Optimization of the Force Modeling between High Temperature Superconductor and Permanent Magnet

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The optimization of the force between a permanent magnet (PM) and a high temperature superconductor (HTS) is studied in terms of frozen image model. The frozen image model is realized by using the Amperian surface current approximation for which the magnetization of the permanent magnet modeled is incorporated with various geometrical configuration of the PM/HTS system. In the optimization study, the bulk current is introduced instead of surface current. It is argued that the force estimation is better for bulk current assumption than that of the surface current. The results indicate that there is an improvement in the calculation of the force between the HTS and PM.

Influence of tape magnetization on magnetic field generated in small Bi-2223 dipole magnet

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Applications of high T_c superconductors to accelerator magnets are attractive from the viewpoint of reduction of cooling efficiency, thermal stability, and the generation of a very high magnetic field. Since most of commercially-available high T_c superconductors are with tape shape, many challenges should be required before their applications to accelerator magnets. We focus on the tape magnetization. Large magnetizations of tapes can deteriorate the quality of the magnetic field, and their characterization is one of the critical issues for realization of accelerator magnets using high T_c superconductor tapes. We had made a small magnet consisting of two racetrack coils wound with Bi-2223 tape and have been made its magnetic field measurements. In this presentation, we report the detailed results of the magnetic field measurements of this coil. The Bi-2223 magnet was cooled in liquid nitrogen to measure its magnetic field. A rotating pick-up coil system was placed in the bore of the magnet, and the multi-pole components of the magnetic field were measured. While a constant current was supplied to the magnet, we observed the temporal changes of the multi-pole components which were caused by the decay of the tape magnetization. The temporal evolutions of the multi-pole components after shutting down the current were studied, because we could see more clearly the behavior of magnetization without the background magnetic field generated by the current. The history of the excitations of the magnet influences the magnitudes and the temporal evolutions of the multi-pole components.

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Development of cryostat for 5 T HTS insert magnet

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The Korea Basic Science Institute (KBSI) has initiated the development of a 5 T high temperature superconductor (HTS) insert magnet system. The objective of the program is the design and fabrication of HTS insert magnet system for GHz class NMR applications. Since the HTS magnet system should be inserted into the conduction-cooled 15 T background magnet with 100 mm room-temperature bore, several ancillary requirements such as space restriction and cryostat structure need technical attention. The design activities of a 5 T HTS magnet system are completed. In this paper, the design of liquid helium cryostat for a 5 T HTS insert magnet is presented, taking into account shape ratio, cryogenic loads and inventory of cryogenic liquid. In addition, the structure of cryostat, minimizing heat flow from room-temperature to cryogenic-temperature, is described in detail. The preliminary results of cooling test for a 5 T HTS insert magnet are also discussed.

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Experimental Studies of Helical Solenoid Model Based on YBCO Tape

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The Helical Cooling Channel (HCC) is a new technique proposed for the six dimensional phase space cooling of muon beams. It is based on hydrogen filled RF cavities inside superconducting magnets that provide superimposed solenoid, helical dipole, and helical gradient field components. To achieve the optimal muon cooling rate, helical solenoids with stronger field and smaller aperture are used. The highest-field section of HCC will use helical solenoid based on HTS conductor. The YBCO tape has certain advantages due to its electrical and mechanical properties. To study and address the design, technological and performance issues related to magnets based on YBCO tapes, a short helical solenoid model based on double-pancake coils was designed, fabricated and tested at Fermilab. This paper summarizes the results of experimental studies of YBCO tape and splices samples, and double-pancake coils in liquid nitrogen and in liquid helium.

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A low-noise quench detection and protection system for HTS coils

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Thermal stability and quench protection of High Temperature Superconducting (HTS) magnet are very important for practical applications. A higher heat capacity and the larger temperature margin of HTS superconductors with respect to low temperature superconductors (LTS) result in a higher stability of the HTS coils against thermal perturbations. However, quench is still possible in an HTS coil. As a result of a much slower Normal Zone Propagation velocity in HTS materials, the measurement of the quench voltage is much more challenging due to the low value of the signal compared to the level of the noise normally present in the system. In this paper a quench detection and a protection system based on a low noise measurement technique are presented and discussed. The system performance is illustrated by test results of small HTS coils.

Fabrication and test of MgB_2 and coated conductor coils for space applications

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Due to the low specific weight and the elevated critical temperature of 39 K MgB_2 is an ideal candidate for space applications. Operation temperatures above 10 K for MgB_2 magnets allow efficient cooling with cryocoolers. Furthermore, liquid hydrogen serving as propellant for rockets, can also be used for cooling of magnets, e.g. for plasma shielding. The availability of superconducting joints even allows persistent mode operation of MgB_2 magnets in space. With second generation RE-Ba-Cu-O high temperature superconductor tapes application temperatures can even be raised up to liquid nitrogen temperature, however, persistent-mode operation is not yet possible due to the lack of superconducting joints.

Application of superconducting coils in space requires lightweight and robust coil structures. The components have to withstand strong vibrations during the launch of rockets. In order to test the mechanical performance of MgB_2 and RE-Ba-Cu-O coated conductor coils under flight-relevant vibration conditions, small coils and also a persistent joint for MgB_2 wires have been constructed. V(I) measurements showed good superconducting properties. Vibration tests for a MgB_2 coil were performed on a shaker at DLR, Berlin. No degradation of the superconducting properties could be observed after the shaker test. Further tests for other coils and a persistent joint are ongoing and the results will be presented.

Operational Characteristics of the Helium Refrigeration System at HANARO

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HANARO, Research Reactor, produced the first cold neutron sources on November 3, 2009 through the neutron guide tube. Cold sources are produced by scattering in the moderator cell filled with liquid hydrogen. It was designed for a capacity of the helium refrigerator has 1500 watts at a supply temperature of 14 K. A helium mass flow of that temperature is 50 g/s. The hydrogen pressure on a cold mode operation is dropped down to 152 kPa which is a pressure for producing the cold sources at HANARO. Originally, the helium refrigeration system was made up of three modules which are composed respectively of the compressor module, the oil removal and gas management modules, and the helium refrigerator modules.

The operational modes of the CNRF (Cold Neutron Research Facility) are divided into 3 stages, which are shut-down, start-up, and normal operation. Normally the helium refrigerator should be operated before starting up the reactor. For this, operation of the helium refrigeration system needs to be on normal state 12 hours before the reactor operation because 6 hours is needed for removing impurities in the cycle helium, 4 hours and 20 minutes is needed for the cold mode operation to cool down the helium gas to 21K, and 1 hour and 20 minutes for stabilizing the pressure of helium gas to 152 kPa.

The cycle helium purification should be done before the cold mode operation of the helium refrigerator. In order to get rid of impurities, we used for the cryogenic adsorber, with activated charcoal, to be filled with LH_2. The gas analyzer attached the helium refrigeration system analyzed and monitored on line real time such as H_2O, N_2, and carbohydrates. The conditions of the operational limit for them are below 1 ppm (volume) less than nearly one tenth of the manufacturers' manual.

This paper describes operational characteristics of the Helium Refrigeration System.

Dual Circuit Large Scale Cryogenic Testing

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The Launch Equipment Test Facility (LETF) at the John F. Kennedy Space Center has a new unique and innovative cryogenic flow testing capability. The system is designed to perform multiple tasks in order to simulate the conditions that would be encountered within the launch facilities at Kennedy Space Center and other dynamic cryogenic fluid flow operations. The cryogenic testing system at the LETF utilizes a modular set of vacuum jacketed pipes to flow either liquid nitrogen or liquid hydrogen. The cryogenic system utilizes a once through approach for liquid hydrogen, and either a once through or recirculation mode for liquid nitrogen. The liquid hydrogen is limited to a once through operation due to restrictions for permanent storage of liquid hydrogen in the Industrial area at Kennedy Space Center. The liquid hydrogen is delivered via tanker truck to the tanker inlet connection and flows under low pressure to one of two test areas. The first test area resides upon and within the vehicle motion simulator that can replicates the dynamic nature of the vehicle and launch facility during prelaunch activities including the motion of the launch vehicle at the time of lift off. The liquid hydrogen and any gas generated is then routed to one of two vent stacks for disposal. The second test area provides piping to enable the insertion of cryogenic components into the flow stream. The test area is designed to accommodate components up to eight inches pipe diameters. The liquid nitrogen can be delivered to the system via a tanker like the liquid hydrogen, but the system also has two 15,000 gallon liquid nitrogen dewars that can be configured such that the liquid nitrogen can be delivered in a once thru manner venting to atmosphere the same as the liquid hydrogen or the system can be configured to operate in a recirculating mode such that the liquid nitrogen is pumped from one dewar and collected in the second for continuous operations. The second dewar acts as a separating vessel to remove the excess gaseous nitrogen generated by the testing. The gaseous nitrogen is routed to the vent stack used in the once thru operations. This paper will describe the unique attributes and design difficulties that were encountered when trying to build a dual use, modular, highly reconfigurable system.

Design of a cryogenic accumulator to mitigate a pressure fluctuation caused by a sudden kW-order heat load.

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An intense spallation neutron source (JSNS) has selected supercritical hydrogen (1.5 MPa and around 20 K) as a moderator material. The cryogenic hydrogen system provides the supercritical hydrogen to the moderators and removes the nuclear heating, which is estimated to be 3.75 kW for a 1-MW proton beam operation. Such the sudden kW-order heat load would bring about a huge pressure fluctuation because the supercritical hydrogen behaves as incompressible fluid. A pressure suppression technology was developed, in which a cryogenic accumulator and a heater functioned as a passive volume controller and an active controller for thermal compensation, respectively. In this work, the cryogenic accumulator, which adopted a bellows structure, was designed based on the numerical analysis. It was confirmed through a 100-kW and a 200-kW proton beam operation that the cryogenic accumulator spontaneously ran without any delay and the pressure fluctuation could be mitigated.

Diagnosis of a Poor Performing Liquid Hydrogen Bulk Storage Sphere

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There are two 850,000 gallon Liquid Hydrogen (LH2) storage spheres used to support the Space Shuttle Program; one residing at Launch Pad A and the other at Launch Pad B. The LH2 Vessel at Pad B has had a high boiloff rate since being brought into service in the 1960's. The daily commodity loss was estimated to be approximately double that of the Pad A tank, and well above the minimum required by the vessel's specification. Additionally, after being re-painted in the late 1990's a "cold spot" appeared on the outer vessel which resulted in a poor paint bond, and mold formation. Thermography was used to characterize the area, and the boiloff rate was continually evaluated. All evidence suggested that the high boiloff rate was caused by an excessive heat leak into the inner sphere due to an insulation void in the annulus. Pad B was recently taken out of Space Shuttle program service which provided a unique opportunity to diagnose the tank's poor performance. The vessel was drained and inerted, and then opened from the manway on the top where a series of boroscoping operations were accomplished. Boroscoping revealed a large Perlite insulation void in the region of the tank where the cold spot was apparent. Perlite was then trucked in and offloaded into the annular void region until the annulus was full. The tank has not yet been brought back into service.

Heater-controlled pressure suppression characteristics of the cryogenic hydrogen system

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At J-PARC, a cryogenic hydrogen system provides supercritical hydrogen (1.5 MPa and around 20 K) to three kinds of hydrogen moderator and removes the nuclear heating of 3.75 kW for a 1-MW proton beam operation. The supercritical hydrogen behaves as incompressible fluid. The pressure suppression system using both a cryogenic accumulator and a heater was introduced in order to mitigate the pressure fluctuation caused by such a sudden kW-order heat load. The effective of it had been confirmed for a 120-kW and a 300-kW proton beam operation. However, partial damage of the cryogenic accumulator was encountered in February 2010. In this work, the heater-controlled pressure suppression procedure was studied in order to resume the operation for as short a time as possible. The cryogenic hydrogen system was temporary altered and the operational procedure was also redeveloped. It was verified through an on-beam commissioning that the pressure fluctuation was 40 kPa for the 120-kW proton beam operation, which was lower than the design value of 0.1 MPa, although it was 10 times higher than for both the cryogenic accumulator and the heater.

Development of an operational procedure of the cryogenic hydrogen system at the J-PARC

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At the J-PARC, the cryogenic hydrogen system provides supercritical hydrogen (1.5 MPa and around 20 K) to three moderators and absorbed the nuclear heating of 3.75 kW for a 1-MW proton beam operation. The cryogenic hydrogen system, in which combustibility hydrogen with high pressure and low temperature exists, is required for ensuring the safety and carrying out the stable operation for a prolonged period. The automatic operational control procedure was developed based on numerical analysis. It was divided into five operational modes such as cool-down mode, beam injection mode, stand-by mode, warm-up mode and quick hydrogen discharge mode. The interlock system was also introduced to protect the equipment if an abnormal event occurs. The operational and the controlled parameters were optimized based on the commissioning data. It was confirmed that the developed operational procedure succeeded in the stable operation of the cryogenic hydrogen system.

PERFORMANCE VALIDATION OF REFRIGERATION RECOVERY FOR EXPERIMENTAL HALL HIGH TARGET LOADS

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The Qweak experiment at Jefferson Lab (JLab) is a 3000 W hydrogen target scheduled to run until the planned shutdown in the spring of 2012 for the 12 GeV installation. As detailed in previous proceedings, support of the cryogenic load of this target was made possible by incorporating modifications to the End Station Refrigerator (ESR) to recover the refrigeration supplied by the Central Helium Liquefier (CHL). Testing and commissioning for these modifications was performed in February 2010 demonstrating that the performance exceeded projected expectations. In this paper, we present the analysis of the testing results in regards to the actual loads capable of being supported and the process boundaries encountered, as well as a discussion of the commissioning results for the cryogenic support of the Qweak target.

CEC-02 Large-Scale Systems, Facilities, and Testing
Poster presentation

LARGE-SCALE SIMULATED RAPID PROPELLANT LOADING SYSTEM TEST FACILITY FOR ADVANCED CRYOGENIC SYSTEMS, COMPONENT AND SOFTWARE TECHNOLOGY DEVELOPMENT

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NASA and its contractor, ASRC Aerospace, Inc., have completed design, installation and validation testing of a Simulated Rapid Propellant Loading (SRPL) System at the Cryogenics Test Laboratory at the Kennedy Space Center, Florida. The modular SRPL System is ideally suited for the following functions: (1) development testing of methods to rapidly chilldown and load a launch vehicle utilizing energy efficient methods, (2) development and qualification testing of advanced cryogenic component technologies, (3) development testing of concepts and processes for entire ground support systems designed for servicing large launch vehicles, (4) commercial-sector testing of cryogenic products and systems (5) development testing of advanced software for fault detection, isolation and recovery (FDIR), and (6) training of personnel in design and operation of large cryogenics systems . This Cryogenic Testbed consists of modular fluid distribution piping and storage and receiver tanks simulating an entire launch vehicle propellant loading system. The SRPL System includes four pumps which can be operated individually or in parallel with flowrates from 1 to 900 gallons per minute (gpm), pressures from 0 to 225 pounds per square inch (psig) and temperatures down to 77K. Fluid line sizes for component testing range from 0.25” to 8”. A state-of-the-art test command and control center provides capability for remote operation, video surveillance, and data recording for all test areas.

Thermal design of recuperator heat exchangers for helium recondensation systems using hybrid cryocoolers

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This paper reports the thermal design of recuperator heat exchangers for a pulse tube refrigerator based helium recondensation system. A valved linear motor compressor delivers helium at a pressure of 2.2 MPa which gets cooled in counter flow heat exchangers and also at two temperature stages of the pulse tube cooler. The intermediate and final J-T valves expand the high pressure stream to produce liquid helium at 4.2 K @ 0.1MPa in the condenser. Liquefied helium gets evaporated in a helium recondenser heat exchanger and flows back to the compressor through the low pressure channels of the recuperative heat exchangers.

The primary objective of this work is to develop the analysis for sizing various components, mainly all recuperative type of heat exchangers in the cycle, considering various counter flow compact heat exchangers like Giauque-Hampson and tube-in-tube heat exchangers. On the basis of the calculated results, the suitability of the heat exchangers at various locations in the circuit can be established, under the given constraints like effectiveness, pressure drop, heat transfer rate and compactness and ease of manufacturing. A computer code for sizing of all the recuperative type heat exchangers has been developed. Results are presented for pressure drops and heat transfer rates on high and low pressure sides by varying the physical dimensions of the recuperator heat exchangers.

Flexible Cryogenic Thermosyphon

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Cryocooler and pulse tubes have been increasingly used in small and large scale cryogenic systems including the superconducting magnet systems as heat sinks to attain and keep the required temperatures. Designing the thermal link between the mechanical refrigerator and the system may present a challenge due to the mechanical stresses developed during the cool-down of the assembled systems. In this paper, a thermosysphon with a flexible fluid link between the evaporator and condenser is presented. The working fluid used in preliminary testing is nitrogen. The results of the initial testing of the flexible thermosyphon are also presented.

In most systems, flexible straps are used to eliminate the problem. However, as the distance between the refrigerator and the contact location increases, thermal efficiency drops due to increased length and the design becomes bulky.

Effect of shroud temperature on startup of a cryogenic loop heat pipe

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Cryogenic loop heat pipe (CLHP) is considered as highly efficient two-phase thermal control device in satellites, spacecrafts, electronics and structures. In some cases, requirements such as vibration isolation, increased transport distance, thermal diode function are needed between cryocoolers and the cooled components. The cryogenic loop heat pipe with flexible transport lines is capable of satisfying these requirements admirably. Whether a CLHP can start up and operate reliably depends on the adequacy of liquid state working fluid in the evaporator. Compared with an ambient loop heat pipe, there are many technical problems for a CLHP. It must be cooled down to the operating cryogenic temperature from a room temperature, and be maintained in the cryogenic temperature range through the whole operation process with only the condenser cooled by cold source. The initial thermal capacitance of shroud and components of the CLHP have an important effect on the startup and operation of the CLHP especially with a lower heat load. It is difficult for the CLHP to start up with a higher temperature of the shroud. This paper presents a cryogenic loop heat pipe operated in the liquid-nitrogen temperature range with nitrogen as working fluid. Tests are performed with different temperatures of the shroud, and the experimental results with the heat load range at the primary evaporator from 0 W to 10 W are shown and discussed.

Helium based pulsating heat pipe for superconducting magnets

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The advantages of pulsating heat pipes (PHP) for transferring heat and smoothing temperature profiles in various room temperature applications have been explored for the past 20 years. This study extends the exploration to low temperature applications, in particular superconducting magnets. An experimental apparatus to investigate the heat transfer properties of a helium-based pulsating heat pipe has been designed, fabricated and operated. The evaporator end of the PHP is comprised of a copper winding in which heat loads up to 10 watts are generated, while the isothermal condenser end is temperature controlled via a Sumitomo RDK408A2 GM cryocooler. Various experimental design features are highlighted. Additionally, performance results in the form of heat transfer and temperature characteristics are provided as a function of average condenser temperature, PHP fill ratio, and evaporator heat load. Results are summarized in the form of a dimensionless correlation and compared to room temperature systems. Implications for superconducting magnet stability are highlighted.

Support for this work from GE Global Research is gratefully acknowledged

A 100-W grade closed-cycle thermosyphon cooling system used in HTS rotating machines

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The cooling systems used for rotating High-Temperature Superconducting (HTS) machines need a cooling power high enough to ensure a low temperature during various utilization states. Radiation, torque tube, current leads usually represent hundreds of Watts of invasive heat. The architecture also has to allow the rotation of the refrigerant. In this paper, a free-convection thermosyphon using two Gifford-McMahon cryocoolers is presented. The cryogen is mainly neon but helium can be added for an increase of the heat transfer coefficient. The design of the heat exchangers was first optimized with FEM thermal analysis to make full use of the refrigerators' cooling power. After manufacture, the whole was assembled for preliminary experiments. The necessity of annealing for the copper parts was studied. A single evaporator was installed to evaluate the thermal properties of such a heat syphon, with one or both cold heads activated. Finally, a 10-kW HTS motor containing eight bulk magnets was cooled down as a first step. The application of this model to 100-kW scale HTS rotating machines is the main objective.

Electrical analogue model of an integrated circulator

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The problem of cooling gimbaled optics and LWIR focal planes can be solved by placing the entire cryocooler on gimbal. However, a large mass penalty is paid for such configurations, because the gimbal itself must grow in size and mass in order to support the cryocooler. To address the requirements of cooling across a two-axis gimbal, flexible joint, or to multiple locations on a spacecraft, we are developing an Integrated Circulator – a lightweight, continuous-flow cooling loop directly integrated into the coldhead of a Pulse Tube Cryocooler (PTC). The basis of the Integrated Circulator is a cold rectifier that converts the oscillating flow of the PTC into a steady flow of cold gas that can readily be distributed over distances of several meters to multiple loads. Because the cooling loop can be made of capillary tubing, it is easily made mechanically compliant by means of coiling, thus allowing the cryocooler to be located off gimbal. In this paper, we describe an electrical analogue model of the cooling loop and use it to investigate the dependence of average mass flow rate on buffer volume size. The calculations agree well with recent measurements.

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Design of a thermosiphon for cooling low-backgroundHPGe arrays

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Atwo-phase nitrogen thermosiphon was developed for the new generation of low-background high-purity germanium (HPGe) arrays. The cooling system for these arrays has to be able to handle the heat load (>20W) presented by a large detector mass while meeting stringent requirements necessary for low-background systems. The HPGe detector modules should operate as close to liquid nitrogen temperature (<80K) as possible to provide adequate operating conditions for a full range of HPGe impurity concentrations. In addition, exceptional temperature stability (<1 K) is needed to reduce electronic gain shifts due to changes in the front-end electronicsoperating temperature. In order to meet the background requirements of state-of-the-art systems these arrays are enclosed in passive lead and copper shielding up to 1 m thick. Active cooling was integrated via a horizontal thermosiphon that can be fabricated using ultra-pure electroformed copper. It was charged with nitrogen to434 kPa at 292 K, which provided afill ratio of 10%. The results showed thatthe thermosiphon can effectively remove in excess of 25 W of heat load.An experimental assessment of the heat leak into the thermosiphonis reported, along with an estimation of the value of different components that contribute to the heat load and cooling time. Measurements of the temperature gradient along the evaporator tube for different heat loads in the range of interest are presented.The expected and experimental heat transfer performance figures are compared.

The Effect of Component Junction Tapering on Miniature Cryocooler Performance

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Due to their relatively smaller volume and available cooling power, miniature cryocoolers are likely to be more sensitive to hydrodynamic losses than their full scale counterparts. Abrupt changes in diameter between cryocooler components are a possible source of such losses as flow separation and recirculation may occur at these points. Underutilization of regions of the regenerator and heat exchanger porous matrices may also occur due to jetting of fluid into these components. Eliminating such abrupt diameter changes by tapering or chamfering transitions between various miniature cryocooler components may therefore improve system performance.

The effects of various tapers and chamfers applied at component interfaces on the overall performance of miniature pulse tube cryocoolers were investigated using system-level CFD models. A miniature scale pulse tube cryocooler design whose suitability for cryocooling under ideal conditions has been theoretically demonstrated was used as the basis for these models. Transitions between different combinations of open and porous regions were considered; tapers or chamfers representing various geometric profiles were applied to these component junctions and the performance predictions for the resulting systems were compared to those for a model with sharp component transitions. Visualizations of the predicted flow patterns were also used to determine the effects of the applied tapers on the flow within the pulse tube.

Application of inertance tube in thermoacoustically driven pulse tube coolers at high operating frequency

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Application of the inertance tube is significantly beneficial at high operating frequency. With the development of miniature thermoacoustic engine, the inertance tube phase shifter becomes more important in the thermoacoustically driven pulse tube coolers. In this paper, an inertance tube phase shifter is modeled and simulated based on linear thermoacoustic theory. The calculated results show that the dimensions of the inertance tube phase shifter do not only influence the performance of the pulse tube cooler, but also that of the thermoacoustic engine, which bring about the optimum phase shift between pressure and flow rate for thermoacoustically driven PTRs different from that for mechanically driven PTRs. In experiments, a linear pulse tube cooler driven by a miniature thermoacoustic engine at operating frequency about 240Hz is constructed and tested. For the inertance tube with inner diameter of 2mm and length of 550mm, an optimized temperature below 80K is reached.

Experimental studies of a thermoacoustic prime mover for the development of a pulse tube cryocooler

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Thermoacoustically driven pulse tube cryoccoler totally eliminates the moving components and hence reliable towards cryogenic applications. In an objective to development such a system, we need to design the thermoacoustic prime mover to drive the pulse tube cryocooler. We have made detailed design and optimization of the standing wave thermoacoustic prime mover based on the procedure outlined by Swift [1] and Tijani [2] with the simplified linear thermoacoustic model of short stack and boundary layer approximations. The theoretical design shows the dependence of the system performance on stack geometry and relative position of different components for different working fluids. Based on the design thermoacoustic prime mover with different resonator lengths have been fabricated and experiments are conducted to evaluate their performance characteristics with respect to several parameters such as working fluid, operating pressure and thermoacoustic efficiencies. Preliminary experimental studies of using such a prime mover to drive a single stage pulse tube cryocooler have been carried out. These results are discussed in this work.

The authors wish to acknowledge the financial support provided by CSIR, New Delhi, which enabled this research work and to the staff of the centre for their help in the fabrication of experimental set up.

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Numerical analysis using CFD on Thermoacoustic prime movers for development of Pulse Tube Cryocoolers

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Thermoacoustic prime movers converts heat energy into acoustic energy and they serve as the ideal choice for driving the Pulse Tube cryocoolers replacing the conventional compressors. The important advantages of using such a drive is that there are no moving components and it can be driven by low grade energy such as fuel, gas, solar energy, waste heat etc. Experimental work is in progress towards the development of such thermoacoustically driven Pulse Tube cryocoolers. The numerical modeling of such a prime mover although may be carried out by several methods such as solving the energy equation [1], enthalpy flow model [2], we have attempted the modeling using the procedures of CFD [3], since this provides a better insight into the velocity and temperature profiles of the flow fields. Fluent software version 6.3.26 has been used for this analysis. The two dimensional model of the actual experimental system was modeled in Gambit to a total cell count of ~58,000. Triangular cells have been chosen due to increased cell density. The CFD analysis has been carried out by varying several parameters such as (a) the temperature boundary conditions across the stack, (b) the stack length, (c) Stack location with respect to the closed end of hot buffer, (d) the resonator length and (d) different fluid medium such as nitrogen, argon, and helium. Wherever possible, the theoretically predictions are compared with the experimental results. They are in reasonably good agreement with each other. The theoretical analysis indicate that (i) Increase in temperature gradient leads to increase in acoustic amplitude (ii) Increased resonator length leads to decreased amplitude of oscillations along with decreasing frequency and (iii) there exists an optimal stack length and its location with respect to the closed end for a given resonator length. CFD analysis of the twin prime mover system with resonator in between has also been attempted and the preliminary results are also presented here.

The authors wish to acknowledge the financial support provided by the Space Technology Cell (STC), which enabled this research work and to the staff of the centre for their help in the fabrication of experimental set up.

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Onset behavior of standing wave thermoacoustic pressure wave generator

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A standing wave type thermoacoustic pressure wave generator for 300 Hz operating frequency is designed and developed using helium as a working fluid. The device is designed as a half wave length resonator. A parallel plate type SS 304 stack is designed and fabricated. An electric heater is used for heat supply to the hot end heat exchanger while a water cooled heat exchanger is used to maintain the other end of the stack near ambient temperature. An acoustic amplifier is used to amplify pressure ratio generated. Experiments are conducted to study the onset behavior of pressure wave generator in terms of temperature range. Observations are recorded using peizoresistive pressure transducer. The results are obtained with different charging pressure and heat inputs. A pressure ratio of around 1.1 to 1.15 has been obtained using Nitrogen as a working fluid. The onset of thermoacoustic oscillations are studied for different filling pressure and for a range of hot end temperature.

Intepreting the Acoustic Impedance of Regenerative Engines

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Acoustic systems are often analyzed using the pressure amplitude, P1, the volume flow rate, U1, and the acoustic impedance, P1/U1. For regenerative engines these concepts produce insights into their behavior. These include 1) The pressure amplitude upstream of the point where U1 and P1 are in phase comes from flow from the compressor, while the pressure amplitude downstream of that point comes from flow from displacer in a Stirling, and the inertance tube or bypass line in a pulse tube. This, in conjunction with the relative dissipations in displacers, inertance tube, and bypass lines explains the relative efficiencies of these coolers. 2) The piston mass has a thermodynamic function in resonant recovery of compressive energy upstream of the in-phase point, while the inertance tube resonantly recovers energy downstream of that point. 3) Valved coolers do not have a mechanism for recovering compressive energy, which causes a significant efficiency loss. In principle, this lost energy can be recovered in many ways, such as by adding a piston, but is prevented in practice by engineering considerations. 4) U1 can be split into components in and out of phase with P1, with only the component in phase with P1 generating power flow through the engine. This component, for ideal gases, can be shown to produce Carnot's efficiency in a lossless engine.

Coupling research in the thermoacoustically driven pulse tube cooler

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In the thermoacoustically driven system, the pulse tube cooler is not only a load of the thermoacoustic engine, but also a resonant component influencing the performance of thermoacoustic engine. For coupling between the thermoacoustic engine and pulse tube cooler, an acoustic transmission line model is built and simulated based on linear thermoacoustic theory. The simulations shows that with the acoustic transmission line, the input pressure amplitude of the cooling system can be amplified and more acoustic power can be transmitted from the thermoacoustic engine to the cooler, which can improve the performance of the pulse tube cooler. The acoustic power output ability of the thermoacoustic engine is mainly determined by both geometry parameters of the acoustic transmission line and acoustic impedance of the pulse tube cooler. The computational results also reveal that the performance of the thermoacoustic engine can be improved by acoustic transmission line with appropriate length and diameter. In experiments, a linear pulse tube cooler driven by a miniature thermoacoustic engine is constructed and tested. Good agreements are obtained between the theoretical analysis and experimental results. This research is instructive for comprehensively understanding the coupling mechanism in the thermoacoustically driven pulse tube cooler.

Coupling of the regenerator and the end load in a standing wave thermocoustic engine

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In the thermoacoustic system, the performance of the regenerator strongly depends on the acoustic field and the geometry parameters of the regenerator. To study the thermoacoustic characteristic of the regenerator, a model of a standing wave thermoacoustic engine, with which a loudspeaker at one end and a load at the other, is built and simulated base on the linear thermoacoustic theory. The load is modeled by a LC load. The acoustic field is characterized by the ratio of the traveling wave component over the standing wave component. The result shows that the acoustic field in the engine varies in a wide range when the load changes. This may suggest a new method to obtain the ideal acoustic field in the regenerator. The performance of the regenerator is influenced by the different load for the change of acoustic field and can be improved by optimizing the geometry parameters and the position in the resonator. The research is useful for us to understand the thermoacoustic characteristic of the regenerator and the coupling mechanism in the thermoacoustically driven system.

Novel test methods and devices based on optical interferometry and acoustic emission to study damage of high-temperature superconductive tapes

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The difficulties of structure defects analysis in high-temperature superconductive (HTSC) tapes are caused by small applied loads, specimen strains and displacements, intrinsic distortions of the specimen surfaces and simultaneous requirements to high accuracy of damage estimation. The work presents the patented in Russia methods and devices for technical control of thin composites and goods (in particular HTSC tapes) solving these problems which ensure (i) modification of composition and measuring schemes leading to raising quality of test results, (ii) expansion of functional possibilities due to coupling in measuring devices linear and angle displacements and also increasing range of measured displacements, (iii) raising accuracy of test results based on the complex correction of the results directly during the test fulfillment and by increasing hindrance protection of the test means from vibrations and various perturbations on the base of own functional possibilities of the device. As proper optic methods there are used (i) under-shining method of control object surface by laser interferometer (LI), (ii) measuring method of small linear and angle displacements by LI, (iii) complex correction method of test results by LI. In order to estimate damage of HTSC tapes in conditions of quasi-static and fatigue bending in created test devices is used the acoustic emission method.

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Dynamic PID loop control

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The Horizontal Test Stand (HTS) SRF Cavity and Cryomodule 1 (CM1 by DESY) of eight 9-cell, 1.3GHz SRF cavities is operating at Fermilab. For the cryogenic control system, how to hold liquid level constant in the cryostat by regulation of its JT- valve is very important after cryostat cool down to 2.0 K. The 72-cell cryostat liquid level response generally takes a long time delay after regulating its JT-valve; therefore, typical PID control loop should result in some cryostat parameter oscillations.
This paper presents a type of PID parameter self-optimal and Time-Delay control method we used to reduce cryogenic system parameters’ oscillation.

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SRF Test Areas Cryogenic System Controls Graphical User Interface

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Fermi National Accelerator Laboratory has constructed a superconducting 1.3 GHz cavity test facility at Meson Detector Building (MDB) and a superconducting 1.3 GHz cryomodule test facility located at the New Muon Lab Building (NML). The control of these 2K cryogenic systems is accomplished by using a Synoptic graphical user interface (GUI) to interact with the underlying Fermilab Accelerator Control System. The design, testing and operational experience of employing the Synoptic client-server system for graphical representation will be discussed. Details on the Synoptic deployment to the MDB and NML cryogenic sub-systems will also be discussed.

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The CERN revamping project of the obsolete cryogenic control systems: strategy and results.

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The cryogenic infrastructure at CERN was originated in the 1960s with the era of bubble chambers and the associated superconducting solenoids. Since then and especially with the construction of the LHC accelerator and its detectors, large and complex cryogenics plants have been installed to provide cooling power from 800 W to 18 kW at different temperatures down to 1.9 K, demanding high and distributed technical capabilities from the control systems. The size and the complexity of the dedicated cryogenics has required the adoption of the CERN standard control framework UNICOS in order to enhance ease of operation and maintenance and, to provide long-term availability.

After the completion of the LHC construction, exploiting the gained experience, CERN has undertaken a project for the upgrade of several obsolete cryogenic control systems of helium refrigerators, different superconducting magnet test facilities and their gas management infrastructures, as well as a krypton calorimeter detector.

The paper will describe (i) the overall project challenges, (ii) the technical procedure used in order to meet the technological operational requirements in terms of installation constraints, reduced manpower and minimal financial impact, and (iii) an advanced methodology for the virtual commissioning of the new control system.

Calibration and linearity verification of capacitance type cryo level indicators using cryogenically multiplexed diode array

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The precision level measurement of cryogenic liquid in the storage tanks is a must from control and safety point of view. Usually, capacitance type level indicators are used for this purpose in large containers. For space applications, triple redundant level sensors are used to ensure fail proof operation. The linearity of each sensor element depends upon the cylindricity and concentricity of the internal and external tubes. In first step of calibration, one of the elements of Liquid Hydrogen (LH_2) level sensor is calibrated using 700mm eleven point discrete diode array. The array consists of eleven diode sets spaced at 70mm for 700mm (LH_2) level sensor. Each diode set consists of three diodes placed 1mm above and below the center diode which provides level measurement accuracy of ±1mm. Four wire method is used for the diode array. The automatic detection and data logging through multiplexers is done using a program developed in LabVIEW 8.5. Thus a calibration curve and equation for the single element of LH_2 level sensor is obtained. In second step, using the above equation, the remaining elements of the same LH_2 sensor and any other level sensors (either Liquid Oxygen (LOX) / LH_2) are calibrated. The linearity of the level sensor elements could be ascertained from the data. It also locates the position of nonlinearity. The accuracy of calibration achieved by the current methodology is within ±1mm while in earlier methods used in the laboratory, it was of the order of ±5mm. The calibration procedure of single element against the diode array and subsequent calibration of other element using the pre-calibrated element are discussed in this paper.

Directional oriented magnetic field induced temperature error of Pt-500 sensor at cryogenic environment

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The parallel and perpendicular magnetic field behaviour of five industrial grade platinum resistance thermometers (Pt 500) has been investigated. Measurements on the sensors were performed at various temperatures between 300 K and 4.2 K in the presence of intense static magnetic fields up to 9 T. The sensor performances were studied for perpendicular and parallel magnetic field. The field dependent temperature errors $\left(\Delta T / T\right)$ and the relative magneto resistance changes $\left(\Delta R / R\right)$ are tabulated as a function of field and the temperature. It is observed that the effect of magnetic field is higher in perpendicular configuration compared to the parallel configuration.The average temperature sensitivity of Pt 500 was found to be 5 times greater than Pt 100. The change in resistance for Pt 100 is 0.385 Ω/K [1] and 1.925 Ω/K for Pt 500. The sensitivity of the sensors sharply decreases as the temperature decreases and have the temperature resolution of ± 0.58 mK with the measuring instrumentation resolution of 0.001Ω. Moreover, the magneto resistance change is more dominant at low temperatures which can be clearly seen at 4.2 K.

Reliability and stability of three cryogenic temperature sensor models subjected to accelerated thermal cycling

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Reliability of a cryogenic temperature sensor is important for any experimental application, but even more so for aerospace applications where there is virtually no opportunity to replace a failed sensor. Many factors affect the stability and longevity of a cryogenic temperature sensor, but one of the most detrimental factors is thermal cycling over an extended temperature range. Strains and stresses caused by thermal contraction can affect both the sensing material and its interface with electrical contacts leading to either calibration shift and/or catastrophic failure of the sensor. Depending upon the aerospace application, a temperature sensor may cycle from cryogenic temperature to near room temperature hundreds of times or more during the lifetime of the mission. Sample groups of three sensors types, Lake Shore Cryotronics models CX-1050-SD (20 samples), DT-470-SD (10 samples), and DT-670-SD (10 samples), were subjected to accelerated thermal shocking from room temperature to 77 K one thousand times. Recalibrations of each group were performed from 1.2 K to 325 K after 10, 25, 50, 100, 250, 500 and 1,000 thermal shocks. The resulting reliability and stability data are presented.

Design parameter evaluation of a copper metal embedded Fiber Bragg Grating sensors for measurement of cryogenic temperature or stress in superconducting devices

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Abstract

There are plenty of complex physical phenomena which remain to be studied & verified experimentally for building an optimized superconducting magnet. The main problem for experimental validations is due to the unavailability of suitable sensors. This paper proposes a Fiber Bragg Gratings (FBG) sensor for this purpose which allows access to the local temperature / stress state. To measure the low temperature (20 K), FBG can be embedded /recoated with materials having high thermal expansion coefficient (HTCE). This can induce a thermal stress for a temperature change, which in turn increases the sensitivity of the sensor. The performance of such sensors has been experimentally studied and reported in earlier paper . This paper aims at evaluation, determination and optimization of different design parameters like selection of embedding material, optimization of material thickness, grating period and the grating length for design of better performance FBG sensor for low temperature/ stress measurements.

Development of moving magnet type linear motor for twin piston compressor for pulse tube cryocooler

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This paper describes the design, fabrication and testing of moving magnet type linear motor for twin piston compressor for pulse tube cryocooler for ground applications. Four radially magnetized rings out of segment magnets were constructed, in which one pair of rings has North-pole on its outer diameter and South-pole on inner diameter, while the other pair is the complementary. The magnets are mounted with similar poles together on the magnet holder with an axial moving shaft and the pistons are mounted on either end of the shaft. The shaft movement is restricted to only axial direction with C- type flexures mounted on both ends of shaft. The net force required for driving such compressor is the sum of forces required for taking care of moving mass, flexure spring, gas spring, magnetic circuit and the required pressure-volume power. Appropriate wire gauge and ampere turns are designed to generate the net force. The flexure spring force estimation is done through simulation carried-out in Ansys 11.0 and is verified experimentally, while the magnet force was determined experimentally. The complete assembly of motor with mounted pistons is tested using home-made electronics capable of driving 140 watts of load. The compressor motor is designed for 100 watts, with a swept volume of 6c.c. The twin piston arrangement will be used to operate two pulse tubes at 180 degree out of phase. This does not require buffer volumes and expected to have better COP.

DEVELOPMENT OF HIGH EFFICIENCY 4 K TWO-STAGE PULSE TUBE CRYOCOOLERS WITH SPLIT VALVE UNIT

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ABSTRACT

SHI has been continuously improving the efficiency and reducing the vibration of a 4K pulse tube cryocooler. A high efficiency 4 K pulse tube cryocooler with split and remote valve unit has been developed. The valve unit of the cryocoolers is split from the cold head by one flexible gas line and two stainless pipes. The experimental data of a high efficiency pulse tube cryocooler with split and remote valve unit is reported in this paper. The diameter of the gas lines between the valve unit and the cold head is optimized. The wall thickness of the tubes on the cylinder is optimized for low vibration with minimum impact on cooling performance. When the valve unit is split with 1 m lines, the cooling capacity is reduced because of increased pressure drop and dead volume. A typical cooling capacity of the prototype units is 35 W at 41.8 K on the first stage and 0.9 W at 4.05 K on the second stage when the compressor is operated at 50 Hz. The vibration acceleration and displacement will be reported in this paper.

A pulse tube cryocooler with 400 W cooling power at 77K

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To meet the need for high operating efficiencies required by commercial high temperature superconducting applications, an electrically driven pulse tube cryocooler with 400 W cooling power at 77 K is in development. Building a pulse tube cryocooler with hundreds of cooling power generally involves some unique challenges, including Rayleigh streaming, increased risk of nonuniform flows, and cold heat exchanger design. To avoid these problems and take full advantage of the experience of developing small pulse tube cryocoolers, four parallel arrayed coldfingers driven by a twin-opposed linear compressor are employed in this large capacity cryocooler. The charging pressure is 3 MPa and the driven pressure ratio of the coldfinger is 1.3. The maximum input electric power of the compressor is 6 kW. Each coldfinger is supposed to offer more than 100 W cooling power at 77 K. The expected relative Carnot efficiency is higher than 20%. In this paper, the design of the coldfingers and the compressor will be introduced in detail and the experimental results from cooling performance tests will also be presented.

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CEC-ICMC_Experimental investigation of a U-shape pulse tube cryocooler with one regenerator and two pulse tubes

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CEC-ICMC_Pulse tube cryocooler has no moving components at cold end, therefore the cold end can support larger mass directly. A new structural cryocooler based on traditional U-shape pulse tube cryocooler and with one regenerator and two parallel pulse tubes has been proposed, which can realize larger and heavier mass supporting without additional supporting components. Hence, the new pulse tube cryocooler can reduce the cooling power loss of the cold plate structure.

Two prototypes of traditional U-shape pulse tube with different connecting tube locations have been manufactured and tested. Two prototypes could gain 120K@7W cooling quantity with 80W electric power input. The experiment result has been discussed in the paper.

Based on the two prototypes of traditional U-shape pulse tube cryocooler, two prototypes of U-shape two-pulse-tube paralleled cryocooler have been designed and tested. The dimension of regenerator is same to traditional U-shape pulse tube cryocooler and the volume of two pulse tubes is equivalent to the volume of single pulse tube of traditional U-shape pulse tube cryocooler. The prototypes gained 120K@6W cooling quantity with 80W electric power input. The experiment reveals that individual phase-shifting is feasible; DC flow could occur under general phase-shifting and reduce the cooling power of the cryocooler.

A two-stage thermally coupled pulse tube cryocooler used in a helium recondensation system

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Performance of a thermally coupled two stage pulse tube cryocooler (PTC), driven by a CFIC linear motor compressor, used in a helium re condensation system is discussed. The cooling process in the recondensation system consists of passing helium gas through the recuperators and then the regenerators of the pulse tube cryocooler connected in series. The cooled helium then flows to additional heat exchangers to further lower its temperature before partially getting liquefied through Joule-Thompson expansion. Design and optimization of two stage PTC has been carried out through the use of well known numerical model REGEN 3.2. Effect of the regenerator material and geometry on the performance on the second stage of two stage pulse tube system is studied. An experimental set up has been constituted in which corresponding heat loads are applied at each stage of the PTC mimicking the actual enthalpy to be removed from the recuperators. Finally, experimental results are compared against the simulations.

Experimental Investigation of Multi-bypass Pulse Tube Cryocooler with Precooling

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Pulse Tube Cryocooler (PTC) that reaches temperature below 20K is one of the research hotspots. To obtain such low temperature ambient, a thermal-couple two stages PTC is fabricated, wherein coaxial pulse tube are used for both stages and the hot end of the second stage PTC (PTC2) are connected with cold end of the first stage PTC (PTC1) with a hot bridge. By changing the cold end temperatures PTC1, performance of PTC2 in low temperature ambient is studied.

Experiments were carried out for such cryogenic system. It is observed that optimal frequency of PTC2 varies with different hot end temperatures, namely cold end temperature of PTC1. In current investigation, it is reduced from 40Hz to 28Hz when the hot end temperature changes from 300K to 80K. Besides, effect of inertance tube on PTC2 is also different when hot end temperature is different. It is found that no-load temperature is reduced by 7K at hot end temperature of 300K when the inertance tube is optimized; however, it is only 2K when the hot end temperature is 80K. Influence of the double inlet and multi-bypass structures are also studied and similar results can be found for different hot end temperature. With optimized phase-modification structure and charge pressure, the cryogenic system can reach a no-load temperature of 11.8K and 0.2W cooling capacity at 21K with 200W input power while the hot end temperature is kept at 60K.

Effects of the inertance tube on the thermal performance and dynamic characteristics of the pulse tube cryocooler

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The inertance tube has become the popular phase-shifting mechanism of the pulse tube cryocooler (PTC) due to its structural simplicity, stable performance and wide phase-shifting ability. The impedance as a result of its resistance, inertance, and compliance effects can affect the thermal performance of the cooler as well as dynamic characteristics of the linear compressor. A variety of combinations of inertance tubes and reservoirs are simulated and tested, and all studies are carried on a series of PTCs developed in our laboratory driven by the flexure bearing linear compressors. The experimental measurements on the key thermodynamic parameters and dynamic ones are conducted, of which the former includes the magnitude and phase of pressure wave, the cooling capacity, while the latter includes the piston amplitude, resonant frequency, input current and voltage, and the electric-acoustic conversion efficiency of the compressor. The effects of the inertance tube on the phase characteristics and the energy or exergy flow have been analyzed. It's shown that the inertance tube can generate an appropriate phase shift and mass flow distributions that will minimize losses associated with the thermal ineffectiveness, pressure drop, axial thermal conduction, etc. Studies of the influence of the dimensions of inertance tubes and reservoirs on the dynamic behavior of the linear compressor provide a better understanding of this phase-shifting mechanism and the dynamic characteristics. The detailed comparisons have been made between the simulation and experimental results, and some meaningful experiences for designing the optimal inertance tubes have been summarized.

Measurement and Analysis of Energy Flow in Stirling-type Pulse Tube Refrigerator

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Operating principles and loss mechanisms of cryocoolers can be described from a view point of energy flow. This paper focuses on the instantaneous measurement and analysis of energy flow in the Stirling-type pulse tube refrigerator. First, a Stirling-type pulse tube refrigerator has been optimally designed in consideration of friction factors and loss mechanisms identified by previous researches. In this design process, the energy flow patterns are estimated under various conditions and the optimal case having the highest efficiency is identified. Second, for confirmation and modification of the first step, the detailed physical conditions of the fluid are measured in each component of the Stirling-type pulse tube refrigerator. At the front of the aftercooler, both ends of the regenerator and the front of the inertance tube, fine hot film probes, temperature and pressure sensors are installed for investigation of physical conditions in the fast oscillating flow. The precise patterns of energy flows are obtained and compared with the estimated values by the measured data. Finally, friction factors and loss mechanisms are adjusted and the mechanism of achieving the optimal condition is carefully investigated. The result of this paper can be used for design of highly efficient cryocoolers and understanding the optimal operation conditions in cryocoolers.

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Design optimization of a 300 Hz two-stage stirling-type pulse tube cooler driven by a thermoacoustic-Stirling engine

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High frequency thermoacoustically driven stirling-type pulse tube cooler has been proven of high reliability and potentially high thermal efficiency. In order to further improve the thermal efficiency and explore its potential, a 300 Hz two-stage pulse tube cooler driven by a thermoacoustic-Stirling engine is suggested and designed with a thermoacoustic module program. Considerable numerical simulations have been done to investigate the key structural parameters those influence the system performance and the coupling mechanism between the subsystems. In addition, the internal energy transfer and acoustic power dissipation are analyzed. With optimization, a lowest cold-head temperature of 30 K could be achieved with 5.0 MPa helium and 500 W heating power input at the engine, and a cooling power of 4 W at 80 K is expected meanwhile, showing great improvement over the single-stage pulse tube cooler driven by a standing-wave thermoacoustic engine.

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Numerical Model for Conduction-Cooled Current Lead Heat Loads

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Current leads are utilized to deliver electrical power from a room temperature junction mounted on the vacuum vessel to a superconducting magnet located within the vacuum space of a cryostat. There are many types of current leads used at laboratories throughout the world; however, conduction-cooled current leads are often chosen for their simplicity and reliability. Conduction-cooled leads have the advantage of using common materials, have no superconducting/normal state transition, and have no boil-off vapor to collect.

This paper presents a numerical model for conduction-cooled current lead heat loads. This model takes into account varying material and fluid thermal properties, varying thicknesses along the length of the lead, heat transfer in the circumferential and longitudinal directions, electrical power dissipation, and the effect of thermal intercepts. The model is validated by comparing the numerical model results to ideal cases where analytical equations are valid. In addition, the XFEL (X-Ray Free Electron Laser) prototype current leads are modeled and compared to the experimental results from testing at DESY's XFEL Magnet Test Stand (XMTS).

Special thanks to Arkadiy Klebaner[1] and Bernd Petersen[2] for organizing this collaborative project. Work supported by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy and by DESY.

A HTS Tape-Based Multi-Line Current Lead

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High Temperature Superconductors (HTS) are now widely used for commercial and research applications where a high current is desirable at low temperature. Packaged as tape, the most common application is probably on magnets, for instance used in MRI systems. In almost all applications, an HTS tape is used in an isothermal system, and any thermal gradient tends to be suppressed. In a previous study we showed that by using traditional microelectronics manufacturing technologies on some commercially available tape we were able to obtain very low heat leak HTS current leads, that can be mounted in between two stages of a cryocooler and that have better performance than optimized normal metal current leads. In this paper, we report a different approach to manufacture such leads, that allows more flexibility and a lower cost. We show a comparison of the leads obtained by the different methods and we discuss their respective applicability to commercially available leads.

Tests of Copper and HTS Current leads with a Two Stage Pulse Tube Drop-in Cooler

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Tests of the MICE spectrometer solenoid in 2009 showed that the heat leak to the first stages of three Coolers was excessive. The sources of the excessive heat load were the copper leads from room temperature and a larger than expected heat load to the shield. By running a cooler test that combines the copper and HTS leads with a cooler, we are able to better understand the copper lead performance and its effect on the cooler performance. When a single PT-415 cooler was tested with a pair of the leads that was actually used in the 2009 magnet, the heat flow at design current was much larger than optimum. The heat leak with no current in the leads was less than it would be for optimum leads. The IL/A of the copper leads used in the magnet was too high. Leads with a much lower IL/A were tested with much improved results. The cooler and lead tests also showed the importance of reducing the total temperature drop between the top of the HTS leads and the cooler first stage. As a result, the design of future magnets that use coolers will be improved.

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Testing a MICE Spectrometer Solenoid with an Added GM Single Stage Cooler

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The MICE spectrometer solenoids are cooled using three drop-in Cryomech PT415 pulse tube coolers. The cooler develops 1.5 W at 4.2 K while developing 40 to 45 W of cooling at 45 K. A test of a MICE spectrometer solenoid in 2009 demonstrated that the heat loads into the pulse tube cooler first stages were excessive. The sources of the extra heat load were the copper leads and a larger than expected heat load to the shield. As a result of an excessive temperature at the tops of the HTS leads, the lead furthest from the three pulse tube coolers burned out. Without the wholesale disassembly of the magnet, two courses of action could be taken to improve the magnet lead cooling. We replaced the copper leads with lower heat leak copper leads, and we added a single stage Cryomech AL-330 GM cooler at the end of the lead string furthest from the pulse tube coolers. This paper discusses the results of using more efficient lead and adding a single stage GM cooler. The combination of the two changes reduced the pulse tube cooler first stage temperature, the lead temperature, and the temperature of the magnet shield.

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Performance test and thermal analysis of conduction-cooled optimized current leads at non-optimum operation

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Current leads are the key components which makes an electrical connection between room temperature power supply and superconducting magnets at 4.2K. In any cryogen-free magnet system, major heat input comes the copper current leads of the magnet. The dimensional optimization of copper part of the hybrid current leads is done for a particular operating current between room temperature to the operating temperature of the 1^{st} stage of cryocooler (CCR). The conduction-cooled magnet may not necessarily be operated at the optimized current all the time. Hence for non-optimum current, the heat input per unit current will be increased both at under-current and over-current operation. The stabilized temperature, of the 1^{st} stage of CCR corresponding to each operating current, would mainly be governed by the dynamic heat input by the current lead. A pair of copper current leads working between the temperatures 300 K to 35 K has been optimized for 85A optimum current. A simple analytical technique has been used for estimation of dynamic heat load at non-optimum operation. This paper describes the optimization procedure, estimation of dynamic heat input, measurement and detailed thermal analysis of conduction-cooled current at non-optimum operation.

Development and test of a cryogenic pulsating heat pipe and a pre-cooling system.

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The need for thermal links in cryogenic applications is increasing, especially because of the use of cryocoolers, which offers a small size cold source. The recently invented Pulsating Heat Pipe (PHP) [1] is a highly promising passive two-phase high performance thermal link. Similarly to conventional heat pipes (HP), it is a closed tube filled with a two-phase fluid able to transfer heat from the evaporator to the condenser. The internal diameter of the tube needs to be lower than the capillary length of the working fluid so that alternating liquid plugs and vapor bubbles form inside it. Unlike HP, no complicated capillary structure is required. The self-sustained oscillation of the pattern of bubbles and plugs inside the tube is the main physical phenomenon responsible for the heat transfer.

A general problem for any two-phase cryogenic thermal link is the pre-cooling of the evaporator so that the liquid condenses in it initially and can be evaporated during the functioning. In conventional HPs, this problem is by-passed with the help of a capillary wick but in the case of PHPs it has to be solved. In previous works [2], the pre-cooling is ensured by using the gravity. For space applications for instance, a special system must be developed.

We have built a PHP working with helium and tested its thermal performance at around 4 K. In parallel, we have designed a novel pre-cooling system which can be used with other systems. First results of these two systems are presented.

[1] H. Akachi, Structure of Micro-Heat Pipe, US Patent 5219020, 15 June 1993
[2] R. Chandratilleke et al., Development of Cryogenic Loop Heat Pipes, Cryogenics, 38 (1998)

Plate Fin Heat Exchanger Model with Axial Conduction and Variable Properties

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Future superconducting radio frequency (SRF) cavities, as part of Project X at Fermilab, will be cooled to superfluid helium temperatures by a cryogenic distribution system supplying cold supercritical helium. To reduce vapor fraction during the final Joule-Thomson (J-T) expansion into the superfluid helium cooling bath, counter-flow, plate fin heat exchangers will be utilized. Due to their compact size and ease of fabrication, plate fin heat exchangers are attractive. However, the design of compact and high-effectiveness cryogenic heat exchangers requires consideration of axial heat conduction along the direction of flow, in addition to variable fluid properties. Here we present a numerical model that includes the effects of axial conduction and variable properties for a plate fin heat exchanger. The model is used to guide design decisions on heat exchanger thermal conductivity and geometry. In addition, the J-T expansion process is modeled with the heat exchanger to analyze the effect of variable heat load and cryogenic supply variations.

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Reducing axial conduction by elongated heat conduction path in cryogenic PCHE (Printed Circuit Heat exchanger)

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PCHE (Printed Circuit Heat Exchanger) is one of the compact heat exchangers. The essential procedure for fabricating PCHE chemical etching. This technology can easily create large heat transfer area for heat exchanger. However, PCHE shows disadvantages of high pressure drop and large axial conduction. Axial conduction is a critical design issue with heat exchangers operated in cryogenic environment with large temperature difference. Elongating heat conduction path is implemented to reduce axial conduction in PCHE in this study. Two identical PCHEs were fabricated, and one of them was modified to have longer heat conduction path. The cross-sectional area of the PCHE has been reduced by more perforation (wire-cut). Heat exchangers are tested in cryogenic environment (300~70 K), and modified PCHE shows better performance. Those experimental result indicates elongating the heat conduction path was effective to increase performance of PCHE. This paper discusses the detailed thermal performance of the modified PCHE by analyzing its experimental data.

A study on the effects of longitudinal heat conduction and ambient heat leakage on the sizing of high-effectiveness cryogenic heat exchangers.

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Thermodynamic and economic considerations make large-scale cryogenic processes very sensitive to the performance of the heat exchangers (HE). For this reason, cryogenic HEs are designed for high efficiency, resulting in large sizes. In air separation units and Liquefaction of Natural Gas plants, they can represent 20-30% of the investment costs. This situation sets the need for accurate models for the sizing of HE.

Both longitudinal heat conduction and ambient heat leakage have a negative impact on HE performance. However, they are usually neglected for traditional applications since they represent a reduction of only a few percent on heat transfer duty. Nevertheless, due to the exponential-type relation between size and effectiveness, the required increase in surface area might be significant for high-efficiency applications, such as cryogenic processes.

In this work, the effects of these two phenomena on the sizing of single- and two-phase HE are studied. The present model considers one-dimensional energy balances for the working fluids and the separating wall. This approach allows considering the variations of heat transfer coefficient as well as physical properties. A reference case is studied, and the required increases in surface area given by both phenomena are considered in a parametric analysis.

Simulation of an ITER TF coil cool-down from 300 K to 80 K using the 4C code

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The cool-down of the ITER magnet system will be subdivided in two stages, namely from 300 K to 80 K and from 80 K to 4.5 K. During the first stage, the inlet He temperature T_{in} will be gradually decreased with a suitable rate to limit the thermo-mechanical stresses in the magnet system to acceptable values. In this paper, we apply the 4C code, recently validated against different types of transients, among which the cool-down from room temperature to ~10 K of a non-planar coil of the W7-X stellarator [1], to the simulation and analysis of the first stage of the cool-down of an ITER Toroidal Field (TF) coil. The conjugate heat transfer, advection-conduction problem in the coil is solved using a compressible 1D model for the gaseous He coolant flow along each of the 14 pancakes, and along each of the 96 cooling channels of the coil casing; the latter is discretized poloidally using a suitable number of 2D cuts, where the heat conduction problem is solved by finite elements. The simulation allows the computation of the cool-down time, for given T_{in} and inlet mass flow rate evolution, that will be compared with the results previously obtained with other codes [2]. The evolution of the maximum temperature difference across the coil will also be computed during the transient, parametrically considering the effect of the insulation materials, and compared to the imposed limits.

[1] R.Bonifetto et al, to appear in Fus.Eng.Des. 2011

[2] N.Peng et al, Cryogenics 2009

A model superconducting helical undulator fabricated using a small filament, Tube Type, multifilamentary Nb_3Sn wire

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A model helical undulator 250 mm in length, with a period of 14 mm, was designed, fabricated and tested in liquid helium bath. The helical coil was wound with multifilamentary, Tube Type type Nb_3Sn strand with 217 subelements. The 0.7 mm OD strand was insulated with S-glass, wound onto the former, reacted, after which the coil underwent vacuum epoxy impregnation. The beam aperture of the coil was 7 mm, the winding bore diameter was 8 mm. The OD of the complete winding was 18 mm. The helical poles were made from 1016 low carbon steel, and projected slightly above the coil pack, with an OD of 19.06 mm. The coil I_c and the magnetic field in the bore was measured at 4.2K in a liquid helium bath using a Hall probe. I_c was found to be 842A, and the bore field reached design specification of 0.8 T. The bore field was also measured as a function of position along the length of the undulator and was seen to behave as expected. Obtained results were compared with FEM based magnetic field modeling. Measured I_c was compared with that obtained from a load line determined from FEM modeling and $I_c(B)$ curve obtained from measurements of a short sample Nb_3Sn strand.

Nb_3Sn Cable Development for the 11 T DS Dipole Demonstration Model

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Fermilab and CERN started the development of 11 T 11-m long Nb3Sn dipoles to replace few regular LHC NbTi dipoles and free space for cold collimators in LHC DS areas. An important step in the design of these magnets is the development of the high aspect ratio Nb_3Sn cable to achieve the nominal field of 11 T at the nominal LHC operating current of 11.85 kA. The keystoned cables 14.7 mm and 15.1 mm wide with and without a stainless steel core were made out of hard Cu wires and Nb_3Sn RRP strand 0.7 mm nominal diameter. The cable optimization process was aimed at achieving both mechanical stability and minimal damage to the delicate internal architecture of the Restacked-Rod-Process (RRP) Nb_3Sn strands with 127 restack design to be used in the magnet short models. The superconducting cables that were produced were therefore obtained with mandrels designed accordingly, which determined quite accurately the number of strands required for each cable geometry. Each cable was characterized electrically for transport properties degradation at high field and for low field stability, and metallographically for internal damage.

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Construction and testing of TAMU3, a 14 Tesla stress-managed Nb_3Sn model dipole

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We report the construction and testing of TAMU3, a 14 Tesla Nb_3Sn block-coil dipole. A primary goal in developing this model dipole is to test a method of stress management in which Lorentz stress is intercepted within the coil assembly and bypassed so that it cannot accumulate to a level that would cause strain degradation in the superconducting windings. Details of the fabrication, tooling, and results of construction and magnet testing will be presented.

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Quench Protection Challenges in Long Nb_3Sn Accelerator Magnets *

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As the magnetic stored energy in accelerator-type dipole and quadrupole magnets increases, effective quench protection becomes ever more challenging. Especially in several meter long magnets this requires significant developments beyond the state-of-the-art. In the frame of the US Large Hadron Collider Accelerator Research Program (LARP), several models of Nb_3Sn quadrupoles for the upgrade of the LHC interaction region have been developed. The LARP magnets include a 1 m long high-gradient quadrupole and a 3.7 m long quadrupole, with stored energies of about 1 MJ m^{-1} and 0.5 MJ m^{-1} respectively. The next major milestone is the realization of a 3.6 m long high-gradient quadrupole with a total stored energy of 4 MJ. Their quench protection relies on protection heaters (made of 25 μm thick stainless steel circuits glued to a 50 μm thick Kapton foil) to bring the winding to the resistive state as uniformly as possible, and on energy extraction into an external dump resistor.

Experiments with such protection heaters were carried out during the tests of the 1 m and 3.6 m magnets. Using these results, a ROXIE** model was developed in order to simulate quenches in the high-gradient magnet and bench-mark our model. In particular the distribution of voltage and of temperature in the windings was analyzed. The study was then extended to the new long high-gradient magnet leading to the definition of a successful protection scheme. The paper presents these requirements and highlights the limitations of present protection heater technology. Innovative solutions addressing length and efficiency challenges for full-size magnets are discussed.

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** ROXIE: Routine for the Optimization of magnet X-sections, Inverse field calculation and coil End design; a software code developed at CERN.

Novel diaphragm based Stirling cryocooler

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Industrial Research Ltd has developed a unique diaphragm based pressure wave generator technology for employment in pulse tube and Stirling cryocoolers. The system uses a pair of metal diaphragms to separate the clean cryocooler gas circuit from a conventionally lubricated mechanical driver, thus producing a clean pressure wave with a long-life drive. We have now extended the same diaphragm concept to support and seal the displacer in a free piston Stirling expander. The diaphragms allow displacer movement without rubbing or clearance gap seals, hence allowing for the development of cost-effective long-life and efficient Stirling cryocoolers. Initial modelling, operating in conjunction with a 200cc swept volume pressure wave generator, predicted in excess of 300W cooling at 77K with a Carnot efficiency of over 25%. A proof of concept prototype has achieved cryogenic temperatures. Details of the concept, modelling, and testing will be presented.

Scaling STI's *Sapphire* Cryocooler for Applications Requiring Higher Heat Loads

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Superconductor Technologies Inc. (STI) developed the *Sapphire* Cryocooler specifically for the SuperLink® product; a high performance superconducting Radio Frequency (RF) front-end receiver used by wireless carriers such as Verizon Wireless and AT&T to improve network capacity, cell coverage and data speeds. STI has built and deployed over 6,000 systems operating 24 hours a day, 7 days a week in the field since 1999. *Sapphire* is an integrated Free Piston Stirling Cycle Cryocooler with a cooling capacity of 5 Watts at 77 Kelvin with less than 100 Watts input power. It has a field-proven Mean Time Between Failure (MTBF) of well over 1 million hours, requires zero maintenance and has logged over 250 million cumulative runtime hours.
The *Sapphire* cooler is built on a scalable technology platform, enabling the design of machines with cooling capacities up to 1 kilowatt. This scalable platform also extends the same outstanding attributes as the *Sapphire* cooler, namely high reliability, zero maintenance, and compact size - all at a competitive cost. This paper will describe *Sapphire's* performance and intended applications, as well as discuss other suitable applications which require higher heat loads and can benefit from STI's scalable technology.

Experimental investigations and improvements for the 10K G-M refrigerators

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With the wide application of high performance cryo-pump, high and low temperature superconducting devices, MRI, infrared detectors and cryogenic electronics, the development of high efficient and reliable 10K G-M refrigerator is of critical importance and awaited by cryogenic industries. The systematical studies have been carried out and experimental tests indicated that the cooling performance of the 10K G-M refrigerator was evidently improved by adding the two additional rectification meshes inside the low temperature regenerator, by optimizing the size of the cylinders and displacers, the quantity and size of the gas inlet and outlet holes in the displacer, and the system charge pressure. Furthermore, a new labyrinth sealing displacer was proposed and fabricated to substitute the traditional piston-ring sealing displacer, intended to improve the operating stability and reliability of the 10K G-M refrigerator. The detailed experimental results and improvements were presented and their optimal cases were also given in this paper.

Temperature instability comparison of micro- and meso-scale Joule-Thomson cryocoolers employing mixed refrigerants.

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Previously we demonstrated cryogenic cooling in a Joule-Thomson microcryocooler (MCC) with mixed refrigerants operating at pressure ratios of 16:1 that achieved stable temperatures of 140 K with transient temperatures down to 76 K. Mixed refrigerants precooled to 240 K are used to improve the minimum enthalpy difference, $(\Delta h_T)_{min}$ compared with pure fluids such as Nitrogen. As the transient temperature fluctuations exhibited by the MCC are not well understood, utilizing the same mixed refrigerants we compare the performance of this micro-JT employing a 25mm long multichannel glass fiber heat exchanger (outer low pressure capillary ID/OD=536µm/617µm, inner high pressure channels ID/OD=75µm/125µm) with a scaled up (mesoscopic) version employing a 20cm long single channel stainless steel heat exchanger (outer low pressure channel ID/OD=580µm/760µm, inner high pressure channel ID/OD=100µm/230µm). An easy to fabricate and modify meso-version has been designed and fabricated to investigate the temperature instabilities at similar operating conditions but for proportionally higher flows of ~ 30cm^3/min. compared with ~ 6cm^3/min. We compare measured pressures, flow rates, temperatures, and stabilities for both micro- and meso-JT cryocoolers to better understand the causes for the temperature instabilities within the micro-JT cryocooler.

Performance analysis of small capacity liquid nitrogen generator based on Joule-Thomson refrigerator coupled with air separation membrane

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Joule – Thomson small capacity refrigerators supplied with gas mixture are studied theoretically and experimentally for a variety of applications. They are especially promising when coupled with membrane air separators. We present liquid nitrogen generation system based on Joule – Thomson cooler joined with air separation membrane. Hollow fiber membrane is used for nitrogen separation from compressed and purified atmospheric air. Joule-Thomson refrigerator operates with nitrogen and chosen hydrocarbons mixture and provides a cooling power used for the separated nitrogen liquefaction. A special attention has been paid to a heat exchanger coupling Joule-Thomson refrigerator with membrane air separator. It has been optimized by the entropy generation minimization method resulting from the second law of thermodynamics. This paper describes the system design, the procedure of mathematical calculations and test results.

Study of a mixed-gases Joule-Thomson refrigerator for cooling down temperature -distributed heat loads from ambient temperature to 80 K

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ABSTRACT

In most large scale reverse Brayton cryogenic refrigeration systems for reaching below 20 K or most helium gas liquefaction systems, precooling with liquid nitrogen is usually used. Those precooling systems provide cooling effect from around 300 K to 80 K by using the latent heat of liquid nitrogen boiling and the sensible heat of the gas phase nitrogen. This kind of precooling is a typical temperature-distributed heat load cooling. Actually, the latent heat of the liquid nitrogen is not necessary for cooling down such a temperature-distributed heat load as the above precooling requirement. The latent heat of liquid nitrogen will increase temperature difference at the lowest temperature. This, of course, increases the exergy loss of the preccoling system from a thermodynamic point of view.

In most cases, an appropriate cryocooler can be used as a substitute for the liquid nitrogen to provide such precooling requirements. For instance, the mixed-gases Joule-Thomson refrigerator can be used to provide the precooling requirement.

In this work, a mixed-gases Joule-Thomson refrigerator was designed, built and tested. A cascade cycle configuration was used, which a vapor-compression system with R404A as refrigerant was used to precool the main mixed-gases cycle. HCFC-124 was used as the coolant to transfer the cooling capacity from the refrigeration unit to the user, which is driven by a self-made magnetic pump. The total input power of two oil-lubricated compressors is about 15 kW. The measured data shows that the minimum temperature of HCFC-124 can reach below 80 K, and a maximum temperature-distributed cooling capacity of about 6 kW is obtained from around 100 K to 300 K, which equals to about 64 liters liquid nitrogen per hour for cooling down a similar temperature-distributed heat load. Compared the power consumption to generate such amount of liquid nitrogen, the mixed-gases Joule-Thomson cryocooler is much more efficient than that of using liquid nitrogen to cooling down a temperature-distributed heat load, especially covering a large temperature span.

Investigations on two-phase heat exchanger for mixed refrigerant Joule-Thomson cryocooler

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Abstract

The design of the recuperative heat exchanger used to pre-cool the refrigerant mixture prior to J-T expansion is crucial for the efficient operation of the mixed refrigerant Joule-Thomson (MR J-T) cryocooler. The multi-component non-azeotropic refrigerant mixture undergoes boiling and condensation heat transfer simultaneously in the heat exchanger. Therefore, it is important to analyze the performance of the heat exchanger in terms of temperature distribution with respect to the mixture of gases used.

A mixed refrigerant J-T cryocooler has been developed [1] in our laboratory. Experiments are being carried out to study the heat exchanger performance with respect to mixture composition and operating parameters. In the present work, temperature measurements are carried out at the ends of the heat exchanger for high pressure stream, while eight sensors are installed equidistantly along the length of heat exchanger to measure temperature of low pressure stream. The paper reports variation in heat transfer coefficient along the length of the heat exchanger. The variation is discussed with respect to temperature distribution across the length and variation in thermo-physical properties of the gas mixture.

Reference

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Development of Novel 4K G-M Cryocoolers with Improved Performance and Reliability

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In order to satisfy requirements in cooling MRI Magnet Systems, Small Superconducting Magnets, SQUIDs, X-ray detectors, etc., Nanjing Cooltech Cryogenic Technology Co., Ltd (NCCT) has been developing a new 4K G-M cryocooler with a long-life compressor. The gap between cylinder and displacer works as a coaxial pulse tube and performs cooling effect by using an internal double inlet phase shift mechanism. It results in cold seal elimination and performance improvement. The comparative experiments between the conventional and NCCT's cold head structure have been carried out. The NCCT's structure presents a better performance. At the second stage, the no-load temperature decreases from 2.37 K to 2.15 K and the temperature with 1W heat load decreases from 3.98 K to 3.66 K. Much effort has been made for a purpose of better performance, lower cost and longer life. A typical cooling capacity of 1.5 W @ 4.01 K at the second stage and 45 W @ 42.8 K at the first stage has been achieved with a 6 HP compressor. The cryocooler system reliability has been improved by developing a new fail safe compressor with nano oil filtering channel technology.