NASA/TM—2016-218920

The 26th Space Cryogenic Workshop: Overview, Description of Presentations, and List of Abstracts

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January 2016

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Acknowledgments

We would like to thank all of our international participants for making this a truly memorable experience. Special thanks goes to members of the Cryogenic and Fluid Systems Branch at NASA Glenn Research Center for their valuable input during all phases of conference planning. This work was supported by the Evolvable Cryogenics Project under the Science and Technology Mission Directorate at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by technical management.

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Summary

This is a summary of the 2015 Space Cryogenics Workshop that was held in Phoenix, Arizona, June 24 to 26, 2015. The workshop was organized by David Plachta and Jason Hartwig of the Cryogenics and Fluid Systems Branch at NASA Glenn Research Center, and continued the tradition of bringing together specialists in the field of space cryogenics to discuss upcoming and potential space missions, and the development of technologies that support or—more often—are enabling for the science and exploration goals of the world's space agencies. The workshop consisted of two days of talks and poster sessions, and provided ample opportunity for more informal discussions that foster collaborations and cooperation in the space cryogenics community. Selected papers from the workshop are published in a special issue of *Cryogenics*, which is expected to be published by the end of 2015.

Overview

With the sponsorship of the Cryogenic Society of America, NASA Glenn Research Center (GRC) chaired the 26th Space Cryogenics Workshop on June 24-26, 2015, in Phoenix, Arizona. All aspects of space cryogenics were represented, with an emphasis related to previous missions as well as future research.

Abstracts were solicited in all areas of cryogenics related to space applications, including:

- Missions
- Cryostats
- Components
- Sensors
- Instruments
- Cryocoolers
- Facilities
- Launch Vehicles

The abstracts received were broad based in subject and in their source, with 64 institutions represented from 10 different countries.

Welcome to the

26th Space Cryogenics Workshop

Description of Presentations

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Near-Term Missions

As has become traditional, the workshop opened with presentations on the nearest-term missions. In this case, the first series of talks by Shirron and DiPirro (both of NASA Goddard Space Flight Center (GSFC)), Ezoe (Tokyo Metropolitan University), and Narasaki (Sumitomo Heavy Industries, Japan) described the Soft X-ray Spectrometer instrument on the Japanese Astro-H mission, which is currently slated for launch in late January, 2016. The instrument is a successor to the X-Ray Spectrometer instrument launched on Astro-E2 in July 2005, but involves a more complex cryogenic system intended to achieve full operational redundancy. The heart of the instrument is a 6 by 6 array of x-ray microcalorimeters cooled to 50 millikelvin by a 3-stage adiabatic demagnetization refrigerator (ADR). The cryogenic system consists of a 30+ liter superfluid helium tank and a 4.5 K Joule-Thomson (JT) cryocooler, and two pairs of 2-stage Stirling cryocoolers that pre-cool the JT cooler and vapor cooled shields within the dewar. The unique instrument configuration allows it to meet its science goals if either the superfluid helium tank or the 4.5 K JT cooler remain operational, and it has some tolerance for degradation or failures of the Stirling cryocoolers.

Figure 1.—Astro-H Satellite

The talks discussed the operation and thermodynamic performance of the ADR, the porous plug and helium dewar, and the cryocoolers. The system has been shown to meet all of its requirements (most importantly 50 mK detector operation and >90% observing efficiency) in both cryogen and cryogen-free modes. The Astro-H satellite is shown in Figure 1 just prior to thermal vacuum testing at the Tsukuba Space Center, Japan. The testing was successful, and now Astro-H moves on to final vibration and acoustic testing, before being shipped to the launch site at Tanagashima Space Center, Japan.

The second mission discussed was the Remote Robotic Mission 3, by Boyle (NASA GSFC), which will demonstrate the transfer and solidification of methane and xenon, as well as the technologies needed to achieve zero-boiloff (ZBO) storage and a no-vent fill. The methane source tank will use conic vanes to position the liquid for transfer. Both it and the receiver tank have cryocoolers to support the ZBO and no vent fill operations. The system features 2 liquid transfer lines and 1 gas transfer line used for condensing and freezing the methane. The demonstration will be conducted on the International Space Station, as is currently expected to launch in April 2017.

Narasaki (Sumitomo Heavy Industries, Japan) also presented on a possible collaboration between with the Russian Space Agency and the European Space Agency (ESA) on the development of the Millimetron Space Telescope that will use a 4.5 K mirror and detectors cooled to 100 mK. The baseline concept is to use passive cooling of shields surrounding the telescope to 30 to 40 K, and active cryocoolers from 20 K down to 1.7 K. The instrument's detectors will then be cooled to 100 mK using the hybrid He-3 sorption cooler and ADR stage developed by Duband (CEA).

Cryocoolers and Sub-Kelvin Cooling

Although other missions currently in formulation, such as Athena (the next major x-ray observatory being studied by ESA), were not presented directly, there were numerous presentations on the technology developments being undertaken to support them. In particular, recent progress in the development of a closed-cycle dilution refrigerator capable of cooling detectors to 50 mK was described by Butterworth

(AirLiquide) and Vermeulen (Neel Institute). The work extends the operation of the open-cycle DR used on Planck to achieve surface tension confinement of the helium-3/helium-4 mixture and phase separation of the two isotopes needed to achieve the necessary circulation rates in a closed system. Recently, a full-scale demonstration unit was tested in -1 g. The helium-3 was circulated using the compressor developed for SHI's 1.7 K JT cryocooler, and a base temperature of 80 mK was achieved, believed to be limited by the suction pressure (8 mbar actual versus 5 mbar required).

Other innovative cooling system developments were presented, including an active magnetic refrigerator capable of cooling into the sub-kelvin regime (Miller, University of Wisconsin-Madison). The concept involves oscillating flow of cold liquid helium created by demagnetizing a packed bed of Gadolinium Gallium Garnet (GGG), driven by the fountain effect caused by magnetizing a second bed. The concept is capable of cooling powers of ~1 mW at 0.75 K. Also pushing into the sub-kelvin regime, Ullom (NIST, Boulder) has extended the concept of cooling based on superconducting tunnel junctions to be able to cool macroscopic objects. The technique has been shown capable of producing ~60 mK from a 290 mK base temperature. Sullivan (NASA GSFC) also discussed on-going work on continuous ADRs and a new piezo-electrically actuated mechanical heat switch.

Cryocooler development talks were not as prominent at this workshop as in the past, but did include the following: Dave Frank discussed work at Lockheed-Martin on their Coax microcooler (whose compressor is <10 cm in length and weighs less than 450 grams) to increase the cooling power to 2.0 W at 105 K. Butterworth (Air Liquide) presented the design of a 15 K pulse tube (PT) cooler to support the operation of the detector cooling system composed of a 2 K JT cooler and the hybrid helium-3 sorption/ADR system, or the closed-cycle DR for the Athena mission. The concept uses a single-stage PT cooler coupled to the upper stage of a 2-stage PT cooler to achieve >0.3 W at 15 K. Butterworth gave a separate talk on a concept for using the gas from a PT cooler, rectified by check valves and buffers, to transfer cooling to the load. The advantage is an ability to couple redundant coolers, and minimize the parasitic load that a failed cooler imposes, without the use of auxiliary heat switches. In a related presentation, Prouve (CEA) investigated redundant PT coolers (with the 30 K and 100 K stages directly linked to each other) and directly measured the parasitic heat leaks from an inactive cooler. Sato (JAXA) reported on continuing efforts to develop and qualify the 1 K-class JT cooler in support of future astronomy satellites, and Narasaki (SHI) also presented a thermodynamic assessment of a JT cooler using 2-stage JT valves, showing the feasibility of increasing the cooling power of SHI's 1.7 K JT cooler from 10 mW to 20 mW.

Cryogenic Fluid Management

Since 2005, NASA's exploration focus has given rise to renewed efforts to develop and demonstrate the technologies needed for managing cryogenic fluids in space. Consequently, a large segment of the workshop was devoted to technologies and methods associated with liquid acquisition, pressure and temperature control, zero-boiloff systems, thermal insulation and chilldown of cryogenic tanks, as well as zero-g experimentation with both cryogenic and simulant fluids.

As mentioned, RRM-3 will use conic vanes for fluid control, but screen channel systems can support higher flow rates based on the higher surface tension forces acting on the fluid at the screen surface. Several papers presented studies of pressure drop (Darr, University of Florida) and bubble point testing (Hartwig, NASA GRC) of screen channel systems, as well as the effectiveness of these devices in liquid H2 outflow tests (Zimmerli, NASA GRC) in the engineering demonstration unit built for the Cryogenic Propellant Storage and Transfer (CPST) project. Modeling of the chilldown and filling process for the same tank was presented by Hedayat (NASA Marshall Space Flight Center (MSFC)), and modeling of the effect of a thermodynamic vent system to control ullage pressure was presented by Majumdar (also of NASA MSFC).

In large-scale systems, the testing by Plachta (NASA GRC) validated model predictions that show that for storage of liquid H2 and O2 propellants, adding a cryocooler (and its power system) to achieve zero-boil-off is the lower mass option when storage times exceed a few weeks. Using broad area cooling to distribute the cooling along the tank walls, a demonstration of ZBO was conducted using a Creare turbo-Brayton cooler (like that used on Hubble's NICMOS instrument) resulted in temperature gradients on the liquid nitrogen tank of less than 4 K and ZBO tank pressure control demonstrated to within ±0.1 psi. From a related paper by Guzik (NASA GRC), while ZBO for a liquid H2 tank would require cooling powers of kilowatts at 20 K, a direct analytical method for reduced boil-off strategies require cooling only to 90 K was presented, which distributes cooling along the shield surrounding the tank. Another ZBO development was presented by Chato (NASA GRC) on the progress and development of the ZBOT (Zero Boil-Off Technology) micro-gravity science experiment, which is slated to fly on Space X 10 and scheduled to launch in year 2016.

In related work, Stephens (NASA GRC) showed that the effect of introducing pressurant gas, in order to transfer liquid H2, into bulk liquid as opposed to the ullage space, significantly increases the amount of gas needed to reach desired pressures, as the gas thermalizes far more rapidly. The side effect is a ~2x times larger heat input from the pressurant gas.

Zero-G Fluid Behavior

Although large-scale investigations of fluids in zero-g, such as CPST (Cryogenic Propellant Storage and Transfer), have not gotten off the ground, so to speak, a number of smaller-scale experiments have made use of drop-towers, sounding rocket launches and zero-g airplane flights to make shorter duration observations. The talks on Cryofenix by Mathey (AirLiquide) and Legrand (CNES) report the first observations of liquid H2 from sounding rocket platforms since the 1960s. With 6 minutes of microgravity, the experiment used a cold gas system to impose accelerations and an array of sensors to monitor pressures, thermal stratification, and settling times (including de-spin). Good agreement between CFD model predictions and observations was reported.

Schmitt (University of Bremen) described drop-tower tests looking at the behavior of liquid H2 in response to step changes in gravity. In particular, the experiment used visualization of the fluid to see the effect of heat inputs to the walls. Fluid flow along the walls was not obviously affected, but the pressure in the vapor bubble that forms was significantly increased.

Other Technology Reports

A number of other noteworthy presentations were made whose topics don't neatly fit into the broad groupings outlined above. In particular, Schlachter (Kahrlsruhe Institute of Technology) summarized testing of a High Temperature Superconducting (HTS) magnet that was designed to divert the plasma produced during re-entry in an effort to mitigate the radio blackout normally experienced. Tests of a 10 cm diameter bore REBCO magnet subjected to 450 K plasma showed an ability to maintain 2 T external fields. Modeling of the plasma distribution shows the ion density is low enough to prevent loss of communication.

Vanapalli (University of Twente) described a heat switch made entirely by additive machining techniques for connecting electronics boxes to radiators for thermal control. Fesmire (NASA Kennedy Space Center (KSC)) presented data on the effectiveness of layered composite thermal insulation using multi-layer insulation and aerogel blankets, and Johnson (NASA GRC) described a test platform for evaluating the performance of large-scale thermal insulation and structural supports as part of the Evolvable Cryogenics (eCryo) Project. Tuttle (NASA GSFC) reported on the thermal absorptance of gold-coated stainless steel tubing, used on the James Webb Space Telescope, in which the absorptance was determined to be higher than that expected from pure gold. Courts (LakeShore Cryotronics) described the effort at LakeShore to produce a standard line of flight-qualified thermometers, including diodes, Cernox, and germanium sensors. The goal is to reduce delivery time and cost.

Pamidi (Florida State University) described a test system for direct caloric measurements of ac losses in superconducting motors for use in aerospace planes. Allen (Michigan Technological University) described a measurement technique for determining evaporation and condensation coefficients for cryogenic propellants, and Kassemi (NASA GRC) presented on the effect of interfacial turbulence and accommodation coefficients in CFD modeling of pressure control in cryogenic storage tanks.

Titan Mission Studies

To conclude this summary, it seems fitting to come back to the central theme of space exploration, and specifically to two talks that presented the most far-reaching and creative thinking: how to explore Saturn's moon Titan. Titan atmosphere is 95% nitrogen at 1.5 bar, and has a methane cycle that is similar to the water cycle on Earth. DeLee (NASA GSFC) presented a study of a cryogenic propulsion system for the Titan Orbiter Polar Surveyor (TOPS). The mission duration would be 10+ years, and any cryogens used in propulsion would have to be preserved for at least 8 years. Power is limited, so no active cooling is possible. The conclusion was that liquid H2/O2, using the most advanced load responsive MLI and launching subcooled, represented the most mass advantageous solution.

But nothing at the workshop compared to the eye-catching subject of Hartwig's (NASA GRC) presentation "Exploring the depths of the Kraken Mare". Kraken Mare, we are to understand, is one of three stable hydrocarbon seas on Titan (the others being Punga Mare and Ligeia Mare, as seen in Figure 2 taken by the Cassini spacecraft), and the goal was to design a submersible vehicle that could navigate in and study these 90 to 96 K oceans, in part to see if hydrocarbon-based life is possible on Titan. The task is complicated by the fact that the seas vary in ethane/methane concentration, so buoyancy and thermal control requirements are different. The concept presented is shown in Figure 3, and was based on maintaining the internal environment near 300 K, while managing heat exchange and power generation for the instruments and submarine communication and propulsion systems. There is too much to the study to describe here, but it's definitely a mission that offers an exciting challenge to the cryogenics community.

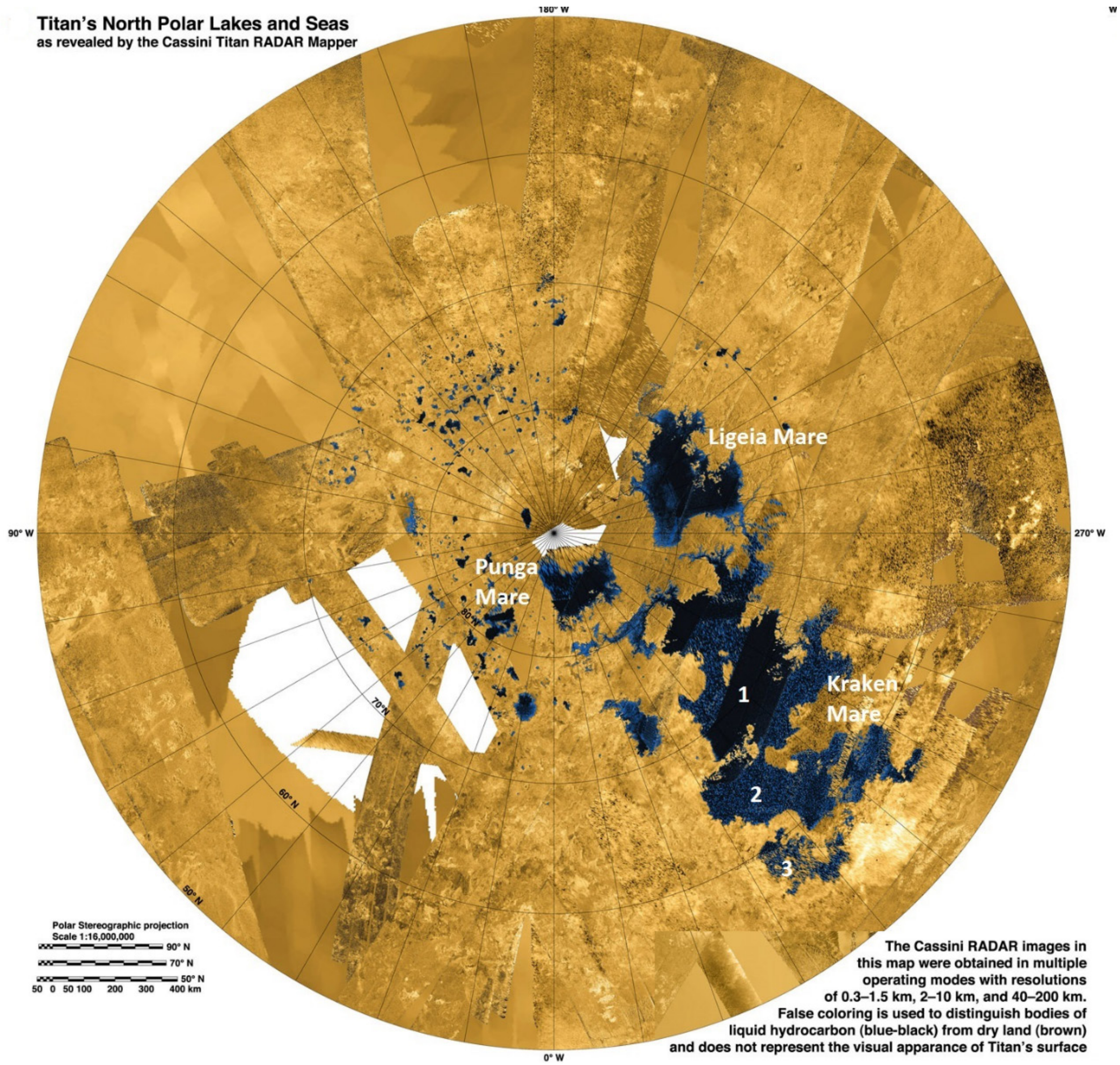

Figure 2.—Cassini Radar Mosaic of Titan's North Polar Regions (stereographic projection: the color table is adjusted to portray liquid hydrocarbon areas as black and blue). Titan's three seas, Punga, Ligeia and the sprawling Kraken Mare are seen, as well as many small lakes. White areas are unimaged by radar at present. Image: NASA/JPL/USGS.

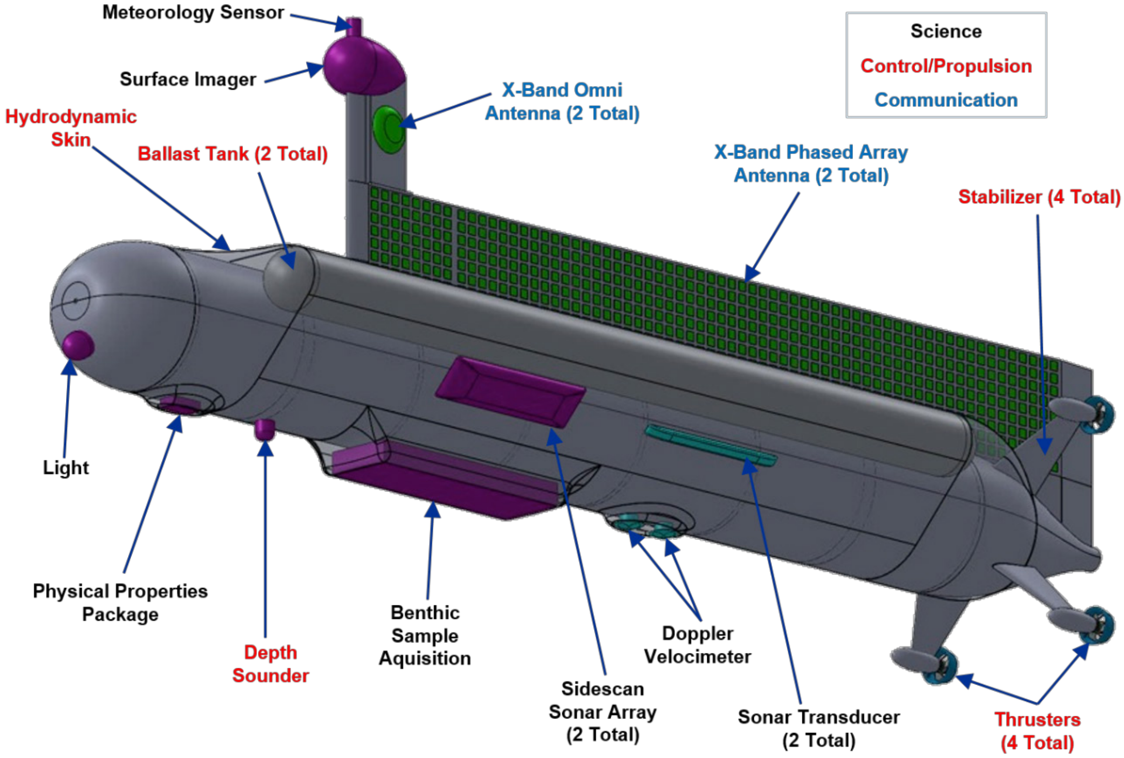

Figure 3.—Titan Submarine Concept

Compiled List of Abstracts

Oral Session: Space Experiments I

Operating Modes and Performance Testing of the Flight ADR for the Soft X-ray Spectrometer Instrument on Astro-H

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Abstract

The Soft X-ray Spectrometer (SXS) is one of 4 x-ray sensing instruments that will be flown on the Japanese Astro-H satellite, planned for launch in late 2015/early 2016. The SXS uses a 6x6 array of microcalorimeters to perform imaging spectroscopy in the soft x-ray band (0.3 to 12 keV). The energy resolution requirement of <7 eV is achieved in part by cooling the array to 50 mK, using a 3-stage adiabatic demagnetization refrigerator (ADR). The detector assembly and ADR, developed by NASA GSFC, is supported by a dewar, developed by Sumitomo Heavy Industries, Japan, that contains a superfluid helium tank, 3 pairs of 2-stage Stirling cryocoolers and a 4.5 K Joule-Thomson (JT) cryocooler. The ADR is configured so that it can use either the superfluid helium (at 1.3 K) or the JT cooler as its heat sink, thereby achieving full redundancy in the cryogenic system. The configuration has other capabilities, such as the ability to maintain launch conditions indefinitely without active pumping, and the ability to reduce the heat load on the liquid helium on orbit. The flight detector assembly, ADR, and dewar were integrated in early 2014, and have since undergone extensive performance and vibration testing prior to delivery for integration with the spacecraft. This paper summarizes the operation and performance of the ADR for all of its operating modes.

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Flight Model Measurements of the Porous Plug and Film Flow Suppression System for the Astro-H Soft X-ray Spectrometer Dewar

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Abstract

This paper describes flight model measurements of Helium flow rate through a porous plug phase separator and a film flow suppression system for the ASTRO-H Soft X-ray spectrometer dewar. ASTRO-H is the sixth Japanese astronomy satellite and will be launched in 2016. The Soft X-ray Spectrometer (SXS) consists of X-ray focusing mirrors and an X-ray microcalorimeter array operated at 50 mK. Superfluid liquid helium is employed as a part of the cooling system. The helium mass flow rate is ~30 μg/s in the nominal condition where the helium temperature is ~1.15 K. Such a small flow rate must be safely vented in zero gravity. At the same time, superfluid He film flow through the vent line must be < 2 μg/s to avoid extra loss of the liquid helium. For this purpose, a porous plug phase separator together with a film flow suppression system is installed. To verify its performance, the flow rates from the flight model dewar are measured by tilting the dewar so that the one side of the porous plug located at the top of the dewar is immersed in the liquid helium and the porous plug separates the liquid and vapor helium by the thermomechanical effect. The flow rates are measured at various temperatures (1.15, 1.3, 1.5, and 1.9 K) and temperature differences across the porous plug are obtained. The results are consistent with component test results, suggesting that the porous plug and the film flow suppression system works properly in the flight model dewar. In this paper, we present the design of the system and the testing results.

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Flight Model Performance Test Results of a Helium Dewar for the Soft X-ray Spectrometer Onboard ASTRO-H

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Abstract

ASTRO-H is a Japanese X-ray astronomy satellite, scheduled to be launched in calendar year 2016. The mission includes a soft x-ray spectrometer instrument, which contains an X-ray micro calorimeter operating at 50 mK by using an adiabatic demagnetization refrigerator (ADR). The heat sink of the ADR is superfluid liquid helium below 1.3 K. The required lifetime of the superfluid helium is 3 years or more. In order to realize this lifetime, we have improved the thermal performance from the engineering model (EM) while maintaining the mechanical performance. Then, we have performed a thermal test of the flight model (FM). The results were that the heat load to the helium tank was reduced to 0.75 mW in the FM from 1.2 mW in the EM. Therefore, the lifetime of the superfluid helium is more than 3 years with 30 L of liquid helium. In this paper, the thermal design and test results are described.

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Thermal Loads, Conductances, and Efficiencies of the Adiabatic Demagnetization Refrigerator Developed for the Astro-H Instrument

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Abstract

The Soft X-ray Spectrometer, developed for the United States contribution to the international Astro-H mission, requires a 50 mK operating temperature stable to better than 2 micro-Kelvin to achieve its required resolution and sensitivity. These specifications are met using a multi-stage adiabatic demagnetization refrigerator (ADR) developed specifically for this mission. The flight ADR and detector array have been integrated into the flight dewar developed by Sumitomo Heavy Industries, Japan and linked to both available heat sinks: a 1.2 K pumped helium bath and a 4.5 K Joule-Thomson cooler. We have quantified the ADR in the flight configuration and present the results in this paper. The heat loads produced by the ADR to each heat sink, the thermal conductances between the ADR stages and the external heat sinks, and the thermodynamic efficiency of the cooler itself will be described.

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Measuring the Heat Load to the SXS Helium Tank

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Abstract

The Soft X-ray Spectrometer (SXS) instrument on-board the ASTRO-H X-ray mission is based on microcalorimeters operating at 50 mK. Low temperature is achieved by use of an adiabatic demagnetization refrigerator (ADR) cyclically operating up to a heat sink at either 1.2 or 4.5 K. The 1.2 K heat sink is provided by a 40 liter superfluid helium dewar. The parasitic heat to the helium from supports, plumbing, wires, and radiation, and the cyclic heat dumped by the ADR operation determine the liquid helium lifetime. To measure this lifetime we have used various techniques to rapidly achieve thermal equilibrium and then measure the boil-off rate of the helium. We have measured a parasitic heat of 650 microwatts and a cyclic heat of 100 microwatts for a total of 750 microwatts. This closely matches the predicted heat load. Starting with a fill level at launch of more than 33 liters results in a lifetime of greater than 4 years for the liquid helium. The techniques and accuracy for this measurement will be explained in this paper.

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Cryogenic Thermal Absorptance Measurements on Small-Diameter Stainless Steel Tubing

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Abstract

The Mid Infrared Instrument (MIRI) on the James Webb Space Telescope include a mechanical cryocooler which cools its detectors to their 6 K operating temperature. The coolant gas flows to the Joule-Thomson valve through small-diameter stainless steel tubing, which is exposed to thermal radiation from its environment. Over much of its length, this tubing is gold-plated to minimize the absorption of this radiant heat. In order to confirm that the cryocooler will meet MIRI's requirements, the thermal absorptance of this tubing was measured as a function of its environment temperature. We describe the measurement technique and present the results.

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Oral Session: Refrigerators

1-D Transient Numerical Model of a Regenerator in a Novel Sub-Kelvin Active Magnetic Regenerative Refrigerator

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Abstract

A sub Kelvin Active Magnetic Regenerative Refrigerator (AMRR) is being developed at the University of Wisconsin, Madison. This AMRR consists of two circulators, two regenerators, one superleak, one cold heat exchanger, and two warm heat exchangers. The circulators are novel non-moving part pumps that reciprocate a superfluid mixture of ^4He-^3He in the system. Heat from the mixture is removed within the two regenerators of this tandem system. An accurate model of the regenerators in this AMRR is necessary in order to predict the performance of these components, which in turn helps predicting the overall performance of the AMRR system. This work presents modeling methodology along with results from a 1-D transient numerical model of the regenerators during operation of the system at cyclic steady state.

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Status of the Closed-Cycle Dilution Refrigerator for Space Applications

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Abstract

A closed-cycle dilution refrigerator for space is under development at Institut Néel and Air Liquide. This system has been baselined for the Core+ mission (ESA M4 candidate). It is also considered as a back-up solution to the ADR for the X-IFU instrument on Athena. Preliminary tests demonstrate the operation of each low temperature component: the mixing chamber can provide close to 1 μW at 50 mK, the still (vapor liquid phase separator) can confine the ^{3}He-^{4}He mixture under negative gravity and liquid ^{4}He can be re-circulated thanks to a fountain pump. Two major components are still needed in order to increase maturity at system level: the ^{3}He compressor needed to recirculate the ^{3}He from the still and, at least on European side, a 1.7 K cooler (providing about ~5 mW cooling power in order to liquefy the incoming ^{3}He) that is the base temperature at which the (Closed Cycle Dilution Refrigerator) CCDR starts to operate. For both system, potential solutions have been identified and studied. We present a status on the CCDR including most recent tests in negative gravity conditions. We also present potential ^{3}He and 1.7 K options together with their development status. Then, we discuss the next steps for the CCDR system development.

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Refrigeration of a Robust, Macroscopic Platform using Superconducting Tunnel Junctions

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Abstract

Sub-Kelvin temperatures are often required for modern science. For instance, ultra-sensitive cryogenic detectors operating at sub-Kelvin temperatures are critical for experiments designed to understand the structure and origins of universe through polarization measurements of the cosmic microwave background. These measurements are performed with terrestrial, balloon-borne, and satellite instruments. Current techniques to reach 100 mK temperatures, dilution refrigerators and adiabatic demagnetization refrigerators, are expensive, bulky, and complex and their operation in space poses additional challenges. To increase the accessibility of these low temperatures, we are developing refrigerators based on Normal-Metal / Insulator / Superconductor (NIS) tunnel junctions. This cooling technique has the potential to provide an economical, light-weight, and compact means of reaching 100 mK that is suitable for space-based applications. In an NIS junction, the hottest electrons in the normal metal preferentially tunnel from the normal metal into the superconductor, transferring heat in the process. By extending the normal metal onto a micromachined membrane, it is possible to cool a galvanically separate payload that is thermally connected to the membrane.

We have pioneered two techniques for coupling NIS refrigerators to sensor payloads. In the first, the sensors and the refrigerators are lithographically integrated on the same silicon chip. In the second, the NIS refrigerators cool a macroscopic platform to which a wide range of payloads can be attached. This approach provides functionality similar to an adiabatic or demagnetization refrigerator subject to the performance limits of the NIS devices. Here, we give an update on our progress cooling a general purpose, macroscopic platform. We demonstrate increased cooling powers and a temperature reduction from 291 to 228 mK. We have also greatly improved the robustness of the macroscopic platform which consists of a copper stage that is thermally isolated using Kevlar cord. We discuss plans to increase the temperature reduction. Performance models indicate that cooling from 300 to 100 mK is possible with a single stage of NIS junctions. This level of performance would make 100 mK temperatures accessible in inexpensive and simple sorption-pumped ^{3}He cryostats.

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Liquid Confinement in the Still of a Negative Gravity Closed Cycle Dilution Refrigerator

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Abstract

We are developing a zero gravity ^3He-^4He closed cycle dilution refrigerator (CCDR) combining the three-stream heat exchanger design of the open cycle dilution refrigerator (OCDR) of the Planck mission with an isotope separator—also known as still—at about 1K. The OCDR works by ejecting the helium mixture into space after dilution. Therefore, the OCDR requires embarking large quantities of ^3He and ^4He limiting the lifetime and the cooling power to 2.5 years and 0.2 μW at 100 mK on the Planck mission. The still of the CCDR allows to close the cycle by separating the helium mixture stream into streams of pure ^4He and of almost pure ^3He for reuse in the refrigerator. Therefore, the CCDR makes it practically possible to satisfy the cryogenic requirements of future space missions (Core, Athena+), namely a cooling power of about 1 μW at 50 mK and a lifetime of 10 years. The coexistence of liquid and vapor phases in the still poses the problem of how to confine the liquid in the still under zero gravity conditions. We have constructed a CCDR to test the confinement of the liquid mixture in the still under "negative gravity" conditions. We present the design of the refrigerator, results of the tests, and reflections on the physical problems in the still such as the repartition of liquid and gas and thermal and concentration gradients.

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A Continuous Adiabatic Demagnetization Refrigerator for Cosmic Microwave Background Experiments

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Abstract

We report on our measurement results for the operation of a Continuous Adiabatic Demagnetization Refrigerator (CADR), which will provide detector cooling for the upcoming PIPER and PIXIE missions aimed at studying the polarization of the Cosmic Microwave Background radiation. The four-stage CADR presently being tested operates continuously at 100 mK, using a 4.2 K liquid helium bath as a heat sink. We discuss our measurements of the CADR cooling power, and the dependence of the refrigeration cycle as the heat loads on the stages are varied.

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Oral Session: Space Experiments II

Exploring the Depths of Kraken Mare—Power, Thermal Analysis, and Ballast Control for the Saturn Titan Submarine

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Abstract

To explore the depths of the hydrocarbon rich seas on the Saturn moon Titan, a conceptual design of an unmanned submarine concept was recently developed for a Phase I NASA Innovative Advanced Concept (NIAC) study. Data from Cassini Huygens indicates that the Titan polar environment sustains stable seas of variable concentrations of ethane, methane, and nitrogen, with a surface temperature around 93K. To meet science exploration objectives, the submarine must operate autonomously, study atmosphere/sea exchange, interact with the seabed at pressures up to 10 atm, traverse large distances with limited energy, hover at the surface and at any depth within the lake, and be capable of tolerating multiple different concentration levels of hydrocarbons. Therefore Titan presents many cryogenic design challenges. This paper presents the trade studies and preliminary design of the power, thermal, and ballast control subsystems for the Saturn Titan submarine.

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Development of the Cooling System of the Millimetron Space Telescope

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Abstract

Among other space telescope missions, there is the Millimetron Mission (Ref. 1) developed by worldwide cooperation. At SCW2013 we made a presentation on the research of materials for the cryogenic telescope (Ref. 2). This presentation deals with the results we have achieved developing the cryogenically cooled mirror and the instrumentation of the Millimetron telescope. We have designed an active-passive cooling system for the 10 m diameter MM&IR mirror of the space telescope. The concept of the cooling system is similar to that used in the Planck space mission (Ref. 3). The passive component of the cooling system includes passive metal-coated polyimide radiation shields providing passive cooling down to 50 K. This system has been designed and tested in the JSC Academician M. F. Reshetnev Information Satellite Systems (Krasnoyarsk) (Ref. 4). The active refrigerating system provides deep cooling of the mirror and receiver down to 4 K and 300 mK. The active refrigerating system is an on-board 4 K Sumitomo space refrigerator-based system (Ref. 5). Subkelvin refrigerators that cool individual elements of the detectors are incorporated into the detector assemblies. For example, the matrix FTS receiver is cooled down to 0.3 K (Ref. 6) by a cryosorption cooler, connected with a 4 K plate of a cooler.

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Long-Term Cryogenic Propellant Storage for the Titan Orbiter Polar Surveyor (TOPS) Mission

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Abstract

Cryogenic propellants such as liquid hydrogen (LH2) and liquid oxygen (LO2) can dramatically enhance NASA's ability to explore the solar system because of their superior specific impulse (Isp) capability. Although these cryogenic propellants can be challenging to manage and store, they allow significant mass advantages over traditional hypergolic propulsion systems and are therefore technically enabling for many planetary science missions. New cryogenic storage techniques such as subcooling and the use of advanced insulation and low thermal conductivity support structures will allow for the long term storage and use of cryogenic propellants for solar system exploration, and hence allow NASA to deliver more payloads to targets of interest, launch on smaller and less expensive launch vehicles, or both. Employing cryogenic propellants will allow NASA to perform missions to planetary destinations that would not be possible with the use of traditional hypergolic propellants. These new cryogenic storage technologies were implemented in a design study for the Titan Orbiter Polar Surveyor (TOPS) mission, with LH2 and LO2 as propellants, and the resulting spacecraft design was able to achieve a 43% launch mass reduction over a TOPS mission that utilized a conventional hypergolic propulsion system with mono-methyl hydrazine (MMH) and nitrogen tetroxide (NTO) propellants. This paper describes the cryogenic propellant storage design for the TOPS mission and demonstrates how these cryogenic propellants are stored passively for a decade-long Titan mission.

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Oral Session: Thermal Control

Layered Composite Thermal Insulation System for Non-Vacuum Cryogenic Applications

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Abstract

A problem common to both space launch applications and cryogenic propulsion test facilities is to provide suitable thermal insulation for complex cryogenic piping, tanks, and components that cannot be vacuum-jacketed or otherwise broad-area covered. Vacuum-jacketed piping systems, whether part of the ground equipment or the flight vehicle, typically include numerous terminations, disconnects, umbilical connections, or branches that must be insulated by non-vacuum means. Broad area insulation systems such as spray foam or rigid foam panels are often the lightweight materials of choice for vehicle tanks, but the plumbing elements, feedthroughs, appurtenances, and structural supports all create "hot spot" areas that are not readily insulated by similar means. Finally, the design layouts of valve control skids used for launch pads and test stands can be nearly impossible to insulate due to their complexity and high density of components and instrumentation, especially if thermal insulation requirements are considered as an afterthought. Primary requirements for such non-vacuum thermal insulation systems include the combination of harsh conditions including full weather exposure, vibration, and structural loads. Further requirements include the right level of system breathability for thermal cycling, reliability, and safety. To meet these requirements and provide a practical solution to the problem, a layered composite insulation system has been developed for non-vacuum applications and extreme environmental exposure conditions. The system, called Layered Composite Insulation for Extreme Conditions (or LCI-EX) is particularly suited for complex piping or tank systems that are difficult or practically impossible to insulate by conventional means. Comprised of several functional layers, the aerogel blanket-based system can be tailored to specific thermal performance requirements. The system is suitable for temperatures from approximately 4 K to 400 K and can be designed to insulate liquid hydrogen, liquid nitrogen, liquid oxygen, or liquid methane equipment. Laboratory test data for thermal and mechanical performance are presented. Different design configurations of the LCI-EX system are discussed. Field demonstration cases and examples in operational cryogenic systems are also given.

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The Structural Heat Intercept-Insulation-Vibration Evaluation Rig

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Abstract

NASA is currently investigating methods to reduce the boil-off rate on large cryogenic upper stages. Two such methods to reduce the total heat load on existing upper stages are vapor cooling of the cryogenic tank support structure and integration of thick multilayer insulation systems to the upper stage of a launch vehicle. Previous efforts have flown a 2-layer MLI blanket and shown an improved thermal performance, and other efforts have ground-tested blankets up to 70 layers thick on tanks with diameters between 2 to 3 meters. However, thick multilayer insulation installation and testing in both thermal and structural modes has not been completed on a large scale tank. Similarly, multiple vapor cooled shields are common place on science payload helium dewars; however, minimal effort has gone into intercepting heat on large structural surfaces associated with rocket stages. A majority of the vapor cooling effort focuses on metallic cylinders called "skirts", which are the most common structural components for launch vehicles. In order to provide test data for comparison with analytical models, a representative test tank is currently being designed to include skirt structural systems with integral vapor cooling. The tank is 4 m in diameter and 6.8 m tall to contain 5000 kg of liquid hydrogen. A multilayer insulation system will be designed to insulate the tank and structure while being installed in a representative manner that can be extended to tanks up to 10 meters in diameter. In order to prove that the insulation system and vapor cooling attachment methods are structurally sound, acoustic testing will also be performed on the system. The test tank with insulation and vapor cooled shield installed will be tested thermally in the B2 test facility at NASA's Plumbrook Station both before and after being vibration tested at Plumbrook's Space Power Facility.

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Oral Session: Experimental Cryogenics I

Liquid Hydrogen Propellant Tank Sub-surface Pressurization with Gaseous Helium

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Abstract

A series of tests were conducted to evaluate the performance of a propellant tank pressurization system with the pressurant diffuser intentionally submerged beneath the surface of the liquid. Propellant tanks and pressurization systems are typically designed with the diffuser positioned to apply pressurant gas directly into the tank ullage space when the liquid propellant is settled. Space vehicles, and potentially propellant depots, may need to conduct tank pressurization operations in micro-gravity environments where the exact location of the liquid relative to the diffuser is not well understood. If the diffuser is positioned to supply pressurant gas directly to the tank ullage space when the propellant is settled, then it may become partially or completely submerged when the liquid becomes unsettled in a microgravity environment. In such case, the pressurization system performance will be adversely affected requiring additional pressurant mass and longer pressurization times. This series of tests compares and evaluates pressurization system performance using the conventional method of supplying pressurant gas directly to the propellant tank ullage, and then supplying pressurant gas beneath the liquid surface.

The pressurization tests were conducted on the Engineering Development Unit (EDU) located at Test Stand 300 at NASA Marshall Space Flight Center (MSFC). EDU is a ground based Cryogenic Fluid Management (CFM) test article supported by Glenn Research Center (GRC) and MSFC. A 150 ft^3 propellant tank was filled with liquid hydrogen (LH2). The pressurization system used regulated ambient helium (GHe) as a pressurant, a variable position valve to maintain flow rate, and two identical independent pressurant diffusers. The ullage diffuser was located in the forward end of the tank and was completely exposed to the tank ullage. The submerged diffuser was located in the aft end of the tank and was completely submerged when the tank liquid level was 10% or greater. The ullage diffuser tests were conducted as a baseline to evaluate the performance of the pressurization system, and the submerged diffuser tests showed how the performance of the pressurization system was compromised when the diffuser was submerged in LH2. The test results are evaluated and compared, and included in this report for various propellant tank fill levels.

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Validation of the Flow-through-Screen Pressure Drop Model for Screen Channel Liquid Acquisition Devices

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Abstract

Screen channel liquid acquisition devices (LADs) are considered the most robust technology for storing and transferring cryogenic propellant in microgravity. Critical to LAD design is determining the flow-through-screen (FTS) pressure drop for a given velocity across the screen. This relationship is a function of three screen properties: the screen thickness, the surface-to-volume ratio, and the void fraction. Comparison of storable and cryogenic FTS pressure drop data indicates that the screen properties are changing with temperature due to the thermal stresses on the screen when placed in a cryogenic liquid. This work uses steady-state finite element analysis (FEA) simulations on a computer-aided-design (CAD) model of a unit cell of the 325x2300 Dutch Twill screen to determine equations for each screen property as a function of temperature. Several FEA simulations were carried out with different temperature boundary conditions to obtain a smooth distribution of points to fit the equations. Rigorous analysis of the screen geometry both externally and internally was carried out to develop the accurate CAD model. The new temperature-dependent screen property equations are used to update the FTS pressure drop model which is then compared to both storable and cryogenic data. Results show that the new model is able to robustly predict the FTS pressure for any liquid temperature.

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Liquid Acquisition Device Hydrogen Outflow Testing on the Cryogenic Propellant Storage and Transfer Engineering Design Unit

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Abstract

As part of the NASA Cryogenic Propellant Storage and Transfer (CPST) Engineering Design Unit (EDU) testing with liquid hydrogen, screen-channel liquid acquisition devices (LADs) were tested during liquid hydrogen outflow from the EDU tank. This paper discusses details of the design, construction, operation and analysis of LAD test data from the CPST EDU liquid hydrogen test. A stainless steel screen mesh (325x2300 Dutch Twill weave) was welded to a rectangular cross-section channel to form the basic LAD channel. Three LAD channels were tested, each having unique variations in thermal design. The LAD channels fed a common outflow sump at the aft end of the 151 cubic foot volume aluminum tank, and included a curved section along the aft end and a straight section along the barrel section of the tank. Wet-dry sensors were mounted inside the LAD channels to detect the presence of vapor in the channels during outflow. The use of warm helium pressurant during liquid hydrogen outflow, supplied through a diffuser at the top of the tank, always led to early breakdown of the liquid column. When the tank was pressurized through an aft diffuser, resulting in cold helium in the ullage, LAD liquid column hold-times as long as 60 minutes were achieved, which was the longest duration tested. The highest liquid column height at breakdown was 58 cm, which is 23% less than the isothermal bubble-point model value of 75 cm.

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Cryogenic Autogenous Pressurization Testing for Robotic Resupply Mission III

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Abstract

A wick-heater system has been selected for use to pressurize the flight source tank of the Robotic Resupply Mission-III on-orbit cryogen transfer experiment payload for the International Space Station. Experimental results of autogenous pressurization of liquid argon and liquid nitrogen using a prototype wick-heater system are presented. The wick-heater generates gas, which increases the pressure in the tank, while maintaining a low bulk fluid temperature. Pressurization experiments were performed in 2013 to characterize the performance of the wick heater. This paper describes the experimental setup, pressurization results, and analytical model correlations.

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The Zero Boil-Off Tank Experiment Contributions to the Development of Cryogenic Fluid Management

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Abstract

The Zero Boil-Off Technology (ZBOT) Experiment involves performing a small scale International Space Station (ISS) experiment to study tank pressurization and pressure control in microgravity. The ZBOT experiment consists of a vacuum jacketed test tank filled with an inert fluorocarbon simulant liquid. Heaters and thermo-electric coolers are used in conjunction with an axial jet mixer flow loop to study a range of thermal conditions within the tank. The objective is to provide a high quality database of low gravity fluid motions and thermal transients which will be used to validate Computational Fluid Dynamic (CFD) modeling. This CFD can then be used in turn to predict behavior in larger systems with cryogens. This paper will discuss the current status of the ZBOT experiment as it approaches its flight to installation on the ISS, how its findings can be scaled to larger and more ambitious cryogenic fluid management experiments, as well as ideas for follow-on investigations using ZBOT like hardware to study other aspects of cryogenic fluid management.

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Experimental and Numerical Analysis of a Thermodynamic Control System for Cryogenic Propellant Storage

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Abstract

A technological barrier for long duration space mission using cryogenic propulsion is the control of propellant tank self-pressurization. Since the liquid propellant submitted to solar fluxes tends to vaporize, the pressure rise must be controlled to prevent mission failure. The Thermodynamic Vent System (TVS) is such a control strategy: liquid propellant pumped from the tank, is cooled down by a heat exchanger and re-injected as a sub-cooled spray inside the tank. The tank pressure drops due to vapor condensation and liquid bath destratification (Refs. 1 to 4). Our research strategy combines an on-ground experimental set up (Ref. 5) and Volume of Fluid (VOF)-based simulations. The cylindrically-shaped tank is filled with a surrogate fluid (Novec1230 by 3M). The thermal input is controlled by an electrical heating coil. An original insulation technique is used to prevent undesirable heat flux from the wall. The double shroud is thermalized by a water loop, regulated to follow the average tank temperature variation. Injection temperature and mass flow rate are fixed during an experiment. Instrumentation gives access to the accurate measurement of the tank vertical temperature distribution and allows to assess the TVS efficiency. To optimize the TVS design, the experiment will be numerically reproduced using an in-house solver based on VOF approach for interface tracking (Ref. 6), and a phase change model taking advantage of a sharp mass transfer rate distribution (Ref. 7). Experimental results, including thermal stratification quantification in the tank will be presented for various heat loads and TVS control parameters. Preliminary numerical results demonstrating the accuracy of the developed solver will be also provided.

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Oral Session: Cryocoolers

Zero Boil-Off System Testing

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Abstract

Cryogenic propellants such as liquid hydrogen (LH_2) and liquid oxygen (LO_2) are a part of NASA's future space exploration due to their high specific impulse for rocket motors of upper stages suitable for transporting 10's to 100's of metric tons of payload mass to destinations outside of low earth orbit and for their return. However, the low storage temperatures of LH_2 and LO_2 cause substantial boil-off losses for missions with durations greater than several months. These losses can be eliminated by incorporating high performance cryocooler technology to intercept heat load to the propellant tanks and modulating the cryocooler to control tank pressure. The active thermal control technology being developed by NASA is the reverse turbo-Brayton cycle cryocooler and its integration to the propellant tank through a distributed cooling tubing network coupled to the tank wall. This configuration was recently tested at NASA Glenn Research Center, in a vacuum chamber and cryoshroud that simulated the essential thermal aspects of low Earth orbit, its vacuum and temperature. Testing consisted of three "passive" tests with the active cryocooler system off, and 7 "active" tests, with the cryocooler powered up. The test matrix included zero boil-off tests performed at 90% full and 25% full, and several demonstrations at excess cooling capacity and reduced cooling capacity. From this, the tank pressure response with varied cryocooler power inputs was determined. This test series established that the active cooling system integrated with the propellant tank eliminated boil-off and robustly controlled tank pressure.

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Pulse Tube Redundancy and Parasitic Heat Losses Estimation

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Abstract

Since mechanical coolers are most of the time used in a redundant configuration in spacecraft architecture, it is necessary to have a good knowledge of the parasitic heat losses of an off cooler. In the framework of the European Space Agency (ESA) Technology Research Program "two stage cooler for detector cooling between 30 and 50K" with Thales cryogenics (compressor) and Absolut System (cryostat), we are developing a two stage coaxial cooler. Usually we have specifications for a single cooler alone, but this time ESA put specifications on a redundant configuration made out of an ON coupled to an OFF cooler. In the temperature and cooling power range requested by ESA (about 1.5 W at 120 K on the first stage, with 0.35 or 0.8 W respectively at 33 or 38 K on the second stage), the parasitic losses become an important part of the cooling power produce by a single cooler. Thus we undertook, on CEA funding, to study the parasitic heat losses of our cooler under several configurations and to compare different methods of measuring the parasitic heat losses.

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Consideration of a JT Cooler with Two-Stage JT Valves

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Abstract

1K-class or 4K-class cooler has been developed to cool far infrared detector for infrared observation or superconductor-insulator-superconductor (SIS) mixers for atmospheric observation. These coolers consist of a two-stage Stirling cooler for pre-cooling and a Joule Thomson (JT) cooler with a single JT valve. Recently, conventional 4K cooler, which consists of a Gifford-McMahon (GM) refrigerator and a JT cooler has been researched and developed for improving its cooling capacity by using two-stage JT valves instead of a single JT valve in the JT cooler. This paper describes theoretical analysis based on enthalpy balance to understand differences and advantages of two-stage JT valves type compare with single JT valve type in JT cooler. Verification of the theoretical analysis by comparing with experimental results obtained from the preliminary test of the conventional 4K cooler with single JT valve or two-stage JT valves are reported in this presentation.

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15 K Pulse Tube Cooler for Space Applications

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Abstract

Air Liquide has been working with European Space Agency (ESA), The French Alternative Energies and Atomic Energy Commission (CEA), and Thales Cryogenics since 2010 to design, manufacture, and test a 15 K Pulse Tube Cooler system. This cooler is particularly adapted to the pre-cooling needs of cryogenic chains designed to reach 0.1 to 0.05K for focal plane cooling on scientific space missions such as ATHENA. The cooler is designed to provide cooling power >0.3 W at temperatures from 15 to 18 K with an electrical power budget less than 300 W (excluding electronics) and a 288 K rejection temperature. Significant cooling power at an intermediate temperature (typically 80 to 100 K) is also available. The design includes two cold fingers mounted on a common warm flange driven by a single high power compressor (240 W PV power) specially developed for this application. The first cold finger is used to pre-cool the second, low temperature stage. An Engineering Model has been manufactured for which the design and the test results will be presented.

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Reduced Boil-Off Sizing

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Abstract

NASA is currently developing cryogenic propellant storage and transfer systems for future space exploration and scientific discovery missions by addressing the need to raise the technology readiness level of cryogenic fluid management technologies. Cryogenic propellants are baselined in many propulsion systems due to their inherently high specific impulse; however, their low boiling points can cause substantial boil-off losses over time. Recent efforts such as the Reduced Boil-off Testing and the Active Thermal Control Scaling Study provide important information on the benefit of an active cooling system applied to LH_2 propellant storage. Findings show that zero-boil off technologies can reduce overall mass in LH2 storage systems when low Earth orbit loiter periods extend beyond two months. A significant part of this mass reduction is realized by integrating two stages of cooling: a 20 K stage to intercept heat at the tank surface, and a 90 K stage to reduce the heat entering the less efficient 20 K stage. A missing element in previous studies, which is addressed in this paper, is the development of a direct method for sizing the 90 K cooling stage. Such a method requires calculation of the heat entering both the 90 and 20 K stages as compared to the overall system masses, and is reliant upon the temperature distribution, performance, and unique design characteristics of the system in question. By utilizing the known conductance of a system without active thermal control, the heat being intercepted by a 90 K stage can be calculated to find the resultant lift and mass of each active thermal control stage. Integral to this is the thermal conductance of the cooling straps and the broad area cooling shield, key parts of the 90 K stage. Additionally, a trade study is performed to show the ability of the 90 K cooling stage to reduce the lift on the 20 K cryocooler stage, which is considerably less developed and efficient than 90 K cryocoolers.

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A Cryogenic Thermal Link using Gas Circulation

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Abstract

In order to relax spacecraft accommodation constraints, it is often desirable to locate a cryocooler remotely from the application to be cooled. The conductance of classic thermal link assemblies decreases as the length increases, effectively limiting the maximum distance between cooler and application. We have developed a thermal link coupled to a Stirling type pulse tube cryocooler, based on helium gas circulation in a capillary tube, where the conductance is almost independent of the length. A small portion of the pressure wave generated by the pulse tube compressor is rectified in order to create a continuous pressure gradient across the thermal link capillary and ensure sufficient gas circulation. This technique has the added advantage that if the pulse tube compressor is stopped, the thermal link conductance falls almost to zero, thereby reducing the parasitic heat load in a redundant system. A prototype thermal link has been tested and initial results give a conductance >0.3 W/K for a cooling power of several Watts, with the potential to easily increase this figure. A small decrease in cooling power is observed at the pulse tube cold tip but in many applications this can be more than offset by the elimination of parasitic losses from the redundant cooler and/or increased thermal link conductance.

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Extended Range of the Lockheed Martin Coax Micro Cooler

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Abstract

This paper describes the expanded performance range of the Lockheed Martin coax Micro cryocooler thermal mechanical unit. The design of the TRL-6 Micro was slightly modified to accommodate twice the input power, greatly increasing the cooling capability. These Micro units are in a split configuration with the cold head separated from the compressor. The unit optimized for cooling at 105K provides cooling over a wide range of temperatures with a weight of 364 grams including the 210 gram compressor. This small unit is ideal for compact instruments. Load lines were obtained over a range of powers and cold tip temperatures.

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Oral Session: Numerical Cryogenics I

Modeling and Analysis of Chill and Fill Process for the EDU Tank

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Abstract

NASA's future missions may require long-term storage and transfer of cryogenic propellants. The Engineering Development Unit (EDU), a NASA in-house effort supported by both Marshall Space Flight Center (MSFC) and Glenn Research Center (GRC), is a Cryogenic Fluid Management (CFM) test article that primarily serves as a manufacturing pathfinder and a risk reduction task for a future CFM payload. The EDU test article, comprises a flight like tank, internal components, insulation, and attachment struts. The EDU is designed to perform integrated passive thermal control performance testing with liquid hydrogen in a space-like vacuum environment. A series of tests, with liquid hydrogen as a testing fluid, was conducted at Test Stand 300 at MSFC during summer of 2014. The objective of this effort was to develop a thermal/fluid model for evaluating the thermodynamic behavior of the EDU tank during the chill and fill processes. Generalized Fluid System Simulation Program (GFSSP), an MSFC in-house general-purpose computer program for flow network analysis, was utilized to model and simulate the chill and fill portion of the testing. The model contained the liquid hydrogen supply source, feed system, EDU tank, and vent system. The modeling description and comparison of model predictions with the test data will be presented in the final paper.

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Numerical Modeling of Self-Pressurization and Pressure Control by Thermodynamic Vent System in a Cryogenic Tank

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Abstract

This paper presents a numerical model of a system-level test bed – the multipurpose hydrogen test bed (MHTB) using Generalized Fluid System Simulation Program (GFSSP). MHTB is representative in size and shape of a fully integrated space transportation vehicle liquid hydrogen (LH2) propellant tank and was tested at Marshall Space Flight Center (MSFC) to generate data for cryogenic storage. GFSSP is a finite volume based network flow analysis software developed at MSFC and used for thermo-fluid analysis of propulsion systems. GFSSP has been used to model the self-pressurization and ullage pressure control by Thermodynamic Vent System (TVS). A TVS typically includes a Joule-Thompson (J-T) expansion device, a two-phase heat exchanger, and a mixing pump and mixing device to extract thermal energy from the tank without significant loss of liquid propellant. For MHTB, the mixing device is a vertical spray bar located near the tank centerline. Two GFSSP models (Self-Pressurization & TVS) were separately developed and tested and then integrated to simulate the entire system. The Self-Pressurization model consists of multiple ullage nodes, a single liquid node and multiple solid nodes; the numerical model computes the heat transfer through Multi-Layer Insulation blankets, the heat and mass transfer between ullage and liquid propellant, and the heat transfer between the ullage and tank wall. The TVS model calculates the flow through J-T valve and vent system, and through the spray bar and heat exchanger system. The GFSSP Self-Pressurization and TVS models are integrated by exchanging data through User Subroutines of both models. The GFSSP integrated-model results have been compared with liquid hydrogen MHTB test data at a 50% fill level. Satisfactory comparison was observed between test data and numerical predictions.

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Numerical Prediction of Liquid Hydrogen Behavior in Cryogenic Tanks for the Design of the Sounding Rocket Experiment CryoFenix

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Abstract

For the future European launchers developments with long ballistic phases and re-ignition capabilities with cryogenic propellants, Air Liquide Advanced Technologies (ALAT) in cooperation with Centre National d'Etude Spatiales (CNES) has developed a computational methodology for the studies and for the prediction of propellant behavior. The Cryofenix sounding rocket is one of the experimental projects conducted by CNES and ALAT to validate this computational methodology. The objective is to use a sounding rocket offering a representative phase of microgravity (around 6 minutes of ballistic flight) with a well instrumented cryogenic tank filled with liquid hydrogen.

The design and the preparation of such a complex experiment is however challenging since the study of the physical phenomena of interest (phase change, boiling, stratification, pressurization) and the objective of numerical tools validation, require appropriate and accurate conditions for both the fluid and the tank. Preliminary numerical simulations were used to support the design of an experiment which fulfills these requirements to optimize the flight sequences.

The objective of this paper is in particular to report the numerical simulations which were performed recently to complete code validation with the data available from ground test experiment and qualification of the Cryofenix module. Different operations (such as pressurization, stratification) were reproduced on ground, and simulations were compared to the results of the experiments with accurate prediction of mass transfer at the liquid / gas interface due to evaporation / condensation. If available, preliminary simulations and comparisons with the results of the experimental data gathered during the real flight will be also presented in the final paper.

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Cryofenix – Cryogenic Sounding Rocket Experiment for Fluid Behavior Study

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Abstract

Prediction of the behaviors of cryogenic liquid propellant in microgravity is a key element for decreasing development risk and optimizing design of a new generation of cryogenic upper stage or cryogenic orbiter with long ballistic phase. For this purpose, Centre National d'Etudes Spatiales (CNES) and Air Liquide Advanced technologies have developed through a partnership, innovative models to be used with a commercial Computational Fluid Dynamic (CFD) tool. Those models mainly focused on the thermal aspect, were validated through analysis of laboratory experiments, but also with microgravity experiments, using magnetic levitation devices or parabolic flights.

The next step to increase our tool Integration Readiness Level (IRL) concerns the global behavior and the use of cryogenic fluid with larger test scale and longer microgravity duration. This is the target of Cryofenix project which will use Materials Science Experiment Rocket (MASER) type sounding rocket, provided by the Swedish Space Corporation. This service offers 6 minutes of microgravity for a 400 kg payload. Inside this payload, well instrumented cryogenic tests cells will be installed. During microgravity phase, behavior and characteristics of the liquid hydrogen will be observed and recorded. Hence comparison between data and simulation will give us a clear status of our tool. And then, additional model improvements and refinement can be engaged.

Cryofenix will be the first European sounding rocket experiment with liquid hydrogen inside. Globally, this project will allow CNES and Air Liquide to get a better understanding of fluid behavior in microgravity and will give confidence in our numerical tool. Thus, our propellant management capacity for long ballistic phases will be improved. The paper will present the Cryofenix project (performed in the frame of Research & Technology program of CNES) and the first results.

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Oral Session: Experimental Cryogenics II

A Standardized Cryogenic Diode Temperature Sensor for Aerospace Applications

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Abstract

The model DT-670-SD cryogenic diode temperature sensor, manufactured by Lake Shore Cryotronics, Inc. has been used on numerous aerospace space missions since its introduction nearly 15 years ago. While the sensing element is a diode, it is operated in a non-standard manner when used as a temperature sensor over the 1.4 K to 500 K temperature range. For this reason, the NASA and MIL-type test and performance standards designed to ensure high reliability of diode aerospace parts do not specify a proper inspection and test protocol for the temperature sensor as written. This mismatch between sensor and test protocol requires each aerospace application to develop a unique test and inspection protocol for a typically small numbers of sensors specifically manufactured for that project, resulting in expensive sensors with long lead times. With over 30 years of experience in supplying cryogenic temperature sensors for aerospace applications, Lake Shore has worked to develop lot screening and qualification test protocols to provide “off-the-shelf” DT-670-SD temperature sensors that should meet the requirements of most high-reliability applications including aerospace. Parts from screened and qualified lots will be available as the base DT-670-SD sensor part with the ability to specify an interchangeability tolerance, calibration range, adaptor, and/or lead extension for final configuration. This work presents details of these screening and qualification test protocols as well as performance characteristics of the DT-670-SD cryogenic temperature sensors when inspected and tested to this protocol.

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A Calorimetric Test Method to Perform AC Loss Measurements of Conductors in Fully Superconducting Rotating Machines

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Abstract

Fully superconducting motors and generators in hybrid electric aircraft and offshore wind applications offer the potential to improve the application efficiency and power density. The stator however is subjected to a rotating field and the AC losses are significant. A thorough characterization of HTS conductors and coils under realistic operating conditions in magnetic field and transport current with high sensitivity is necessary. This paper describes the experimental setup to calorimetrically measure ac losses and stability properties of superconductors at temperatures as low as 15 K under simultaneous AC transport current and rotating and pulsating magnetic field of rotating machine stators with phase shift. The experimental facility uses a novel design of multiple layers of stationary, but rotatable, magnets to shift from an alternating to a rotating field at the expense of field magnitude. The sample orientation to the field can also be varied. Details of the experimetal design tradeoffs and set up are presented. A calibration set of representative data is discussed from non-ideal low AC loss MgB2 samples to help validate the measurement technique.

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Liquid Parahydrogen Reorientation with Non-Isothermal Walls Upon a Gravity Step Reduction

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Abstract

Future launcher concepts use liquid hydrogen (LH_2) as propellant and liquid oxygen (LOX) as oxidizer. They may experience long ballistic phases with varying acceleration levels. For propellant management and safe operation of the spacecraft, it is important to understand the response of cryogenic fluids (liquid and vapor) to these disturbances. Furthermore, superheated tank walls influence the moving free surface of the liquid in partially filled tanks. This study investigated the free surface reorientation of liquid hydrogen upon a sudden gravity step reduction in presence of a superheated wall. The pressure was set around normal pressure leading to a saturation temperature of 20 Kelvin.

The experiment consisted of a glass cylinder partly filled with liquid hydrogen enclosed in a cryostat to insulate it from ambient conditions. Several temperature sensors along the outside of the cylinder and in the vapor region of the experiment recorded the temperature progression throughout the entire test campaign. Pressure inside the cylinder was recorded with a pressure transducer and optical access was enabled with an endoscope. Various heating elements were glued to the cylinder for thermal control of the experiment. Thermal stratification in the liquid phase could be neutralized and wall heating elements were used to establish a wall temperature gradient in the vertical direction. Experiments were carried out in the ZARM drop tower at the University of Bremen. The provided microgravity lasted 4.74 seconds. Six experiments with varying wall temperature gradients were performed. Temperature progression at the cylinder wall and in the vapor region, and the pressure inside the experiment were recorded throughout the free fall test. The reorientation of the free surface could be recorded focusing on wall and center point location. A final equilibrium surface position could not be achieved due to limited experiment time.

This study showed an influence of the wall superheat on the reorientation of the test liquid. Increasing wall temperature retarded the advancing liquid layer along the cylinder wall. This led to an increasing center point oscillation with a decrease of its amplitude. The estimated final center point deflection decreased with increasing wall superheat as well. Reorientation processes also affected the ullage. Temperature sensors in the vapor region were positioned in the vicinity of the expected reorienting free surface. It was expected to record a temperature drop caused by evaporating mass. For a sophisticated understanding of temperature progression in the vapor region numerical simulations are needed.

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Gas-Gap Heat Switch Panel for Temperature Control

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Abstract

We report on the development of a gas-gap heat-switch panel for temperature control of components at ambient temperatures close to 300 K. The targeted On conductance is greater than 800 W/m^2K and the Off conductance lower than 10 W/m^2K. A first generation gas-gap heat-switch panel measuring 50 mm by 50 mm and a thickness of 5.7 mm is realized and experiments were performed on the device. The results of the first prototype will be presented. A second generation prototype with improvements to the design is currently being fabricated. A scaling up study of the device to larger dimensions of 300 mm by 300 mm is performed and it suggested that scaling up substantially improves the performance of the heat switch. This presentation will describe the physical principles and the current status of this technology.

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Application of a Conduction-Cooled HTS Magnet in Radio Blackout Mitigation Experiments

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Abstract

A conduction-cooled high-temperature superconducting (HTS) magnet has been developed in the framework of the Helmholtz-Russia Joined Research Group “COMBIT” to provide a high magnetic field for a radio blackout mitigation experiment. The phenomenon of radio blackout is well-known since the early days of space exploration. During hypersonic flight or reentry of space vehicles into a planet’s atmosphere, a dense plasma layer is formed that can attenuate or reflect radio waves so that all communication with ground stations or satellites is blocked – in particular voice communication or data telemetry. The aim of COMBIT is to demonstrate that a radio blackout can be avoided or mitigated with the help of magneto-hydrodynamic effects using crossed electric and magnetic fields in the vicinity of a sender or antenna. This should lead to a local reduction of the plasma number so that radio waves can pass through the plasma layer. First ground experiments have been performed in an arc-heated high enthalpy wind-tunnel (L2K) at the German Aerospace Center in Cologne and numerical simulations of the plasma flow have been performed at Ioffe Institute in St. Petersburg. The conduction-cooled HTS magnet with a cryogenic system that is able to withstand the high temperatures caused by the plasma during the experimental campaigns has been developed at Karlsruhe Institute of Technology. It consists of five RE-Ba-Cu-O coated conductor double pancakes and has an outer diameter of 70 mm. Despite the strong restrictions in size the magnet is able to provide a high and tunable magnetic field in the plasma beam. We present details about the design of the superconducting magnet and the cryogenic system and about the performance during the plasma experiments. In a first experimental campaign in 2014, magnetic fields of 2 T have been achieved in the plasma outside the cryostat, corresponding to a field of 5.16 T at the magnet winding. After a revision of magnet and cryostat, further experiments are planned in early 2015.

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FPGA-Based Instrumentation Withstands the Chill of Deep Space

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Abstract

Current and future NASA robotic-flight missions to outer planets and asteroids require avionics systems, computers, controllers and data-processing units capable of enduring the extreme low temperature environments of deep space and outer planets. With recent technological advances in Field Programmable Gate Arrays (FPGAs), it has become possible to architect a complete System-on-Chip (SoC) using a single FPGA. Large FPGAs that are radiation-hardened by design (RHBD) have increased the number of gates per square inch, reduced power consumption per gate and included microprocessors, soft and hard IP, arithmetic modules, sizable onboard memory and analog-to-digital convertors. B&A Engineering Inc. (BAENG), in cooperation with NASA, conducted studies with the Xilinx Virtex-5 mixed-signal RHBD FPGA to address NASA's need for protected, reliable data acquisition controllers and computer electronics able to operate in cryogenic temperatures. This RHBD FPGA will be the workhorse of future NASA computer and data-handling systems targeted for outer-planet landing, orbiting, and sample-retrieval missions.

BAENG designed and built a test board based on Xilinx Virtex-5 FPGA and initial testing showed that the FPGA is operational down to –150 °C. What is remarkable is that we found that the commercial chip works at temperatures well below specifications for commercial parts and even well below specifications for a space-grade Xilinx FPGA.

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Poster Session

Experimental Investigation on No-Vent-Fill Process Using Tetrafluoromethane (CF_4)

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Abstract

No-vent filling (NVF) method is a cryogenic fluid transfer technology and one of the most promising techniques for a long-term space mission. It saves the amount of cryogenic propellant and eliminates the venting process which causes unintended momentum change on a space vehicle. In order to demonstrate a successful NVF process including no-vent pre-chill down process, we prepared an experimental apparatus consisting of a cryogenic storage tank, a transfer line, and a receiver tank, which is conductively cooled by a precooler. A Stirling cryocooler (CryoTel GT, Sunpower) is utilized for thermal conditioning of the receiver tank around the saturation temperature of CF_4 and to achieve a cryogen-free pre-chill down process. Vacuum condition of the experimental apparatus is maintained below 10^{-3} torr to minimize heat leak and to simulate space condition. Tetrafluoromethane (CF_4) is selected as a working fluid due to the similarity in a molecular structure with Methane (CH_4), which has been considered as an attractive future cryogenic propellant, and the safety. Liquid CF4 is obtained by heat exchange with liquid nitrogen in the supply tank. The initial wall temperature of the receiver tank is pre-regulated by the cryocooler to identify its impact to NVF. The flow transfer conditions (the mass flow rate, the pressure, and the temperature) of the working fluid are also varied with care to investigate the experimental parameters of the NVF process. NVF process is achieved without losing any transfer fluid even in the pre-chill down process. An equilibrium NVF model is developed to find an optimum condition of the required filling volume and is validated with the experimental results. We also perform other parametric studies to investigate the critical influencing factors for NVF.

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Robotic Resupply Mission III Fluid Management Device Design

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Abstract

The current development progress of the fluid management device (FMD) for the Robotic Resupply Mission-III (RRM-III) cryogen source dewar is described. RRM-III is an on-orbit cryogenic transfer experiment payload for the International Space Station. The fluid management device is a key component to ensure the ullage bubble is located away from the outlet. This paper describes the design of the fluid management device and progress of hardware development. The preliminary design of the RRM-III FMD is a number of concentric cones of mylar which maximizes the volume of liquid in contact with the FMD in the source dewar.

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Screen Channel LAD Bubble Point Tests in Liquid Nitrogen

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Abstract

The primary parameter for gauging performance of a liquid acquisition device is the bubble point pressure, or differential pressure across a screen pore that overcomes the surface tension of the liquid at that pore. Recently, cryogenic bubble point tests were conducted in liquid nitrogen across a parametric trade space to examine the influential factors that govern LAD performance. Three fine mesh screen samples (325x2300, 450x2750, 510x3600) were tested over a wide range of liquid temperatures (67 to 114 K) and pressures (0.032 to 1.83 MPa), using both autogenous (gaseous nitrogen) and non-condensable (gaseous helium) pressurization schemes. Experimental results in liquid nitrogen are compared to recently reported results in liquid hydrogen, oxygen, and methane. Results indicate a significant gain in performance over the room temperature bubble point is achievable over the baseline 325x2300 reference value by using a finer mesh, operating at a colder liquid temperature, and pressurizing and subcooling the liquid with the noncondensable pressurant.

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Overall Mass Transfer Coefficient of Evaporated LOX Into Bubbles in Helium Bubbling Process

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Abstract

Helium bubbling method is used as a forced convection system for cooling a propellant in pipeline, thermal conditioning system for preventing thermal stratification of cryogenic propellant in a storage tank, and pressurization system in rocket application. In this process, cryogenic liquid is evaporated into helium bubbles by partial pressure difference of evaporated liquid in bubbles. For precise prediction of the dynamics of evaporation process, the overall mass transfer coefficient of evaporated liquid into bubbles should be known. In this paper, the empirical correlation of overall mass transfer coefficient of evaporated liquid into bubbles is presented with test results. The bubbling tests were performed at some conditions as different diameters (50, 100, 200, 400 mm) of test vessel, different levels of liquid, different temperatures (77, 90, 288 K) of helium gas and different cryogenic liquids (liquid oxygen, liquid nitrogen). The presented empirical correlation shows good agreement with test results.

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A Piezoelectric Cryogenic Heat Switch

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Abstract

We report on our measurement results of the thermal conductance at cryogenic temperatures of a mechanical heat switch actuated by a piezoelectric positioner, the PZHS (PieZo electric Heat Switch). PZHS operation was demonstrated between 4 and 10 K, and on/off conductance ratios of 100 to 200 were obtained when the positioner applied its maximum force of 8 N. We discuss the advantages of using this system in space flight cryogenic applications, and estimate the ultimate performance of an ideal PZHS.

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Optimization of Air Liquefaction Plant Parameters Using MATLAB

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Abstract

The air liquefaction system for oxygen plants in gas industries is based on the Claude cycle. The effect of process parameters on the overall system is difficult to analyze via manual calculations and this provides the motivation to use process simulators for understanding the steady state and dynamic behavior of such systems. In this paper, a mathematical model for an oxygen plant that produces 80 m^3/hr of oxygen at Mitt oxygen Pvt. Ltd. Bhavnagar is developed and analyzed. The parametric study of this system via MATLAB simulations provides useful guidelines for preliminary design of air liquefaction systems based on the Claude cycle.

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Real and Imaginary Thrust Augmentation/Cryogenic Shockwave Piercing

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Abstract

SCRAM rockets, missiles and aerospace planes have been an elusive enigma since the advent of the Goddard liquid rocket March 26, 1916. The reason is adiabatic shock divergence at speeds in excess of Mach-3 and supersonic combustion extremity of Mach-2. In order to beat shockwave and combustion constraints in the hypersonic domain CRYSONIX cryogenic shockwave piercing was invented in July 2010, SURD supersonic ram detonation in January 2012, SPINNX hypersonic vortex transformation May 2013, STAG centripetal thrust augmentation in December 2013, HYCORE hybrid constellation rocket engine in January 2014 and iSTAG imaginary centripetal thrust transformation in December 2014 whereby hypersonic/SCRAM acceleration may be rationally sustained through M20. The art of IMAGINARY (centripetal) SCRAM detonation and CRYSONIX (cryogenic) shockwave piercing constitutes a profound advancement in rocket science which rivals the efficacy of HIGH bypass fan jets with a specific impulse in excess of 5,000 sec. The presentation will hence focus on (1) the art of cryogenic shockwave piercing / supersonic ram detonation / centripetal thrust augmentation / imaginary thrust augmentation has been mastered over the period July 2010 through December 2014 starting at Virginia Tech July 2010 and culminating in Los Angeles December 2014 and (2) computational means in support thereto.

The presentation will focus on (1) the art of cryogenic shockwave piercing/supersonic ram detonation/centripetal thrust augmentation/imaginary thrust augmentation has been mastered over the period July 2010 through December 2014, (2) design/fabrication/testing of the SURD/HYCORE supersonic ram detonation (constellation) rocket engine, INCRO cryogenic tanks, SPINNX superconductive nosecone, iMARC integrated modular avionics, SOLAR stochastic optimal liquefaction algorithm destined for the period 2015 and 2016, and (3) flight testing destined for 2017.

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Stirling-Type Pulse Tube Refrigerator with Cold Compression: Cold Compressor, Colder Expander

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Abstract

This research paper focuses on the performance prediction and its validation via experimental investigation of a Stirling-type pulse tube refrigerator (PTR) equipped with a cold linear compressor. When the working gas is compressed at cryogenic temperature, the acoustic power (pressure/volume work) can be directly transmitted through the regenerator to the pulsating tube without experiencing unnecessary precooling process. The pressure/volume work produced by the linear compressor, furthermore, can be significantly diminished due to the small specific volume of the working gas at low temperature. The PTR can reach lower temperature efficiently with higher heat lift at the corresponding temperature than other typical single-stage Stirling-type PTRs. Utilizing a cryogenic reservoir as a warm-end and regulating the entire operating temperature range of the PTR will enable a PTR to operate under space environment.

In this research, the experimental validation as a proof of concept is carried out to demonstrate the capability of PTR operating between 80 and 20 K. The linear compressor is submerged in a liquid nitrogen bath and 5 W of cooling power is expected at 20K. The test results are analyzed with the simple numerical computation which considers the dynamic characteristics of the cold linear compressor with thermo-hydraulic governing equations for each of the sub components of the PTR. All the mass flows and pressure waves are assumed to be sinusoidal.

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Development of 1K-Class Joule-Thomson Cryocooler for the Next-Generation Astronomical Mission

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Abstract

The next-generation astronomical mission such as Space Infrared Telescope for Cosmology and Astrophysics (SPICA) and Advanced Telescope for High Energy Astrophysics (ATHENA), the active cooling for the telescope and the detector is essentially required to achieve superior sensitivity and high spatial resolution. The SPICA spacecraft has the large cryogenic infrared (IR) telescope, which is cooled down to below 6K by the cryogen-free cooling system combined with the mechanical cryocoolers and the passive radiators. The Fourier Transform imaging spectrometer SAFARI, one of the scientific instrument for far-infrared observation on-board the SPICA payload module, needs the cooling chain of the Adiabatic Demagnetization Refrigerator (ADR) (50 mK/300 mK), the Sorption (300 mK/1.7 K), and the 1 K-Joule Thomson (JT) cryocooler (1.7 K/300 K).

Based on heritage of the ASTRO-H and the SMILES 4K-JT cryocooler, Japan Aerospace Exploration Agency (JAXA) and Sumitomo Heavy Industries (SHI) are now developing the 1K-JT cryocooler with the nominal cooling power of 10 mW at 1.7 K and the lifetime of more than 5 years that will be achieved by maximum power consumption 75 W without precooler. The 1K-JT cryocooler is configured with four units of the JT compressors and the three-staged heat exchanger in the closed cycle JT loop. The flexure bearings are adopted for piston support in the JT compressors for less mechanical wear and disturbance. The ^{3}He is used for working gas due to its higher saturation pressure at 1.7 K. The 20K-class two-stage Stirling cooler is also used for precooling. In this development program, two engineering models of the 1K-JT cryocoolers are fabricated to demonstrate its design cooling performance and lifetime. The survivability tests of mechanical and thermal vacuum environment as qualification level were completed without remarkable change in the required compressor performance of He gas flow rate 1 NL/min and inlet/outlet pressure 7 kPa/700 kPa. The mechanical disturbance and the electromechanical compatibility (EMC) and the gas contamination level of the JT compressors were also measured. This paper describes the latest development status of the 1 K-JT cryocooler.

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Magnetic Shield Performance Validation as Part of the Development of a Focal Plan Assembly for Space Projects

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Abstract

SRON Netherlands Institute for Space Research is part of the consortium for two of the last decade Space surveys, namely ATHENA as x-ray observatorium and SAFARI in the far-infrared spectrum region. In both, one of the SRON responsibilities is the development of the Focal Plane Assembly (FPA) that provides the thermal and mechanical support to the Transition Edge Sensor (TES) detector array. Additionally, sufficient magnetic field attenuation over the full array is essential to meet the operational requirements. The magnetic shielding key requirements are a) the absolute residual normal component magnetic field is less than 1 microTesla and b) the maximum normal magnetic field noise is less than 0.2 nT/√Hz. Taking into consideration the mechanical design and constraints, the magnetic shield is a combination of two shields: an outer high permeability one and an inner superconducting one. In this way the effect of topological flux trapping is limited. In this work we will present the conceptual design of the magnetic shield as well as the cryogenics tests performed to verify the performance under space-like cooling conditions.

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Oral Session: Numerical Transfer II

A New Experiment for Determining Evaporation and Condensation Coefficients of Cryogenic Propellants

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Abstract

Passive and active technologies have been used to control propellant boil-off, but the current state of understanding of cryogenic evaporation/condensation in microgravity is insufficient for designing large cryogenic depots critical to the long-term space exploration missions. One of the key factors limiting the ability to design such systems is the uncertainty in the accommodation coefficients (evaporation and condensation), which are inputs for kinetic modeling of phase change.

A novel, combined experimental and computational approach is being used to determine the accommodation coefficients for liquid hydrogen and liquid methane. The experimental effort utilizes the Neutron Imaging Facility located at NIST to image evaporation and condensation of hydrogenated propellants inside of metallic containers. The computational effort includes numerical solution of a model for phase change in the contact line and thin film regions as well as a Finite Element Analysis (FEA) effort for determining the appropriate thermal boundary conditions for the numerical solution of the evaporation liquid. Using all three methods, the accommodation coefficients can be extracted from the experimental observations. The experimental and computational efforts will be discussed in detail along with recent experimental observations, evaporation/condensation rates, and computational results.

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Numerical Studies of the SOURCE-2 Sounding Rocket Experiment for Fluid Behavior Under Micro-gravity Conditions

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Abstract

Propellant behavior in microgravity is a critical issue for the ballistic flight sequence of spatial launchers with re-ignition capabilities and for long term cryogenic storage. Indeed the effects of the low gravity conditions on the fluid, especially for the heat transfer with condensation/evaporation and nucleate boiling phenomena, are still not well understood. Furthermore, the development of appropriate methodologies for computational fluid dynamics (CFD) prediction for the propellant fluid evolution is of great importance in particular for the space industry. For the validation of the simulations and to understand fluid behavior, experiments using a sounding rocket were considered in the framework of the European COMPER project. In particular The SOURCE-2 (SOUnding Rocket Comper Experiment) campaign offered the possibility to study the behavior of fluid similitude for representative phase of micro-gravity during around 6 minutes.

The aim of this paper is to present the numerical simulation performed by Air Liquide Advanced Technologies (ALAT) in collaboration with the CNES in the framework of Research & Technology program. Several sequences are reproduced with for instance pressurization and liquid filling operations, pool boiling in micro-gravity for subcooled and saturated fluid and immerged jet impinging the free surface. For each situation, the numerical prediction of the free surface evolution, the pressure and the temperature evolution are compared to the experimental data. For each simulation, the objective of this work is to evaluate the capability of the numerical methodology developed by ALAT for the prediction of the fluid behavior in micro-gravity, in particular without any tuning parameters.

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TankSIM: A Cryogenic Tank Performance Prediction Program

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Abstract

Accurate prediction of the thermodynamic state of the cryogenic propellants in launch vehicle tanks is necessary for mission planning and successful execution. Cryogenic propellant storage and transfer in space environments require that tank pressure be controlled. The pressure rise rate is determined by the complex interaction of external heat leak, fluid temperature stratification, and interfacial heat and mass transfer. If the required storage duration of a space mission is longer than the period in which the tank pressure reaches its allowable maximum, an appropriate pressure control method must be applied. Therefore, predictions of the pressurization rate and performance of pressure control techniques in cryogenic tanks are required for development of cryogenic fluid long-duration storage technology and planning of future space exploration missions.

This paper describes an analytical tool, Tank System Integrated Model (TankSIM), which can be used for modeling pressure control and predicting the behavior of cryogenic propellant for long-term storage for future space missions. It is written in the FORTRAN 90 language and can be compiled with any Visual FORTRAN compiler. Thermodynamic vent system (TVS) is used to achieve tank pressure control. Utilizing TankSIM, the following processes can be modeled: tank self-pressurization, boil-off, ullage venting, and mixing. Details of the TankSIM program and comparisons of its predictions with test data for liquid hydrogen and liquid methane will be presented in the final paper.

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Effect of Interfacial Turbulence and Accommodation Coefficient on CFD Predictions of Pressurization and Pressure Control in Cryogenic Storage Tank

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Abstract

Pressurization and pressure control in cryogenic storage tanks are to a large extent affected by heat and mass transport across the liquid-vapor interface. These are, in turn, controlled by the kinetics of the phase change process and the dynamics of the liquid and vapor turbulent recirculating flows. In this work, the effects of accommodation coefficient and interfacial turbulence on tank pressurization and pressure control simulations are examined. Comparison between numerical predictions and ground-based measurements in two large liquid hydrogen tank experiments, performed in the K-site facility at NASA Glenn Research Center (GRC) and the Multi-purpose Hydrogen Test Bed facility at NASA Marshall Space Flight Center (MSFC), are used to show the impact of accommodation coefficient and interfacial turbulence damping on evolution of pressure and temperatures in the cryogenic storage tanks. In particular, the pressurization comparisons indicate that: (1) numerical predictions are essentially independent of the magnitude of the accommodation coefficient; and (2) surprisingly, laminar models sometimes provide results that are in better agreement with experimental self-pressurization rates, even in parametric ranges where the bulk flow is deemed fully turbulent. In this light, shortcomings of the present CFD models, especially, numerical treatments of interfacial mass transfer and turbulence, as coupled to the Volume-of-Fluid (VOF) interface capturing scheme, are pinpointed and future paths for their improvement are discussed.

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