Improving MRI magnet thermal performance using variable density Multilayer Insulation (MLI)

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Careful techniques for MLI wrapping of MRI magnet cryostats have been shown to be critical in establishing a net Zero Helium Boil Off. Traditional Multilayer insulation (MLI) together with a cryocooler have been used in such ‘Zero Boil Off’ cryostats for many years. This paper discusses how the evolution in design of MRI magnet cryostats is challenging traditional MLI. By looking at the fundamental design equations for MLI, new insight can be gained into improving the design using variable density insulation. A new, proprietary method for creating variable density in MLI was devised and the resulting blankets were applied to MRI magnets. Results show a 30% improvement in insulation performance and a 15% improvement in material cost of the MLI. This new Variable Density MLI also holds promise for application to other liquid helium cryostats.

Influence of tee-piece connectors on the thermal performance of MLI

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An optimal thermal performance of multi-layer insulation (MLI) can be achieved at developable surfaces like a cylinder surface. This thermal performance of MLI is often degraded by cut-off points at tee-piece connectors. For the investigation of this degrading effect the calorimetric measurement principle is used. As a reference the heat load from ambient temperature through MLI to a smooth cylinder filled with liquid nitrogen, a diameter of 219 mm and a height of 1820 mm was measured. In addition the heat load to an insulated cylinder with eighteen tee-piece connectors was measured. Here several experiments with different kinds of insulation techniques were performed. Both objects, the smooth cylinder and the cylinder with the tee-piece connectors have the same outer surface for a comparison of the results.

The article describes the experiments and their results with a discussion. It was shown that the cut-off points a tee-piece connectors have a significantly degrading influence of the thermal performance of MLI. The effective heat conductance of such a degraded MLI is in the order of microspheres.

THERMAL PERFORMANCE OF LOW LAYER DENSITY MULTILAYER INSULATION USING LIQUID NITROGEN

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In order to support long duration cryogenic propellant storage, the Cryogenic Fluid Management (CFM) Project of the Exploration Technology Development Program (ETDP) is investigating the long duration storage properties of liquid methane on the lunar surface. The Methane Lunar Surface Thermal Control (MLSTC) testing is using a tank of the approximate dimensions of the Altair ascent tanks inside of a vacuum chamber to simulate the environment in low earth orbit and on the lunar surface. The thermal performance testing of multilayer insulation (MLI) coupons that are fabricated identically to the tank applied insulation is necessary to understand the performance of the blankets and to be able to predict the performance of the insulation prior to testing. This coupon testing was completed in Cryostat-100 at the Cryogenics Test Laboratory. The results showed the properties of the insulation as a function of layer density, number of layers, and warm boundary temperature. These results aid in the understanding of the performance parameters of MLI and help to complete the body of literature on the topic.

Measurement and analysis of the dependence of multi-layer insulation performance on interstitial gas pressure

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The thermal performance of a diverse selection of multi-layer insulation (MLI) blankets has been studied. The sample blankets differed in the number of shield layers, layer density, and spacer materials. For each, the heat leak was measured over a range of interstitial gas (nitrogen) pressures from less than 10^{-6} Torr up to one atmosphere. At each fill pressure the system was allowed to arrive to steady state. All measurements were performed using the same cylindrical calorimeter with identical thermal boundaries (room temperature and liquid nitrogen), thus allowing for direct quantitative comparisons. In each case the familiar step in heat leak, as the system transitions from the free molecular to the continuum regime, is clearly defined. It is found that all curves become nearly coincident when plotted versus the inverse Knudsen number, K_i, which is proportional to both the pressure and the system's characteristic length scale, namely, the inter-layer spacing. A simple calculation based on molecular collision probabilities accurately reproduces the shape and width of the transition. A practical curve-fitting procedure is developed using four physically meaningful fitting parameters. These are (1) the low-pressure heat leak limit, which is given by the physical properties and configuration of the MLI; (2) the high-pressure heat leak limit, given by the gas properties and the geometry of the calorimeter; (3) the transition pressure, occurring at $K_i \sim 1$; and (4) the transition width, which is related to the variation of the collision probability with pressure. A simple expression for the heat leak via the interstitial gas is found, and this is incorporated into an overall MLI heat leak equation.

Thermal Insulation Performance of Hybrid Aerogel-MLI Insulation for Cryogenic Storage in Space Applications

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Returning to the moon to build a sustainable, long-term human presence and building vehicles to explore Mars and beyond will require breakthroughs in the preservation and control of cryogens. Long duration maintenance of cryogenic fluids is essential for propulsion, power, life-support, and scientific research in these future missions; hence, an efficient, reliable thermal insulation system is a key to success in space exploration missions. A novel hybrid insulation system is being developed by Aspen Aerogels that consists of hydrophobic fiber-reinforced aerogel material integrated with multi-layer insulation (MLI) and is a promising candidate for in-space cryogenic fuel storage applications. This hybrid aerogel-MLI system will afford a more reliable alternative to standard MLI because it is less fragile, easier to install, and less sensitive to edge effects and localized compression. The core component of the system is a low density and highly resilient aerogel optimized for relevant space environments. Prototype hybrid composites of aerogel-MLI and a baseline MLI system were fabricated by Aerospace Fabrication & Materials. Thermal performance testing was performed at cryogenic temperatures across a vacuum range from 10^{-5} to 760 torr by the Cryogenics Test Laboratory at NASA Kennedy Space Center. The test results and design implications of various aerogel-MLI combinations will be discussed.

Testing and Analysis of Spray-on Foam Insulation for Hydrogen Fuel Tanks

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Spray-on Foam Insulation (SOFI) was used to insulate the hydrogen fuel tanks that are used on the High Altitude Long Endurance (HALE) aircraft. The foam is five inches thick and the external surface is exposed to a wide range of environmental conditions both during preflight and descent operations. This report will describe the testing and analysis that was conducted to ensure the foam had sufficient insulating properties given widely varying operating environments. This testing included evaluating the effects of moisture absorption and temperature cycling on structural stability and overall thermal conductance. Test setups and the results will be discussed and the analysis used to apply the test results to full scale hydrogen tanks will be covered.

Vibration Considerations for Cryogenic Tanks Using Glass Bubbles Insulation

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The use of glass bubbles as an efficient and practical thermal insulation system has been previously demonstrated in cryogenic storage tanks. One such example is a spherical, vacuum-jacketed liquid hydrogen vessel of 218,000 liter capacity where the boiloff rate has been reduced by approximately 50 percent. Further applications may include non-stationary tanks such as mobile tankers and tanks with extreme duty cycles or exposed to significant vibration environments. Space rocket launch events and mobile tanker life cycles represent two harsh cases of mechanical vibration exposure. A number of bulk fill insulation materials including glass bubbles, perlite powders, and aerogel granules were tested for vibration effects and mechanical behavior using a custom design holding fixture subjected to random vibration on an Electrodynamic Shaker. The settling effects for mixtures of insulation materials were also investigated. The vibration test results and granular particle analysis are presented with considerations and implications for future cryogenic tank applications. As thermal performance is linked to mechanical behavior, further possibilities for optimizing the glass bubbles system are also discussed.

Cryogenic Studies for the proposed CERN Large Hadron electron Collider (LHeC)

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The LHeC (Large Hadron electron Collider) is a proposed future colliding beam facility for lepton-nucleon scattering particle physics at CERN. A new 60 GeV electron accelerator will be added to the existing 27 km circumference 7 TeV LHC for collisions of electrons with protons and heavy ions. Two basic design options are being pursued. The first is a circular accelerator housed in the existing LHC tunnel which is referred to as the "Ring-Ring" version. Low field normal conducting magnets guide the particle beam. Superconducting (SC) RF cavities are installed at two opposite locations at the LHC tunnel to accelerate the beam and are cooled to 4 K or if required to 2 K. In addition a 10 GeV re-circulating SC injector machine is needed for this version. The second option, referred to as the "Linac-Ring" version, consists either of a straight 7 km long linear accelerator or of a re-circulating energy-recovery type machine with two 1 km long straight acceleration sections arranged as race-track. In both cases the high field SC cavities cooled to 2 K require large refrigeration capacities comparable to the LHC. An independent cryogenic system is needed for the particle detector comprising two concentric 12 m long SC solenoids of diameter 6.5 m and 7.5 m, respectively, several small sized central insertion magnets and a small toroidal magnet operating at 4 K. Liquid argon calorimeters are proposed which operate at 90 K. This paper gives an account of the preliminary studies in progress for the cryogenic systems of the accelerator complex scenarios and the detector.

Final cryogenic requirements for the JT-60SA tokamak

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The superconducting tokamak JT-60SA is part of the Broader Approach Programme agreed between Japan and Europe. CEA is in charge of the cryogenic system procurement including the warm compression station, the storages, the refrigerator cold box and an Auxiliary Cold Box (ACB) which should be installed on the JAEA Naka site before 2016. This paper summarizes the final cryogenic requirements for the tokamak JT-60SA cryogenic system of about 9 kW equivalent at 4.5K, with helium flow supplies at 3.7 K for cryopumps, at 4.4 K for superconducting magnets, at 50 K for HTS current leads and at 80 K for thermal shields. The variable heat loads coming from magnet system cooling loops (Toroidal Field coils loop and Poloidal Field coils loop) to Auxiliary Cold Box of the cryogenic system, estimated by thermohydraulic calculation will be presented. Moreover, the possible management of these pulsed heat loads will be addressed for the reference plasma scenarios and after a disruption of the plasma by an increase of the supply temperatures and a reduction of the mass flow rates in the supercritical helium loops of the magnets.

Submission category: CEC-01 Large-Scale Refrigeration and Liquefaction

First operational experience and performance optimization of the ATLAS magnet cryogenic system

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The ATLAS magnet system - consisting of a superconducting central solenoid and three superconducting toroids - together with its service systems have been successfully powered up for the first time to the nominal operational current of 20.4 kA on 4th August 2008. Since then, new cryogenic operational challenges have been raised, like the smoothing of steady-state parameters, the enhancing of transient procedures to minimize thermal shocks on the magnet cold masses, the optimization of the complex cryogenic system in order to reduce the compressors electric consumption, and how to avoid regular clogging of the shield refrigerator by water contamination. This paper presents the heat load identification of the various cryogenic sub-systems done at 4.5 K and how some of these loads were reduced, what was gained – in term of electrical consumption – by tuning the turbines settings of the main refrigerator and finally the first consolidation of the cryogenic system that was implemented in order to minimize the detector downtime during LHC beam runs.

Conceptual Design of the FRIB Cryogenic System*

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The Facility for Rare Isotope Beams (FRIB) is a new nuclear science facility funded by the DOE Office of Science and Michigan State University (MSU). FRIB is currently under design and will be located on the MSU campus. The centerpiece of FRIB is a heavy ion linac utilizing superconducting RF cavities and magnets which in turn requires a large cryogenic system. The cryogenic system consists of a commercially produced helium refrigeration plant and an extensive distribution system. Superconducting components will operate at both 4.5 K and 2 K. This paper describes the conceptual design of the system including the expected heat loads and operating modes. The strategy for procuring a custom turnkey helium refrigeration plant from industry, an overview of the distribution system, the interface of the cryogenic system to the conventional facilities and the proposed schedule are also described.

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The Ras Laffan Helium Project

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While helium is scarce worldwide, the helium market is growing steadily, by an average of +4% a year, due to the development of technology in many market segments such as medical, electronics, fiber optics, space etc. Qatar has been a major helium producer since 2005, and its position in the Middle East makes it an ideal supplier for both Europe and Asia.
In this context, Air Liquide announces that it has been awarded a contract by RasGas Company Limited on behalf of Ras Laffan Liquefied Natural Gas Company Limited (3) and Qatargas Liquefied Gas Company (2, 3 and 4), for a large turn-key helium recovery unit (HeRU) to be installed in Ras Laffan, Qatar. The new unit will be the largest in the world, with a production capacity of 20 Tons of Liquid Helium per day. The technology used to purify and liquefy helium at very low temperature (-269°C) is a proprietary Air Liquide advanced technology. For this project, Air Liquide will provide the largest helium liquefier in the world, which will be operated by RasGas.
This project arises out of the existing partnership between Air Liquide, RasGas and Qatargas, which was formed for the successful development of a previous helium unit on the same site in 2003. The combined production of these two units will be 30 Tons of Liquid Helium per day, making Qatar a leading producer of helium, with 25% of worldwide production.
The Ras Laffan Helium Recovery Unit HeRUII is a world-class facility. The process of this purification and liquefaction plant will be presented.

The cryogenic system for NEUROSPIN laboratory: Main features and Refrigerator commissioning

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NEUROSPIN, a CEA Life Science Division laboratory located in Saclay, France, uses superconducting magnets for MRI applications. The aim of this lab, unique imaging platform in Europe, is to study the central nervous system. Several superconducting magnets will be operated, among which a 11.75 T magnet (french-german project Iseult/INUMAC) which needs 1.8K refrigeration, and specific shielding.
AIR LIQUIDE DTA was in charge of the design and manufacturing of a specific Helium Refrigerator dedicated to this application. This system, based on a HELIAL Evolution refrigeration system, HELIAL MF, has to be able to provide in nominal configuration simultaneously refrigeration power at 4.5K (to compensate heat losses), liquefaction rate (to supply 1.8K refrigeration system with liquid helium) and refrigeration power at 50K (shielding of the magnet).
The Refrigeration system has been completed and tested successfully at AIR LIQUIDE Factory at the end of 2010.
The aim of this paper is to present the main technical features of the overall cryogenic system and the main results of the commissioning phase of the refrigerator.

Cryogenic system for Pohang Light Source II (PLS-II) at PAL

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The Pohang Light Source (PLS) is a 3rd generation synchrotron light source, managed by Pohang Accelerator Laboratory (PAL), subsidiary of the Pohang University of Science & Technology (POSTECH) in Pohang, Korea. The PLS, operated for 15 years, will be upgraded the PLS-II by 2011 to produce 100 times higher brightness synchrotron radiation. To reach such performance, this facility requires three superconducting 500 MHz RF cryomodules to be installed into the PLS-II storage ring. The SRF cryomodules (including LHe-cooled niobium RF cavity) will supply sufficient power to the electron beam to make up for power losses to synchrotron light in the dipoles and insertion devices as well as power that is coupled through the ring impedances and dissipated in the walls of the vacuum chamber.

After recent successful projects in the field of cryogenics for synchrotrons: NSRC I and II (Taiwan), SOLEIL (France), Diamond (United Kingdom) and SSRF (China), Air Liquide DTA has been selected to provide the cryogenic system to supply Liquid Helium to the supraconductive cavities of PLS-II.

Besides the main function to provide cooling capacity, the cryogenic system (consisting in Refrigerator, Compressor, Transfer lines, Nitrogen supply system, Helium storage) has to fulfill many other requirements: reliability, accurate control of operation parameters, safety management and specific transient operations management.

The purpose of this paper is to give an overview of the specification and main features of cryogenic system designed for PLS-II.

Effect of Quench and Cooling Cycles on the vacuum and cryogenics conditions of large magnets i.e. the ATLAS Toroids

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The ATLAS Detector Magnet System comprises three large superconducting toroids (and a much smaller solenoid), in total about 700 tons of cold masses housed in three large size cryostats of about 1200 m^3 in total.

The cryogenic system serves to maintain the magnets at 4.7 K during normal detector operation, to recover the cold masses after a fast dump at which the cold mass temperature raise to about 65 K and finally to keep the cold masses below 100 K during yearly maintenance periods.

The vacuum system provides the thermal insulation from room temperature and comprises a robust system of diffusion pumps to keep the cryostat pressures below 10^{-6} mbar under normal conditions. This condition, however, may be violently upset by a sudden release of trapped gasses accumulated on the cold masses and thermal shields during the long periods of normal operation. Certain gasses are released in waves at specific temperatures when a cold mass rises in temperature from 4.7 K upwards to 100 K.

We report on various interesting events of gas release and re-condensation observed during fast dumps following a quench as well as the effect of starts and stops of cooling cycles. Obviously the installed pumping capacity must be appropriate to cope with such events.

When not properly handled peak pressures can go up to 10^{-3} level or even higher leading to a drastic reduction of pumping capacity or even halting of diffusion pumps and cold or icy vacuum vessels.

This research is supported by the ATLAS Collaboration, a joint enterprise of about 174 institutes in 38 countries putting the resources together to engineer and operate the ATLAS Experiment at the Large Hadron Collider.

Future Trends of AFRL Cryocooler Research

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Over the past year, AFRL has "significantly" defined the science and technology (S&T) path forward for cryocoolers in support of Air Force space missions. There are two trends that are emerging for cryocooler S&T: the first is missile warning and the second is responsive space. Missile warning is moving towards larger Focal Plane Arrays, which generate large heat loads. Responsive space is moving towards a cheap, fast alternative to augment, or reconstitute space capabilities. At first glance, these two trends require completely different approaches to cryocooler S&T. However, decreasing the size, weight, and power of cryocoolers supports both trends. This paper will discuss the technology path chosen by AFRL to meet the AF mission needs for cryocoolers to include AFRL's research path, and potential BAA opportunities to help support the research goals.

Modified Methodology for Technology Forecasting: Case study of Cryocooler Efficiency and Vibration

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ABSTRACT

Although the performance of space cryocoolers has improved dramatically since the 1960s, future technology needs include lower cold-tip temperatures, higher cooling loads, and lower exported vibration. The problem is to develop a consistent and analytical method of projecting the industrial base capability to achieve those future needs.

This paper presents a methodology for forecasting cryocooler technology performance, featuring a step-by-step methodology for the analysis of historical space cryocooler trends across four dimensions (time, vibration, specific power, and technology compression). The analysis shown includes the data set from which the performance over time relationships were derived (adjusted to protect proprietary interests). Within the methodology are multiple trends in technology improvement –cold-tip temperature, and the changes in efficiency while approaching the Carnot limit. A proposed method for the construction of a performance, by time and Technology Readiness Level (TRL), has also been derived and postulated.

The result of the forecasting methodology is a graphic of Carnot efficiency and induced vibration trends by cold-tip temperature from the 1960s with projections out to 2030. The analysis of the historical trends provides a tool for the prediction or evaluation of future industrial capability versus technology needs.

On-Orbit Performance of the TES Cryocooler System and Instrument – Six Years in Space

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The Tropospheric Emission Spectrometer (TES) instrument pulse tube cryocoolers began operation 39 days after launch of the NASA EOS Aura spacecraft on July 15, 2004. TES is designed with four IR Mercury Cadmium Telluride focal plane arrays in two separate housings cooled by a pair of NGAS single-stage pulse tube cryocoolers. The instrument also makes use of a two-stage passive cooler to cool the optical bench. The instrument is a high-resolution infrared imaging Fourier transform spectrometer with spectral coverage from 3.2 to 15.4 microns. The cryocooler system design is tightly coupled with the overall thermal control design to maximize performance of the TES instrument. The instrument primary science objective is the investigation and quantification of global climate change, both natural and anthropogenic. After four weeks of outgassing, the instrument optical bench and focal planes were cooled to their operating temperatures to begin science operations. During the early months of the mission, ice contamination of the cryogenic surfaces including the focal planes led to increased cryocooler loads and the need for periodic decontamination cycles. After a highly successful 5 years of continuous space operations, TES was granted an extension for an additional 2 years of operations.

This paper reports on the TES instrument cryogenic system performance including the two-stage passive cooler. After a brief review of the cryogenic design, the paper presents detailed data on the highly successful space operation of the pulse tube cryocoolers and instrument thermal design over the past six years since the original turn-on in 2004. The data shows that the cryogenic contamination decreased substantially to where decontamination cycles are now performed every six months. The cooler stroke required for constant-temperature operation has not increased indicating near-constant cooler efficiency and the instrument's thermal design has also provided a nearly constant heat rejection sink. At this time TES continues to operate in space providing important Earth science data.

Qualification Test Results for the TIRS Cryocooler

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Ball Aerospace has completed qualification testing of its flight Stirling-cycle mechanical cryocooler for the Thermal Infrared Sensor (TIRS), an instrument slated to fly on the Landsat Data Continuity Mission (LDCM) platform. The TIRS cooler, developed under subcontract to NASA Goddard Space Flight Center, consists of a sophisticated and highly reliable, two-stage, fixed regenerator Stirling cryocooler and its drive electronics. The TIRS cooler provides 2 W of 40 K cooling to the TIRS detectors and greater than 3 W shield cooling to less than 100 K for less than 225 W total input power. Performance test results are reported.

Test Results for a High Capacity Cryocooler with Internal Thermal Storage

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Ball Aerospace and Redstone have been developing a space cryocooler for cooling complex optical systems whose loads are intermittent. An example of such a system would be an earth observation satellite that images for only a fraction of its orbit. If a cooler can store refrigeration during a lull, and provide it when the system is active, it can be considerably smaller than one sized to provide the full load continuously.

Our cooler provides two stages of refrigeration, a stage of intermittent cooling at 35K for a focal plane assembly, and a stage of continuous cooling at 85K for cooling the thermal shields that surround it. It provides the intermittent cooling by collecting liquid neon in a unique internal thermal storage tank on the cryocooler and sending it to the focal plane when the heat loads are high.

Our paper presents extensive performance data for neon at 35K. It carries 2 watts at 35 K for 30 minutes, plus the 8.5 watts of continuous cooling at 85K, for less than 300 Watts of DC power. It is ready to cool again in an hour. For contrast the same hardware was filled with nitrogen and tested at 82K. It carries 5 Watts for 25 minutes, plus 15 watts of continuous cooling at 130K, for less than 220 Watts of DC power. It is ready to cool again in a little over an hour.

The system has many features for space system compatibility. Because the storage is located within an active control loop, the cooler can maintain the 35K interface temperature to better than +/- 0.1K independent of the heat load. It can be located remotely because it circulates liquid, which solves many compatibility issues. And because of careful liquid management, it can work in any orientation and in 0-g. In this paper our flight like equipment will be described, and its continuing evolution to flight will be discussed.

Very High Capacity Aerospace Cryocooler

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Lockheed Martin's Advanced Technology Center has developed an aerospace cryocooler with very high cooling capacity. This robust pulse tube cryocooler was designed to provide 20 W of cooling at 70 K while rejecting heat at 300 K. The pulse tube is driven by our M5Midi compressor which is capable of very high power density. The input electrical power into the compressor can exceed 600 W, and the mass of the pulse tube cryocooler and compressor is just 8 kg. The motivation for such high cooling capacities is oxygen liquefaction and storage, both for propellant generation and human breathing supply. However, the large cooling capability could also be used to cool optical structures or other devices with high heat loads. Test data will be presented, mapping the cryocooler performance across a broad range of operating conditions.

Large Cooling Power HEC Pulse Tube Cooler

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The space flight high efficiency cooler (HEC) was originally designed in 1999 for 10W @ 95K and has been delivered with customized cold heads to provide both 1 and 2 stage cooling over a broad temperature range of 40K to 200K. The 4 Kg coolers of this design have been in orbit in their single stage in-line cold head version since 2005. The coolers are in orbit or scheduled for launch on a total of 8 different payload designs. Cooler capability of this design was limited to 25W @ 150K determined by the 180W output limitation of the current flight electronics. To meet higher cooling power requirements with greater efficiency in this temperature range with this small low mass cooler we have redesigned the pulse tube cold head so that the cooler can produce its maximum capability limited by the cooler itself. The pulse tube cooler maintains its vibrationally balanced compressor with an integral configuration to the new coaxial pulse tube cold head. The single thermal and mechanical mounting interface of this integral configuration eases integration with a payload and reduces its complexity compared to a split cold head version that requires two warm interfaces rather than one. In this paper we present the performance of the single stage HEC coaxial cold head cooler in its integral configuration and compare its performance with the previous linear cold head version.

Cryocoolers for Aircraft Superconducting Generators and Motors

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The proposal by NASA to use high temperature superconducting (HTS) generators and motors on future (~2035) aircraft for turboelectric propulsion imposes difficult requirements for cryocoolers. Net refrigeration powers of about 5 kW to 10 kW at 50 K to 65 K are needed for this application. A 2010 survey by Ladner of published work between 1999 and 2009 on existing Stirling and Stirling-type pulse tube cryocoolers showed efficiencies in the range of 10 to 20 % of Carnot at 50 K, much less than the 30 % of Carnot needed to make the concept feasible. A cryocooler specific mass less than about 3 kg/kW of input power is required to keep the cryocooler mass somewhat less than the superconducting machinery. Current cryocoolers have specific masses about 5 to 10 times this desired value, even for those designed for airborne or space use. We discuss loss and mass sources and make suggestions where improvements can be made. For Stirling and Stirling-type pulse tube cryocoolers most of the mass occurs in the compressor. We show that frequency and stroke can have a major influence on reducing the compressor mass. Frequencies up to about 120 Hz and average pressures up to about 5 MPa may significantly reduce the overall cryocooler size and mass while maintaining high efficiency. Other suggestions for reduced mass are given.

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Development and Design of a 4 Kelvin Pulse Tube Cryocooler Characterization Test Facility

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Recent advances in superconducting electronic systems are requiring larger envelopes for cooling power, efficiency, and operational environments from commercial based cryogenic cooling systems. One such system targeted at meeting these requirements is the pulse tube cryocooler. While the pulse tube cryocooler is a well-documented technology at moderate cryogenic temperatures (40-80 Kelvin), its behavior at 4 Kelvin is not well understood. Recent modeling results using REGEN3.3 and a developed CFD model have shown that 4 Kelvin pulse tube cryocoolers can be successfully utilized for superconducting electronic systems. To gain confidence in the modeling predictions, experimental validation is required. This paper discusses a test facility designed and constructed to allow for precise measurement of all relevant regenerator and pulse tube energy flows when operating over the temperature range of 4-35 Kelvin, frequency range of 10-45 Hz, and cold end phase angle range of -10° to -50°. The novel features of this test facility include independent regenerator and pulse tube characterization, modulation of the system phasing using a commercial expander operating at 4 Kelvin, precise off-axis rotation, and rapid experimental turnaround time. A comparison of REGEN3.3 modeling predictions and initial experimental measurements for a regenerator matrix of $Er_{50}Pr_{50}$ are presented with discussion.

Co-axial Pulse Tube Development

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Industrial Research Ltd (IRL) previously developed a single-stage, inline, pulse tube for use with their metallic-diaphragm pressure wave generator (PWG), achieving 45 W of cooling power at 77 K, with 19.5 % of Carnot efficiency (based on the PV input power). This paper describes the conversion of the inline pulse tube to a co-axial configuration that provides a more accessible cold finger. Sage pulse tube simulation software was used to model the modified pulse tube and predicted 55 W of cooling power at 77 K, with an indicated input power of 850 W. The pulse tube operated at 50 Hz, with a mean helium working pressure of 2.5 MPa and was closely coupled to a 60 ml swept volume PWG. Details of the development, experimental results and correlations to the Sage model are discussed.

Key words: Pulse-tube; Sage; Pressure wave generator; Cryocooler

STUDY OF LOW VIBRATION 4 K PULSE TUBE CRYOCOOLERS

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ABSTRACT

SHI has been continuously improving the efficiency and reducing the vibration of a 4K pulse tube cryocooler. One advantage of pulse tube cryocooler over GM cryocooler is low vibration. In order to reduce vibration, both displacement and acceleration have to be reduced. The vibration acceleration can be reduced by split the valve unit from the cold head. One simple way to reduce vibration displacement is to increase the wall thickness of tubes on the cylinder. However, heat conduction loss increases while the wall thickness increases. To overcome this dilemma, a new method to reduce vibration displacement is to optimize the wall thickness of tubes on the cylinder. The new method will be introduced in this paper.

Study on G-M type pulse tube cryocooler with a novel active gas distribution system

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In order to overcome disadvantages of traditional gas distribution system of G-M type pulse tube cryocooler, such as high irreversible losses during the intake and exhaust processes and power consumption, a novel active gas distribution system with middle stage reservoir is proposed. Different from the traditional intake and exhaust processes, a refrigeration cycle of cryocooler with the active gas distribution system consists of intake process from the middle stage reservoir, intake process from the compressor, exhaust process to the middle stage reservoir and exhaust process to the compressor. Theoretical analysis shows that active distribution system can reduce the power consumption of the compressor due to the reduction of irreversible losses during the intake and exhaust processes. The seld-made pulse tube cooler with the active gas distribution system was tested. Experimental results show that the active gas distribution system decreases the power consumption of compressed inlet gas by 27% and entropy generation by 37% when the proportion of opening time of the middle stage reservoir is 30%. And cryocooler reaches a lower temperature with minor decrease of cooling power. Besides, active gas distribution system increases the life time for valves.

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A study on moving-magnet Stirling-type linear compressor for miniature pulse tube cryocooler at 80K

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Abstract

Pulse tube cryocoolers are widely utilized in many circumstances, particularly in space and electronic fields owning to its high stability and low mechanical vibration. Most pulse tube cryocoolers designed for 80K are driven by small size Stirling-type linear compressors which allow various volumes of compressing space and different operating pressure and frequencies. In recent years moving-magnet linear compressors have attracted increasing interests and a significant number of developments to such compressors have been achieved, which in turn have allowed to drive different sizes of pulse tube cryocoolers over a high range of frequencies, for its higher efficiency comparing to traditional moving-coil compressors at similar scale, apart from the relatively complex designing and further coordination of counterbalance with pulse tubes.

In this paper, the analyses of the regeneration improvement, overall efficiency enhancement and phase modulation of a co-axial miniature pulse tube cryocooler are firstly carried out. A dual-piston moving-magnet linear compressor is designed and developed. The compressor contains a new design of linear motor and, the main advantage of its structure is to some extent of increasing its magnetic force at axis direction when pistons are already away from their counterbalance positions. The mass flow and temperature distributions of the pulse tube are optimized to better coordinate with the linear compressor. The integration of the linear compressor and the pulse tube cryocooler reach a satisfying cooling efficiency and a relatively faster cool down time.

Keywords: Moving magnet; Linear compressor; Pulse tube; Coordination

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Investigation of a special configuration of the pulse tube for large cooling power

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Pulse tube coolers with large cooling powers at 80 K could play key roles in superconducting applications such as cooling cables, transformers and fault current limiters, etc. Although a pulse tube cooler with 300 W cooling power has been reported by Praxair with a relative Carnot efficiency of 19%, there are many critical points that need to be further studied, especially for the coolers with higher cooling powers. One of the key issues is the smooth transition between the regenerator and the pulse tube due to their big difference in diameter. The configuration of the cold heat exchanger, sandwiched in between, is strongly related to the transition choice. This paper proposes a special configuration of the pulse tube with a bell-mouthed cold end, which eases the configuration of the cold heat exchanger with enough heat transfer area for large cooling power delivery. An experimental setup is to be reported here with extensive experimental results.

A novel Stirling type pulse tube cryocooler suppressing the third type of DC gas flow

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Pulse tube cryocooler (PTC) is a small-scale regenerative refrigerator without any moving components at cryogenic temperature. The lack of moving parts in the cold end gives the advantage of less vibration, higher reliability, and lower cost to the PTC. Furthermore, for the merit of light weight, small size and high efficiency, Stirling type PTC has been one of the promising candidates for a lot of practical applications cooling from high Tc superconducting devices to infrared equipments.

G-M type PTC working at low frequency can easily reach 4.2 K. However, until recently, single stage Stirling type PTC can hardly attain liquid hydrogen temperature. The third type of DC gas flow we have previously discovered and verified in PTC is one of the key reasons why it is more difficult to obtain low temperature for Stirling type PTC. This paper analyze the zero and first order pressure drop along the pulse tube system and present a simple but elegant way eliminating this type of DC gas flow which makes Stirling type PTC to be more efficient. However, the optimization of PTC especially the adjustment of phase angle between pressure and mass flow has significant influence on the suppressing method of the third type of DC gas flow. Hence we have done a series of experiments on a Stirling type multi-bypass PTC to attain the lowest refrigeration temperature. After the multi-bypass PTC reaches its lowest temperature, we open the metering valve to the best degree which connects the back pressure chamber of the linear compressor to the reservoir. For this novel type of PTC, the lowest refrigeration temperature drops from 30.9 K to 26.8 K and the refrigeration power is 1 W at 40 K after opening the metering valve.

Visualization study of silent film boiling in He II under microgravity and under normal gravity

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The visualization study for the heat transfer mechanism of film boiling of He II under film boiling was carried out using drop shaft. The all components of experimental apparatus were experienced free fall more than 30 times with safety. In this experiment, thin wire heater was used for inducing film boiling in the closed test vessel with optical windows. The measurements of heater temperature and vapor thickness by imaging have successfully conducted. The vapor behavior of film boiling under μ-g were distinguished the silent film boiling. With comparison between the silent film boiling under μ-g and under one-g, the heat transfer mechanism of He II film boiling was studied..

A comparison of different seed particles for visualizing counterflow in He II*

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Our understanding of counterflow in He II has recently advanced considerably through the application of particle visualization techniques. By this method, neutral-density, micron-scale particles are seeded into the liquid helium and their motion is monitored using modern optical recording equipment. Still, there is an incomplete understanding of the interaction between the seed particles and the He II. Solid hydrogen particles at low velocities either propagate at v_n (the normal fluid velocity) or are trapped on superfluid vortex lines. On the other hand, at higher velocities, particles are seen to follow only the normal fluid component, but at a velocity somewhat less than v_n. This behavior may be considered as two different regimes of particles motion. One corresponding to a relatively dense vortex tangle with velocity of particles ~$0.5v_n$, another to a relatively dilute vortex tangle with velocity of particles ~v_n In this context, results from our recent He II counterflow visualization experiments will be discussed.

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Use of Particle Image Velocimetry (PIV) for Further Investigation of a Magnetically Suspended Sphere Oscillating in Helium II

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Oscillatory motion of a sphere in Helium II is further studied by means of particle image velocimetry (PIV). A solid niobium sphere, 3 mm in diameter, is magnetically suspended in the liquid by a set of Nb-Ti superconducting coils. A quadrupole magnet suspends the sphere about a stable equilibrium position while another solenoid just below this quadrupole elevates the sphere above this point, producing an initial height. Current to the lower solenoid is shut off, setting the sphere into vertical oscillation. An injector valve is used to seed particles into the liquid surrounding the sphere. Using a low power emitting laser and a high speed CCD Camera, instantaneous velocity fields are measured and discussed.

Modeling and Development of a Superfluid Magnetic Pump with No Moving Parts

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Current state of the art superfluid-stirling and superfluid pulse tube refrigerators employ the use of multiple bellows pistons to execute the superfluid stirling cycle by displacing the helium from the warm end to the cold end and vice versa. The large number of moving parts in these systems makes them unsuitable for space flight coolers. These types of displacers can be replaced by a Superfluid Magnetic Pump (SMP) with no moving parts. The modeling of the SMP consisting of a cylindrical canister, containing small crushed particles of Gadolinium Gallium Garnet (GGG), with a superconducting solenoid wound around the canister, shows a mass flow production of 33 mg/s. The model assumes a maximum applied magnetic field of 2 Tesla applied by the superconducting magnetic coil with a cycle time of 100 s. A prototype of this pump with the same properties used in the model is used to demonstrate the pumping effect. The mass flow rate produced by this pump is measured by a venturi flow meter. The pressure taps of the venturi flow meter are connected to a dielectric differential pressure gauge, fabricated at UW-Madison, capable of reading a pressure difference as small as 1 Pascal. The corresponding pressure difference for the specified mass flow rate is in the range of several hundred Pascals. The experimental results will be compared to the model, and deviations from the model will be investigated.

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Steady-State Heat Transfer through Micro-Channels in Pressurized He-II

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The operation of the Large Hadron Collider superconducting magnets for current and high luminosity future applications relies on the cooling provided by helium-permeable cable insulations. These insulations take advantage of a He-II micro-channels network constituting an extremely efficient path for heat extraction. In order to provide a fundamental understating of the underlying heat transfer mechanisms, a test was setup to investigate heat transport through single He-II channels typical of the superconducting cable insulation network, where deviation from the macroscale theory can appear. Microfabrication techniques were exploited to etch down to a depth of 20 micrometers the channels connecting an isothermal closed volume to the bath. The heat transport properties were measured in static pressurized He-II, and analyzed in terms of the laminar and turbulent superfluid helium laws.

Hydraulic Characteristics and Thermal Counterflow in Helium II Forced Flow Through Orifice Plates*

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The purpose of the present research is to measure and analyze the temperature changes and the pressure difference variations through orifice plates in superfluid helium (He II) forced flow at the high Reynolds number. The flow of He II is generated with a bellows pump through a 1 m long, 73 mm inner diameter experimental channel containing orifice plates: the ratios of orifice diameter to tube diameter are 10 % and 20 %. The range of Reynolds number is between 3.0 X 10^6 and 1.2 X 10^7. The hydraulic characteristics for adiabatic orifice forced flow He II are examined by comparing with measured pressure drops across the orifice plates and correlations for classical fluids at high Reynolds number. The temperature rise through the orifice plate due to the Joule-Thomson (JT) effect in He II forced flow was also measured. Results are compared to expected temperature changes based on known values for the JT coefficient to investigate He II thermal counterflow through the orifice.

Acknowledgements
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A Method for Numerical Simulations of Superfluid Helium

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Superfluid helium Transport phenomena can be described using the two-fluid *Landau-Khalatnikov* model and the Gorter-Mellink mutual friction. We have continued our previous work devoted to the formulation of a system of equations to describe the heat and mass transport in superfluid helium, and its numerical solution. The main advantage of the approach proposed is that it yields explicitly pressure and temperature as system variables, which can be used to stabilize the numerical solution. In the paper we describe the numerical implementation of the method proposed, and first results on simple test cases that prove the stability and convergence of the procedure.

Heat transfer through Rutherford superconducting cable with novel pattern of polyimide electrical insulation in pressurized superfluid helium environment

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The LHC inner triplet upgrade using standard NbTi Rutherford cable will require an improvement in heat extraction from the cable to the helium. To avoid the cable temperature increase above the critical value, a polyimide electrical insulation should allow more intensive heat transfer then presently observed. New polyimide electrical insulation wrapping schemes of the Rutherford cable have been developed and their permeability at room temperature has been shown to have increased significantly. Heat transfer properties of the polyimide layer are strongly dependent on the insulation wrapping scheme. Heat transfer through the different insulation patterns has been experimentally determined. The paper presents description of new polyimide insulation schemes, a measurement methodology and experimental results.

CEC-18 Helium II Properties and Systems

Overhead Superconducting Power Cables

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There has been significant development worldwide of *underground* superconducting power transmission cables, however overhead cables are orders of magnitude more important in the grid (both in length and energy transmitted). In this paper we present the arguments for overhead HTS power cables. In order to achieve maximum utilization the HTS power cable cooling system must be much simplified from the system presently used in prototype underground cables. We have previously published details of a novel cooling system ('distributed cooling') which we have implemented in a 100 ft suspended test section at LANL. This test section operates at low voltage, but is designed to carry high currents. We present the design of the LANL suspended cable (cooling system, suspension, terminations, thermal insulation) and the experimental results of the high current tests. Our work indicates that overhead HTS cables carrying up to 1000MW at voltages of 100kV are a real possibility with cryogenic stations up to 100 kilometers apart (for dc transmission, tens of kilometers apart for ac transmission). This would enable the transmission of bulk power on wooden poles rather than steel towers: significantly reducing the visible impact and required right of way. This may allow a consequent reduction in public concern and difficulty in obtaining permits for a transmission line.

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Design of a MW-class Superconducting Power Transmission Cable for Airborne Applications

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The design of a MW-class high temperature superconductor (HTS) electrical power transmission cable was studied for airborne applications, with operating voltage ≤ 270 Volts and 30-60 meter total length. A cryogenic-cooled system was designed using commercial-off-the-shelf (COTS) parts including Bi-Sr-Ca-Cu-O or Y-Ba-Cu-O HTS wires, cryogenic vacuum lines and components, and cryocoolers. The performance of the superconductor system operating at ≤ 77K and either DC or AC 60 hz was compared to Cu-wire cables. For 5 MW or 20 kA power transmission in DC mode at 270 Volts, the superconductor system provided significant benefits including reducing weight ~ 80kg/meter, reducing volume ~ 10x, and reducing heat loss ~ 1 kw/meter. A cross-over point exists in the design at 1-2 kA, above which the advantages of the superconducting system are realized. The crossover point, however depends on the specifics of the design and tradeoff parameters, including cable architecture, operation temperature, and choice of cryogenic components. The system design, cost and technology readiness level (TRL) of all components will be presented, and compared to Cu-wire cables. Ref. T. Haugan, et al, *Int. J. Aerosp.*, **1(1)**, 1088 (2008).

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Progress and Status of a 2G HTS Power Cable in Long Island Power Authority (LIPA) Grid

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Underground High Temperature Superconductor (HTS) power cables have attracted extensive interest in recent years due to their potential for high power density. With funding support from the United States Department of Energy, the world's first transmission voltage level HTS power cable has been designed, fabricated and permanently installed in Long Island Power Authority (LIPA) grid. The HTS cable was successfully commissioned on April 22, 2008. In 2007, a new DOE Superconductor Power Equipment (SPE) program to address the outstanding issues for integrating HTS cables into the utility grid was awarded to the current project team (LIPA II). The goal of the LIPA II is to develop and install a replacement phase conductor manufactured using AMSC's second generation wire. In addition, the team will also address the outstanding components development necessary for full scale integration into a transmission grid including integral management of thermal shrinkage of the cable conductor, optimization of the cryostat design to mitigate the implications of potential cable damage, and the development and demonstration of a field splice in the operating utility grid and modular higher efficiency refrigeration system. The 2G cable is planning to be manufactured and installed in LIPA grid in 2011. This paper will report on the status of the development of the project.

Progress on the Helium Gas Cooled Superconducting DC Cable Project

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The paper will present progress on the helium gas cooled superconducting DC cable effort being carried out at The Florida State University Center for Advanced Power Systems (FSU-CAPS), in collaboration with Ultera (a Southwire – nkt cables joint venture). The project is funded by Office of Naval Research. The main purpose of the project is to demonstrate the potential of superconducting DC cables and to understand the implications of cryogenic helium gas environment on structural and dielectric properties in design considerations of the cable. The current phase of the project is to fabricate and test a superconducting DC monopole cable with nominal rating of 1 kV and 3 kA at 77 K. The cable will operate in 50-60 K temperature at an expected current of 6 kA. The cable will be cooled using circulating cryogenic helium gas. The cryogenic system has been designed and tested to operate at the required temperature range. Multiple one-meter long test cables were fabricated for electrical and dielectric tests to validate design parameters. This paper will present transport measurements at variable temperatures, ac loss measurements, and results of dielectric characterization.

Evaluating Cryostat Performance for Naval Applications

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The Navy intends to use High Temperature Superconducting Degaussing (HTSDG) coil systems on future Navy platforms. The Navy Metalworking Center (NMC) is leading a team that is addressing cryostat configuration and manufacturing issues associated with fabricating long lengths of flexible, vacuum-jacketed cryostats that meet Navy shipboard performance requirements. The project includes provisions to evaluate the reliability performance, as well as proofing of fabrication techniques. Navy cryostat performance specifications include less than 1 Wm^{-1} heat loss, 2 MPa working pressure, and a 25 year vacuum life. Cryostat multi-layer insulation systems developed on the project have been validated using a standardized cryogenic test facility and implemented on 5-meter-long test samples. Performance data from these test samples, which were characterized using LN_2 boil-off and flow-through measurement techniques, will be presented.

The NMC is working with an integrated project team consisting of Naval Sea Systems Command, Naval Surface Warfare Center Carderock Division, Southwire Company, nkt cables, Oak Ridge National Laboratory, ASRC Aerospace, and NASA Kennedy Space Center to complete these efforts. This work was conducted by NMC, operated by Concurrent Technologies Corporation under contract number N00014-06-D-0048 to the Office of Naval Research as part of the U.S. Navy Manufacturing Technology Program.

Liquid air as a coolant for thermal management of long-length HTS cable systems

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Direct current (dc), high temperature superconducting (HTS) cable systems have been suggested as an effective method of transmitting massive quantities of electric power (up to 10 GW) over very long distances (thousands of kilometers). This is made possible mainly by the high-current-carrying capability of the HTS materials when operated below their critical temperatures and by their near zero resistance to constant current. Most HTS cable concepts rely on liquid nitrogen or gaseous helium as the coolant. As an alternative, liquid air offers certain benefits and is discussed here as a cable system coolant. Air has a lower freezing temperature than nitrogen, it can be produced locally, and a liquid air leak will not displace the oxygen in a closed compartment. The dc cable design concept proposed by the Electric Power Research Institute (EPRI) in which the coolant flows in a cryogenic enclosure that includes the cable and a separate return tube, and refrigeration stations positioned every 10 to 20 km is assumed for this analysis. Both go and return lines are contained in a single vacuum envelope. The thermal management of this superconducting cable concept with liquid air in long-distance HTS power cables is developed in this paper. The results will be compared to the use of liquid nitrogen and gaseous helium.

Research sponsored by the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, Advanced Cables and Conductors Program, under contract No. DE-AC05-00OR22725 with UT-Battelle, LLC, and by EPRI under contract No. EPP35856-C16271.

Experimental study of counterflow cooling using a test loop to simulate the thermal characteristics of a HTS cable system

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The counterflow cooling configuration is a compact, efficient, and relatively low cost thermal management approach for long-length HTS cable systems. In the counter-flow cooling configuration the coolant flow, typically liquid nitrogen, is initially supplied through the center of the cable turning around at the far end of the cable and returning through the annular space between the cable and the inner cryostat wall, using a single cryostat. The temperature distributions along the cable and the nitrogen flow streams are extremely difficult to measure in an operating HTS cable because of the issues associated with installing thermometers on high voltage components. A 5-meter long test loop has been built that simulates a counter-flow cooled, HTS cable using a heated metal tube to simulate the cable. The test loop contains calibrated thermometers to measure the temperature distribution along the tube and the return liquid nitrogen stream. Measured temperature distributions in the return flow stream and along the tube wall for varying flow rates and heating conditions to simulate a HTS cable will be presented and discussed.

Research sponsored by the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, Advanced Cables and Conductors Program, under contract No. DE-AC05-00OR22725 with UT-Battelle, LLC.

Methane Cryogenic Heat Pipe for Space Use with a Liquid Trap for On-Off Switching

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A methane cryogenic heat pipe with a liquid trap for on-off actuation was developed by ATK for use on JPL's Space Interferometer Mission - Lite (SIM-Lite) pre-Phase A hardware technology demonstration tests. The cryogenic heat pipe coupled to a cold radiator at 160K provides cooling to the CCD camera focal planes. The heat pipe was designed for a transport capacity of 15W across a 1.5m span through a near room-temperature spacecraft environment. A key and driving requirement for the heat pipe was the need for switching the heat pipe on and off needed to support low power decontamination cycles to near room temperature of the cryogenic focal planes. The cryogenic heat pipe is turned off by removing the methane working fluid from the heat pipe and storing in the liquid trap. The heat pipe is turn-on by simply re-introducing the working fluid from the liquid trap. This on-off switching capability is a key requirement for cryogenic heat pipes used with passive or active cryocoolers for cooling focal planes or optics. The switching capability provides a means to decouple a cold focal plane or optics from a redundant stand-by cryocooler or a passive cooler when in need for a decontamination cycle.

After a brief description of the SIM-Lite cryogenic system design, detailed thermal test data is presented showing the successful cryogenic performance of the methane cryogenic heat pipe during thermal vacuum testing at JPL. The heat pipe performance will be compared to other cryogenic technologies available with on-off switching capability. Potential applications of this technology on future cryogenic instruments and missions at JPL will be reviewed and presented.

Airborne earth-observing hyperspectral imagers utilizing commercial cryocoolers

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JPL is developing airborne hyperspectral imagers, for the near-IR and thermal-IR bands, utilizing commercial cryocoolers as the primary cooling. Stability of the spectral calibration of the spectrometers is of paramount importance in the instrument performance. The use of mechanical cryocoolers, as opposed to liquid cryogens, results in operational and design advantages and disadvantages, especially in the areas of vacuum maintainence, thermomechanical stability, and operation from undeveloped airfields. We describe the cryogenic package and the overall fielded system, and discus design details associated with utilizing mechanical cryocoolers for this application.

Large volume liquid helium relief device verification apparatus for the Alpha Magnetic Spectrometer

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Here we present details of a test for verifying the liquid helium vessel relief device for the Alpha Magnetic Spectrometer (AMS02). The relief device utilizes a series of burst disks designed to rupture in the event of a vacuum failure of the AMS02 cryogenic system. A failure of this type is classified to be a catastrophic loss of insulating vacuum accident. This apparatus differs from other approaches due to the size of the test volumes used. The verification apparatus consists of a 250 liter vessel used for the test quantity of liquid helium that is located inside a vacuum insulated vessel. A large diameter valve is suddenly opened to simulate the loss of insulating vacuum in a repeatable manor. Pressure and temperature vs. time data will be presented and discussed in the context of the AMS02 hardware configuration.

Reorientation of Cryogenic Liquids under Non-isothermal Boundary Conditions

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Estimations of the liquid-vapor interface motion and of the related tank pressure and temperature evolutions are of a major importance for the rocket propellant management in the future re-ignitable cryogenic upper stages. Accordingly, the interface oscillations of liquid argon and liquid methane have been experimentally investigated in a partly filled cylinder in the Drop Tower in Bremen. Axial wall temperature gradients of averaged 0.15 K mm^{-1} – 1.93 K mm^{-1} were applied above the normal gravity (1g) interface position. The oscillations take place during the reorientation (axial sloshing) from the 1g interface position towards a new position upon step transition to microgravity (10^{-6}g). The situation is similar to the end of thrust in a rocket tank when the cold propellant flows along the warmer tank wall driven by capillary forces. The apparent contact line motion and the apparent contact angle were affected in the experiments by the temperature difference between the slightly subcooled cryogenic liquid and the superheated cylinder wall. The contact line exhibited a transition from an aperiodic to an oscillatory motion, depending on the axial wall gradient value. The frequency and damping of the of the interface center point oscillation followed the contact line motion. The ullage pressure evolution was found to follow the contact line motion too, presumably due to extra evaporation from the contact line. Nucleation boiling was observed for the highest gradient values.

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Experimental and Numerical Investigation of Reduced Gravity Fluid Slosh Dynamics for the Characterization of Cryogenic Launch and Space Vehicle Propellants

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The understanding of slosh dynamics in cryogenic fuel tanks under micro-gravity conditions has long been severely limited through the lack of numerical predictions anchored to experimental data. As space programs increasingly investigate various options for long duration space missions the accurate prediction of propellant behavior over long periods of time in micro-gravity conditions has become increasingly imperative. This has driven the development of a detailed, physics-based understanding of slosh behavior of cryogenic propellants over a range of conditions and environments that are relevant for rocket and space storage applications. Recent advancement of computational capabilities and hardware capacities has also driven a greatly increased usage of computational fluid dynamics (CFD) for complex modeling of fluid behavior in space. Historically, launch vehicles with moderate duration upper stage coast periods have contained very limited instrumentation to quantify propellant stratification and boil-off in these environments, thus the ability to benchmark these complex computational models is of great consequence.

Recent work has been undertaken to establish an extensive experimental database, along with development of enhanced CFD modeling techniques. This has produced data that can now be utilized for characterization of cryogenic propellant behaviors in micro-gravity conditions. In addition, a mass gauging system specifically designed to provide high fidelity measurements of both liquid stratification and liquid/ullage position in a micro-gravity environment has been developed. This publication will summarize the various experimental programs established to produce this comprehensive database.

Cryogenic Orbital Testbed (CRYOTE) – Applications to both Space and Ground Systems

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The Cryogenic Orbital Testbed (CRYOTE) provides an in-space environment where the unique properties and fluid flow of cryogenic propellants can be demonstrated in micro- or zero- gravity. With partnerships across industry and NASA, the CRYOTE project has developed a flight system concept and has fabricated a unique ground test article that can demonstrate chilldown and fill of a flight-weight tank with cryogenic fluids. The ground test article contains a flight-weight tank mounted inside of an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) with a composite skirt. It contains a fill and vent system that can test several chilldown and fill sequences. It can also accommodate a variety of thermal protection systems. Results from the ground test will help anchor analytical models for optimizing cryogenic fill and storage capability for various environments, including the CRYOTE flight demonstration. The CRYOTE flight article is launched as a Rideshare payload and utilizes residual liquid hydrogen (baselined) or liquid oxygen (alternate) to demonstrate cryogenic fluid management (CFM) on orbit. Experiments can be conducted for several months in a micro-gravity environment, depending on the configuration of CRYOTE.

This paper will discuss the objectives of cryogenic fluid chilldown, fill, and storage demonstrations and how CRYOTE ground test article can support these needs.

Methane Lunar Surface Thermal Control Test

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Abstract

NASA is currently developing the propulsion system concepts for future exploration missions including human return to the lunar surface. Studies have identified high performance, cryogenic methane (LCH4) and oxygen (LO2) as a propellant combination for consideration for the main and reaction control system (RCS) lunar surface ascent propulsion system, and they point to operating pressures of approximately 350 psia and surface stay requirements of over 200 days. To meet this requirement, we prepared a test article with state-of-the-art insulation competitively procured and tested it in a representative lunar environment at NASA GRC. Our primary goals were to test a system to store the methane for 210 days, unvented, with a low density state-of-the-art Multi-layer Insulation (MLI) system to protect the propellant tanks from the lunar surface and solar environmental heating and with the LCH4 initially densified LCH4 at 93K and starting with tank ullage of approximately 15% at the KSC launch pad. The evaluation of the data collected is anticipated to help better characterize thermal control and multi-layer insulation systems applied to cryogenic propellant tanks. Such characterization is key support data for the architecture teams responsible for accurate modeling of flight vehicles, such as in-space cryogenic depots or in-space cryogenic upper stages. Boil-off and pressurization testing was performed under vacuum and thermal environments of 140, 250, and 350 K as well as simulated ground and ascent environments. Preliminary findings are that the MLI heating was higher than expected, that the coupon testing confirmed this, and that model correlations indicate that the Lockheed-type MLI performance equations exhibit varying degrees of dependency on the environmental temperature, most pronounced at low temperatures. The significance of the work seen at this time are that cryogenic methane thermal control system has been characterized for lunar lander propulsion; modeling, construction, and penetration insulation insight has been gained; that coupon correlation provided a solid basis for tank applied testing; and that the ground/ascent integrated heating profile found that this portion of the mission was equivalent to an extra 3.5 days of storage time to the mission.

A Modeling study on the Geometry of Active Magnetic Regenerator

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Magnetic refrigeration technology needs further development not just by the improvement of magnetocaloric properties but also the optimization of the cooling system design. One of the important problems in the cooling system design is the geometry of regenerator for the efficient heat transfer between magnetic material and fluid which is the major loss mechanism in cooling system. Two kinds of regenerators are widely used. One is flat plate regenerator which can offer the best heat transfer to pressure drop ratio (Sarlan, 2008) for common regenerator design; another is porous media regenerator which can obtain a large temperature span experimented by lots of groups such as Toshiba. But until now, only a few research papers actually study on the geometry of regenerator. This paper is focus on the influence of regenerator geometry to the performance of AMRs. Two kinds of model have been constructed and compared with velocity field, pressure loss, heat transfer rate, cooling capacity. The goal of this study is to provide a suggested geometry for a prototype AMR.

Numerical Simulation for Hydrogen Magnetic Refrigeration

In this paper, we will describe a simulation model for hydrogen magnetic refrigerator. Recently, we built an AMR test apparatus operated with an external gas displacer to transfer the heat from magnetic material unit (AMR bed). Details will be shown in another paper of this conference (Hirano et al.).

Because finding an optimum parameter of experiment is not easy, numerical simulation is needed to confirm the experimental conditions. First we construct a one-dimensional model.This model has been calculated separately for heat exchange fluid and magnetic material. We already confirmed that simulation results agreed with experimental data for the internal gas displacer, and we estimate the experimental parameters in external gas displacer system.

We will show the comparison between simulation and experimental results, and some extensive numerical methods like 2-dimentional one.

A High Efficiency Traveling-wave Thermoacoustic Refrigerator for Cryogenic Cooling Operation: Thermodynamic Design and Experimental Verification

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The most obvious advantage of pulse tube cryocoolers is its higher reliability because of totally non-moving parts in its cold box. Modern advanced pulse tube cryocoolers (double-inlet and inertance-tube types) have been developed to run after the high efficiency of Stirling cryocoolers. However, unlike the Stirling cryocoolers, the advanced pulse tube cryocoolers can not recover the acoustical power coming from their cold end, consequently leading to an intrinsically lower efficiency. A few years ago, a totally non-moving-part traveling-wave thermoacoustic refrigerator was proposed to recover the dissipated acoustical power in the orifice vale or in the inertance tube of pulse tube cryocoolers, but no any research on such a thermoacoustic refrigerator for cryogenic cooling has been reported so far.

This paper theoretically and experimentally studied a traveling-wave thermoacoustic cryocooler, simultaneously comparing with an inertance-tube pulse tube cryocooler operating in liquid nitrogen temperature range. The same core thermodynamic components including the main hot-end exchanger, regenerator, cold-end exchanger, pulse tube, and secondary hot-end exchanger are fixed and used in the both cryocoolers. Firstly, thermodynamic design and optimization mainly on their phase shifting devices are made under the same operating conditions such as operating pressure, frequency, and pressure ration, etc. For 77K operation, the theoretical results show that the inertance pulse tube cryocooler and the traveling-wave thermoacoustic refrigerator achieve relative Carnot efficiencies of about 33% and 38%, respectively. In addition, it is found that the traveling-wave can improve much more in higher cooling temperature such as 120 K for natural gas liquefaction. Then, the experiments on both cryocoolers driven by a linear compressor were conducted, demonstrating a larger cooling power and a higher efficiency for the newly developed travelling-wave thermoacoustic refrigerator. It is believed that the traveling-wave thermoacoustic refrigerator will provide a higher and better performance compared with the convention pulse tube cryocooler for above 77K cooling.

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A numerical model of a hybrid regenerator by combining the gas Stirling regenerative refrigeration effect with the active magnetic regenerative refrigeration effect

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A new type of hybrid magnetocaloric refrigeration cycle was introduced in this paper, in which magnetic refrigeration materials were utilized as the regenerator matrix for both the gas Stirling regenerative refrigerator and the active magnetic regenerative refrigerator. The magnetic field is provided by a permanent magnet which varies from 0 to 1.5 T with a specially designed rotation configuration. Gas helium is used as the heat transfer medium for this new designed hybrid refrigerator. Combined the effects of both gas Stirling regenerative refrigeration and active magnetic regenerative refrigeration so that to build a kind of environmental-friendly and high efficient refrigeration cycle.

Most efforts were made to build a numerical method for this hybrid regenerator in the work. The numerical model is a one dimensional periodic unsteady flow model. The energy equations, continuity equation, momentum equation of gas, energy equation of magnetic matrix are included in this model. Implicit control volume method is used to solve these equations. By this model, the working mechanism of the hybrid regenerator was simulated. The obtained result was also verified with some measured data of a prototype, which is useful for understanding how this hybrid refrigerator works.

A standing-wave thermoacoustic engine driven by liquid nitrogen

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Thermoacoustic oscillation at cryogenic temperature, such as Taconis oscillation is typically suppressed in the former researches, few efforts have been made to enhance it. In fact, thermoacoustic engines can enhance pressure oscillation whenever there exists a large enough temperature difference between the both ends of the stack or the regenerator. We proposed a standing-wave thermoacoustic engine driven by the cold exergy instead of the conventional heat exergy. Experimental and theoretical work has been performed on a self-made standing-wave thermoacoustic engine driven by liquid nitrogen to demonstrate the feasibility and explore the operating characteristics of the engine with cold exergy. Experimental results show that with helium of 0.63 MPa as working gas, the onset temperature difference of the engine driven by liquid nitrogen is decreased by 28.9% compared to that of the conventional thermoacoustic engine driven by a high temperature heat source. And with the same temperature difference of 232.7 K across the stack, the pressure amplitude of the engine driven by liquid nitrogen reaches 11.99 kPa, which is 4.5 times as large as that of the conventional engine. Besides, with nitrogen as working gas, new phenomenon of continuous alternation of the onset and damping progresses is observed and also analyzed qualitatively. Theory analyses and experiments show that the thermoacoustic engine driven by the cold exergy, such as liquid nitrogen and liquefied nature gas (LNG) may be an alternative for recovering of cold energy and low-grade thermal energy.

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Performance improvement of a traveling-wave thermoacoustic engine by heat transfer intensification

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Thermoacoustic engine, converting thermal energy into acoustic energy without any mechanical moving parts, is promising in power generation, refrigeration and gas separation. Hot end heat exchanger is the place where thermal energy is input and is one of the key components of thermoacoustic engine. The performance of the hot end heat exchanger determines the temperature of the working gas inside it, which has a strong influence on the energy conversion efficiency of the thermoacoustic engine. On the basis of linear thermoacoustic theory, computational optimization is carried out on one traveling-wave thermoacoustic engine and then a new hot end heat exchanger is designed and manufactured. The output characteristics of the thermoacoustic engine are then experimentally studied by a variable R-C load and linear generator respectively. Emphasis is put on the acoustic impedance matching between the thermoacoustic engine and loads. As a result, the thermal efficiency and output capacity of the thermoacoustic engine increase remarkably after the optimization, which sets a good basis for further research on electricity generation.

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Design and experiment on a small scale traveling wave thermoacoustic engine

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The traveling wave thermoacoustic engines generally outperform standing wave based ones, due to the ideally reversible heat transfer in the regenerators. Therefore, more attraction has been focused on the traveling wave thermoacoustic engines in recent years and wide application is greatly expected. A small scale thermoacoustic engine with a resonator about 1 m in length has been designed, constructed and tested. Details about the effects of the operating parameters on the system performance are given in this paper. The experimental results indicated that the engine has a lower onset temperature and a higher efficiency compared with standing wave based ones. The maximal pressure ratio reached over 1.2, which demonstrated the potential of the combination of the engine and a relatively high frequency pulse tube cryocooler. However, optimizations are expected for a stable oscillation mode.