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Cryogenics, Superconductivity and Low Temperature Physics

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Proceeding of
Twenty Seventh National Symposiumon Cryogenics and Superconductivity (NSCS-27)

Hosted by
Indian Institute of Technology, Bombay (IITB), Mumbai
January (16-18), 2019

November, 2019

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Indian Journal of Cryogenics

(A yearly journal devoted to Cryogenics, Superconductivity and Low Temperature Physics)

All the papers received for publications in “Indian Journal of Cryogenics” are reviewed by a large number of Professors, Scientists and Engineers from Universities, Government Institutions and Corporate Sectors across the country in an honorary capacity. Papers are also sent to experts abroad for reviewing.

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Indian Journal of Cryogenics

(A yearly journal devoted to Cryogenics, Superconductivity and Low Temperature Physics)

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B) IJC is the only Indian journal which publishes research work in low temperature physics, superconducting materials, superconducting magnets and the cryogenics. IJC gives utmost importance to the publication of articles on cryogenic engineering. The Editorial Board encourages work on indigenous development of cryogenic and superconducting magnet systems as import substitutions and publishes in IJC.

C) As per the decision of the Editorial Board we started publishing one review article (by invitation) in each volume of the IJCS beginning with Vol.41. These articles are invited from peers with long experience in the field of superconductivity, low temperature physics, cryogenic engineering or covering the status of major cryogenic related projects in India.

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PREFACE

The 27th "National Symposium on Cryogenics and Superconductivity" (NSCS-27) was organized by the Indian Cryogenics Council and the IIT Bombay during 16-18th January 2019 at IIT Bombay.

We added a few new features to the symposium first time, such as conducting Short Introductory Courses on Cryogenics and Superconductivity for students, researchers and the teachers as a part of the Pre-Symposium Workshop on 15th January 2019, Industry-Academia panel discussions, and a Symposium App for quick accessibility to all the events during the symposium. Two themes selected for Pre-Symposium Workshop were (i) Cryocoolers and (ii) Superconducting Magnets and Materials. The Course Instructors for Cryocoolers were Prof. H. B. Naik of SVNIT Surat and Prof. Kasturirengan ex. IISc Bengaluru. The Course Instructors for Superconducting Magnets and Materials were Prof. V. Selvamanickam of Houston Uni. USA and Dr. R. G. Sharma of IUAC, New Delhi.

The pre-symposium workshop was attended by around 90 young researchers. The symposium portal had around 520 users who signed up. About 280 participants from across the country attended the symposium. We received a total of 191 abstracts out of which 171 were accepted after a critical peer-review. These selected abstracts were categorized into oral and poster presentations based on the reviewers' suggestions. The symposium organizing committee ensured that none of the oral sessions was cancelled or altered. All the papers slated in a oral session were presented by the authors who had confirmed their presence to the organizers well in advance. This way all the oral sessions were carried out without the absence of any oral presenter. Poster sessions were conducted in 2 slots. Each oral session was preceded by plenary and invited talks. A total of 13 invited speakers presented their research work in their respective research areas. Plenary talks were delivered by very eminent scientists which included Prof. Venkat Selvamanickam, Dr. T. S. Dutta, Dr. Ziad Ahmad Melhem and Dr. P.P. Kulkarni.

For the ease of knowing the symposium schedule details, a symposium app was developed and made available to the participants. This proved to be helpful to the participants in getting information about various sessions, plenary talks, and short courses. The feedback received shows that the participants found the app extremely useful.

An industry academia panel discussion was conducted with industry experts and research scientists. The discussion gave an opportunity to the young researchers to know the expertise and strength of the Indian industry and interact with them.

The ICC Lifetime Achievement Awards for the year 2018 were given away to Shri P. K. Kush and Prof. R. Nagarajan. Most of the papers presented were very rich in research contents and were of high quality. This symposium was a successful one and has set high standard for future conduct of NSCS. As many as 20 industry booths were put-up during the symposium, which were kept open all through the symposium. Not only this, most of the industry persons remained present throughout the duration of the symposium and interacted with the participants.

The Organizing committee extends heartfelt gratitude to all the speakers, participants, exhibitors, and volunteers, for making the symposium a grand success.

Prof. M. D. Atrey
Chair NSCS-27
Dept. of Mechanical Engineering
IIT Bombay, Mumbai

Prof. Himanshu Bahirat
Co-Chair NSCS-27
Dept. of Electrical Engineering
IIT Bombay, Mumbai

EDITORIAL

It is a matter of great satisfaction that, year after year, we are able to bring out successive issues of our esteemed journal, the "Indian Journal of Cryogenics" on time. Volume no. 44 for the year 2019 is now out. As per the policy of the ICC and the journal we encourage our young researchers to publish papers and many of them happen to be first timers. Very often, our distinguished reviewers have tough time and have to suggest many corrections and modifications in the manuscripts and ask for revision. I admire their endurance and stamina. This is all in the interest of the ICC, the Journal and our community. I thank all the referees profusely. Vol. 44 is the proceedings of the "27th National Symposium on Cryogenics and Superconductivity" (NSCS-27) held at Indian Institute of Technology, Bombay (IITB), Mumbai during January 16-18, 2019.

This issue contains 38 papers in all out of a total of 92 papers submitted that were presented at the NSCS-27 at IITB, Mumbai. In keeping with our policy each paper of this issue was reviewed by two of the experts on our panel of referees from within and outside India. In case of conflicting reports the final decision on the acceptability of the paper is taken by the editorial board.

Like the previous issues Vol. 41 - Vol. 43, this issue too begins with an invited review article written by Dr. N. K. Gupta, Ex. Dy. Director Liquid Propulsion Systems Centre, ISRO. Dr. Gupta is a veteran cryogenic engineer with vast experience in the design and development of Cryogenic Engine and cryogenic rocket propulsion. In this paper Dr. Gupta has given an overview of the different types of rocket propulsion used in space exploration, their principle of working and the performance. He has explained how ISRO has come a long way in the field of cryogenic propulsion. The GSLV MKII and GSLV MKIII have proved ISRO's capabilities in the field of cryogenic propulsion with world class performance.

I take this opportunity to compliment all the members of the Editorial Advisory Board for their help and cooperation. I thank Dr. TS Datta and Dr. Soumen Kar who were always available for consultation and help which enabled us to bring out this issue (Vol. 44) of the IJC. I express my gratitude to the reviewers, who in spite of being deeply involved with their academic work always found time to review multiple papers. I thank Prof. Avinash C. Pandey, Director IUAC and the IUAC administration for their help and support for the publication of the journal. I thank all our authors who repose faith in IJC and cooperate in revising manuscripts if so desired. I also greatly acknowledge the help from Ms. Sofia Gomes, the Secretarial Assistant, for having kept the line of communication alive between the journal HQ, the referees and the authors. In a short time Ms. Sofia mastered the skill of journal publication and has been proactive all through. I thank Mr. Satish Gupta of the New United Process for taking good care of printing.

We place on record our gratitude to **SERB (DST)** for its support to the publication of this journal.

R.G. Sharma
Chief Editor
IUAC, New Delhi

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Indian Journal of Cryogenics doi: 10.5958/2349-2120.2019.00001.3 *Vol. 44, 2019*

Review (Invited)

Cryogenics in Space with particular reference to ISRO programs

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Indian Space Research Organization (ISRO) has developed Polar Satellite Launch Vehicle (PSLV) and Geosynchronous Satellite Launch Vehicles (GSLV MK II and GSLV MK III). Earth Storable Propulsion System was used in PSLV. Cryogenic engines were developed for their application in GSLV. This review paper describes the development history of cryogenic engines in ISRO. Cryogenic engine has put India in 4-tonne class satellite launch capability in GTO. Also for ISRO's missions like Chandrayan – 2 and Human Space flight, it forms part of GSKLV MK III.

Key words: Cryogenic engine, Polar Satellite Launch Vehicle (PSLV), Geosynchronous Satellite Launch Vehicles (GSLV)

Indian Journal of Cryogenics doi: 10.5958/2349-2120.2019.00002.5 *Vol. 44, 2019*

Recent improvements in the indigenously developed cryogenic systems at CrTD, BARC

Mukesh Goyal[1], Anindya Chakravarty[1, 2], Naseem A. Ansari[1], Rajendran S. Menon[1], Mohananand M. Jadhav[1], Tejas R. Rane[1], Sandeep R. Nair[1], Jitendra Kumar[1], Naveen Kumar[1], Satish K. Bharti[1], Abhilash Chakravarty[1], Ankit Jain[1] and D. S. Pilkhwal[1]

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To achieve self-sufficiency in the field of helium cryogenic systems for various departmental programs of national/ international importance, in-house helium refrigeration/ liquefaction systems are developed at Cryo-Technology Division (CrTD), Bhabha Atomic Research Centre (BARC), Mumbai. Due to the recent developments/ improvements in the cryogenic equipment, the liquefaction rate of the indigenously developed helium liquefier is increased from the earlier demonstrated capacity of 32 l/hr to 42 l/hr. The indigenously developed 20 K refrigeration system is modified through innovations introduced in its process in order to make it suitable for different types of client heat loads and its refrigeration capacity is increased from the earlier demonstrated capacity of 470 W at 20 K to 850 W at 17.5 K.

Key words: Helium liquefier, Helium refrigerator, Turboexpander, LHe Dewar

Indian Journal of Cryogenics doi: 10.5958/2349-2120.2019.00003.7 *Vol. 44, 2019*

Turbomachinery selection: Generating the selection charts and extending their use beyond the conventional for cryogenic plants

Mohananand Jadhav [1,2], Anindya Chakravarty [1,3] and M. D. Atrey [2]

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Non-dimensional analysis of turbomachinery reviewed and presented in a nutshell. Momentum equation of the inward flow radial (IFR) turbine is used to correlate efficiency of the turbine with the parameters, specific speed (n_s) and specific diameter (d_s). The design points satisfying the momentum and energy equations simultaneously for the specific but common design case of $c_u/u = 1$, are extracted from the Balje charts. It is shown that for such a case d_s and the isentropic efficiency can directly be correlated with specific speed n_s for constrained optimization studies of the cryogenic cycles. An attempt has been made to extend the use of the concept of n_s-d_s charts for selection and design of the cryogenic process cycles where the design demands maximum possible plant efficiency, plant compactness and impurity management. As an elucidation of the concept, optimization and performance maps of a two stage reverse Brayton cycle based refrigerator are generated and presented.

Key words: Turbomachinery, Ns-Ds diagram, Cryogenic cycle design

Indian Journal of Cryogenics doi: 10.5958/2349-2120.2019.00004.9 *Vol. 44, 2019*

Conceptualization and preliminary studies on the development of a 2K refrigeration system at BARC

Anindya Chakravarty[1, 2], M. M. Jadhav[1], Mukesh Goyal[1], and D. S. Pilkhwal[1]

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Conceptualization and preliminary studies on the development of a 2K helium refrigeration system at BARC are reported in this article. Two different refrigeration schemes are considered and studied. In Scheme A, a separate cold box with 2 heat exchangers, a liquid helium bath and a sub atmospheric heat exchanger is considered and 2K refrigeration capacities for different liquid helium flow rates corresponding to LHP 50 and LHP 100 (BARC helium liquefiers), are computed and reported. In Scheme B, the 2K refrigeration system is considered to work in tandem with a back-up 4.5K helium liquefier (LHP 50/LHP 100), receiving a stream of cold supercritical helium from the liquefier. Different cases, with and without liquid nitrogen precooling options of the 4.5K liquefier, are considered. After preliminary studies, Scheme B is preferred over Scheme A and the process inputs for the sub atmospheric pressure heat exchanger are also arrived at and presented.

Key words: 2K refrigerator, Helium liquefier, Sub atmospheric heat exchanger

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Development of aerostatic bearing system for balancing of ultra-high speed turboexpander rotors used in helium liquefiers/refrigerators

Ankit Jain, Mohananand M. Jadhav, Naveen Kumar, Rajendran S. Menon, Anindya Chakravarty, Mukesh Goyal, and D.S. Pilkhwal

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Balancing of high speed turboexpander rotors is necessary to minimize vibration and noise, increase bearing life and to maintain stable operation of turboexpanders which can otherwise lead to cryogenic plant unavailability. In general, a dynamic balancing machine is based on mechanical roller bearing supports. This article reports an attempt to modify a dynamic balancing machine by replacing the existing line contact roller bearing system with a gas film supported aerostatic bearing system to eliminate erroneous and inconsistent unbalance readings. An aerostatic bearing system has been designed to balance a typical turboexpander rotor of 16 mm diameter. Experiments have been conducted to compare the performance of roller bearing and air bearing systems on the balancing machine. It has been found that consistency is improved by using air bearings and rotor can be balanced to a lower unbalance value.

Key words: Aerostatic bearing, Dynamic balancing, Balancing machine, Precision balancing

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Performance evaluation of indigenously developed helium liquefier in mix mode operation

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An indigenously developed helium liquefier of 50 L/h liquefaction capacity has been designed, fabricated and commissioned at RRCAT. All the components of this system were either manufactured in-house or built through local manufacturers as per our design specifications. In order to improve the performance, the system was experimentally tested in mix modes of operation. System has been subjected to heat input through an electrical heater installed at the bottom of liquid helium collection container inside the cold-box to evaluate its performance as refrigerator. With reciprocating expansion engines and plate fin heat exchangers, the measured refrigeration power is 40 W at 4.2K without nitrogen precooling. There is also provision for liquid nitrogen precooling to further increase the refrigeration capacity. The maximum compressor power input for the system is 110 kW that can also be varied with variable frequency drive. In this paper, experimental results obtained from the system are presented and simultaneously validated with developed numerical model for the same conditions.

Key words: Helium liquefier, Reciprocating expanders, Mixed mode operation.

Indian Journal of Cryogenics doi: 10.5958/2349-2120.2019.00007.4 *Vol. 44, 2019*

Development of a 1000 *l* liquid helium dewar at CrTD, BARC

Naseem A. Ansari, Mukesh Goyal, Rajendran S. Menon, Mohananand M. Jadhav, Naveen Kumar and D. S. Pilkhwal

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A liquid helium (LHe) Dewar, with 1000 L nominal capacity, is developed at Cryo-Technology Division (CrTD), Bhabha Atomic Research Centre (BARC), Mumbai. The Dewar is designed for a normal evaporation rate (NER) of less than 1 percent per day. The Dewar is being successfully used as a LHe receiver vessel connected to a helium liquefier cold box. The measured evaporation rate as per the reduction in the weight of the Dewar is about 2.8 l/ day for liquid nitrogen (LN_2) and 10 l/day for LHe.

Key words: Liquid helium dewar, Helium liquefier, Multilayer super insulation, Thermal shields

Indian Journal of Cryogenics doi: 10.5958/2349-2120.2019.00008.6 *Vol. 44, 2019*

A study setup for a GM cooler based helium liquefier

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A helium liquefier study setup has been developed at IUAC using a 1.5 watt at 4.2K Gifford Mac Mahon (GM) cryocooler, for understanding the heat transfer mechanism between the gas and the cryocooler surface at all the four stages of cooling. A thermo-siphon loop is added to the liquefier bottom with a heater to know the precise liquefaction rate under various study conditions. Inclusion of thermo-siphon loop reduces the consumption of helium gas by utilising the evaporated gas in a controlled manner. The study setup has other capabilities to measure the liquefaction rate under various conditions such as varied pressure, with or without heat exchanger at both cooling stages, and with or without nylon shroud in the regenerator regions etc. The experimental setup is successfully put in place and preliminary experimental results have started coming in. A liquefaction rate of 18.4 liters per day (lpd) has been measured at STP condition with the basic configuration.

Key words: GM Cryocooler, Liquefier, Heat exchanger

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Development of test facility at BARC for large flow turboexpanders

Rajendran S. Menon[1], Anindya Chakravarty[1, 2], Mukesh Goyal[1], Mohananand M. Jadhav[1], Naveen Kumar[1], and D. S. Pilkhwal[1]

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High speed high flow turboexpander test setup is an important and necessary facility for performance evaluation of a new class of aerostatic bearing based turboexpanders involving rotor dynamic and thermodynamic studies and establishing the reliability of operation. The large flow turboexpander test facility is developed along with its various subsystems and emergency systems. The set-up development process along with trial runs with turboexpanders conducted on the test facility are reported in this paper.

Key words: Test facility, Helium refrigerator, Aerostatic turboexpander

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Development and performance testing of phase separator for liquid nitrogen distribution network

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Phase separators of different design are in use widely all over the world for cryogenic transfer systems. The cryogenic facility [1] at IUAC along with other facilities consist of a large network of LN2 distribution lines. The transfer loss has become a serious concern due to problems associated with it such as pressure loss and economical utilization of liquid nitrogen. A phase separator suitable for the existing distribution system has been developed indigenously and measurements of quality improvement by this phase separator has been analyzed. This paper describes in detail about its design and fabrication along with test results.

Key words: Phase separator, Vacuum jacketed transfer line

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Test set-up and results of indigenous prototype 80 K helium purifier of He plant

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A Helium refrigerator/liquefier, of refrigeration 1 kW at 4.5 K, being developed at IPR, will have in-built two He purifiers inside the cold box to remove impurities like N2, O2, Ar at ~80 K and H2 & Ne at ~20 K. A prototype He purifier adsorber bed for flow rate of 30 g/s has been designed and manufactured indigenously for operation at ~80 K. To simulate the condition of operation of purifier inside the He plant a test facility has been developed indigenously, in which this prototype purifier will be tested. In this test facility, vacuum chamber is not used and certain insulations have been wrapped over the low temperature components to reduce the external heat load. Test result shows that even at high impurity inlet of 300 PPM (part per million), outlet impurity was 0 PPM. This report will give details of these.

Key words: Helium, Purifier, Adsorber bed, Test facility, Cryogenic, Helium liquefier

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Numerical studies on aerostatic journal bearings for cryogenic turboexpanders

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The reported study uses a model for evaluating both static and dynamic stiffness. It has been shown in the article that the dynamic component of the stiffness contributes mostly to the cross coupled component, which in turn contributes to the rotor instabilities. Different bearing configurations are proposed and studied for reduction of the cross coupled stiffness component. A numerical aerostatic journal bearing solver which includes the effects of shaft angular velocity, is developed and validated by experimental studies. A comparative study among the various configurations along with bearing parameters is presented which can serve as a guide for design and further development of high speed aerostatic journal bearings.

Key words: Turboexpander, Aerostatic Journal bearing, Cross coupled stiffness

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Experimental studies on spiral groove thrust bearings

Satish K. Bharti[1], Mohananand M. Jadhav[1], Anindya Chakravarty[1,2], Rajendran S. Menon[1], Ankit Jain[1], Naveen Kumar[1], Mukesh Goyal[1] and D. S. Pilkhwal[1]

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This article discusses about the role of bearing parameters including those of the grooves on the stiffness and load capacity of Spiral Groove Thrust Bearings (SGTB) at high rotational speeds. A tandem arrangement of Aerostatic Thrust Bearing (ASB) with an SGTB assembly is investigated. Studies revealed that optimization of groove depth and land area of SGTB play a key role in its load carrying capacity. The optimum inner land radius of SGTB developed by BARC for its cryogenic turboexpanders is found to be 17-19 mm, any variation on either side leading to a reduction in bearing stiffness. After development of the set-up with the mentioned tandem bearing arrangement, a preliminary experiment was conducted with the rotor running up to 3000 Hz.

Key words: Spiral groove thrust bearing, Aerostatic thrust bearing, Turboexpanders

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Parameter estimation of equipment for development of an experimental setup of a reverse brayton cryocooler for cooling HTS cables

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Reverse Brayton Cryocooler (RBC) can suitably provide continuous cooling to High Temperature Superconducting (HTS) cables used for low-loss power transmission. These HTS cables may impose periodic heat load to the RBCs, which are designed to operate at steady heat load conditions. Performance of RBCs at such conditions needs to be investigated and steps towards mitigation of the effects need to be taken. Building an experimental setup to serve both the purposes is underway at IIT Kharagpur using an existing decommissioned 15 L/hr helium liquefier. It was necessary to know the design and operating parameters of every equipment to reuse them in the setup. However, most of them were unavailable requiring estimation for unknown parameters for equipment like heat exchangers, turbo-expander etc. A parameter estimation method was used for this purpose and dynamic simulations were performed to verify those estimated values of each equipment as presented in the paper.

Key words: HTS cable, Parameter estimation, Helium liquefier, Reverse Brayton cryocooler, Dynamic simulation

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Performance comparison of a thermoacoustic engine having different stack geometry using CFD simulation

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Thermoacoustic heat engines (TAHE) convert heat energy into acoustic energy without using any moving component. The acoustic energy can lead to a high frequency linear oscillating motion in a gas which in turn can be used to drive a pulse tube (PT) cryocooler or a thermoacoustic refrigerator. Thus, the system becomes less vibrating as well as contamination free offering a long maintenance free life with high reliability. Conversion of heat energy into acoustic energy takes place near the stack region. The objective of the present studies is to compare the performance of various stack geometries in a given resonator through CFD simulation. Among the geometries such as parallel plate, tube array and pin array, the pin array stack geometry is found to provide the best performance.

Key words: Thermoacoustic heat engine, Stack, Numerical analysis

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Development of a linear compressor for a stirling cycle based cryocooler

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With a view to minimize the power consumption, a method to evaluate the factors influencing the performance of a compressor driving a Stirling cycle based cryocooler has been proposed. An experimental as well as a numerical approach has been employed to analyze the flexure bearing stiffness. Additionally, gas spring stiffness has been found analytically. Consequently, the undamped natural frequency, of the flexure bearing spring system employed in the compressor has also been calculated. Additionally, in contrast to the traditional and often employed method of assuming the gas spring to be constant, an attempt has been made to find out the variation of the gas spring/stiffness during the compression stroke of the compressor. The effect of leakage of the working gas from the clearance between the piston and cylinder has also been considered.

Key words: Stirling cycle based cryocooler, Flexure bearings, Gas spring stiffness, Leakage from clearance

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Numerical analysis of a single stage Gifford-McMahon type pulse tube refrigerator

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In this paper, a step by step design methodology has been proposed to design a single stage GM-Type pulse tube refrigerator. A numerical model has been developed that solves continuity, momentum and energy equations for fluid, and also energy equation for solid matrix, by using finite volume method. This numerical model predicts the mass flow rate, pressure history, temperature variations etc. in each discrete control volume. By using the information so obtained from the numerical model, a heat exchanger (shell and tube type) was designed by using ∈-NTU approach and then fabricated. Structural analysis was also performed to ensure the safety of various components of GM-type PTR, and to calculate the various forces for the design of flanges of regenerator and pulse tube. Numerical analysis shows that, the present setup can produce a refrigeration capacity up to 25.8 W @ 70 K and 12 W @ 40 K.

Key words: GM-Type DIPTR, Waiting time, Shell and tube heat exchanger

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Pumping speed studies of different activated carbons in a cryocooler based cryosorption pump

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The development of cryopumps with higher pumping speeds is needed for fusion related applications. Towards this goal, pumping speeds of different Activated Carbons (ACs) have been studied by adhering them on cryopanels mounted on two stage Cryocoolers, to arrive at the best pumping speed. The standard American Vacuum Society (AVS) procedures have been adopted in pumping speed measurements. Although cryopanels fabricated with Knitted Carbon Cloth (KCC) have higher pumping speeds in the specific pressure range of interest suitable for fusion applications, their sorption capacities are quite low, due to the lower masses of ACs. On the other hand, Cryopanels with pelleted ACs are found to perform better than KCC cryopanels, due to the increase mass of ACs and hence tolerate higher gas loads compared to KCC cryopanels. The present studies indicate the need for larger mass of ACs in cryopanels for better pumping speed with higher sorption capacities.

Key words: Activated carbon, Fusion systems, Cryosorption, Pumping speed, Helium

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Performance validation of passive radiant cryo-cooler for meteorological payload of INSAT-3D satellite through in-orbit data

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INSAT-3D satellite built by ISRO carries Imager - advanced meteorological payload, wherein infra-red detectors are cooled to 90 K by means of passive radiant cooler. Heat load from detectors is around 20 mW. Passive radiant cooler works on the concept of staged radiator cooling. Imager cooler consists of three stages. Stages are designed such that successive stages have higher degree of isolation from the external loads and each stage is radiant to space. The first stage temperature is around 200 K, the second around 120 K and third stage is around 90 K. Infra-red detectors are mounted on the third stage. The in-orbit temperature and control heater power data over five years of Imager cooler of INSAT-3D validates its intended performance and shows insignificant degradation.

Key words: Radiant cooler, Cryo-cooler, Infra-red detector, Meteorological satellite, INSAT-3D

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A Volume-of-Fluid (VOF) methodology for prediction of Direct Contact Condensation (DCC) of gaseous oxygen jets in subcooled flowing liquid oxygen

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A Volume-of-Fluid (VOF) interface capturing method used for modeling Direct Contact Condensation (DCC) of gaseous oxygen in liquid oxygen at the inlet duct to the main LOX pump of India's indigenous semi-cryogenic rocket engine SCE-200. The numerical simulations were performed for 60%, 100% and 105% thrust conditions in 3-D inlet duct geometry with 16 orifices for gas injection, which is an extension of the previous work [1] where 2-D simulations with a single orifice were performed. Lee [2] phase change model has been implemented to predict the condensation effects. The isovolumes of gaseous oxygen volume fraction were plotted at different instants of time to predict the nature and extent of condensation. Further, the variation in amount of gaseous oxygen with time at the exit of the inlet duct estimated to provide design recommendations.

Key words: Volume-of-Fluid, Direct Contact Condensation, Oxygen, Semi-cryogenic, LOX pump

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Stress and safety analysis of 9T superconducting solenoid magnet for RIB facility

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A high field superconducting solenoid magnet is required for the beam- line of radioactive ion beam facility at VEC Centre, Kolkata. The superconducting solenoid magnet generates a magnetic field of 9T and large magnetic stress due to magneto mechanical forces. A micro slip movement in the coil due to the magnetic force can generate local heating and coil may become resistive. This phenomenon is called quench. In order to restrict any such movement in the coil and thereby prevent quench, a detailed analysis of quench and quench-induced stress is essential. In this paper, a detailed stress analysis have been formulated analytically for pre-stress, thermal stress and magnetic stress and compared with simulation results obtained by ANSYS code. Quench analysis of the magnet has also been discussed in detail. The temporal variations of current, temperature rise, voltage drop and normal zone propagation during quench have been carried out by using a quench solver computer code OPERA. The quench protection techniques and its effects on temperature rise and voltage drop has also been discussed.

Key words: Quench, Superconducting magnet, Stress

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Performance analysis of coiled finned tube heat exchanger for medium size helium liquefier

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In this work, a numerical model has been developed for theoretical analysis of coiled heat exchanger in the temperature range of 77 K – 300 K. The numerical model is validated with the experimental data available in the literature. The objective of this study is to design and optimize the heat exchanger to achieve the desired effectiveness and therefore, the drop in the temperature of the hot gas. Numerical simulations have been carried out by varying the geometrical parameters like fin density, coil diameter, etc., and operating parameters like pressure and mass flow rate. It is observed that mass flow rate in the range of 2-2.5 g/s results in heat exchanger effectiveness of more than 0.95 for a charging pressure range of 11-15 bar. For different mass flow rates, the minimum requirement of the product UA for achieving effectiveness values greater than 0.95 is also mentioned.

Key words: Finned tube heat exchanger, Helium liquefaction, Optimization

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Thermal performance evaluation method of multistream plate fin heat exchanger

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Multistream plate fin heat exchangers (MSPFHEs) are vital components of large cryogenic systems. A computer program is developed for layer by layer analysis of thermal performance of MSPFHEs and is validated against the published experimental results. Cross layer conduction between the streams in non-adjacent layers and heat transfer between the streams in consecutive layers are computed using analytical formulation. This avoids the need of fin discretisation along its height. Heat exchanger is discretised along the flow direction to take care of the effects of axial heat conduction and material property variation. Finite difference method (FDM) is used to convert the energy balance equations into a system of linear algebraic equations, which are solved iteratively. The developed computational method is found to be of adequate accuracy, capturing all the effects and can be used for MSPFHE design for cryogenic systems.

Key words: Multistream plate fin heat exchanger, Cross layer conduction

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Development of lab scale sub-cooled liquid nitrogen facility for high temperature superconductor applications

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The technological advances in high temperature superconductors (HTS) have led to its use in various high voltage and high current applications. HTS based devices have huge application prospect compared to low temperature superconductors (LTS) owing to their higher engineering current density, higher critical temperature (hence higher operating temperature) resulting in high power density and lower investment on cryogenics. Here we report the development of sub-cooled liquid nitrogen facility for cooling small scale HTS application with single phase liquid nitrogen under a temperature range of 64 K – 77 K. We have sub-cooled liquid nitrogen inside commercially available 50 L Dewar by boiling nitrogen under reduced pressure. As a proof of principle, we have cooled a 1 meter long vacuum insulated flexible cryogenic transfer line to 70 K using sub-cooled nitrogen. This same facility can be used to efficiently cool future High Temperature Superconductor (HTS) based applications at a laboratory scale.

Key words: HTS, Sub-cooling, Dewar, Sub-cooled liquid nitrogen

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Comparison of cryogenic insulation materials in temperature range of 300K to 80K

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The thermal property of agricultural waste (Rice husk) was investigated with purpose of their use. The experiments have been conducted for using sample of perlite, rice husk and mixture of rice husk and perlite as materials of thermal insulation. Comparison of Experimental results of perlite, rice husk and mixture of rice husk and perlite was carried out. Performance is carried out in different operating parameters like pressure, density, temperature boundary condition etc. These results are helpful to select insulation material for a particular cryogenic application.

Key words: Perlite, Vermiculite, Rice husk, Thermal conductivity

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Selection criteria of cost-effective cryogenic system for a cryopump based on heat load estimation

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Cryopumps creates vacuum by capturing gas molecules on cryogenic temperature surfaces. Modern commercial cryopumps are cooled by a cryocooler and performance of the cryopumps largely depends on cooling capacity of the cryocooler. This paper discusses estimation method of radiant heat loads on a cryopump. Thermal load was calculated for different emissivity of surfaces and different volume of chamber. Based on calculation, a cost effective cryogenic system for a cryopump was selected from commercially available cryocooler.

Key words: Vacuum technology, Cryopump, Radiative heat transfer, Cryocooler.

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CFD analysis of the evaporating two-phase flow in the slug flow regime of a cryogenic fluid in a microchannel

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Flow boiling in a microchannel is investigated in the present work using the multiphase CFD. Cryogenic fluid nitrogen is used as a working fluid for the CFD simulations. A single bubble is patched in the upstream of the microchannel and the bubble profile, velocity and temperature profile and the heat transfer performance is evaluated. Effect of parameters, like wall heat flux and inlet flow rate or Reynolds number, are studied. It is found that the passage of the bubble significantly alters the parabolic velocity. The passage of the bubble and the evaporation at the interface also significantly reduces the wall temperature due to the enhanced heat transfer. Heat flux does not seem to have any effect on the average heat transfer coefficient, while the heat transfer coefficient increases with the inlet flow rate. The numerical framework employed to perform this study is the open source CFD package OpenFOAM with the volume of fluid interface capturing method.

Key words: CFD, Heat transfer, Microchannel, Cryogenics

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Performance analysis of a NbTi level sensor while filling LHe into a cryostat

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A mathematical model for simulating the operation of the superconducting level sensor inside a cryostat was developed earlier which was experimentally validated using NbTi and MgB2 level sensors in LHe. It was observed that the operation of these sensors is highly dependent on heat transfer phenomenon in the vapor phase inside the cryostat. As the condition of vapor phase and consequently the heat transfer phenomenon changes during different stages of cryostat operation, such as filling, normal operation, operation during high heat in-leak and draining, etc., it is important to investigate the sensor operation during the same. Hence, the operation of NbTi level sensor under different liquid boil-off conditions was studied earlier. The present article discusses the operation of NbTi sensor while filling LHe into a cryostat. It was observed that both one-current and heating current-measuring current (two-current) method provide accurate level measurement, with later having better linearity for voltage versus liquid level curve.

Key words: Liquid helium, NbTi wire, Superconducting level sensor, One-current method, Two-current method.

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Development of a complete cold electronic based discrete level sensor

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A complete cold electronics based cryogenic level sensor with six discrete levels is presented here. Each level consists of a series arrangement of 3 diodes separated by 1 mm distance, forming a series-parallel diode arrangement. The method of feeding a constant current to only one selected level at a time has greatly improved the current requirement to (1-2mA). Likewise, multiplexing and monitoring the voltage across one level at a time using a cold electronics multiplexer circuit has negated the shortcoming of reduced sensitivity at higher number of levels. The level is determined by the series voltage of the diodes obtained from the output of op-amp circuit and corresponding to the delta diode voltage, digitization of the voltages has been done to represent immersed or exposed diodes in LN_2. With this series-parallel method of measurement, both the shortcomings of conventional diode based level sensors namely; requirement of large supply current for diodes and the thermal-voltage saturation error at higher levels are improved. Experimental results from the calibration are also presented here.

Key words: Cryogenic level sensor, Cold electronics, Multiplexed diode array

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Capacitance measurement circuits for void fraction sensors for cryogenic fluids

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In the two-phase flow of fluids, the void fraction is an important parameter which determines the various aspects of the flow such as mass flow rate, heat transfer etc. Since the vapor and liquid have different dielectric constants, this results in capacitance variation of the flowing fluid. Hence, the void fraction sensors can be based on capacitance measurements. However, since variation of dielectric constants between the liquid and vapor is very small suitable electronic circuits need to be developed to measure very small changes in capacitance. Three circuits namely 555 timer circuit, Differentiator circuit using IC 741 and C to V converter using LM2917 have been developed and studied for their performances using capacitance-based level sensor. These are discussed in this paper. The studies indicate that the differentiator circuit as well as the C-V converter circuit are more suitable for the implementation in Void fraction sensor.

Key words: 555 timer, Differentiator circuit, C to V converter, Void fraction, Cryogenic fluid flow

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AC Characterization of modular superconducting fault current limiter unit

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A second-generation high-temperature superconductor (HTS) based superconducting fault current limiter (SFCL) module has been characterized by different prospective fault currents at the output voltages of 20 V_{rms} and 40 V_{rms}. The current limiting characteristics of the modular SFCL unit and their recovery under load characteristics have been analyzed. The dynamic thermal profiles of the HTS tape during the fault and recovery have been studied experimentally at liquid nitrogen temperature. This paper briefly presents the investigation of the behavior of YBCO tape-based modular SFCL unit at the 20 V_{rms} and 40 V_{rms}.

Key words: High-temperature superconductor, Superconducting fault current limiter

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Quench dynamics study in 2nd generation HTS tapes

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The faster quench detection is required for high temperature superconductor (HTS) to avoid the local damage of conductor due to overheating. This problem is particularly challenging for high temperature superconducting magnets due to the slower normal zone propagation velocity (NZPV) in comparison to low temperature superconductor (LTS). As a result, quench detection and protection for HTS coils is matter of concerned for fusion community working for the 2nd generation high field tokomak. The Di-BSCCO HTS tape samples of critical current around 160 A are selected to study the quench dynamic experiment. The Normal zone voltage rise and the temperature evolution after thermal quench were experimentally measured in Di-BSCCO tapes. The measured voltage and temperature signals have been analysed and elaborated in this paper.

Key words: HTS, LTS, Thermal quench, NZPV

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Post-Quench electromechanical analysis of 1.5 T whole body clinical MRI system

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A 1.5 T superconducting magnet has been designed for the whole-body clinical MRI scanner. The stored energy (~4.5 MJ) of the magnet if released during a quench, can adversely affect the coil by raising its temperature and the associated voltage across the coil. Any quench in the MRI magnet induces an eddy current on various components of the magnet system such as bobbin, thermal radiation shield, etc. A passive quench protection scheme has been designed and simulated for the MRI magnet. The hot-spot temperature and the peak voltage in the magnet respectively are 136 K and 2.15 kV. The quench induced eddy current and the associated mechanical stresses have also been simulated for the various components. The peak density of the eddy current on the magnet bobbin and the thermal radiation shield are 375.5 A/cm^2 and 2316 A/cm^2 respectively. Whereas the peak mechanical stresses are 40.48 MPa and 11 MPa for the bobbin and the thermal radiation shield respectively. This paper briefly discusses the quench protection scheme, quench-induced eddy current and its associated mechanical stresses on various components of the magnet system.

Key words: Quench, Eddy current, Stress, MRI.

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Development of high homogeneity and high stability 1.5T superconducting magnet for whole body MRI scanner

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A multi-coil actively shielded 1.5T superconducting magnet has been designed for a whole-body MRI clinical scanner. The magnet has six primary coils and two active shield coils that have a reverse polarity of current with respect to the primary coils. The spatial field homogeneity achieved in 45cm of the field of view is ±5 ppm at its iso-center. The peak field on the coils is 4.3T. The MRI magnet would be operated in a persistent mode to achieve the temporal field stability of 0.1ppm/hr. The wire-in-channel (WIC) NbTi conductor with copper to superconductor ratio of 10 will be used for all the eight coils of the 1.5T magnet. To achieve the desired field stability in the persistent mode of operation, superconducting joint technology has been developed and the joints have been tested at 4.2K using an indigenously developed field decay test probe. In zero field, the minimum joint resistance achieved is 1.3x10 $^{-13}$ Ω. Since the inter-coil joints will be placed in a 0.5T field region we have measured the joint resistance in 0.5 T field as well. In the 0.5T background field, the joint resistance is found to be 7x10^{-12} Ω, low enough to provide required field stability.

Key words: Superconducting magnet, MRI magnet, Superconducting joint, Active shield coil

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A study on high temperature superconducting (HTS) double pancake field coils for HTS synchronous machines applications

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The High Temperature Superconducting (HTS) synchronous machines having compact size, lower weight and higher efficiency are finding more and more applications in various industrial domains. The most promising topology for such machines is copper winding based stator along with HTS winding based rotor. The rotor field winding of such HTS synchronous machine can be realized with racetrack shaped double pancake type HTS coils. These HTS coils can be designed for unprecedentedly higher ampere-turns and magnetic flux densities. Worldwide limited number of such double pancake type HTS coils has been developed for synchronous machine applications. A brief account on these developments have been presented in this paper along with various design aspects and considerations needed to be followed during design and development stage of such coils. In line with this, a prototype double pancake HTS coil has been developed and tested and the results are also presented in this paper.

Key words: HTS coil, Racetrack shaped double pancake type HTS coil, HTS synchronous machine

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Experimental investigations on cryogenic adsorption of nitrogen over activated charcoal

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Three samples of activated charcoal were tested for nitrogen adsorption capacity at 77 K. Adsorption isotherms have been generated for the samples with equilibrium pressures ranging from µbar levels to the saturation pressure. The isotherms' shape is of Type-I and has a linear p/V vs p relationship which is consistent with the behavior of microporous adsorbents. Adsorption capacities for Sample 1 are 11 % w/w at µbar equilibrium pressure levels and around 34 % w/w at near saturation pressure. Similarly, for Sample 2 and 3, the corresponding capacities are 6 % w/w, 8 % w/w and 30 % w/w, 28 % w/w. Based on the data, design of inline purifiers for Helium refrigerator/ liquefier cold boxes and external Helium purifiers can be made more precise. Knowledge of capacity variation with impurity concentration will enable the designer to select a suitable average adsorption capacity over the range of concentration desired in the purifier.

Key words: Adsorption, Charcoal, Isotherm, Purifiers

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Theoretical and experimental investigations on magnetic abrasive finishing (MAF) for finishing of flat and cylindrical components for cryogenic applications

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Magnetic Abrasive Finishing (MAF) can be employed for finishing of flat and cylindrical turboexpander components' surfaces at nano-level. MAF can nano-finish surfaces to the order of 20 nm and better. Using the Design of Experiments (DoE) technique, experiments were carried out on an existing MAF setup. By mathematical modelling of the experimental data using regression technique, a correlation between the critical process parameters of the MAF process and final surface roughness, R_a, of the work surface has been developed. This regression model has been compared with a theoretical model for the MAF process from literature. Working gap between the work piece and the magnet, and Rotational speed of the work piece were observed as two of the most influential MAF process parameters. Both these parameters have optimum values (Gap = 1.25 mm, Speed = 800 RPM), at which the lowest R_a value was obtained for the existing MAF setup.

Key words: MAF, Magnetic, Abrasive, Finishing, Turboexpander

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Theoretical comparison of thermo-mechanical behavior of a tension rod and a coil as dewar support

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Dewars continue to be the popular means of cryogen storage. Heat in leak through the insulation and the support system holding the two vessels is the main parameter determining the hold-up time of a Dewar. Support systems for dewars are designed by taking motivation from the design methodologies available for high temperature pressure vessels. While implementing these design guidelines, the mismatch between the material behaviors at these conditions are being taken care of by using various safety factors. The scientific motivation behind these safety factors are not apparent. The use of these factors add to the weight and cost of the storage system, thereby increasing the payload. In this paper, a mathematical model has been presented to determine the stress and temperature distribution in a support structure. The model has been solved by employing an FEM formulation using the commercial software ANSYS®. The thermal and structural behavior of two support systems has been compared by solving the model equations.

Key words: Dewar, Support systems, FEM, Tension rods, Helical coil

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