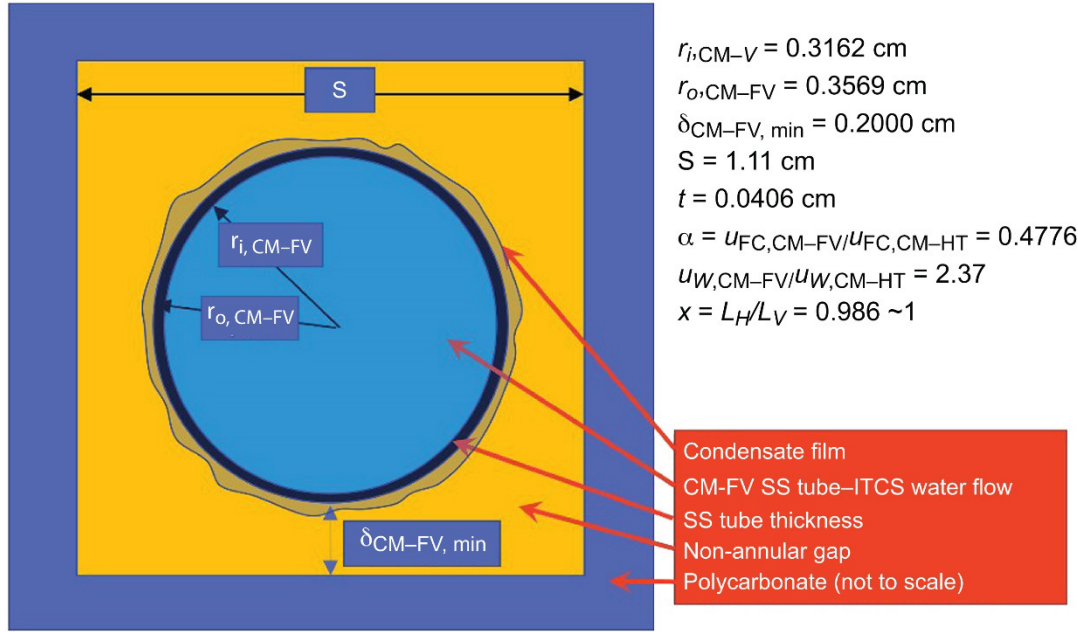


Figure 22.—Condensation Test Module 2 cross section.

TABLE 5.—CONDENSATION TEST MODULE 2 TEST MATRIX MAP

Number of runs	Inlet quality	Inlet Pressure kPa	nPFH flow rate g/s	Water flow rate, g/s	Test duration after reaching SS, min.
21	1	130	2 to 13	10, 20, 25	5
21	1	160	2 to 13	10, 20, 25	5
12	0.4 to 0.8	130	4 to 14	25	5
12	0.4 to 0.8	160	4 to 14	25	5

Condensation Test Module 2 will be designed to facilitate high-speed video analysis of the condensing film. The test module shall withstand a maximum operating pressure of 160 kPa. In Condensation Test Module 2, the nPFH vapor will be supplied through a square transparent annulus with an inner width of 1.11 cm as shown in Figure 22. The cooling water will be supplied through a central stainless steel tube with 0.63 cm i.d. in counterflow to condense the vapor along the inner tube's outer wall. These dimensions result in a minimum gap width of 2 mm. These dimensions were derived based on the equivalency of the condensation length between Condensation Test Module 1 and 2, and based on the nPFH vapor superficial velocity ratio in Condensation Test Module 1 to that in Condensation Test Module 2 of 0.48.

In Condensation Test Module 2, interfacial behavior will be imaged with temporal and spatial resolutions to capture flow behavior for flow velocities in the range of 0.7 to 7 m/s. Digital image sequences will be recorded simultaneously at three selected locations within the same viewing plane along the flow direction (inlet, midpoint and outlet). These images will be used for film thickness measurements. A fourth camera oriented orthogonal to the middle camera and having an overlapping field of view with the middle camera will record digital images simultaneously with the other three cameras. Visualization regions will be located near the beginning, in the middle and near the end of the of the condensation length of Condensation Test Module 2. Visualization will be centered on the central stainless tube and bulk water thermocouples.

3.3.1 Condensation Test Module 2 Test Matrix Map

The test matrix for Condensation Test Module 2 is summarized in Table 5.

4.0 Approximate Module Masses and Dimensions

The total masses and volumes for each FBCE module, as estimated from the assembly drawings, are summarized in Table 6. Masses will be updated when final system is weighed prior to system integration in the FIR Ground Integration Unit.

5.0 Test Section Constraints

The matrix below Table 7 describes the capabilities and constraint of the test sections.

TABLE 6.—FBCE MODULE MASS AND SIZE APPROXIMATIONS

Module name	Estimated mass, kg	Estimated length, m	Estimated width, m	Estimated height, m
Flow Boiling Test Module	N/A	0.8890	0.2794	0.2413
Condensation Test Module 1	N/A	0.8890	0.2794	0.2413
Condensation Test Module 2	N/A	0.8890	0.2794	0.2413
Fluid Module 1	66.56	0.6604	0.406	0.3145
Fluid Module 2	28.45	0.5144	0.267	0.159
Heater	28.45	0.3785	0.210	0.323
Avionics 1	N/A	0.4310	0.2794	0.1397
Avionics 2	N/A	0.4310	0.2794	0.1397
Power Filter	4.30	0.180	0.180	0.101

TABLE 7.—FBCE CAPABILITIES AND CONSTRAINTS

FBCE Capabilities			
	Flow Boiling Test Module	Condensation Test Module 1	Condensation Test Module 2
Test Module Assembly Volume, cm ^{3a}	86×24×24	86×24×24	86×24×24
Flow Rate Envelope, g/s	2.5 to 40	2.5 to 13	2.5 to 13
Maximum Cooling, W	~20	~800	~800
Maximum Heating, W	340	0	0
Max. Number of TCs	14	61	18
Max. Number of Pressure Transducers (Test Fluid)	5	2	2
Degassing	Upon need	Upon need	Upon need
FBCE Constraints			
	Flow Boiling Test Module ^b	Condensation Test Module 1	Condensation Test Module 2
Operating Pressure, kPa	100 to 190	100 to 190	100 to 190
Controls	Heater Shutdown	None	None
ITCS Water Flow Rate, g/s	N/A	25	25
FIR Bench Volume, cm ³	91×121×48	91×121×48	91×121×48
Return ITCS cooling temperature, °C	< 49	< 49	< 49
FBCE Maximum Power Available, W	1540+340	1540	1540
FBCE Maximum Cooling, W	1540+340	1540	1540
Maximum nPFH Temperature, °C	100	100	100
Maximum Surface Temperature, °C	132	100 ^c	100 ^c

^aIt is anticipated that any future test module that is used in FBCE will have to conform with the constraints in Table 7.

^bMaximum surface temperature is dictated by safety requirements for nPFH.

^cMaximum surface temperatures are dictated by the nPFH and water thermodynamic conditions not to exceed 100 °C.

Appendix A.—Acronyms

Acronym	Definition
BHM	Bulk Heater Module (FBCE Heater)
°C	Degrees Celsius
CCU	Confocal Control Unit
CHF	Critical Heat Flux
DC (or dc)	Direct Current
EMI	Electromagnetic Interference
EPCU	Electrical Power Control Unit
FBCE	Flow Boiling and Condensation Experiment
FCF	Fluid Combustion Facility
FIR	Fluid Integration Rack
GPI	General Package Interfaces
ICD	Interface Control Document
I/O	Input/Output
IOP	Input/Output Processor
IPSU-CL	Imaging Processing and Storage Unit - Camera Link
ISS	International Space Station
ITCS	Internal Thermal Control System
nPFH	normal Perfluorohexane
PCB	Printed Circuit Board
PI	Principal Investigator
QD	Quick Disconnect
RTD	Resistance Temperature Detector
SAMS	Space Acceleration Measurement System
SSR	Solid State Relay
TMA	Test Module Assembly
TSH	Tri-axial Sensor Head
UML	Universal Mounting Location
V	Volt
VES	Vacuum Exhaust System
WIP	Water Interface Panel

