International Cryocooler Conference 21

Preliminary Program and Abstracts Book

December 02, 2020

ICC21 Committee

Conference Chair

Sastry Pamidi
Florida State University, USA
pamidi@eng.famu.fsu.edu

Conference Planning/Webmaster

Ron Ross, Retired-JPL, USA
rgrossjr@jpl.nasa.gov

Treasurer

Ryan Taylor, Ball Aerospace
Email: rtaylor2@ball.com

ICC Registered Agent

Ray Radebaugh, Retired, USA
radebaugh@boulder.nist.gov

Proceedings Co-editors

Ron Ross, Retired-JPL, USA
rgrossjr@jpl.nasa.gov

Jeff Raab, Retired-NGAS, USA
jlraab2@cox.net

Saul Miller, Retired-Aerospace

Program Chair

Carl Kirkconnell, West Coast Solutions, USA
icc21program@cryocooler.org

Program Committee

Cole McNeal, West Coast Solutions, USA
Mostafa Ghiaasiaan,Georgia Institute of Technology, USA
Wolfgang Stautner, GE, USA
Ladan Amouzegar, NGAS, USA
Sangkwon Jeong, KAIST, Republic of Korea
Ted Conrad, FLIR, USA
Chul Kim, Florida State Univ., USA
Zhihua Gan, Zheijiang Univ, China
Ingo Rühlich, AIM Infrarot-Module, Germany
Jeff Olson, Lockheed Martin ATC, USA
Julien Tanchon, Absolut System SAS, France
Mark Zagarola, Creare LLC, USA

ICC Board

Sastry Pamidi, Florida State Univ., USA - Chair ICC21
Mark Zagarola, Creare, USA - Past Chair ICC20
Dean Johnson, JPL, USA- Past Chair ICC19
Martin Crook, Rutherford Appleton Lab, UK
Wei Dai, Technical Institute of Physics and Chemistry, China
Lionel Duband, Commissariat a l'Engergie Atomique, France
Zhihua Gan, Zhejiang University, China
Carl Kirkconnell, West Coast Solutions, USA-Past Chair ICC15
Franklin Miller, Univ. of Wisconsin, USA
Jeff Raab, NGAS (Retired), USA – Past Chair ICC17
Ron Ross, Jet Propulsion Lab (Retired), USA - Past Chair ICC8
Peter Shirron, NASA GSFC, USA
Julien Tanchon, Absolut System SAS, France
Ryan Taylor, Ball Aerospace, USA
Marcel ter Brake, Univ. of Twente, The Neatherlands

Table of Contents

Welcome

On behalf of the ICC 21 Organizing and Program Committees, we welcome you to the 21th International Cryocooler Conference (ICC 21) being held this year as a Virtual Conference on December 7-10, 2021. The ICC is held every other year and is the preeminent international conference on the development and usage of cryocoolers. It attracts international participants from all continents representing academia, government laboratories, and industry.

At this meeting you will have the opportunity to learn of the latest developments in cryocooler technology and read about these developments from authors from around the world. In lieu of our normal three-day conference of Oral & Poster paper presentations, this year's conference is formatted as a four-day conference featuring four Plenary Talks and four Panel Discussions featuring the four Theme areas of conference.

Day 1 (Dec 7): Aerospace Applications and Stirling & PT Cooler Devel.

Day 2 (Dec 8): Brayton, J-T and Low Temperature Cooler Devel.

Day 3 (Dec 9) PT & Stirling Cooler Components and Modeling

Day 4 (Dec 10) Commercial & Lab Cooler Applications & Integ.Tech.

Author submitted papers will not be presented real time, but instead will be available on the ICC website from December 7 through January 31, 2021 for extended viewing by registered attendees. As with past ICC conferences, authors' submitted manuscripts will be published in our peer reviewed hardcover proceedings *Cryocoolers 21,* which is included in the registration fee of all registered attendees.

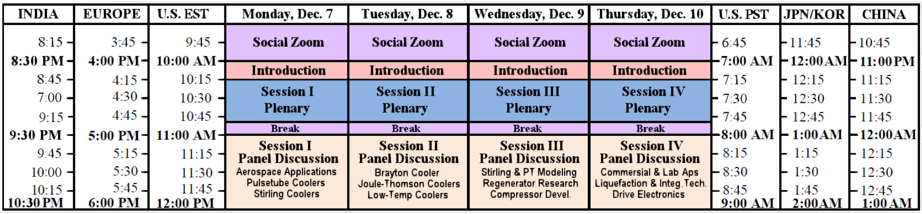
Attendees at ICC 21 include educators and students, particularly those interested in cryogenics and/or thermal management; cryogenic component manufacturers and suppliers; mechanical, electrical, and software engineers engaged in cryocooler design, manufacture and sales; system engineers responsible for selecting and/or integrating cryocoolers; and commercial and government cryocooler users.

We hope you find this new ICC21 Virtual Conference with Plenary talks, Panel Discussions and web-based author presentations, enjoyable, interesting to participate in, and technically valuable. Welcome to our Virtual ICC 21!

Sastry Pamidi, Conference Chair

General Information

As shown in the table below, the ICC21 Conference will consist of four days of meetings, each day about two hours in length, and consisting of a Plenary talk featuring that day's Theme, followed by a panel discussion describing the submitted papers associated with that day's theme. Also included is a 30-minute open-mic session preceding each Plenary for ICC folks to informally socialize via Zoom.



INDIA	EUROPE	U.S. EST	Monday, Dec. 7	Tuesday, Dec. 8	Wednesday, Dec. 9	Thursday, Dec. 10	U.S. PST	JPN/KOR	CHINA
8:15	3:45	9:45	**Social Zoom**	**Social Zoom**	**Social Zoom**	**Social Zoom**	6:45	11:45	10:45
8:30 PM	**4:00 PM**	**10:00 AM**	**Introduction**	**Introduction**	**Introduction**	**Introduction**	**7:00 AM**	**12:00AM**	**11:00PM**
8:45	4:15	10:15	**Session I** **Plenary**	**Session II** **Plenary**	**Session III** **Plenary**	**Session IV** **Plenary**	7:15	12:15	11:15
7:00	4:30	10:30					7:30	12:30	11:30
9:15	4:45	10:45	**Break**	**Break**	**Break**	**Break**	7:45	12:45	11:45
9:30 PM	**5:00 PM**	**11:00 AM**	**Session I** **Panel Discussion** Aerospace Applications Pulsetube Coolers Stirling Coolers	**Session II** **Panel Discussion** Brayton Cooler Joule-Thomson Coolers Low-Temp Coolers	**Session III** **Panel Discussion** Stirling & PT Modeling Regenerator Research Compressor Devel.	**Session IV** **Panel Discussion** Commersial & Lab Aps Liquefaction & Integ.Tech. Drive Electronics	**8:00 AM**	**1:00AM**	**12:00AM**
9:45	5:15	11:15					8:15	1:15	12:15
10:00	5:30	11:30					8:30	1:30	12:30
10:15	5:45	11:45					8:45	1:45	12:45
10:30 PM	**6:00 PM**	**12:00 PM**					**9:00 AM**	**2:00AM**	**1:00 AM**

Individual papers will not be presented in real time, but will instead be posted on the ICC website for viewing by paid attendees during the conference and up through the end of January 2021. The posted papers will consist of prerecorded YouTube-style videos of slides with narration AND a stand-alone PowerPoint slide packages for those wanting to quickly scan through the charts.

Plenary Talks & Panel Discussions

The four Theme areas of the conference include:

Day 1 (Dec 7): Aerospace Applications and Stirling & PT Cooler Devel.

Day 2 (Dec 8): Brayton, J-T and Low Temperature Cooler Devel.

Day 3 (Dec 9) PT & Stirling Cooler Components and Modeling

Day 4 (Dec 10) Commercial & Lab Cooler Applications & Integration Tech.

The Plenary titles and speakers on each day are described on pages 4, 6, 8, and 10 in this book. Each Plenary talk will be followed by a panel discussion involving leading cryocooler researchers in that theme area. Our Conference Program Chair, Carl Kirkconnell, will be moderating the panels. The panelists are described on pages 5, 7, 9, and 11. The goal is for the discussion panelists to highlight author papers of particular note and to discuss important worldwide events and accomplishments in that day's theme area.

Author Submitted Papers

The Program of Author Submitted papers is drawn from abstracts submitted to our Spring-2020 Call-for-Papers **and** 23 new Late News papers covering recent important cryocooler achievements since our Spring-2020 Call. The Table of Contents of Submitted Papers is located on pages 12 to 21 of this book, and is followed by abstracts of each of the Author Submitted papers.

As with past ICC conferences, Formal written manuscripts covering the details of the Author's work will be published in our hardcover proceedings book *Cryocoolers 21*, shipped to paid attendees approximately six months after the conference.

Registration

ICC21 Registration is web-based and became available starting on November 2, 2020; it will be available anytime up through the last day of the conference on December 10. There are two fee structures: a higher one ($200) for regular attendees, and a reduced fee ($100) for students and retirees. All registered ICC21 attendees will be listed on the website with Attendee privileges, meaning they have access to the Zoom Plenary and Panel Discussion presentations, the recorded Author presentations, and the contact information database of fellow attendees...and will receive the *Cryocoolers 21* hardcover Proceedings approximately 6 months after the conference.

Author Instructions

Detailed instructions for Plenary Speakers, Panel Discussion Panelists, and ICC21 Contributed Paper authors are described under the “Authors” tab on the ICC website: https://cryocooler.org/Authors.

December 7, Theme 1 Plenary Presentation

Overview of European Space Cryogenic Missions and Developments in 2020 (and Beyond)

T. Tirolien[1], M. Linder[1], M. Branco[1]

[1]**ESA-ESTEC, Noordwijk, The Netherlands**

After almost 30 years of technological developments spearheaded by innovative institutes and companies and supported by national and international agencies, space cryogenics is now a mature engineering domain, embraced by instruments and payload designers. This state of affair leads to a multiplication of missions in various stages of developments that require cryocooling solutions in various forms and sizes and with a vast array of specificities. It is an exciting time to be involved in space cryogenics.

After a rapid rundown of the major historical European space cryogenic missions, this paper will describe the cryogenic aspects of European missions currently in-orbit, in development or in preparation. The driving requirements will be spelled out as well as the associated baseline and alternative solutions.

Finally, the paper will lay out the current landscape of space cryogenic developments in Europe.

The Speaker

After working a few years in EADS Launch Vehicles (Paris) and CNES (Toulouse), **Thierry Tirolien** was hired in 2009 by the European Space Agency in the Netherlands to tackle thermal and (mainly) cryogenics matters. As the focal points in Cryogenics and Focal Plane Cooling for the Directorate of Technology, Engineering and Quality at ESA-ESTEC, he is in charge of preparing the roadmap on this subject and ensuring the smooth implementation and follow-up of the development activities. Thierry Tirolien also enjoys dealing with Cryocoolers and their side effects in the frame of the various projects that he supports (Meteosat Third Generation, ARIEL, LSTM, CO2M).

December 7, Theme 1

Panel Discussion Panelists

Aerospace Applications and Stirling & PT Cooler Development

Jeff Olson
Principal Research Scientist,
Lockheed Martin ATC,
Palo Alto CA, USA

Elaine Lim
Senior Project Leader
Aerospace Corp.
El Segundo, CA USA

Tonny Benschop
Product Policy Manager
Thales Cryogenics
Eindhoven, Netherlands

Weibo Chen
Thermal/Cryo Sys Engineering
Jet Propulsion Labatory
Pasadena CA, USA

Ingo Ruehlich
Head of Division Cryocoolers
INFRAROT-MODULE GmbH
Stuttgart, Germany

Franklin Miller
Associate Professor
University of Wisconsin-Madison
Madison, WI USA

December 8, Theme 2 Plenary Presentation

Cryogenic Applications and Technology Investments: Enabling a Wide Range of NASA Missions

***Michael Meyer*[1], *Dean Johnson*[2], *Peter Shirron*[3]**

[1]NASA Langley Research Center, Hampton, VA;
[2]NASA Jet Propulsion Laboratory, CIT, Pasadena CA;
[3]NASA Goddard Space Flight Center, Greenbelt, MD

ABSTRACT

The National Aeronautics and Space Administration (NASA) pursues missions that cover a broad spectrum of goals, each with extremely challenging and exciting scientific and engineering requirements. The missions range from research and technology development for future aircraft systems, to scientific exploration of our planet and its near and distant neighbors, to enabling humans to live and explore in space. Over the last several decades, advances in capability and experience with cryogenic refrigeration across the entire cryogenic temperature regime has increasingly become integral to the successful achievement of many of NASA's goals.

The talk begins with an overview highlighting cryogenic requirements, challenges, and successes of several recent or in-development NASA missions involving low temperature systems. As more in-depth examples, the application of cryogenic advancements to the Artemis program for human lunar exploration, the critical need for advances in cryogenic refrigeration for crewed Mars missions, and the potential application of cryogenic systems to future aircraft electric propulsion are described.

In closing, we describe NASA's approach to partnering with industry and academia in research, technology development, and system level demonstration, emphasizing strategic improvements in cryogenic refrigeration capabilities for both near term and more distant future applications.

The Speaker

Mike Meyer is currently NASA's Technical Fellow for Cryogenics where he leads a cross-agency team, augmented by industry, academia, and other government experts, to address high risk technical issues related to cryogenic systems. Mike began his NASA career in 1989 as a research engineer in space propulsion at NASA's Glenn Research Center (GRC). Over the years he has led research efforts on a wide variety of new space propulsion systems involving cryogenic densification of propellants and use of cryogenic propellants for in-space missions. More recently he has served as Branch chief within and Division chief of GRC's In-Space Propulsion Division. He has authored over 50 technical publications, is on CSA's Board of Directors, is an Associate Fellow of AIAA, and has received numerous awards including the NASA Exceptional Leadership Award.

December 8, Theme 2

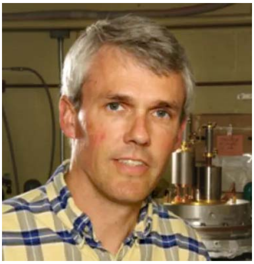
Panel Discussion Panelists

Brayton, J-T and Low Temperature Cooler Development

Mark Zagarola
Principal Engineer
Creare, LLC
Hanover, NH USA

David Glaister
Senior Manager
Ball Aerospace
Boulder, CO USA

Steffen Grohman
Head Refrig. and Cryogenics
Karlsruhe Inst. of Technology
Karlsruhe, Germany



Peter Shirron
Senior Research Scientist
NASA Goddard Space Flight Center
Greenbelt, MD USA

Sangkwon Jeong
Professor of Mech. Engineering
Korea Adv.Inst.of Science and Tech.
Daejeon, South Korea

Vince Kotsubo
Cryogenics
NIST
Boulder, CO USA

December 9, Theme 3 Plenary Presentation

Development of a Stirling-Type Pulse Tube Cooler – a Personal Experience

Prof. Wei Dai

Technical Institute of Physics and Chemistry
Chinese Academy of Sciences, Beijing, China

Ever since the invention of the orifice type pulse tube cooler in the 1980s, the technology has undergone rapid development and several key innovations have taken its performance up to a level comparable to the Stirling cryocooler or GM cryocooler. As more applications have seen the use of pulse tube coolers since the early 2000s, the innovation potential now seems to have come to a plateau. This paper generalizes some advances of our group in the past decade. On the one hand, a retrospective view of the fundamental thermodynamics and impedance match mechanism may help to deepen our understanding of the related physics. Typical examples are the impedance match between the linear compressor and the cold head and the pulse tube cooler with an ambient rod-less displacer. On the other hand, research on how to make the system more compact and how to reduce the manufacturing cost, which is strongly related to the practical applications, is also an important part of this paper. Two examples that will be presented are the annular pulse tube and the pulse tube without a flow straightener. Hopefully, this paper and aroused discussions may provide some clues to the further improvement of pulse tube cooler.

The Speaker

Wei Dai received his Ph.D. from Shanghai Jiaotong University in 2000. Since 2010, he has been working as a full-time professor in Technical Institute of Physics and Chemistry of Chinese Academy of Sciences in Beijing. With more than 40 published international journal papers, his current research interests mainly include pulse tube cryocoolers, magnetic refrigeration for both room temperature and sub-Kelvin temperature and heat transfer technologies.

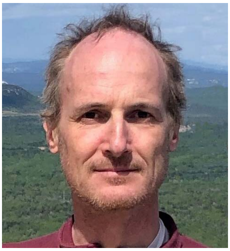
December 9, Theme 3

Panel Discussion Panelists

Pulse Tube and Stirling Cryocooler Components and Modeling

Dr. Mostafa Ghiaasiaan
Professor of Heat Transfer, Combustion and Energy Systems, Georgia Tech. University
Atlanta, GA USA

Julien Tanchon
R&D Manager
Absolut System
Seyssinet-Pariset, France



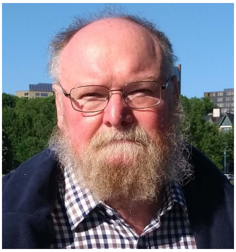
Jean-Marc Duval
Head of laboratory
CEA / DSBT
Grenoble, France

Jeff Cha
Thermal/Cryo Sys Engineering
Jet Propulsion Laboratory
Pasadena, CA USA

Dr. Ray Radebaugh
Principal Cryogenics, Retired
NIST
Boulder, CO USA

Ian McKinley
Thermal /Cro Engineering
Jet Propulsion Labatory
Pasadena CA, USA

Ladan Amouzegar
Thermal/Cryocooler Engineer
Northrop Grumman AS
Redondo Beach, CA USA



Paul Bailey
Cryogenic Engineering Group
University of Oxford
Oxford, UK

December 10, Theme 4 Plenary Presentation

Actualizing the Abstract - How the Cryo Industry Takes Ideas and Provides Proven Technology for Diverse Applications

Parminder Banga, Xihuan Hao, Timothy Hanrahan
Cryomech, Inc., Syracuse, New York

Over the past 55 years, Cryomech has been a leading supplier of low-temperature cryogenic solutions for Industrial and Laboratory applications. Many of these solutions begin with just a paper concept to fulfill the needs of a diverse application challenge. Involvement in this industry has provided us a unique window into some of the world's most cutting-edge cryogenic applications. In this talk we explore three of these diverse and scientifically challenging applications of cryogenic cooling. In particular we will delve into applications in fusion energy, black hole imaging, and superconducting squid technology. Specific examples in each of these areas will describe both the application and the cryogenic technology we developed to support the application.

The Speakers

Parminder Banga is the Engineering Manager at Cryomech. After graduating from University at Buffalo in 2007, Parminder joined Cryomech and over the past 12 years has led a number Engineering and Operations teams with primary focus on product realization, new product integration and product qualification.

Dr. Xihuan Hao is a Cryogenic Research & Development Engineer at Cryomech, holds a Ph.D. in Cryogenic Engineering, and has over a decade of experience working in the US cryogenic industry. He has expertise in developing 4K and 10K cryocoolers, helium compressors, cryopumps and compact helium liquefiers. Xihuan has authored over 30 peer reviewed scholarly papers, holds four patents and has won numerous honors and awards including the George T. Mulholland Memorial Award for Excellence in Cryogenic Engineering, awarded by Cryogenic Society of America (CSA) in 2015.

Tim Hanrahan joined the Research and Development team at Cryomech in 2016 after graduating from Syracuse University. His focus has been in new and custom product development for a variety of applications. Tim has worked on an array of new cryogenic products including cryocoolers, cryostats, and cold helium circulation systems, with a primary emphasis on thermal analysis, new product testing and system qualification.

December 10, Theme 4

Panel Discussion Panelists

Commercial & Lab Cooler Applications and Integration Technology

Ted Conrad
Sr. Principal Cryocooler Engineer
FLIR Systems
Santa Barbara, California

Sonny Yi
Thermal Engineer
Raytheon
El Segundo, CA USA

Wolfgang Stauter
Principal Engineer Cryogenics
GE Global Research
Schenectady, NY USA

Ravi Bains
President and CEO
Advanced Research Systems, Inc.
Macungie, PA USA

Chul Kim
Research Faculty II
Florida State Univiersity
Tallahassee, FL USA

Robert Hon
Senior Systems Engineer
West Coast Solutions
Huntington Beach, CA USA

Monica Guzik
Senior Project Leader
NASA Glen Research Center.
Cleveland, OH USA

ICC21 Contributed Paper Organization

As shown below, the ICC21 Contributed Papers are organized into 13 subtopic areas on the ICC website. These are grouped under the four ICC21 Theme areas for easy scanning by interested attendees

Aerospace Applications and Stirling & PT Cooler Devel.

1. Aerospace Applications
2. PT Cooler Development & Testing
3. Stirling Cooler Development & Testing

Brayton, J-T and Low Temperature Cooler Development

4. Brayton Cooler Development
5. J-T/Sorption Cryocooler Development
6. Low-Temp Cryocooler Development

PT & Stirling Cooler Components and Modeling

7. PT & Stirling Cryocooler Performance Modeling
8. Phase Shifting and Displacer Research
9. Regenerator Research
10. Linear Compressor Development

Commercial & Lab Cooler Applications & Integ. Technology

11. Commercial and Laboratory Applications
12. Cryocooler Integration Technologies
13. Cryocooler Drive Electronic

ICC21 Contributed Paper Table of Contents

1 Aerospace Applications

2 Pulse Tube Cooler Development & Testing

2.5 Design of a 600g Micro Pulse Tube Cryocooler
T. Feng, Y. Xun, H. Chen, Q. Tang, M. Liang, J. Liang, Chinese Academy of Science (CAS), Beiging, China

2.6 A Lightweight 7W/80K Pulse Tube Cryocooler
N. Wang, M. Zhao, H. Chen, J. Liang, J. Cai, Q. Zhu, M. Zheng, Tech. Inst. of Physics and Chemistry, CAS, China

2.7 A 4 K Gas-Coupled Two-Stage High-Frequency Pulse Tube Cryocooler
X.M. Liu, L.B. Chen, J.J. Wang, Y. Zhou, Chinese Academy of Sciences, Beijing, China

2.8 24K Single-Stage Coaxial PulseTube Cryocooler without Double-Inlet Phase Shifter
N. Wang, M. Zhao, H. Chen, L. Wei, J. Liang, J. Cai, Key Lab of Tech. on Space Energy Conv., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

2.9 Large Pulse Tube Cooler with a Heat Interceptor
M.B.C. Branco, C. Buti, L. Desjonqueres, T. Tirolien, M. Linder, European Space Research & Technology Center, The Netherlands

3 Stirling Cooler Development & Testing

3.2 Cost Effective Split and Integral Linear Stirling-Type Cryocoolers for HOT IR Imaging
A. Veprik, S. Zehctzer, A. Daniels, R. Refaeli and A.Wise, CryoTech Ltd, Israel

3.3 Design and Performance Test of Miniature Linear Stirling Cryocoolers
X. Wang, W. Dai, E. Luo, Key Laboratory of Cryogenics of Chinese Academy of Sciences, China; and L. Yang, Y. Zhang, H. Li, Lihan Cryogenics, China

3.4 High-Availability Stirling Coolers
D. Willems, T. Benschop, R. Arts, B. de Veer, and P. Bollens, Thales Cryogenics BV, Eindhoven, The Netherlands

3.5 The Study on High Efficiency and Low Vibration Flexure Bearing Stirling Cryocooler
C. L. Yin, Y. Gao, H. Yan, F. Wang, Q. Hong, X. H. Fan, Z. Wang, Inst. of Cryogenics and Electronics, Hefei, China

3.6 A kW-class Free-Piston Stirling Cooling Prototype for Ultra-Low Temperature Freezing
K.Q. Luo, Y.L. Sun, Z.J. Jiang, E.C. Luo, J.Y. Hu, L.M. Zhang, Z.H. Wu, Z.L. Jia, Y. Zhou, Chinese Academy of Sciences, Beijing, China

3.7 Development of Integral Rotary and Split Linear Stirling Cryocoolers for SWaP Applications
A. Osterman, K. Dovrtel, F. Megusar, Le-tehnika, Kranj, Slovenia

4 Brayton Cooler Development

5 J-T Cryocooler Development

5.7 Experimental Validation of a Numerical Model for Nitrogen-Activated Carbon Sorption Compressor Cells
N. Tzabar, A. Davidesko and A. Hamersztein, Thermal Energy Science & Tech. Laboratory, Ariel Univ., Ariel, Israel

5.8 Development of Thin-Plate Square-Shape Sorption Compressor for 5 K J-T Cooler
J. Bae, D. Kwon, S. Jeong, Korea Adv. Inst. of Science and Tech. (KAIST), Daejeon, Korea

5.9 Development of a Capillary Tube Orifice for Expansion Device of Joule-Thomson Cryocooler
J. Kim, H. Lim, S. Han, Korea Aerospace Research Inst., Korea

5.10 Numerical and Experimental Investigation of Miniature Cryocooler Constructed in LTCC Technology
B. Baran, M. Chorowski, K. Malecha, Z. Malecha, W. Nawrot and Z. Rogala, Wroc³aw Univ. of Science and Tech., Wroclaw, Poland

5.12 Research on the Influence of Linear Compressors on Space Hybrid 4K J-T Cooler
Y. Ma, Z. Liu, J. Quan, J. Wang, Y. Liu, J. Li and J. Liang, Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

5.13 Heat Transfer Analyses and Experimental Study of a Gas-Gap Heat Switch for a Sorption Cooler
Y.L. Lei, Y.N. Zhao, J. Quan, G.T. Hong, Key Lab of Tech. on Space Energy Conv., CAS, Beijing, China

5.14 Research on Counter-Flow Heat Exchangers of Space 2.5K Hybrid Joule-Thomson Cryocooler
Z.Y. Liu, Y.X. Ma, J. Quan, Y.J. Liu, J. Wang, J.G. Li, J.T. Liang, Key Lab of Space Energy Conv. Tech., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

515 Experimental and Numerical Study of Heat Transfer Characteristics of an Oil-Free Valved Linear Compressor for J-T Throttle Refrigerator
J. Sun, J. Lib, Y. Ma, Z. Huang, Y. Liu and J. Cai, Univ.of CAS, Beijing, China and Key Lab of Tech. on Space Energy Conv., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

5.16 Study on Piston Offset and Efficiency of Linear Compressor for Large Refrigerating Capacity J-T Throttle Refrigerator
J. Sun, J. Li, Y. Ma, Z. Huang. Y. Liu. J. Cai, Univ. of CAS, Beijing, China and Key Lab. of Tech. on Space Energy Conv., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

6 Low-Temp Cryocooler Development

6.1 Magnet Hysteresis Loss in Adiabatic Demagnetization Refrigerators
P. Shirron, M. Kimball, R. Ottens, J.Tuttle, and A. Jahromi, NASA/Goddard Space Flight Center, Greenbelt, MD

6.2 Numerical Analysis for a Continuously Operating Adiabatic Demagnetization Refrigerator (ADR) between 4.2 K and 2.0 K
D. Kwon, J. Bae, S. Jeong Cryogenic Engin. Laboratory, Korea Adv. Inst. of Science and Tech., Daejeon, Korea

6.3 The Development of an Active Magnetic Regenerative Refrigerator (AMRR) for sub-Kelvin Cooling of Space Science Instrumentation
C.M. Gunderson, G.F. Nellis, F.K. Miller, Univ. of Wisconsin - Madison, Madison, WI

6.4 Adiabatic Expansion of ^{3}He in Superfluid t He
A.T.A.M. de Waele, Eindhoven Univ. of Tech., Eindhoven, The Netherlands

6.5 Thermodynamic Process and Analysis of Dilution Refrigerator
M. Zheng, J. Liang, P. Lin , L. Wei and M. Zhao , Chinese Acadamy of Science, Beijing, China

6.6 The Latest Developments in Low Cost, Low-Power Cooling to below 1 Kelvin
P. McInnes, L.C. Kenny and S.T. Chase, Chase Research Cryogenics Ltd, Sheffield, UK

6.7 Calculation Analysis and Preparation Optimization of Silver Powder Sintered Heat Exchangers at Extremely Low Temperature
Z.J. Pan, L.J. Wei, M.W. Zheng, M.G. Zhao, L.J. Liang, Key Lab of Space Energy Conv. Tech., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

7 Pulse Tube & Stirling Cryocooler Modeling

7.1 CFD Simulation of a Hybrid Cryocooler with Pulse Tube Precooling
S. Yang; W. Yang; C. Wang; D. Qin, Univ. of Chinese Academy of Sciences, Beijing, China

7.2 Effect of Aftercooler Configuration on the Performance of Pulse Tube Cryocoolers
Y. Yasukawa, Fuji Electric Co., Tokyo, Japan; and Y. Ueda, Tokyo Univ. of Agriculture and Tech., Tokyo, Japan

7.3 Design of High Capacity Pulse Tube Cooler with C-Type Flexure for High Temperature Super Conductor Applications
M. Sudheer, B.T. Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

7.4 Reverse Application of a Coaxial Free Piston Stirling Engine for Space Applications
P.S. Adithian, B.T.Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

7.5 Thermodynamic Analysis and Design of Miniature BLDCM Driven Crank Driven Cooler
K. Santhosh, B.T. Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

7.6 Advances in a Resonance Tube-Coupled Duplex Stirling Cooler
G.Y. Yu, H.Y. Ma, Y. Ma, W. Dai and E.C. Luo, TIPC, CAS, China; X.W. Li, CSDDC, China

7.7 Research of a High Capacity Coaxial Pulse Tube Cryocooler Working at 170 K
L.J. Wei, N.L. Wang, M.G. Zhao, J.H. Cai, L.T. Liang, Technical Institute of Physics and Chemistry, CAS, Beijing China

7.8 Study of the Effect of Gas Contamination in Stirling Cryocoolers
C. L. Yin, Y. Gao, K. Yang, Z .Wang, X. H. Fan, S .S .Chen, Inst. of Cryogenics and Electronics, Hefei, China

7.9 Lumped Element Thermoacoustics Applied to Pulse Tube Cryocoolers
V. Kotsubo, NIST, Boulder, CO

7.10 Thermal Losses in a Coaxial Pulse Tube Cryocooler
H. Rana, M. A. Abolghasemi, R. Stone, M. Dadd, P. Bailey ,Univ. of Oxford, UK

7.11 Boundary Layer Losses in a Miniaturized Tapered Pulse Tube
A. Ghavami, S.M. Ghiaasiaan, Georgia Tech, Atlanta, GA; C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

8 Phase Shifter and Displacer Research

8.1 External Phase Shifting Tuning Mechanism in a Miniature Pulse Tube Cryocooler Using a Semi-Active Electromagnetic Damping System
Y. Greenberg, G. Grossman, Technion – Israel Inst. of Tech., Israel

8.2 An Exploration about a Micro-Cryocooler with Warm-Displacer Phase Shifter
Z.M. Guo, Tongji Univ., Shanghai, China and Univ.of Wisconsin-Madison, WI, USA; J.M. Pfotenhauer, Univ. of Wisconsin-Madison, WI, USA; S.W. Zhu, Tongji Univ., Shanghai, China

8.3 Detailed Analysis of a Coaxial Stirling Pulse Tube Cryocooler with an Active Displacer
M.A. Abolghasemi, H. Rana, R. Stone, M. Dadd, P. Bailey, Dept. of Engin. Science, Univ, of Oxford, Oxford, UK; K. Liang, Dept. of Engin. and Design, Univ. of Sussex, Brighton, UK

8.4 A Passive Displacer for a Stirling Pulse Tube Cryocooler
H. Rana, M.A. Abolghasemi, R. Stone, M. Dadd, P. Bailey, Dept. of Engin. Science, Univ. of Oxford, UK

8.5 Optimization of Phase Controller for Pulse Tube Cryocooler
D. Abraham and B.T Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

8.6 Development of Stirling Cryocooler Model that Includes a Full Simulation of the Appendix Gap
T. Rawlings, M. Crook, M. Hills, STFC Rutherford Appleton Laboratory, Harwell, Oxford , UK

8.7 Application of Signal Analysis in the Study of Dynamic Characteristics of Displacer in Cryocoolers
Z. Wang, Y.D. Lu, C.L. Yin, Y. Gao, The Provincial Key Laboratory of Cryogenic Technology, Hefei, China

9 Regenerator Research

9.1 A Temperature Instability in 4 K Cryocooler Regenerators Caused by Real Fluid Properties
R. Snodgrass, V. Kotsubo, J. Ullom, and S. Backhaus, NIST, Boulder, CO

9.2 Leveraging Real Fluid Effects as a Tool for Power Flow Measurements in 4K Cryocooler Regenerators
R. Snodgrass, V. Kotsubo, J. Ullom, and S. Backhaus, National Institute of Standards and Technology, Boulder, CO

9.3 Theoretical and Experimental Investigations on the HoCu2 and GOS as Regenerative Materials at 4-20K
R. Cao, X. Zhi, C. Huang and L. Qiu, Inst. of Refrig. and Cryogenics, Zhejiang University, Hangzhou, China

9.4 Effects of Structural Asymmetry on Regenerator Temperature Non-Uniformity in a High-Power Stirling-Type Pulse Tube Cryocooler
T. Wei, X. Tao, X. Zhi, X. You, J. Wang, L. Qiu, Inst. of Refrig. and Cryogenics, Zhejiang Univ., Hangzhou, China

9.5 Optimization of the Transition Regenerator for Two-Stage Thermal-Coupled Stirling-Type Pulse Tube Cryocooler
Q.L Zhu, Y.J Liu, J.Quan, J.T Liang, Key Laboratory of Space Energy Conv. Tech., Tech. Inst. of Physics and Chem., CAS, Beijing, China

9.7 Cold Head Maintenance of GM Cryocoolers with Minimal Service Interruption
R. Verma, Nat'l Inst.of Tech., Jalandhar, India; H.N. Nagendra, G.A. Vivek, S. Kasthurirengan, U. Behera, Centre for Cryogenic Tech., Indian Inst. of Science, Bangalore, India; N.C. Shivaprakash, Instr.& Applied Physics, Indian Inst. of Science, Bangalore, India

9.8 Measurement of Thermal Conductivity of Some Candidate Regenerator Materials at Cryogenic Temperatures
A. Ghavami, S. M. Ghiaasiaan, Georgia Tech, Atlanta, GA; C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

9.9 Development of a 2D/3D Computational Fluid Dynamic Code for Analyzing Regenerators
A. Ghavami, S.M. Ghiaasiaan, Georgia Tech, Atlanta, GA; C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

10 Linear Compressor Development

10.1 Moving Iron Based Pressure Wave Generators: Preparing Air Liquide's New Generation Pulse Tube Cryocoolers
G. Coleiro, P. Barbier, J-M Niot, T. Wiertz, Air Liquide Adv. Tech., Sassenage, France; G. Aigouy, K. Benoit, F. Claeyssen, CEDRAT Tech., Meylan, France; and C. Daniel, CNES, Toulouse, France

10.2 Design of Oil-Free, Resonating Linear Compressors for Five-Stage Cascade System with New Refrigerants
A. Vidhate , B. T. Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

10.3 High Frequency Steel Flexure Acoustic to Electric Transducer for Cryocoolers
T.W. Steiner, Etalim Inc., Vancouver BC, Canada

10.4 Enhancement of Linear Compressor Power and Performance Improvement of Pulse Tube Refrigerator
B. Kim, J. Bae, S. Jeong, Korea Adv. Inst. of Science and Tech. (KAIST), Daejeon, Korea

10.5 Design of Resonating, Linear Compressors for Five-Stage Cascade System with New Refrigerants
V.A. Santosh, B.T. Kuzhiveli, Centre of Adv. Studies in Cryogenics, Nat'l Inst. of Tech., Calicut, India

11 Commercial and Laboratory Applications

11.1 Configuration of Cryocoolers in Large Electric Power Systems for Superconducting Electrified Transportation Applications for Enhanced Resilience
S. Telikapalli, P. Cheetham, C.H. Kim, S. Pamidi, Florida State Univ., Tallahassee, FL

11.2 Performance Analysis of Pulse Tube/3He Joule-Thomson Cryocooler for Thermometer Calibration
T. Shimazaki, NMIJ, AIST, Tsukuba, Japan

11.3 Cryocooler Technology for Electron Particle Accelerators
G. Lawler, N. Majernik, A. Fukasawa, J. Rosenzweig, UCLA, Los Angeles, CA

11.4 Storage Time and Venting Characteristics for Cryogenic Air Supplies after Turning Off Their Cryocoolers
L. Yan, R. Fernando, D.S. Yantek, J.L. Carr, M.A. Reyes, C.R. DeGennaro, J.A. Yonkey, J.R. Srednicki, CDC/NIOSH, Pittsburgh, PA

11.5 Closed Cycle Cryocooler Simplifies the Cryogenic Logistics Workflow
D. Dutta, Bhabha Atomic Res. Centre, Dept. of Atomic Energy, GOI, India

11.6 Closed Cycle Cryocoolers in Low Temperature Silicon Analysis
D. Dutta, Bhabha Atomic Research Centre, Dept. of Atomic Energy, India

11.7 Development and Validation of a Small-Scale Hydrogen Liquefier Using a Modified Linde-Hampton Cycle
S.Y.Kim and J. Lee, Hylium Industries, Korea; S.W. Park, Korean Inst. of Science and Tech., Korea

11.8 The Modified Linde-Hampson Cycles with GM-JT Refrigeration for Small-Scale Hydrogen Liquefaction Processes
J. Park, S.W. Karng, Korea Inst. of Sci. and Tech., Seoul, Korea; H. Lim, G.W. Kim, G.H. Rhee, Univ. of Seoul, Seoul, Korea; S.Y. Kim, Hylium Industries, Seongnam, Korea

12 Cryocooler Integration Technologies

13 Cryocooler Drive Electronics

Aerospace Applications, Paper No. 1.1

Thermal Design of the Earth Surface Mineral Dust Source Investigation (EMIT)

J.S. Cha, D.L. Johnson, and L.D. Fonseca. Jet Propulsion Laboratory, Pasadena, CA; O. Deng, D.G. Gilmore, The Aerospace Corp., El Segundo, CA

The Earth Surface Mineral Dust Source Investigation (EMIT) instrument, designed and built by the NASA Jet Propulsion Laboratory, will map the surface mineralogy of arid source regions in the visible and short-wave infrared (VSWIR) from the International Space Station. EMIT requires a long-life mechanical cooler that provides cooling at 150K and a heat rejection system (HRS) that can effectively absorb, transfer, and reject instrument waste heat to space. The Thermal Control System (TCS) consists of a combination of active and passive components to maintain components within the allowable flight temperature (AFT) limits. The active components include a mechanical cryocooler and variable conductance heat pipes. The focal plane detector and spectrometer are cooled to 155K and 235K, respectively, by a single-stage pulse tube cryocooler. High performance Pyrolytic Graphite Sheet (PGS) thermal links are used to transport operational and parasitic heat loads from the FPA and spectrometer to the cooler cold tip. The HRS absorbs, transfers, and rejects cryocooler and avionics waste heat to Space from ELC 1 FRAM 8 via two radiators. The passive TCS include multi-layer and single layer insulation, flexible thermal links, and coatings. This paper provides an overview of the EMIT instrument TCS architecture, cryocooler and instrument/ISS thermal requirements and key design drivers, and top-level thermal design and analysis approach.

Aerospace Applications, Paper No. 1.2

Enabling Ambitious Space Science Missions Thanks to 10K-20K Cryocooling

S. Carpentier, P.Barbier and J. Butterworth, Air Liquide Adv. Tech., Sassenage, France; S. Martin, I. Charles, J.M. Duval, Univ. Grenoble Alpes, Grenoble, France; F.Fontani, W.Errico, Sitael S.P.A., Pisa , Italy; J. Mullié , G. de Jonge, Thales Cryogenics, Eindhoven, The Netherlands, M. Branco, M. Linder, ESA-ESTEC, Noordwijk, The Netherlands

In the past years, Air Liquide Advanced Technologies has developed a HiPTC, standing for Heat intercepted Pulse Tube Cooler, for space science missions. This cooler includes a compressor designed and built by Thales Cryogenics b.v., a dual stage cold finger developed with CEA and an electronics developed by SITAEL. This work has funded by the European Space Agency (ESA). Tests performed on one engineering model showed that the cooler reached 6.9K zero load temperature. This makes it suitable for a large number of science missions requiring cooling in the 10K-20K temperature range. This is the case for ATHENA mission, for which the cryocooler is developed and purposed to supply thermal shielding around 80K-100K, and pre-cooling at 15K for lower temperature coolers aimed at detector cooling. Recent activities on this cooler include: • Development of a TRL 6 engineering model • Study and testing of several cooler architectures, passive phase shifting or active phase shifting at the low temperature stage • Improvement of overall efficiency • Development of a new driving electronics with damping of µvibration • Preliminary studies for integration of the cooler on several space science missions projects The results show the availability of a compact, efficient and low vibration cryocooler for space science applications. The power consumption of the cooler is less than 500W including electronics. Total cooler mass is around 36 kg including drive electronics and the cooler fits in a reduced volume. Recently, ALAT has been awarded of a new ESA contract centered on the overall cooler system also including the development of Cryocooler Control Electronic realized by SITAEL. This project aims to increase the maturity of the cooler to reach Technological Readiness Level 6 at Cooler Mechanical Assembly level and be able to go to lifetime test in support to a future qualification program.

Aerospace Applications, Paper No. 1.3

Integration of a Tactical Cryocooler for 6U Hyperspectral Thermal Imager

C.S. Kirkconnell, West Coast Solutions; M.A. Nunes, Hawaii Space Flight Laboratory, HA; I. Ruehlich, AIM Infrarot-Module, Germany; H R. Papinsack, American Infrared Solutions; M.V. Zagarola, Creare, Hanover, NH; S.B. Rafol, JPL, Pasadena, CA

All of the usual considerations for spacecraft cryocooler integration, including radiation harness, exported vibration, electromagnetic interference (EMI), and heat rejection, become increasingly challenging as the size of the spacecraft decreases. Small satellites (smallsats) invariably have low power budgets due to the limited volume available for solar panels and batteries, so the thermodynamic efficiency of the cryogenic system (thermomechanical unit and cryocooler electronics) becomes a critical consideration in every design trade. Of course packaging volume, and to a lesser extent mass, is a major driver, particularly down in the CubeSat range of smalllsats. This paper describes how these challenges are being addressed on an ongoing University of Hawaii-JPL led program called the Hyperspectral Thermal Imager (HyTI), which is a 6U hyperspectral spacecraft slated for launch in 2021 to perform a variety of environmental science missions. The HyTI Cryocooler System consists of an AIM SF-070 Cryocooler and a Creare Microcryocooler Control Electronics (MCCE). The selection of this approach and how it is meeting the wide range of integration challenges is discussed.

Aerospace Applications, Paper No. 1.4

Study for Continuity of Cooling Operation of SPICA Cryogenic System by Adding Refrigerant Circulation System

K. Narasaki, Sumitomo Heavy Industries, Ltd., Niihama, Ehime, Japan

SPICA (Space Infrared Telescope for Cosmology and Astrophysics) is a pre-project mission of JAXA to launch a large infrared observatory to the second Sun-Earth Lagrangian liberation point (L2) in the 2020s. A unique feature of SPICA cryogenic system is a warm launch system using radiative cooling and a large number of mechanical coolers in orbit to cool 2.5m telescope below 8K and its detectors in sub kelvin. SPICA uses two sets of 1K Joule-Thomson (1K-JT) coolers and two sets of 4K Joule-Thomson (4K-JT) coolers with three sets of double-stage Stirling (2ST) coolers used as pre-coolers respectively for redundancy and reliability. Additionally, two 2ST coolers are used to cool the telescope shield. The pre-coolers for 1K-JT cooler should be separated from 4K-JT cooler because of the influence of the pre-cooler's failure as well as a required pre-cooling temperature for 1K-JT cooler lower than that for 4K-JT cooler.

Aerospace, Paper No. 1.5

Lifetime Verification and Applications of the 1K-Class Joule Thomson Cooler for Space Science Missions

K. Shinozaki, JAXA/ISAS; Y. Sato, K.Tanaka and H. Sugita, JAXA/R&D; N.Y. Yamasaki and T. Nakagawa, JAXA/ISAS; K. Mitsuda, NAOJ; S. Tsunematsu, K.Ootsuka, K. Kanao and K.Narasaki, SHI, Japan

Space-qualified Joule Thomson coolers with significant cooling below 2K enable a variety of missions ranging from large infrared space telescopes, superconducting detectors for astrophysics and quantum applications. In JAXA, a 1K-class Joule-Thomson cryocooler (1K-JT) has been developed with the specified cooling power of 10mW at 1.7K for application to upcoming next-generation astronomy missions. The lifetime test is one of the most critical items to be verified, while the mechanical tests, the thermal vacuum environmental tests, the electromagnetic noise and mechanical disturbance measurements were completed with the engineering models prior to the lifetime test. This paper provides current status of the lifetime verification result with the engineering model. The lifetime test was started on May 2015, and recently achieved 4 years continuous operation without any critical degradations. The recent research, 1K-JT applications including the cooler system demonstration for the ESA X-ray mission Athena, and the cooling performance test with straight heat exchanger for the space infrared telescope mission SPICA are also presented.

PT Cooler Devel. & Testing, Paper No. 2.1

Characterization Testing of Space-Flight Lockheed Martin Micro1-2 Cryocooler for the Mapping Imaging Spectrometer for Europa (MISE)

I.M. McKinley, D.L. Johnson, J.I. Rodriguez, Jet Propulsion Laboratory, Pasadena, CA

The Mapping Imaging Spectrometer for Europa (MISE) instrument on the Europa Clipper mission uses a Lockheed Martin “high power” Micro1-2 pulse tube cryocooler with a heat rejection temperature around 220 K. This paper describes the acceptance testing and performance testing and results of the space-flight Lockheed Martin Micro1-2 cooler optimized for these conditions. The cooler passed random vibration and thermal vacuum cycling acceptance testing. The thermal performance was measured in vacuum during thermal cycle testing for heat reject temperatures between 190 K and 290 K. The cooler was driven with input powers up to 40 W and drive frequency between 125 Hz and 150 Hz. In addition, the exported forces and torques of the space-flight cooler were measured and are reported.

PT Cooler Devel. & Testing, Paper No. 2.2

Qualification of Northrop Grumman MiniCoolerPlus Thermal Mechanical Unit for a Space-Flight Mission

L. Amouzegar, M. Petach, and L. Abelson, Northrop Grumman AS, Redondo Beach, CA

Northrop Grumman Space Systems (NGSS) recently introduced their new class of pulse tube cryocooler, the Mini Cooler Plus (MCP) [1]. This thermal mechanical unit (TMU) is an extension of our space qualified pulse tube coolers and is designed to provide a long-life (over ten years), low-mass, high cooling capacity for hyperspectral and infrared imaging payloads in tactical airborne and space applications. The cooler is of modular split configuration allowing flexibility in the compressor and cold head placements to meet the available envelope. The cold head assembly can be oriented at any position relative to the compressor assembly and the transfer line (length and shape) can be customized to individual applications. The system weighs less than 3kg and can lift 1.5 W at 46 K with 150 W electrical input at 300 K reject. This paper reports on qualification testing of the MCP to a technology readiness level (TRL) of 8 for a planned upcoming spaceflight mission and presents the test data obtained in its flight configuration over a range of input powers and reject temperatures. The cooler was subjected to launch vibration and thermal cycling conditions for the range of operating and standby conditions appropriate to its space application. The measured load lines and unchanged refrigeration performance of the cooler throughout the qualification program demonstrated the readiness of the design for flight.

PT Cooler Devel. & Testing, Paper No. 2.3

LPT6510 Test Results up to TRL6

E. Jansen, R. Arts, J. Mullié, Thales Cryogenics B.V., The Netherlands; J. Tanchon, T. Trollier, Absolut System SAS

The LPT6510 is a compact integral pulse-tube cryocooler for 50-120K applications, with a design derived from the Thales Cryogenics MPTC compressor developed under ESA TRP and the Absolut System SSC80 pulse-tube. In this presentation, the results of the test campaign on a flight-representative Engineering Model will be presented, demonstrating Technology Readiness Level 6 for the product. Detailed cryogenic performance results will be shown over the entire operational envelope, the environmental test campaign will be highlighted, and specific aspects such as off-state parasitic losses and induced vibrations will be discussed. The planned life time test campaign will be presented, as well as the parallel space cooler drive electronics developed in partnership with STEEL Electronique.

PT Cooler Devel. & Testing, Paper No. 2.4

AIM Cryocoolers for Harsh Environments

M. Nussberger, I. Rühlich, M. Mai, C. Rosenhagen,
T. Wiedmann and S. Zehner, AIM Infrarot-Module, Germany

State-of-the-art high performance IR-sensors still require cooling by means of cryocoolers to achieve their electro-optical performance. In many applications such as guided missiles, rifle and gunner sights, fighter aircrafts, helicopters or launch vibrations for space applications, the system including cryocooler has to withstand Harsh Environments. Depending on requirements like heat load, operating temperature, size weight and power constraints (SWaP) as well as exported vibrations different types and sizes of coolers are used. Several aspects of compressor and coldfinger design like moving magnet driving mechanism, flexure bearing design, transferline or stiffness of coldfinger/dewar will be discussed. Design features to meet such requirements will be presented for different single and dual piston linear compressors. This includes compact single piston cryocoolers for high operating temperature (HOT), low SWaP coolers like SX020 and long life flexure bearing coolers like SF400 pulse tube cryocoolers for space applications. Specific modifications, vibration profiles and testing results will be discussed.

PT Cooler Devel. & Testing, Paper No. 2.5

Design of a 600g Micro Pulse Tube Cryocooler

T. Feng, Y. Xun, H. Chen, Q. Tang, M. Liang, J. Liang, Chinese Academy of Science (CAS), Beiging, China

A new coaxial micro pulse tube cryocooler has been designed for infrared detector, which has the characteristics of low vibration, long life, and high reliability. Due to the optimization of linear compressor volume and the coupling with a 10mm cold finger, it has a compact structure and 120Hz optimal frequency. The entire system weight is 600 grams, including the 380 gram compressor. The pulse tube cryocooler has achieved a minimum temperature of 51K, and a cooling capacity of 1.2W at 80K with an input power of 45W. It takes less than 3 minutes to cool down from 300K to 80K with payload. This paper describes the components and presents test data of this pulse tube cryocooler.

PT Cooler Devel. & Testing, Paper No. 2.6

A Lightweight 7W/80K Pulse Tube Cryocooler

N. Wang, M. Zhao, H. Chen, J. Liang, J. Cai, Q. Zhu, M. Zheng, Tech. Inst. of Physics and Chemistry, CAS, China

For the demands of higher cooling power, lower mass and higher efficiency of the pulse tube cryocooler (PTC) used in space, a lightweight single-stage coaxial 7W/80K PTC was successfully developed by the Key Laboratory of Space Energy Conversion Technologies, CAS. In this paper, the details of the cooling performance are presented at different input powers ranging from 65W to 150W. Experimental results shows that this PTC typical provides a cooling power over 7W at 80K with an electric power of 150W. By means of increase operating frequency, the weight of PTC was decreased a lot. At present, the optimal frequency is 78Hz, the mass of compressor is about 2.0kg, the mass of cold-finger and phase-shifter is 1.2kg. Therefore, the total PTC is only 3.2kg in weight. The specific mass (cooling capacity/mass) is up to 2.2W/kg.

PT Cooler Devel. & Testing, Paper No. 2.7

A 4 K Gas-Coupled Two-Stage High-Frequency Pulse Tube Cryocooler

X.M. Liu, L.B. Chen, J.J. Wang, Y. Zhou, Chinese Academy of Sciences, Beijing, China

The high-frequency pulse tube cryocoolers (HPTCs) feature high energy flow density, low vibration, good stability and reliability. Here we report a gas-coupled two-stage HPTC, which adopts a coaxial structural arrangement, is driven by only one compressor, and has an extremely compact structure. The cryogenic double-inlet, cold inertance tube and cold gas reservoir are adopted as the phase shifter for the second stage. Moreover, the multi-bypass structure is also applied in the second stage to further enhance cooling performance. Under the condition of a 2.25 MPa charging pressure and a 25 Hz operating frequency, the experimental prototype obtains a no-load temperature of 4.3 K, and provides a cooling power of 50 mW at 6.5 K with a 425 W input electric power. This paper also introduces the structure of the prototype and its cooling performance under different operating conditions, including charging pressure, frequency and input power.

PT Cooler Development & Testing, Paper No. 2.8

24K Single-Stage Coaxial PulseTube Cryocooler without Double-Inlet Phase Shifter

N. Wang, M. Zhao, H. Chen, L. Wei, J. Liang, J. Cai, Key Lab of Tech. on Space Energy Conv., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

Several 40K pulse tube cryocoolers(PTCs) have been developed to meet the demand of long wavelength infrared detectors. Traditionally, the multi-bypass or double-inlet arrangement is often employed to realize temperatures below 40K for PTC. To minimize the complexity and guarantee the required long-term stability of PTC, for our designed cooler, the inertance tubes together with the reservoir become the only phase-shifter. At present, the cooler prototype has achieved a no-load temperature of 24 K and can typically provide 2.1W cooling power at 40K with 150W electric input power rejecting at 300K. The relative Carnot efficiency is up to 9.1% at 40K. The key parameters and performance of the designed PTC are presented at details.

PT Cooler Development & Testing, Paper No. 2.9

Large Pulse Tube Cooler with a Heat Interceptor

M.B.C. Branco, C. Buti, L. Desjonqueres, T. Tirolien, M. Linder,
European Space Research & Technology Center, The Netherlands

Following on the hegemony over many years of the Oxford/Bae Stirling Coolers on Space missions, the Large Pulse Tube Cooler (or LPTC), by Air Liquide, has established itself as Europe's de facto workhorse cryocooler, having been chosen for the Meteosat Third Generation, IASI-NG on Metop-SG and being currently considered for plenty other Earth Obseration missions as well as Space Science Observatories. Following on the work carried with heat interceptors by I Charles [1] on the Mini Pulse Tube Cooler, and earlier by D.L. Johnson and R.G Ross [2] on the Bae Stirling Cooler, an LPTC Engineering Model was tested at the Cryocooler Performance Characterisation Facility at the European Space Research and Technology Center (ESTEC), for its cooling capabilities employing a heat interceptor, at different positions on the cold finger, at temperatures ranging from 150 K to 200 K. Such an application might render the LPTC a suitable alternative for the 30 K - 40 K range, namely on missions already employing passive cooling, compatible with the interceptor, e.g. ATHENA or ARIEL. A significant increase in performance was measured, compared to the same cryocooler's measured performances without the interceptor, especially at a higher intercept position and for a lower intercept temperature. The heat load at the interceptor was also measured, in order to reflect on the passive cooling requirements. Considerations on the physical behaviour of the pulse tube cooler with the interceptor are also described in this paper, as well as the test setup and the experimental protocol. [1] I. Charles et al, "A New Mini Pulse Tube with a Heat Interceptor," CEC, Vol. 53, 2008; [2] D.L. Johnson and R.G. Ross, Jr. "Cryocooler Coldfinger Heat Interceptor," Cryocoolers 8, 1994.

Stirling Cooler Devel. & Testing, Paper No. 3.2

Cost Effective Split and Integral Linear Stirling-Type Cryocoolers for HOT IR Imaging

A. Veprik, S. Zehctzer, A. Daniels, R. Refaeli and A.Wise, CryoTech Ltd, Israel

Development of cost effective, long life and low size, weight and power cryogenic cryocoolers is imperative for further advancement of existing and appearance of new sectors in cooled infrared imaging marketplace. CRYOTECH LTD reports on further progress towards development of two novel (patent pending) Stirling type split and integral linear cryogenic coolers for high operational temperature infrared imagers. The authors present the outcomes of the full scale feasibility study, characterization and initial optimization along with updated predictions of theoretical performance.

Stirling Cooler Devel. & Testing, Paper No. 3.3

Design and Performance Test of Miniature Linear Stirling Cryocoolers

X. Wang, W. Dai, E. Luo, Key Laboratory of Cryogenics of Chinese Academy of Sciences, China; and L. Yang, Y. Zhang, H. Li, Lihan Cryogenics, China

In order to meet continuous requirements of lighter weight, smaller size and lower power consumption for micro IR applications, miniature linear Stirling cryocoolers have recently been developed and manufactured in small batches at Lihan. The design specifications of the cryocoolers are also presented with numerical and engineering optimizations. The cryocoolers consist of two dual opposed linear moving magnets drive motors and a split Stirling cryocooler are expected to provide 0.5 W of cooling power at 80K with smallest size and lowest weight. The impact of stepped and rod-less displacer on system performance and size are numerically analyzed and experimentally tested. The experimental results show that the weight both of two cryocooler systems weight can be controlled below 300 grams. The experimental results also show that the cryocooler with stepped displacer could acquire 0.5W of cooling power at 80 K with 12 W of electric input power and the cryocooler with rod-less displacer could acquire similar cooling power but more electric power consumption.

Stirling Cooler Devel. & Testing, Paper No. 3.4

High-Availability Stirling Coolers

D. Willems, T. Benschop, R. Arts, B. de Veer, and P. Bollens, Thales Cryogenics BV, Eindhoven, The Netherlands

Thales Cryogenics has recently introduced a range of coolers for applications requiring high availability. The availability is a figure of merit describing the reliability of a cooler in applications with long-term and continuous (24/7) or near-continuous operation. A high availability is synonymous with and extremely low failure probability. A well-known solution for a high-availability application is a pulse-tube cooler, such as those produced by Thales Cryogenics, which have an intrinsically high availability due to the absence of moving parts in the cold head. However, other aspects such as power density, power efficiency, or cool-down time prohibit the use of pulse tubes in some applications. High-availability Stirling coolers can be considered in these cases. A range of Stirling coolers is available for such applications. In this paper, we will present these coolers and some of the improvements that have taken place. The improvements to the coolers, in the 100 W to 200 W input power range, are not only intended to increase the availability – or reliability – of the coolers, but are also aimed at improving the performance, by either increasing the efficiency or extending the operating window. In addition to performance and reliability improvements, the integration aspects of these cooler types will be presented, and system-level considerations discussed.

Stirling Cooler Devel. & Testing, Paper No. 3.5

The Study on High Efficiency and Low Vibration Flexure Bearing Stirling Cryocooler

C. L. Yin, Y. Gao, H. Yan, F. Wang, Q. Hong, X. H. Fan, Z. Wang, Inst. of Cryogenics and Electronics, Hefei, China

In this paper, a high efficiency and low vibration Stirling cryocooler has been designed and manufactured. The high efficiency compressor implementing the technology of dual opposed moving magnet motor and flexure bearing has been optimized to drive pneumatically a Stirling cold finger also implementing flexure bearing technology. Through theoretical study and experimental study, the cryocooler can reach performance of 3W/80K under 60 WAC of electrical power. The vibration of compressor is suppressed by reducing the weights of moving-masses and controlling the process of assembling. The vibration suppression of the cold finger is implemented in terms of a mass-spring passive balancer. The vibrations of compressor and the cold finger could be decreased to below 5.6 mg and 1.9 mg respectively under the above solutions.

Stirling Cooler Devel. & Testing, Paper No. 3.6

A kW-class Free-Piston Stirling Cooling Prototype for Ultra-Low Temperature Freezing

K.Q. Luo, Y.L. Sun, Z.J. Jiang, E.C. Luo, J.Y. Hu, L.M. Zhang, Z.H. Wu, Z.L. Jia, Y. Zhou, Chinese Academy of Sciences, Beijing, China

In recent years, the demand for ultra-low temperature freezer has been growing rapidly. It can not only be used for some special food deep freezing, but also be popularly utilized in biological storage. There are some conventional cooling technologies such as Freon-based two-stage cascade and single-stage mix-gases J-T refrigeration system. However, because of having better performance potential in environmental-friendliness and energy efficiency, the free-piston Stirling cooler is getting attention for the development for ultra-low temperature freezing. In this paper, we designed and built a kW-class free-piston Stirling cooling system for ultra-low temperature freezing, which can operate in temperature range from -100°C to -60°C. Our experimental results show that the system can obtain a cooling capacity of nearly 1000W@-80°C with a corresponding COP around 0.5 under a charging pressure of 3MPa, a working frequency of 50Hz and an input pressure ratio of 1.3. As a result, it demonstrated that the free-piston Stirling cooling system has good potential of achieving high efficiency and large cooling capacity for the ultra-low temperature freezing application.

Stirling Cooler Devel. & Testing, Paper No. 3.7

Development of Integral Rotary and Split Linear Stirling Cryocoolers for SWaP Applications

A. Osterman, K. Dovrtel, F. Megusar, Le-tehnika, Kranj, Slovenia

Current development of SWaP cryocoolers at LE-TEHNIKA is finishing prototype phase for two new products, both based on a Stirling cooling cycle. The aim is to broaden our Stirling cooler product range also for the aplications where small, light and efficient low power coolers are required. The first one is a split linear cooler (SLC) and the second one is an integral rotary cooler (IRC). IRC has 0.5W of cooling power at 130K while its mass (without electronics) is below 100g. Both cryocoolers are based on motors with moving permanent magnets, have separated electronics and integrated position sensors. With promising results regarding cooling power, noise and induced vibrations, both types are now entering industrialization phase which should provide data on lifetime and MTTF. Considering several design improvements over larger cryocoolers existing in production, substantial extension of lifetime is expected also in presented new generation of Swap coolers.

Brayton Cooler Development, Paper No. 4.1

Space Exploration Applications for Development of High Capacity Reverse Turbo-Brayton Cycle Cryocoolers

B.T. Nugent, M.C. Guzik, and W.L. Johnson, NASA GRC, Cleveland OH; J.R. Stephens, NASA MSFC, Huntsville, AL

Long term storage of cryogens is necessary to enable NASAs long duration crewed missions to both the lunar and Martian surfaces. Such missions require in-space transport systems such as Nuclear Thermal Propulsion (NTP), and descent/ascent vehicles for transportation to and from the lunar and Martian surfaces. NTP systems and Lunar/Martian landers utilize cryogenic fluids to minimize architectural volume and mass. To further enhance the capability of these cryogenic systems, the Agency is putting emphasis on reusability, which requires the NTP and ascent/descent elements be replenished on-orbit via tankers or propellant depots, or on the lunar or Martian surface using liquefied in-situ produced propellants. NTP is one of the leading propulsion option for human Mars missions and requires liquid hydrogen to be stored on-orbit for over four years. For such a long duration mission, near “Zero Boil-Off” (ZBO) must be achieved which requires an optimized suite of passive Cryogenic Fluid Management technologies and active cooling (cryocoolers). Tens of Watts of 20K cooling is required to achieve ZBO conditions for NTP, however two-stage cooling using both 20K and 90K systems can lead to a significant reduction in both active cooling mass and power. The use of in-situ resources for lunar and Martian missions will require 150 Watts of 90K cooling for oxygen liquefaction and 300 Watts of 20K cooling for hydrogen liquefaction (lunar only). Descent/Ascent vehicles, propellant depots, and tankers will also require the use of cryocoolers to achieve ZBO conditions. To support these programs, NASA is developing high capacity 20K and 90K reverse turbo-Brayton cycle cryocoolers which offer a scalable, high efficiency, low vibration solution.

Brayton Cooler Development, Paper No. 4.2

Efficiency Improvements for Turbo-Brayton Cryocoolers for Space

M.V. Zagarola, K.J. Cragin, R.W. Hill, J.A. McCormick, Creare LLC, Hanover, NH

The thermodynamic performance of turbo-Brayton cryocoolers is predicted to first order by the efficiency of the compression and expansion processes, and the thermal effectiveness of the recuperation between the high and low pressure streams. Other performance factors such as recovery of expansion work (a benefit); pressure losses in tubing, fittings and components; thermal parasitics from the environment; real-gas effects; and thermal performance of heat rejection and load interface heat exchangers can have negligible impact on cryocooler performance through proper design. The key then for optimization of turbo-Brayton cryocooler performance is to optimize the performance of the compressor, turbine and recuperator. Recuperator optimization involves maximizing the heat transfer per unit volume while maintaining low axial conduction and ability to withstand launch loads. Optimization of turbines and compressors is similar and involves optimization of the aerodynamic design of the rotating and stationary flow elements while minimizing overhead losses associated with viscous drag and electromagnetic losses and not compromising reliability and lifetime. This paper presents the advances in analysis, design and fabrication techniques for the turbomachines, in particular, that have led to milestone advances in turbo-Brayton cryocooler performance.

Brayton Cooler Development, Paper No. 4.3

High Effectiveness Micro-Tube Recuperators for Low-Capacity Turbo-Brayton Cryocoolers for Space

A.L. Niblick, K.J. Cragin, M.V. Zagarola, Creare LLC, Hanover, NH

In 2014, Creare with our partners at Edare and Mezzo Technologies started to develop a micro-shell-in-tube recuperator for high-capacity turbo-Brayton cryocoolers. This technology was initially pursued for a 20 W at 20 K cryocooler because the cost, size and mass of existing recuperator technologies did not scale well to high mass flow rates. The microtube technology has inherently high heat transfer rates per unit volume, which is ideal for high capacity cryocoolers because several kilowatts of heat must be transferred in a turbo-Brayton recuperator. The challenges of using this technology for high-performance cryogenic recuperators are minimization of two critical performance penalties - axial conduction within the core structure and flow mal-distribution. Axial conduction is typically a non-factor for high-capacity cryocoolers. Flow distribution was addressed in the case of the 20 W at 20 K cryocooler by a combination of design features of the headers and core and using 5 modules in series to allow mixing. We recently applied the microtube technology to a low capacity cryocooler producing less than 500 mW at 10 K. Here mass flow rates are an order of magnitude less than at high capacities and thermal effectiveness requirements are commensurate (0.99 per module). This paper reviews the design features, analyses and thermal performance test results of a low-capacity microtube recuperator, and compares the technology to prior space-proven technology.

Brayton Cooler Development, Paper No. 4.4

Characterization of Copper Mesh as a Heat Transfer Matrix at Low Temperatures

A. Onufrena, T. Koettig, T. Dorau, M.L. Laguna and J. Bremer, CERN, Geneva, Switzerland; T. Tirolien, ESA, Nordwijk, The Netherlands; and H. J. M. Ter Brake, Univ. of Twente, The Netherlands

Woven metal mesh is a highly porous material that has a great potential as an internal structure for high-effectiveness compact counter-flow heat exchangers and regenerators due to its large surface area and remarkably high transversal-to-axial conductivity ratio. This paper outlines an experimental characterisation and preliminary investigation into the copper mesh as a heat transfer matrix. Measurements of the thermal conductivity of the mesh in plane (45º to the fibre) and through-plane directions in the 10 K – 290 K temperature range are presented. These data are used to determine the mesh RRR and tortuosity as well as to estimate thermal conductivity in plane at 0º angle to the fibres. The temperature-dependent in- to through-plane conductivity ratio reached values in the range of 1000-10000. The stress-strain profile of a 100-layer mesh stack was measured at 77 K and 290 K to further support the application of the stacked mesh layers. Moreover, the corresponding contact thermal conductance between copper mesh and different wall materials has been studied (copper, bronze, stainless steel) in 10 K – 290 K temperature range. Copper and bronze wall to copper mesh contacts were found to have the largest thermal conductance. Analysis and interpretations of all the obtained results are offered.

J-T Cryocooler Development, Paper No. 5.1

A Neon JT Cooler for ARIEL

M. Hills, M. Crook, A. Eagles, G. Gilley, B. Green, S. Kendall, C. Padley, C. Pulker, T. Rawlings, STFC Rutherford Appleton Laboratory, Harwell, Oxford , UK

The Atmospheric Remote-sensing Infrared Exoplanets Large-survey (ARIEL) is the fourth medium (M4) mission selected in the ESA Cosmic Vision 2015-2025 programme, with a launch planned in 2028. The spacecraft will carry two instruments: a Fine Guidance System (FGS) and the ARIEL InfraRed Spectrometer (AIRS). AIRS requires active cooling of both its channels to below 42 K and this will be provided by a neon Joule-Thomson (JT) cooler developed by the Rutherford Appleton Laboratory. This paper describes the design of the cooler to meet the requirements of the ARIEL mission. We summarise the overall cooler architecture and design of the main sub-systems: the compressors, ancillary panel and JT heat exchanger assembly. Performance modelling of the compressors and heat exchangers – which permits system level trade-offs to be performed – is described. The outcomes of these trades are reported along with results from mechanical and thermal analyses. Preliminary tests have been performed on the heat exchanger sub-assembly and these results are presented. We conclude with a summary of the current status and future developments for the flight model cooler.

J-T Cryocooler Development, Paper No. 5.2

Design, Fabrication, and Testing of a 1 Watt at 22 Kelvin Joule Thomson Cryogenic Refrigerator

W. Notardonato, Eta Space, Rockledge, FL; A. Swanger, NASA KSC, FL; J. Baik, Meta Vista USA, Orlando, FL; R. Roy, Skyre Inc., West Hartford, CT

Eta Space and Meta Vista have partnered with the NASA Kennedy Space Center to develop a novel cryogenic refrigeration cycle that has many applications to the space industry as well as for terrestrial energy markets. The cryocooler is sized to produce 1 W cooling at 22 K. Key features of this cryocooler include high efficiency, low vibration, no electromagnetic interference, high reliability and long life. The operating principles of this cryocooler are presented and the current state of development is given. The optimum refrigeration cycle state points have been established and detailed design of the compressor and cold box is complete. All fabrication has been finished and subsystem test results are presented. The compressor has been integrated with the cold box and integrated testing is ongoing. The advantages of this refrigeration cycle are of interest to the space science and exploration community for use in many potential applications. A survey of different space applications has completed and several possibilities are discussed. These applications range over several orders of magnitude in size and have a wide variety of environmental constraints. A scaling analysis has been completed to show increasing size by two or more orders or magnitude is feasible, and an assessment on modifications to meet microgravity, vacuum, radiation and thermal requirements has been completed. This report concludes that this new refrigeration cycle appears to have many space applications and development and testing of these systems will continue to be pursued.

J-T Cryocooler Development, Paper No. 5.3

Performance Testing of a 2K Joule-Thomson Closed-Cycle Cryocooler

M. Crook, M. Hills, G. Gilley, T. Rawlings, C. Pulker, B. Green, STFC Rutherford Appleton Laboratory, Harwell, UK

The Rutherford Appleton Laboratory (RAL) have developed a 2K Joule-Thomson cooler for future space missions requiring low temperatures, such as the ESA's Athena X-ray telescope. The design, modelling and heat exchanger testing of the cooler was presented in Cryocoolers 19. In this follow-on paper, we describe the assembly of the compressors and ancillary panel, and we present the results of thermal and mechanical testing. The cooler demonstrated 20 mW of cooling at 2 K, with a pre-cooler temperature of 12 K, and 14 mW of cooling at 2 K, with a pre-cooler temperature of 15 K. The total input power to the compressors to achieve these performances was 90 W. The compressors and ancillary panel successfully passed mechanical testing comprising a 25-g high sine test and an 11.7-gRMS random test in all axes. These units also completed thermal cycling between -20°C and +50°C (operating) and 35°C and +70°C (non-operating). The lessons learnt from this development are summarised and we discuss how they are being applied to the Engineering Model 2K cooler that is currently under development at RAL as part of an ESA Core Technology Programme.

J-T Cryocooler Development, Paper No. 5.4

Evolution of Stratification and Self-Pressurization of Liquid Nitrogen for JT Cryocooler under Elevated Gravity Condition

Vishnu S.B., B.T.Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

The prediction of thermal stratification in a cryogenic storage tank is necessary for the successful execution of the prolonged working of a J-T cryocooler in space-related applications. The working fluid may be stored in the subcooled conditions, and the possibility of heat infiltration may lead to an increase of temperature as well as the pressure of the cryogenic fluid. Commonly used stratification models are based on temperature and velocity correlation developed for flow over a flat plate. The evolution of stratification during lift-off and accelerated conditions will be different from that during normal ambient conditions. During lift-off, the gravity value can reach up to 6g. So modeling of stratification in the cryogenic tank is essential to determine the state of cryogen during a space mission. A multiphase axisymmetric computational model is developed, which can simultaneously account for the heat exchanges within the storage tank and also heat transfer from the ambient condition during lift-off. VOF method is used and heat and mass transfer models are also incorporated to study the effect of phase change on thermal stratification. The model is validated with the experiments conducted at cryogenic test facility at CASC lab.The results show that the temperature of bulk fluid temperature will be higher during lift-off and accelerated state, and reduction in the rate of pressure rise after lift-off was noted, which was due to turbulence created by the liquid. Since the geometry used is a perfect cylinder, further studies about stratification are required by considering actual tank geometries.

J-T Cryocooler Development, Paper No. 5.5

Investigation of Energy Conversion Processes in High Length-to-Diameter Ratio Coiled Resonant Tubes Driven by Periodic Mass Injection Conditions in Thermo-acoustic Expansion Device

Z. Hu, Cryowave Adv. Tech., RI, USA

Themoacoustic Expansion Devices (TAEDs) produce cooling power through a steady pressure drop in DC flowing conditions. The TAED cooling performance imperatively relies on its energy conversion component, a bundle of resonant tubes in which pressure energy released from the constant pressure drop is converted to heat by pressure wave systems, and rejected to high temperature reservoir by resonant-tube surface. This paper reports the experimental and numerical investigations on a high length-to-diameter ratio coiled resonant tube used in TAED under periodic mass injection conditions. The results of experiments and numerical simulations demonstrate the cooling mechanism under high modes of gaseous oscillation, and provide the guidance to design and miniaturize TAED run under cryogenic conditions, especially in the cases of variable temperature and density of supply stream encountered in the recuperative cooling of a TAE cryocooler system, where TAED's inlet temperature is continuously depressed before expansions. The influences of variable boundary conditions that drive high length-to-diameter ratio resonant tubes to carry out energy conversion and transportations are discussed in comparison to the configuration of conventional pulse tube that is operated under the dynamic moving boundary condition (moving piston or temperature gradient).

J-T Cryocooler Development, Paper No. 5.6

Comparison of Experimental and Modeling Results for Mixture Optimization of a Mixed-Gas Joule-Thomson Cycle

J. Detlor, J. Pfotenhauer, and G. Nellis, Univ. of Wisconsin, Madison, WI

This research experimentally validates a computational tool that is used to optimize the gas mixture composition for a Joule-Thomson (JT) cycle for specified operating parameters. A mixture optimization model was previously developed which is capable of determining optimal three-component mixtures based on the analysis of the maximum value of the minimum isothermal enthalpy change, Δh_T, that occurs over the operating temperature range coupled with an evaluation of the percent of the heat exchanger that exists in a two-phase state within that range. A more detailed heat exchanger performance model has also been developed that considers the effect of operating parameters, geometry, mixture composition and quality on the conductance and pressure loss. This detailed model is capable of making more precise predictions of the performance and is also used as a design tool for the cryostat. A prototype mixed gas JT cryocooler was constructed and installed in a test facility to investigate optimal mixture selection, particularly in the 120-150K cold head temperature range. The test facility is capable of providing a range of gas composition, mass flow rate, and pressures. The prototype has been operated while charged with several gas mixtures over a range of operating pressures. The experimental mass flow rate, temperature at the outlet of the JT valve, and cooling load are compared to the expected values based on the modeling tools. These results are used to refine the model in order to enable reliable mixture optimization as well as cryostat design.

J-T Cryocooler Development, Paper No. 5.7

Experimental Validation of a Numerical Model for Nitrogen-Activated Carbon Sorption Compressor Cells

N. Tzabar, A. Davidesko and A. Hamersztein, Thermal Energy Science & Tech. Laboratory, Ariel Univ., Ariel, Israel

Joule-Thomson (JT) cryocoolers operating with sorption compressors don’t have moving parts, therefore, they have the potential for long life and vibration-free operation. In the frame of our ongoing research on sorption compressors, a one-dimensional dynamic heat and mass transfer numerical model is developed, aiming for optimizing the sorption cell design against different target functions. The current paper presents an experimental validation of the numerical model, including some adjustments in the model. The main modifications in the numerical model are; a three-to-one dimensions correcting factor, incorporating temperature dependent thermal properties and adjustments of the contact heat resistances. The results show a satisfying agreement between experimental and calculated results, over a range of operating conditions.

J-T Cryocooler Development, Paper No. 5.8

Development of Thin-Plate Square-Shape Sorption Compressor for 5 K J-T Cooler

J. Bae, D. Kwon, S. Jeong, Korea Adv. Inst. of Science and Tech. (KAIST), Daejeon, Korea

A sorption compressor, which utilizes adsorption characteristic, can be applied to a J-T (Joule-Thomson) cryocooler. The adsorbent material which fills the compressor cell can adsorb and desorb the adsorbate according to its temperature. The pressure swings in the cell are, therefore, generated by heating and cooling the cell. In addition, it is necessary to rectify the mass flow from the cell by passive check valves to afford continuous pressure gradient in the J-T cooler. The compressor cell in this paper is designed as a thin-plate shape to minimize the heating and cooling time so that the pressure swing is accelerated. As a result, it can increase the cooling capacity of the J-T cooler by reducing the total cycle time. Furthermore, the thin-plate geometry can take advantage of the fast response to operate without any heat switch to isolate the heat flow during the heating cycle. Its width, height and the thickness are 100 mm, 100 mm and 4.6 mm, respectively. In the cell, cubic pillars with one side length of 1 mm, are arranged to reinforce the structural rigidity and thermal diffusion into the adsorbent. Activated carbon is used in the cell to adsorb and desorb helium for 5 K cooling. For heating the cell, a polyimide film heater is attached to the top surface of the cell. For cooling the cell, the cold head of commercial GM(Gifford-McMahon) cryocooler is thermally connected to the cell via copper thermal link. The commercially available miniaturized check valves are tested at cryogenic temperature and equipped to rectify the gas flow from the compressor cells. The mass flow rate from the compressor and its efficiency are measured to compare the performance with other thermal compressors. Consequently, the strategy to increase the mass flow rate and the efficiency of the compressor are discussed.

J-T Cryocooler Development, Paper No. 5.9

Development of a Capillary Tube Orifice for Expansion Device of Joule-Thomson Cryocooler

J. Kim, H. Lim, S. Han, Korea Aerospace Research Inst., Korea

An expansion device is necessary for Joule-Thomson cryocoolers to achieve the refrigeration effect by the expansion from high pressure to low pressure. Generally, an orifice or a capillary tube or a valve is used as the expansion device. However, these traditional expansion devices have limits in some special conditions such as high pressure, low flow rate, and cryogenic temperature especially in aerospace applications. For the aerospace applications, a single hole orifice is the best option because its structure is simple and the weight is light. On the other hand, the single hole orifice is easy to be plugged by the foreign object particles or ice particles of residual gas at cryogenic temperature when the diameter is less than 0.1 mm. To solve these problems, we developed a new three dimensional orifice modifying the conventional capillary tube orifice. A prototype of the new expansion device is fabricated and tested in various conditions to ensure the reliability of the compartment. In this paper, the concept of newly developed expansion device is introduced, and the test results of life test, vibration test, strength & leak test, rupture test, and temperature environmental test are summarized.

J-T Cryocooler Development, Paper No. 5.10

Numerical and Experimental Investigation of Miniature Cryocooler Constructed in LTCC Technology

M. Chorowski, K. Malecha, Z. Malecha, W. Nawrot and Z. Rogala, Wrocław Univ. of Science and Tech., Wroclaw, Poland

The Low Temperature Cofired Ceramic technology proved its maturity and successful application in number of micro- and nano-size devices and Lab-on-chip systems. It allows stable and controlled performance of number of processes including transportation, mixing, (bio)chemical reactions, detection of micro and nanoliter volume samples. The main advantage of LTCC technology is its manufacturing flexibility and very high endurance. It allows for a safe performance in extreme thermal and pressure conditions. In this study, LTCC technology was used to manufacture a miniature cryoccoler based on Joule-Thomson cycle. The size of the whole device was less than 100mm, the heat exchanger channel width ~ 1 mm and channel width of J-T section ~ 0.1 mm. The applicability of the LTCC technology for microcooling and its performance was investigated numerically using the conjugate heat transport approach. The miniature cryocooler was designed, manufactured and pressure tests on the device were performed in Wroclaw University of Science and Technology.

J-T Cryocooler Development, Paper No. 5.12

Research on the Influence of Linear Compressors on Space Hybrid 4K J-T Cooler

Y. Ma, Z. Liu, J. Quan, J. Wang, Y. Liu, J. Li and J. Liang,
Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

The oil-free linear J-T compressor is one of the key components in space 4K J-T cooler. The performance of the J-T compressor affects the performance of the hybrid J-T cooler directly. Based on the J-T compressors developed by our laboratory, series of experimental research is carried out to explore the influence of the JT compressor on the performance of the JT cooler at different operating conditions. When only the power consumption of JT compressors is considered, the coefficient of performance (COP) of the JT cycle is proposed to evaluate the performance of JT cycle. And experimental results suggest that two-stage compression presents higher COP comparing with one-stage compression

J-T Cryocooler Development, Paper No. 5.13

Heat Transfer Analyses and Experimental Study of a Gas-Gap Heat Switch for a Sorption Cooler

Y.L. Lei, Y.N. Zhao, J. Quan, G.T. Hong, Key Lab of Tech. on Space Energy Conv., CAS, Beijing, China

The gas-gap heat switch (GGHS) is a critical component for a sorption cooler (SC). In order to explore the characteristics of the thermal performance of the GGHS in a wider temperature region (4-300 K) and verify the gap structure by a simpler test at the room temperature, a thermal model evaluating the heat flux through the GGHS for a wider temperature region was established. To verify this model, a GGHS was tested with 4He as the working medium at 10 K and 295 K. The experimental results are in agreement with the theoretical data, and the thermal performances at 10 K and 295 K are compared in this paper. This model can help to assess the heat load of the SC in different working conditions and to detect the gap structure.

Research on Counter-Flow Heat Exchangers of Space 2.5K Hybrid Joule-Thomson Cryocooler

Z.Y. Liu, Y.X. Ma, J. Quan, Y.J. Liu, J. Wang, J.G. Li, J.T. Liang, Key Lab of Space Energy Conv. Tech., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

Heat exchangers are one of key components of hybrid Joule-Thomson (J-T) cryocoolers. Three tube-in-tube counter-flow heat exchangers were used in our hybrid J-T cooler. In this paper, the effect of heat transfer and flow resistance of the counter-flow heat exchanger are calculated. As the length of heat exchangers increases, the effect of heat transfer will be improved. Simultaneously the fluid resistance will also increase, which directly affects the pressure on both sides of the J-T valve. The 3rd stage counter-flow heat exchanger of J-T cycle has the important role in precooling high-pressure gas before throttling. According this calculation, a new 3rd stage counter-flow heat exchanger was designed and used in J-T cryocooler. This J-T cryocooler reached a no-load temperature of 2.51 K, suppling 3.0 mW cooling power at 2.55 K with 310 W electric power consumed.

J-T Cryocooler Development, Paper No. 5.15

Experimental and Numerical Study of Heat Transfer Characteristics of an Oil-Free Valved Linear Compressor for J-T Throttle Refrigerator

J. Sun, J. Lib, Y. Ma, Z. Huang, Y. Liu and J. Cai, Univ.of CAS, Beijing, China and Key Lab of Tech. on Space Energy Conv., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

As the core component of the pre-cooled J-T throttle refrigerator, the efficiency of the valve linear compressor has a decisive influence on the performance of the whole refrigerator。At present, the motor and mechanical efficiencies of linear compressors for J-T throttle refrigerator are relatively higher than the isentropic efficiency and very close to their limits. Therefore, it is very important to carry out research on the heat transfer characteristics of linear compressors and improve their isentropic efficiency. This paper presents a thermal analysis of an oil-free valved moving coil linear compressor focusing on the overall heat transfer characteristics in linear compressor, and the energy loss of each component in the linear compressor was found. First, the linear compressor was divided into several control volumes, and its thermal performance was analyzed by maintaining the whole energy balance throughout the heat transfer analysis for each control volume. Next, during the steady-state operation of the J-T throttle refrigerator, the basic measurement of temperature and pressure was performed by some thermometers and pressure sensors, and a heat transfer network of all control volumes by using a correlation for the energy balance. In addition, a thermal infrared imager was also used to obtain the temperature distribution in the compressor. The energy loss of each control volume of the compressor was ranked. Meanwhile, the overall heat transfer simulation of the linear compressor was developed, and the simulation results are in good agreement with the experimental results. The studying is useful to the design and optimization of linear compressors.

J-T Cryocooler Development, Paper No. 5.16

Study on Piston Offset and Efficiency of Linear Compressor for Large Refrigerating Capacity J-T Throttle Refrigerator

J. Sun, J. Li, Y. Ma, Z. Huang. Y. Liu. J. Cai, Univ. of CAS, Beijing, China and Key Lab. of Tech. on Space Energy Conv., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

The valved linear compressor provides the pressure ratio and flow rate of the J-T throttling cycle, and its efficiency has a key influence on the performance of the J-T throttling refrigerator. Large refrigeration capacity J-T throttling refrigerator requires a large capacity, high pressure ratio, high efficiency linear compressor, so it is necessary to improve the capacity and efficiency of the compressor. Due to the imbalance of the gas pressure on both sides of the piston, the piston of the valved linear compressor will be offset. The piston offset increases the clearance volume (dead volume), which seriously affects capacity and efficiency of the linear compressor. This paper tests the piston offset of the valved linear compressor under different working conditions, which is consistent with the simulation results of the linear compressor piston offset model. In addition, the relationship between piston offset and compressor capacity and efficiency has been systematically studied through three methods: AC + DC voltage drive, increasing spring mechanical stiffness, and pre-adjusting the compressor mover mechanical center.

Low-Temp Cryocooler Devel., Paper No. 6.1

Magnet Hysteresis Loss in Adiabatic Demagnetization Refrigerators

P. Shirron, M. Kimball, R. Ottens, J.Tuttle, and A. Jahromi, NASA/Goddard Space Flight Center, Greenbelt, MD

Adiabatic demagnetization refrigerators (ADR) are often combined with mechanical cryocoolers to extend the operating range to lower temperature or to improve efficiency. For example, new architectures have been, and are being, designed to enable continuous operation at temperatures below 1 K using a 4 K-class GM, pulse tube, or Joule-Thomson cryocooler. Continuous operation involves cyclic magnetization and demagnetization of the refrigerant on short time scales – from 10s of minutes to 10s of seconds. This is achieved by charging and discharging a superconducting magnet over field excursions of up to a few tesla. The hysteresis heat generated can be a significant fraction of the total heat rejected during operation, and therefore can significantly reduce efficiency. Recent measurements of magnet hysteresis heat generation have been made at NASA/GSFC using magnets (NbTi and Nb3Sn) produced for both flight (Astro-H) and research projects. Results of these measurements, which have been used to derive scaling laws, will be presented.

Numerical Analysis for a Continuously Operating Adiabatic Demagnetization Refrigerator (ADR) between 4.2 K and 2.0 K

D. Kwon, J. Bae, S. Jeong Cryogenic Engin. Laboratory, Korea Adv. Inst. of Science and Tech., Daejeon, Korea

An adiabatic demagnetization refrigerator (ADR) is numerically investigated to predict the cooling performance below 4.2 K. The previous research experimentally investigated an ADR system with a passive lead heat switch for the warm end and a thermosiphon for the cold end. The warm end of the ADR, which was connected with the second stage of G-M cooler, was maintained at 5.7 K while the bottom of the thermosiphon (cold end) was always maintained at the lower temperature between 2.6 and 3.4 K as a no-load condition. In the case of heat switch for the warm side, however, the lead intrinsically has low on-off ratio due to its high operating temperature. Hence, the lead straps which have geometrically high thermal resistance did not shorten the cycle time. The newly proposed system consists of helium thermosyphon for the warm side and a magneto-resistive tungsten heat switch for the cold side. By adapting appropriate heat switching method for the warm and the cold sides, the cycle time has been significantly reduced while the passive operation of heat switches were remained. The numerical analysis was conducted with the 1-dimensional heat diffusion model considering thermal contact resistance in ADR. The calculation results show that the ADR can produce 9.2 mW cooling power at 2 K when the temperature of the warm end is maintained as 4.2 K. The detailed design methodology and the results are presented and discussed.

Low-Temp Cryocooler Devel., Paper No. 6.3

The Development of an Active Magnetic Regenerative Refrigerator (AMRR) For sub-Kelvin Cooling of Space Science Instrumentation

C.M. Gunderson, G.F. Nellis, F.K. Miller, Univ. of Wisconsin - Madison, Madison, WI

Sub-Kelvin operating temperatures are required for a wide range of space science instrumentation. Consistent and reliable cooling of these instruments is critical in order to ensure top performance in high sensitivity applications. This research works towards the development of a sub-Kelvin Active Magnetic Regenerative Refrigeration (AMRR) system that can provide distributed cooling to space instrumentation via circulation of a 3He-4He mixture. A Superfluid Magnetic Pump (SMP) is used to circulate superfluid 3He-4He mixture throughout the rest of the system, which consists of two hot heat exchangers, one cold heat exchanger, and two magnetic regenerators. This presentation will discuss the design and experimental results from early testing of a proof-of-concept AMRR.

Low-Temp Cryocooler Devel., Paper No. 6.4

Adiabatic Expansion of ^{3}He in Superfluid ^{4}He

A.T.A.M. de Waele, Eindhoven Univ. of Tech., Eindhoven, The Netherlands

In Cryogenics Vol.96 (2018) pp.83-89 we described a technique which enables continuous cooling in space to subkelvins using two expansion units which operate in counterphase. Each unit needs two external coolers. In the present work attention is paid to the cooling chain between the expansion units and the radiative cooler at about 50 K. It will be shown that only two (and not four) JT coolers are needed. These two JT coolers run continuously, but by using two-way valves they are alternatively switched between the two expansion units. Also no heat switches are needed to thermally connect/disconnect the JT coolers to the expansion cells. This simplifies the system considerably.

Low-Temp Cryocooler Devel., Paper No. 6.5

Thermodynamic Process and Optimization of Dilution Refrigerator

M. Zheng, J. Liang, P. Lin , L. Wei and M. Zhao , Chinese Acadamy of Science, Beijing, China

The dilution unit which directly determines the performance of dilution refrigerator is the most important part of the whole dilution refrigerator system. In order to improve the performance (lower temperature and more cooling power) of dilution refrigerator, separate thermodynamic models of the components in dilution unit and a integrated thermodynamic model were developed considering thermodynamic balance and the Kapitza boundary resistance. And an optimization calculation based on that model was carried out to obtain some meaningful results on the dilution unit design. The route and scope of optimization and theoretical optimal working condition were carefully presented. A concept called “saturated flow rate” was introduced.

Low-Temp Cryocooler Devel., Paper No. 6.6

The Latest Developments in Low Cost, Low-Power Cooling to below 1 Kelvin

P. McInnes, L.C. Kenny and S.T. Chase, Chase Research Cryogenics Ltd, Sheffield, UK

Self-contained, sealed 4He sorption modules, interfaced to low-power mechanical precoolers, provide simple, reliable and economical access to temperatures below 1K. The technology for low-power sub-Kelvin cooling is well established and available products offer fully automated operation, require no special supporting infrastructure and little or no cryogenics expertise. In this paper we present breaking developments with the very latest products of this type. CRC's compact GL4 modules are designed to interface to the Sumitomo RDK101 cold head, run from a CNA-11 compressor, which is air-cooled, utilises single-phase electricity, and is small enough to fit under a desk or even into a 19-inch rack. A medium-size GL4 module runs at a base temperature of approximately 800mK and typically provides around 40 hours run time under a 100μW applied load. We are testing a new design of GL4 incorporating many improvements to give more consistent performance. We also compare and contrast the performance obtained using the RDK101 cold head with a new cold head in development by Sumitomo, the 2KGM. This new cold head, an evaluation version of which has kindly been made available to us by Sumitomo, is even smaller than the RDK101. It has superior cooling power to the RDK10I at the second stage, and hence reaches a lower operating temperature while still using the compact CNA-11 compressor. Our results clearly demonstrate that the lower temperature of the 2KGM produces significantly better performance from our GL4 modules, enabling longer run times and greater heat lift. Operational characteristics such as cooldown time and GL4 recycling time are the same for both RDK101 and 2KGM. The new medium-size GL4 provides a run time of around 45 hours when operated under a 100μW applied load with the RDK101/CNA-11 combo, but the 2KGM further improves the new GL4's performance under all load conditions.

Low-Temp Cryocooler Development, Paper No. 6.7

Calculation Analysis and Preparation Optimization of Silver Powder Sintered Heat Exchangers at Extremely Low Temperature

Z.J. Pan, L.J. Wei, M.W. Zheng, M.G. Zhao, L.J. Liang, Key Lab of Space Energy Conv. Tech., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

Due to the Kapitza resistivity, a sharp deterioration of heat transfer occurs between solid and liquid in the heat exchanger of the dilution refrigerator at extremely low temperature. It is necessary to use silver powder sintered heat exchangers to optimize the interface heat transfer. A theoretical calculation of heat exchangers at extremely low temperatures was carried to analyze the influence of the Kapitza resistivity on heat transfer performance. Silver powders with different particle sizes of 50nm, 200nm and 500nm were selected for the preparation of sinters. Their micro-scale sintering conditions, porosity, thermal conductivity and specific surface area were carefully presented. Combining theoretical calculations with experimental results, the performance of the sintered heat exchangers at extremely low temperatures could be optimized.

PT & Stirling Cryocooler Modeling, Paper No. 7.1

CFD Simulation of a Hybrid Cryocooler with Pulse Tube Precooling

S. Yang; W. Yang; C. Wang; D. Qin, Univ. of Chinese Academy of Sciences, Beijing, China

Stirling/Pulse tube hybrid cryocooler (SPC) combines the high efficiency feature of Stirling cryocooler and the high reliability feature of pulse tube cryocooler, which is attractive for space applications with tight requirements on the cryocooler. In this paper, the modelling of a U-type hybrid Cryocooler with a one-stage stirling and two-stage pulse tube is presented. The influence of pulse tube precooling on the temperature field and velocity field in the pulse tube is studied with FLUENT. It is found that precooling can change the internal temperature distribution of the pulse tube and has a great influence on the cooling capacity of the second stage. Without precooling of the pulse tube, the cryocooler outputs its cooling capacity with its second stage of 0.7W@30K and its first stage of 7W@80K, which the input PV power is 133W. When the first stage cold finger is connected to the middle part of pulse tube via a heat bridge, the input PV power is maintained and the cooling capacity changed to 1.2W@30K and 6W@80K respectively. It is found that the precooling of the pulse tube can improve the two-stage capacity of the U-type hybrid cryocoolers.

PT & Stirling Cryocooler Modeling, Paper No. 7.2

Effect of Aftercooler Configuration on the Performance of Pulse Tube Cryocoolers

Y. Yasukawa, Fuji Electric Co., Tokyo, Japan; and Y. Ueda, Tokyo Univ. of Agriculture and Tech., Tokyo, Japan

The demand of performance improvement for miniature pulse tube cryocoolers (PTCs) recently increases. To increase the performance, we focus on an aftercoolder. This is because an aftercooler is the main part connecting inside and outside of the system. The heat path in an aftercooler is based on the heat transfer between helium gas and the heat exchanger elements and the outside casing. It is important to enhance the heat transfer and to reduce the heat contact resistance. In this work, the some kinds of aftercooler were constructed and their thermal characteristics were experimentally obtained using DC and oscillatory (AC) flow. The obtained results show the difference betweent the thermal performance of the aftercoolers with DC flow and that with AC flow. Therefore, we performed numerical calculation to understand this difference and found important knowledge to improve the cooling performance of PTCs.

PT & Stirling Cryocooler Modeling, Paper No. 7.3

Design of High Capacity Pulse Tube Cooler with C-Type Flexure for High Temperature Super Conductor Applications

M. Sudheer, B.T. Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

High-capacity Stirling-type pulse tube coolers (PTCs) are promising candidates for cooling High Temperature Superconducting device applications. A compressor for a cooler demands less vibration, high reliability, and low cost. The piston and cylinder are arranged to be non-contacts in order to improve reliability in the developed compressor. The moving element including the piston is supported with C type flexure bearings on one side of this piston and low cost have been realized. A clearance seal constituted with the piston and the cylinder is maintained by optimizing rigidity of flexure bearings and the distance between flexure bearings. Design of compressor has to be done by using SAGE and ANSYS structural analysis. Design and analysis of Stirling type pulse tube cryocooler to obtain 50K, at No load condition by giving 5W as input power to the compressor. SAGE and REGEN 3.3 software analysis has to be done for Regenerator and Pulse tube cooler to find out optimum parameters.

PT & Stirling Cryocooler Modeling, Paper No. 7.4

Reverse Application of a Coaxial Free Piston Stirling Engine for Space Applications

P.S. Adithian, B.T.Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

Owing to their advantages of high overall thermal efficiency, fuel flexibility, low noise, vibration and low emissions, Stirling engines, especially dynamic Stirling engines (i.e., free-piston Stirling engines, FPSEs) are promising candidates for space power applications. It has a high efficiency and can achieve that efficiency at low engine temperature ratios. Low temperature ratios and high efficiencies allow power system operation at high cold-end temperatures. Free-piston Stirling engines can be designed to very low power levels. The space power Stirling converter can be designed to operate at a fixed power output. As other options are considered, the Stirling engine can be designed to load follow. The approach would be to add a small displacer drive linear motor, which would control the displacer stroke, thereby modulating the power output. The selection of free-piston Stirling power conversion systems offers the system designer great flexibility in the overall system integration. Proper system trade-offs must be made to optimize overall system mass using a free-piston Stirling engine. The free-piston Stirling machine has been used as either thermal engine, cryocooler, or heat pump, due to its compact structure, high efficiency, and reliability. A compact engine-refrigerator dual-functional coaxial free-piston Stirling engine can be designed. As a refrigerator or cryocooler, it is normally driven by a linear motor and operating with dynamic noncontact gap seal technology. The compressor piston and the displacer (moving parts) are fully non contacting with the cylinder. Free-piston Stirling cryocoolers (FPSC) have been widely used in aerospace applications. Design of the stirling unit is done with a target cooling power of 100 W. Design and analysis are done with sage6.0. Fluid flow medium is studied with Ansys.

PT & Stirling Cryocooler Modeling, Paper No. 7.5

Thermodynamic Analysis and Design of Miniature BLDCM Driven Crank Driven Cooler

K. Santhosh, B.T. Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

Stirling cryocoolers are widely used in the cooling purpose of military, satellite imaging cameras and other applications. Stirling cryocooler working is based on Stirling cycle. The cryocooler consists mainly compression piston, regenerator and expansion piston. Generally crank driven compressors driven by BLDC motor. These are smooth, silent and at the same time system runs with low vibration and acoustic noise. Helium gas used as refrigerant. Crank used in the design to maintain a ninety-degree phase difference between compression piston and expansion piston to achieve realistic process. There are many losses in the cryocooler such as conduction loss through solid bodies, temperature swing loss, regenerator ineffectiveness loss, pressure drop loss, shuttle conduction loss etc.sage 6.0 and regen3.3 are Graphical interface that support simulation and optimization. Sage software is used to model and optimize Stirling cycle engines and coolers, pulse-tube cryocoolers, and other types of cryocoolers. Mass, momentum, energy equations are solved by numerical analysis for 1-D fluid flow with charge pressure of 30 bar. In order to reduce losses in regenerator a clear study helps us to find optimum parameters which are suitable to give better coefficient of performance. In this step the length of regenerator bed, diameter are fixed, and the two ends of regenerator such as, warm end and cold end are maintained at a temperature of 300 K and 80 K respectively. The use of multi mesh in the regenerator helps in enhancing the performance of the cooler. In the later stage complete cryocooler is studied by a software tool sage6.0. A systematic Sage software model is made with each and every component and analysis done for cryocooler to get 1.5 W cooling capacity with less than 20 W compressor input power. The variation of COP, refrigeration effect, Work input and other with the operating parameters are studied.

PT & Stirling Cryocooler Modeling, Paper No. 7.6

Advances in a Resonance Tube-Coupled Duplex Stirling Cooler

G.Y. Yu, H.Y. Ma, Y. Ma, W. Dai and E.C. Luo, TIPC, CAS, China; X.W. Li, CSDDC, China

A resonance tube-coupled duplex Stirling cooler is thermally driven and thus possesses remarkable advantages of high exergy efficiency, high reliability and resilience. This novel configuration has been preliminarily validated through experiments. Although later a numerical optimization has been conducted and an intriguing heat-to-cooling-power exergy efficiency of 26.8% was obtained, experimental verification is lacking. Based on recent progresses in both free piston Stirling heat engine and cryocooler operating around 50 Hz, the duplex system was optimized accordingly. A special concern was imposed on the resonance tube and several types of resonance tube were investigated. Among the numerical results, by using a converging-and-diverging resonance tube, a heat-to-cooling-power exergy of 28% and a cooling power of 1.0 kW were obtained at 110 K with a mean pressure of 5 MPa, hot temperature of 923 K, ambient temperature of 303 K, operating frequency of 50 Hz.

PT & Stirling Cryocooler Modeling, Paper No. 7.7

Research of a High Capacity Coaxial Pulse Tube Cryocooler Working at 170 K

L.J. Wei, N.L. Wang, M.G. Zhao, J.H. Cai, L.T. Liang, Technical Institute of Physics and Chemistry, CAS, Beijing China

A high cooling capacity coaxial PTC working at middle temperature is designed by SAGE software, and the outer diameter and the length of the regenerator are 40mm and 32 mm, respectively. As the cold finger structure is short and thick, the jet flow from the inertial tube can obviously affect the flow field in the pulse tube and influence the cooling performance of the cold finger. In order to analyze the hot-side flow straightener on the fluid flow in the pulse tube and the cooling capacity of the PTC, a two-dimensional axisymmetric CFD model is built using FLUENT software to prove the importance of the flow straightener. A test system is built to investigate the cooling performance of the manufactured PTC and study the influence of the mesh number of the straightener on the cooling capacity. The experimental results show that when a 100ss mesh is applied in the hot-side flow straightener, the PTC achieves the best performance. With an electric power of 200W added to the compressor, the PTC obtains a no-load temperature of 59K and a cooling power of 45 W at 170 K, and the system efficiency can reach 22.5%.

PT & Stirling Cryocooler Modeling, Paper No. 7.8

Study of the Effect of Gas Contamination in Stirling Cryocoolers

C. L. Yin, Y. Gao, K. Yang, Z .Wang, X. H. Fan, S .S .Chen, Inst. of Cryogenics and Electronics, Hefei, China

One of the most important characteristics of spaceborne stirling cryocooler is its reliability over a lifetime. The wear abrasion and gas contamination exsiting in stirling cryocooler are the main failure modes that influence the reliability of sapceborne stirling cryocooler. While design improvements have reduced the probability of the wear abrasion, the excessive gas contamination is still a major risk, typically in excess of 10 years. Aimed at gas contamination failure mode in stirling cryocooler, experiments were realized in order to study the effect of contamination on the working gas in the stirling cryocooler operating at 60 K in the paper. The accelerated contamination experiments were performed to quantify the effect of impurity gas. The curve of the outgassing rate in the stirling cryocooler as a function of the time was obtained and discussed. The results supported the reliability design and test of stirling cryocooler.

PT & Stirling Cryocooler Modeling, Paper No. 7.9

Lumped Element Thermoacoustics Applied to Pulse Tube Cryocoolers

V. Kotsubo, NIST, Boulder, CO

Lumped element thermoacoustics is an approach to describing regenerative coolers, where pressure amplitude and volume flow rate, instead of pressure amplitude and mass flow rate, are the flow variables. Energetics are described using enthalpy flow, entropy flow, and acoustic power, instead of simply enthalpy flow as in conventional descriptions. The two main pulse tube components- the regenerator and thermal buffer tube (pulse tube), are simply compressible volumes that support temperature gradients, with flow entrances at the warm and cold ends. The compressible volume behavior allow the complex volume flow rates to be separated into components in-phase and in-quadrature with the pressure amplitude. The component in-quadrature generates the pressure amplitude- essentially compression of a gas in a can, while the component in-phase with the pressure amplitude time-averages with the pressure amplitude to provide acoustic power. This deconstruction separates the compliant, or gas spring behavior of the pulse tube from the power conversion behavior of the pulse tube, and provides a very simple picture of many of the processes within the cooler. These basic concepts have been generally developed for thermoacoustic systems, so in this paper I summarize the specific application to an idealized pulse tube and discuss implications regarding cooler performance.

PT & Stirling Cryocooler Modeling, Paper No. 7.10

Thermal Losses in a Coaxial Pulse Tube Cryocooler

H. Rana, M. A. Abolghasemi, R. Stone, M. Dadd, P. Bailey ,Univ. of Oxford, UK

Conductive and radiative losses in pulse tube cryocoolers are difficult to predict, particularly in a coaxial configuration. The static losses in a pulse tube must be accounted for and factored when determining the cooling power, and the thermal losses as a result of radiation must be quantified to establish their significance. Studies have previously shown that there is a discrepancy between computationally simulated cooling performances and experimentally measured values. This could be attributed to the under-prediction of thermal losses in numerical models. A lumped parameter model using ESATAN-TMS was created to determine the thermal losses in a coaxial pulse tube cryocooler in order to improve model validation between experimental and computed values. The thermal losses simulated were found to significantly improve the correlation between numerical and experimental data for a coaxial pulse tube using an active displacer. An analysis of the variation of the losses at different regions in the pulse tube and its impact on cooling performance is presented.

PT & Stirling Cryocooler Modeling, Paper No. 7.11

Boundary Layer Losses in a Miniaturized Tapered Pulse Tube

A. Ghavami, S.M. Ghiaasiaan, Georgia Tech, Atlanta, GA; C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

Miniaturized cryocoolers are a vital components for cooling of infrared sensors in small satellites. Smaller cryocoolers have lower compression and expansion swept volumes and achieve cooling by operating at high frequencies (100-300 Hz range). Previously, we studied high frequency straight pulse tube, and investigated the effects of diameter, aspect ratio of pulse tube, bounding temperatures and frequency on the boundary layer losses. In this follow-up study the role of design parameters and operating conditions on the tapered pulse tube boundary layer losses is investigated. Computational fluid dynamics (CFD) is used for this investigation. The results show the existence of a size threshold, where smaller high frequency tapered pulse tube cryocoolers can no longer be useful due to their high boundary layer losses.

Phase Shifter and Displacer Research, Paper No. 8.1

External Phase Shifting Tuning Mechanism in a Miniature Pulse Tube Cryocooler Using a Semi-Active Electromagnetic Damping System

Y. Greenberg, G. Grossman, Technion – Israel Inst. of Tech., Israel

A semi-active electromagnetic damping mechanism was developed to externally control the phase shift and amplitude at the hot end of a pulse tube (PT) cryocooler. The semi-active phase shift (SAPS) mechanism was designed, built and tested, and included a voice coil suspended on a silicon diaphragm and a flexural bearing. The development included theoretical calculations, numerical optimization using SAGE®, flexure bearing optimization and development, off-the-shelf voice coil selection and modal simulations of the entire system using ANSYS® finite element software. The goal was to obtain the optimum phase shift between pressure and flowrate and thus reach the optimal cryocooler performance. During experiments, a stick-slip phenomenon inherent to the voice coil influenced the cryocooler performance, and the lowest temperature observed in the experiments was 225K (without vacuum in the containing chamber) at 100 Hz operational frequency. However, the results show that the system was capable of externally tuning the cold end temperature, and provided a proof of concept for the application of external phase shift and amplitude tunable mechanism.

Phase Shifter and Displacer Research, Paper No. 8.2

An Exploration about a Micro-Cryocooler with Warm-Displacer Phase Shifter

Z.M. Guo, Tongji Univ., Shanghai, China and Univ.of Wisconsin-Madison, WI, USA; J.M. Pfotenhauer, Univ. of Wisconsin-Madison, WI, USA; S.W. Zhu, Tongji Univ., Shanghai, China

The displacer type pulse tube cryocooler can theoretically achieve any phase angle between the pressure and volume flow oscillation, and recover the expansion work at the pulse tube warm end. Significant developments with the displacer approach have demonstrated very promising improvements to the efficiency, as compared with the other phase shifting options. Extending this same phase shifting approach to a miniature pulse tube cryocooler may provide advantages over the other alternatives, since for example even inertance tubes are severely limited in their phase shifting capability when the associated acoustic power decreases below 20W. The detailed design method associated with the displacer is shown in this work, introducing the method for choosing the major parameters of the displacer in order to obtain a desired phase angle for a micro-cryocooler. An example case displays the coupled relationship between the displacer radius and mass, piston axial length, frequency and spring stiffness. The same parameters couple the piston displacement to the phase angle between the piston displacement and piston force. A number of 3D parametric maps are generated relating the various key design parameters and providing the means for a rough initial displacer design. Additionally, the displacer-rod diameter ratio is shown to influence the micro displacer piston performance. Rod diameter ratios in the range of 0.14 to 0.32 were explored in this work.

Phase Shifter and Displacer Research, Paper No. 8.3

Detailed Analysis of a Coaxial Stirling Pulse Tube Cryocooler with an Active Displacer

M.A. Abolghasemi, H. Rana, R. Stone, M. Dadd, P. Bailey, Dept. of Engin. Science, Univ, of Oxford, Oxford, UK; K. Liang, Dept. of Engin. and Design, Univ. of Sussex, Brighton, UK

Coaxial pulse tube cryocoolers are the configuration of choice as they allow better access to the cold head. Hence, a previously built and tested in-line pulse tube cryocooler which uses an active displacer for phase control has been modified into a coaxial configuration. The active displacer allows the mass flow and the pressure pulse at the cold end of the pulse tube to be easily adjusted for optimum performance. The displacer also allows the expansion power at the warm end of the pulse tube to be recovered in order to operate more efficiently. A numerical Sage model is used to demonstrate this by examining the work flows throughout the cryocooler and it is shown that more than 6% of the power required to drive the cryocooler comes from the warm end of the pulse tube via the displacer. When using an inertance tube or orifice, this expansion power is dissipated as heat which is why using a displacer can lead to a more efficient cryocooler. Moreover, the effect of changing the displacer phase and stroke on cryocooler performance and pressure characteristics is examined both experimentally and numerically.

Phase Shifter and Displacer Research, Paper No. 8.4

A Passive Displacer for a Stirling Pulse Tube Cryocooler

H. Rana, M.A. Abolghasemi, R. Stone, M. Dadd, P. Bailey, Dept. of Engin. Science, Univ. of Oxford, UK

Stirling pulse tube cryocoolers (SPTCs) can operate by incorporating a displacer into the warm end of a pulse tube cryocooler. Previous studies have shown that SPTCs running with an active displacer demonstrate good performance and higher efficiencies than pulse tube cryocoolers that utilise inertance tubes. Having an actively driven displacer requires a second phase from the power electronics, and the extra motor and electrical feedthrough adds to the complexity of the design, so it is desirable to have a passively driven displacer. This study presents the analysis and design of a passive displacer driven by the pressure difference across the displacer piston and shaft. A harmonic analysis and design of the displacer unit was completed, in conjunction with a numerical model constructed in Sage. This permitted the correct characteristics for the displacer to be designed in order to operate with the existing compressor and cold head. This included testing and analysis of different spring assemblies, optimisation of the displacer dimensions, and the piston moving mass. The passive displacer will replace the active displacer in an existing 80 K coaxial SPTC.

Phase Shifter and Displacer Research, Paper No. 8.5

Optimization of Phase Controller for Pulse Tube Cryocooler

D. Abraham and B.T Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

The development of pulse tube cryocoolers has increased rapidly because of its mechanical simplicity and high reliability due to the absence of moving parts in the cold region. Pulse tube cryocoolers are suitable for cooling of infrared sensors, low noise electronic applications, liquefaction of gases, etc. A Pulse Tube Cryocooler performance depends on the phase controller. The phase controller used here is inertance tube-bounce space. The phase difference between the compressor and bounce space flow is around 180º. If this phase difference is utilized, the inertance tube-bounce space combination can act as a compact phase shifter. The objective of this paper is to optimize the dimensions of the inertance tube and bounce space for the best performance of Pulse Tube Cryocooler. The performance of a Stirling pulse tube cryocooler is maximum when the pressure and mass flow are in phase at the midpoint of the regenerator. To achieve this phase shift in acceptor, the pressure should lag the mass. A Cryocooler system was designed using Sage software, which uses inertance tube-bounce space as a phase shifter. The maximum power input to the cryocooler was limited to 100W. Simulations were conducted for varying inertance tube dimensions (diameter and length), reservoir volume, frequency, and charge pressure. This model was used to maximize the cooling effect for the highest COP. The COP of the optimized cryocooler was found to be 0.043, which is 16% of the Ideal COP of pulse tube cryocoolers.

Phase Shifter and Displacer Research, Paper No. 8.6

Development of Stirling Cryocooler Model that Includes a Full Simulation of the Appendix Gap

T. Rawlings, M. Crook, M. Hills, STFC Rutherford Appleton Laboratory, Harwell, Oxford , UK

A new Stirling cryocooler model has been developed at the Rutherford Appleton Laboratory. This one-dimensional finite difference model is able to simulate single and two-stage cryocoolers. The model uses the latest friction factor and heat transfer correlations from the literature and simulates turbulence generation and thermal penetration depths. It runs fast enough to be useful for optimisation, thanks to a robust artificial convergence technique. The model includes a full representation of the cold head, including the displacer motion and flow past the displacer; this enables the optimisation of certain parameters that could not be assessed previously. The model has been used to optimise the geometry of an existing single-stage cryocooler and predicts that significant performance improvements can be made by changing the geometry.

Phase Shifter and Displacer Research, Paper No. 8.7

Application of Signal Analysis in the Study of Dynamic Characteristics of Displacer in Cryocoolers

Z. Wang, Y.D. Lu, C.L. Yin, Y. Gao, The Provincial Key Laboratory of Cryogenic Technology, Hefei, China

Pressure sensors and laser ranging are often used to test the dynamic characteristics of pistons. The test results obtained by them are intuitive and accurate. However, the debugging process is complex. In order to simplify the test process of displacer dynamics in cryogenic coolers, the vibration signal analysis method is used to test the dynamic characteristics of the displacer, and the results obtained can meet the analysis requirements. The signal analysis method can provide a quantitative basis for the debugging and fault detection of cryogenic coolers.

GM, PT & Stirling Regenerator Research, Paper No. 9.1

A Temperature Instability in 4 K Cryocooler Regenerators Caused by Real Fluid Properties

R. Snodgrass, V. Kotsubo, J. Ullom, and S. Backhaus, NIST, Boulder, CO

The thermodynamic and fluid properties of helium vary dramatically at pressures near 1 MPa and temperatures below 30 K. Depending on the temperature, these properties can either improve or degrade the cooling ability of regenerative cryocoolers. For example, the thermal expansion coefficient multiplied by temperature peaks near 9 K, resulting in less enthalpy flow down the regenerator and locally improved cooling power. The same product starts to rapidly decrease below 6 or 7 K, and local cooling power instead drops. Such dramatic changes in properties over small ranges of temperature are a potential mechanism for temperature instability, where if one portion of the regenerator is at a slightly different temperature than another, the local differences in cooling power may overcome stabilizing processes (e.g. heat conduction) and grow into a large temperature asymmetry. Using a densely-instrumented, commercial 4 K pulse tube refrigerator, we have measured temperature differences of up to 19 K across the diameter of a 3 cm diameter, second-stage regenerator. These large azimuthal temperature asymmetries can appear and disappear over small changes in end conditions (e.g. with only 0.1 K changes in cold end temperature) but do so in a predictable manner related to real fluid properties. We propose stability criteria that may govern the temperature asymmetries. We also consider the instability's effect on cooling power at the cold end and at intermediate positions along the second-stage regenerator.

GM, PT & Stirling Regenerator Research, Paper No. 9.2

Leveraging Real Fluid Effects as a Tool for Power Flow Measurements in 4 K Cryocooler Regenerator

R. Snodgrass, V. Kotsubo, J. Ullom, and S. Backhaus, National Institute of Standards and Technology, Boulder, CO

The real fluid properties of helium have a major impact on the thermodynamics of pulse tube and Gifford-MchMahon cryocoolers operating near the critical point, i.e., below about 30 K and pressures around 1 MPa. These real fluid properties limit the available cooling power at the lowest temperatures (below approximately 6 K), but they can also be leveraged to absorb a significant additional heat load in the 8 K to 15 K temperature range. This additional cooling capacity has been leveraged in several applications, but a deep understanding of the physical processes and the best approach to leverage them are lacking. We have densely instrumented the second stage of a two-stage pulse tube refrigerator to closely investigate the details of these thermo-fluid processes with a goal of validating physical models and developing design tools to integrate this additional cooling to best support lower-temperature cryogenic refrigeration stages. We discuss the design of the experiment, present preliminary data, and discuss initial interpretations of the results in the context of thermodynamic models of these processes.

GM, PT & Stirling Regenerator Research, Paper No. 9.3

Theoretical and Experimental Investigations on the HoCu2 and GOS as Regenerative Materials at 4-20K

R. Cao, X. Zhi, C. Huang and L. Qiu, Inst. of Refrig. and Cryogenics, Zhejiang University, Hangzhou, China

It is still hard for the Stirling type pulse tube refrigerator (SPTR) to work at liquid helium temperatures with high efficiency. One of the reasons is the large regenerative loss under such low temperatures. In this work, the cooling performance of the regenerative materials, HoCu2 and GOS, at liquid helium temperatures are theoretically and experimentally investigated. A Sage model is established based on a three-stage SPTR, and simulations on the regenerative performance in different proportions of HoCu2 and GOS are carried out. Theoretical investigations indicate that under different precooling temperatures and refrigeration temperatures, the preferable proportions of HoCu2 and GOS will be different. The influence of heat conduction and specific heat should be taken into consideration comprehensively. A three-stage SPTR is tested and the experimental results show that the components and proportions of the regenerative materials have a great effect on the cooling performance. Only when the temperature decreases to about 5.2 K can GOS contribute to improving the regenerator performance, since its specific heat ratio is higher than the HoCu2's one at this temperature zone. While using HoCu2 as the only regenerative material, the SPTR can achieve a lower refrigeration temperature better than using GOS. The experimental results are consistent with simulations.

GM, PT & Stirling Regenerator Research, Paper No. 9.4

Effects of Structural Asymmetry on Regenerator Temperature Non-Uniformity in a High-Power Stirling-Type Pulse Tube Cryocooler

T. Wei, X. Tao, X. Zhi, X. You, J. Wang, L. Qiu, Inst. of Refrig. and Cryogenics, Zhejiang Univ., Hangzhou, China

High-power Stirling-type pulse tube cryocoolers (SPTC) has the advantages of compact structure, low maintenance and long service life, and are expected to be an ideal candidate for high temperature superconductivity (HTS) application. The regenerator temperature non-uniformity which significantly deteriorates the cooling performance is still a key problem for the high-power SPTC. Previous studies mainly focused on combinations of regenerator filling to reduce the temperature non-uniformity. However, the physics of regenerator temperature non-uniformity are still unclear. In this study, the effects of asymmetry of inertance tube, cold end heat exchanger and aftercooler on the regenerator temperature non-uniformity haves been extensively investigated on a self-made high-power Stirling-type pulse tube cryocooler working at liquid nitrogen temperatures. Experimental results show that the structure of the aftercooler has a great influence on the temperature non-uniformity of the regenerator. When the water inlet and the outlet direction of the aftercooler are adjusted, the circumferential temperature distribution in the middle of regenerator also changes greatly. The non-uniform cooling water temperature is verified to be an inducement for the non-uniformity temperature in the regenerator. These results would be helpful for further geometry optimization and performance improvement of high-power SPTCs.

GM, PT & Stirling Regenerator Research, Paper No. 9.5

Optimization of the Transition Regenerator for Two-Stage Thermal-Coupled Stirling-Type Pulse Tube Cryocooler

Q.L Zhu, Y.J Liu, J.Quan, J.T Liang, Key Laboratory of Space Energy Conv. Tech., Tech. Inst. of Physics and Chem., CAS, Beijing, China

For the purpose of transferring the PV power from the compressor to the regenerator hot-end of the low-temperature cryocooler, and preventing excessive energy dissipation at the same time, a section of regenerator without pulse tube called transition regenerator is added between the compressor outlet and the regenerator hot-end of the low-temperature cryocooler. The transition regenerator can establish a certain temperature gradient for the gas to play a thermal buffer function. At present, the transition regenerator as an important component causing PV power loss of the two-stage thermal-coupled Stirling-type pulse tube cryocooler, but there are few related researches on it. This article optimizes the experiment from the length, diameter and filling method of the stainless steel wire mesh. The results show that the cooling capacity at 20K is increased by 18.6%, meanwhile, a cooling capacity of 168.6mW@20K and a relative Carnot efficiency based on acoustic power input of 5.2% can be reached.

GM, PT & Stirling Regenerator Research, Paper No. 9.7

Cold Head Maintenance of GM Cryocoolers with Minimal Service Interruption

R. Verma, Nat'l Inst. of Tech., Jalandhar, India; H.N. Nagendra, G.A. Vivek, S. Kasthurirengan, U. Behera, Centre for Cryogenic Tech., Indian Inst. of Science, Bangalore, India; N.C. Shivaprakash, Instr. & Applied Physics, Indian Inst. of Science, Bangalore, India

Multistage GM Cryocoolers produce very low temperatures with large refrigeration powers. With the rare earth based regenerator materials, the cold head temperature gets extended below 4K. Further, in view of the orientation independent nature of GM Cryocoolers when compared to the PT cryocooler, they are being used extensively for cooling of superconducting magnets (SC). In particular, they are used for cooling the SC magnets of MRI systems starting from room temperature known as dry magnets. Although, refilling liquid helium at regular intervals and the associated infrastructures are avoided allowing the MRI systems to be operational continuously, the maintenance of the cryocooler need to be carried out at designated intervals. Hence, the MRI system has to be shut down causing the interruption of this medical diagnostic tool. It is desired to have the maintenance time periods as short as possible. In order to achieve the above, experimental studies on the cold swap maintenance on a two stage GM cryocooler have been carried out and their results are discussed here. In the above study, initially the GM cryocooler is made to cool an equivalent thermal mass simulating SC magnet. On switching off the cooler, heaters on cold heads warm up the cryocooler to ambient temperature. The temperature profiles of warm up of the cold head as well as the thermal mass have been studied with different heating methods. These results are analyzed to obtain the optimum heating procedure which leads to the shortest maintenance time for the GM cryocooler. The results of our preliminary experimental studies are presented here.

GM, PT & Stirling Regenerator Research, Paper No. 9.8

Measurement of Thermal Conductivity of Some Candidate Regenerator Materials at Cryogenic Temperatures

A. Ghavami, S. M. Ghiaasiaan, Georgia Tech, Atlanta, GA; C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

In this experimental study, the thermal conductivities of some regenerator materials that have recently been the focus of attention for incorporation in miniature or highly efficient Stirling and pulse tube cryocoolers are measured over a wide range of cryogenic temperatures. The experimental apparatus utilized for these experiments has been designed based on adaptation of the guarded-comparative-longitudinal heat flow technique (ASTM E1225-13).

GM, PT & Stirling Regenerator Research, Paper No. 9.9

Development of a 2D/3D Computational Fluid Dynamic Code for Analyzing Regenerators

A. Ghavami, S.M. Ghiaasiaan, Georgia Tech, Atlanta, GA; C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

Regenerators are critical components of pulse tube and Stirling cryocoolers. The design of such cryocoolers is often centered around a careful and accurate design and analysis of their regenerator(s). Industry standard design tools such as SAGE and REGEN are efficient, however, they are 1D and cannot capture pore-level multi-D flow and heat transfer effects. Computational fluid dynamic (CFD) analysis of regenerators with commercial software such as ANSYS Fluent or COMSOL, furthermore, is a very time consuming due to the occurrence of periodic flow . A fast-running, flexible and efficient 2D/3D computational fluid dynamic (CFD) code is under development at Georgia Tech, specifically for the analysis of regenerators. Pore-level simulations can be carried out with this code for arbitrary and complex regenerator fillers. The computations are minimized by focusing only on critically important parameters. The theoretical and computational characteristics of this code are discussed, and typical code predictions representing friction, heat transfer and entropy generation, are presented and compared with experimental data as well as the predictions of the ANSYS Fluent CFD code.

PT/Stirling Compressor Development, Paper No. 10.1

Moving Iron Based Pressure Wave Generators: Preparing Air Liquide's New Generation Pulse Tube Cryocoolers

G. Coleiro, P. Barbier, J-M Niot, T. Wiertz, Air Liquide Adv. Tech., Sassenage, France; G. Aigouy, K. Benoit, F. Claeyssen, CEDRAT Tech., Meylan, France; and C. Daniel, CNES, Toulouse, France

Pressure wave generator is the most determining component in the Pulse Tube cryocoolers performances. Key performances are cryogenic efficiency, micro-vibration levels and magnetic field levels. Since five years, Air Liquide has developed different pressure wave generator prototypes, with the support of French Space Agency CNES, and in cooperation with CEDRAT Technologies who brings its expertise related to linear actuators for space application. The consortium studied and tested several actuator topologies and sizes. Electromagnetic linear actuators driving opposed piston is the most typical architecture. CEDRAT technologies develops compact moving iron actuators (the MICA™) exhibiting excellent efficiency. Air Liquide has integrated MICAs into a TRL4 compressor which has been used to test and develop technological blocks and assembly architectures. This dismountable compressor multiplies the possible test configurations and assess: • Actuator and CPA assembling and alignment strategies • Piston alignment method • Clearance gap adjustment and design • Management of the moving part guidance Test results exhibit excellent cryogenic efficiency when coupled with AirLiquide LPTC pulse tube cold fingers. Moreover, the compressor shows low heat generation and encouraging EMC level. The presentation will first show the different pressure wave prototypes and the breadboard compressor developments. Then the breadboard cryogenic performances and EMC level will be presented.

PT/Stirling Compressor Development, Paper No. 10.2

Design of Oil-Free, Resonating Linear Compressors for Five-Stage Cascade System with New Refrigerants

A. Vidhate , B. T. Kuzhiveli, Centre for Adv. Studies in Cryogenics (CASC), Nat'l Inst. of Tech., Calicut, India

Due to its reliability & high efficiency compared to other systems, VCR systems are most famous systems being used for refrigeration purpose nowadays. To make this system more efficient, ecofriendly, durable and compact, linear compressor seems to be advantageous over the conventional compressor. The linear motor has been proved to be electrically more efficient than that of rotary induction motor. Along with this, absences of slider crank mechanism make linear compressor drive mechanically more efficient and durable. Oil-free operation is also possible which leads to compact design of heat exchangers. Cascade refrigeration system is one of the ways to reach low temperatures. It consists of number of VCR cycles cascaded together & each cycle run by its own individual compressor. The evaporative temperature for liquefaction of air (78.8 K) can be achieved by cascading 5 VCR systems each run by individual linear compressor. In this work, cascade system with cooling capacity 5 W at the evaporative temperature of 78.8 K and condenser temperature of 40 °C has been taken into consideration and oil-free, resonating linear compressors for each stage have to be designed for this purpose. Due to restrictions on HCFCs, design is being carried out considering ecofriendly refrigerant R1270 as a working substance in first loop. For the subsequent loops, propane (R270), ethylene (R1150), methane (R50) & air (R729) will be used in order. As assumed evaporative & condenser temperatures for first loop falls in the range similar to that required for air conditioning applications, this compressor design may serve dual purpose. It would form one of the loops in cascade system & this individual loop can directly be used in the air conditioning applications. The new linear compressors are expected to be efficient, compact & more durable compared to the conventional compressors run by rotary induction motor.

PT/Stirling Compressor Development, Paper No. 10.3

High Frequency Steel Flexure Acoustic to Electric Transducer for Cryocoolers

T.W. Steiner, Etalim Inc., Vancouver BC, Canada

A steel flexure acoustic to electric transducer developed for a thermoacoustic engine is proposed for use as a driver for cryocoolers. This transducer operates at around 500 Hz and will thus allow for the construction of simpler, more reliable, more compact and higher power density cryocoolers. The transducer is characterised by high efficiency (90%), high power (1 kW), lack of any sliding parts and was designed for very long maintenance free life. The transducer uses a moving iron only flux switching alternator to allow for efficient small motion actuation. Furthermore, the alternator is external to the pressure vessel and thus there is no possibility of contamination of the working gas by outgassing. A 77K cryocooler using such a transducer was simulated using thermoacoustic code vetted on an engine and the results are very competitive with a Stirling cryocooler.

PT/Stirling Compressor Development, Paper No. 10.4

Enhancement of Linear Compressor Power and Performance Improvement of Pulse Tube Refrigerator

B. Kim, J. Bae, S. Jeong, Korea Adv. Inst. of Science and Tech. (KAIST), Daejeon, Korea

The performance improvement of pulse tube refrigerator is investigated by amplifying the power of the cold linear compressor. In a previous research, the cold linear compressor which operated at liquid nitrogen temperature successfully demonstrated producing sufficient PV power for operating a pulse tube refrigerator to reach 20 K. Although the pulse tube refrigerator using a cold compressor achieved the cooling power of 0.4 W at 20 K, it was found that the regenerator performance was poor because of the insufficient output power from the compressor. To increase the output power using the same linear motor, a new piston-cylinder assembly has been fabricated. The diameter of the piston is enlarged from 27 mm to 33 mm and the surfaces of the piston and the cylinder are coated with PTFE and Nickel, respectively. The linear compressor using new piston produces about 80 W of PV power, which is 60% larger than the previous result. The cooling performance of the pulse tube refrigerator is, therefore, improved accordingly with more input power. The pulse tube refrigerator achieves no load temperature of 17.8 K and the cooling capacity of 1.1 W at 20 K. The paper elucidates the detailed design issues of incorporating a cold linear compressor for pulse tube refrigerator.

PT/Stirling Compressor Development, Paper No. 10.5

Design of Resonating, Linear Compressors for Five-Stage Cascade System with New Refrigerants

V.A. Santosh, B.T. Kuzhiveli, Centre of Adv. Studies in Cryogenics, Nat'l Inst. of Tech., Calicut, India

Due to its reliability and high efficiency compared to other systems, VCR systems are most famous systems being used for refrigeration purposes. To make this system more efficient, eco-friendly, durable and compact, linear compressor seems to be advantageous over the conventional compressor. The linear motor has been proved to be electrically more efficient than that of rotary induction motor. Along with this, absence of motion conversion mechanism makes linear compressor drive mechanically more efficient and durable. Also, oil-less operation is possible in this case which have its own benefits. Cascade refrigeration system is one of the ways to reach low temperatures. It consists of number of VCR stages cascaded together and each run by its own individual compressor. In this study, cascade system with total cooling capacity of 20 W at the temperature of 78.8 K had been taken into consideration. This cascade system consisted five stages with refrigerant R1270, R290, R1150, R50 and R729 in series. The first loop of cascade system (with R1270) was designed such that it could be used as dual purpose, either one of the loop in cascade system or individually for air conditioning purpose. The aim of this study was design of linear compressors for each stage for resonating and oil-free operation. The variation of gas spring stiffness had been observed and with some allowance on natural frequency, design had been done for resonating operation. For oil-free operation, enthalpy leakage rate due to transfer of refrigerant past the radial clearance between piston and cylinder had been found out and its effect on overall system performance was also studied. By putting maximum limit on drop in COP of the system due to this transfer of refrigerant, maximum radial clearance that could be provided for oil-free operation had been found for these five stages

Commercial and Laboratory Applications, Paper No. 11.1

Configuration of Cryocoolers in Large Electric Power Systems for Superconducting Electrified Transportation Applications for Enhanced Resilience

S. Telikapalli, P. Cheetham, C.H. Kim, S. Pamidi, Florida State Univ., Tallahassee, FL

Superconducting power devices provide the necessary power density to facilitate the development of electric transportation as long as the required cryogenic environment is maintained. For electric transportation applications, there is the need to ensure a high level of system reliability and the loss of a single component should not lead to a system-level failure. Our research focuses on the development of an integrated central cryogenic cooling loop for multiple superconducting devices. In such a system failure of the central cryo-plant would cause the entire superconducting power system to fail. As a continuation of our research on large superconducting power systems, we are exploring the need for additional redundancies to build in resiliency to the cryogenic system while still achieving the targeted power density for the power network. The power density requirement dictates that redundancy would need to be achieved at the system level and not the device level. This study explored the tradeoffs between cryocooler capacity and the required number of cryocoolers to service the cooling loads of the superconducting distribution network in case of partial failure of a superconducting device or when an individual component requires maintenance. The goal is to develop a more resilient cryocoolers based superconducting power system for electrified transportation applications.

Commercial and Laboratory Applications, Paper No. 11.2

Performance Analysis of Pulse Tube/3He Joule-Thomson Cryocooler for Thermometer Calibration

T. Shimazaki, NMIJ, AIST, Tsukuba, Japan

Joule-Thomson (JT) cooling circuits can enhance the cooling capability of mechanical refrigerators. We have been developing JT cryocoolers for thermometer calibration for more than ten years. Owing to the nature of thermometer calibration, the cryocooler requires a wide operational temperature range with a high temperature control stability rather than a high cooling power. A pulse tube/3He JT cryocooler for precise thermometer calibration was developed. It comprises a commercial two-stage 4 K pulse tube refrigerator and JT cooling circuit, which was designed and built at National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST). The developed cryocooler uses 3He as the working fluid for the JT cooling circuit to reduce the minimum temperature below 0.5 K. This cryocooler utilizes a needle valve that can vary flow impedance for JT expansion. An oil rotary, mechanical booster pumps and a compressor were used for 3He circulation. The value of cooling power was typically 1 mW at 0.65 K. A sub-millikelvin temperature stability can be obtained at the thermometer comparison block that is installed in the cryocooler. The cryocooler has been used for the precise resistance thermometer calibration and evaluation at the temperature range from 0.65 K to 25 K. This paper describes the construction and performance of the developed cryocooler in detail.

Commercial and Laboratory Applications, Paper No. 11.3

Cryocooler Technology for Electron Particle Accelerators

G. Lawler, N. Majernik, A. Fukasawa, J. Rosenzweig, UCLA, Los Angeles, CA

Particle accelerator technology is ubiquitous in modern discovery science. Accelerators are no longer limited to the more well-known high energy physics applications. They are of vital importance to many diverse fields as far reaching as biology, chemistry, condensed matter physics, medicine, and industrial manufacturing procedures. It has then of the utmost importance to develop better understanding of the physics and engineering principles necessary for advanced particle accelerator design. The Particle Beam Physics Laboratory (PBPL) at the University of California, Los Angeles (UCLA) is uniquely equipped to handle these problems and is on the forefront of these studies. One major thrust in accelerator physics in general and PBPL in particular is the application of cryogenic technology to accelerators. The presentation will focus on the use of cryogenic technology in general accelerator R&D research as well as particular developments taking place at UCLA. Discussion will involve studies into normal conducting cryogenic copper accelerating structures for high gradient electron acceleration and in particular the effects of cryogenic temperatures on the reduction of harmful electrical breakdown rates in accelerating structures. A general overview of cryostat design and cryocooler integration into an electron photoinjector will further be presented.

Commercial and Laboratory Applications, Paper No. 11.4

Storage Time and Venting Characteristics for Cryogenic Air Supplies after Turning Off Their Cryocoolers

L. Yan, R. Fernando, D.S. Yantek, J.L. Carr, M.A. Reyes, C.R. DeGennaro, J.A. Yonkey, J.R. Srednicki, CDC/NIOSH, Pittsburgh, PA

Cryogenic air supplies are one of the methods to provide breathable air and to mitigate heat and humidity buildup within refuge alternatives used in underground mines. Before cryogenic air is supplied to an occupied RA, the temperature of the cryogenic air is kept constant at -195°C (-318°F) inside a large dewar using a cryocooler, which uses electrical power. In some cases, the cryocooler might lose power due to a planned or unplanned power outrage, such as relocation of the cryogenic air supply or loss of power during a mine emergency. Without cooling provided by the cryocooler, the temperature of the liquid air will begin to rise and the pressure within the cryogenic air supply's storage dewar will increase due to the buildup of vapor pressure. Once the pressure in the dewar is high enough, the cryogenic air vents through a relief valve to ensure safety. The maximum storage time and the venting characteristics for an underground mine cryogenic air supply when cooling is interrupted needs to be determined before its deployment in a mine. In this paper, researchers at the National Institute for Occupational Safety and Health (NIOSH) investigated the maximum storage time and venting pattern on two different cryogenic systems with no cooling. The two systems differ in size and dewar orientation (horizontal vs vertical). The testing shows that about 7.7 liters of cryogenic air was lost per day by the vertical dewar system. For the horizontal dewar system, the cryogenic air vented about every 2 hours, and about 25.6 liters of cryogenic air was lost per day. The information in this paper could be useful for manufacturers and mines considering the use of a cryogenic air supply as a source of breathable air and/or heat mitigation for refuge alternatives.

Commercial and Laboratory Applications, Paper No. 11.5

Closed Cycle Cryocooler Simplifies the Cryogenic Logistics Workflow

D. Dutta, Bhabha Atomic Res. Centre, Dept. of Atomic Energy, GOI, India

A new way to ship and transport cellular materials puts patients front and center. Logistics is critical to the cell therapy workflow, because if a patient's cell therapy doesn't get there at the right time and in good shape, nothing else matters. Cell therapy companies are facing the challenges with existing liquid nitrogen-based shipments. Scheduling must be rigid to ensure that there is enough liquid nitrogen in the 'dry shipper' for door-to-door shipment. Shipments are put at risk if the manufacturing workflow is delayed, there is a transport hold-up, or the clinical site is not able to receive or manage the shipper. To mitigate the risk of running out of liquid nitrogen, which could lead to unacceptable warming of the sample inside, oversized shippers are used to add extra hold time.Aims are to change all this with features that extend beyond the logistics process right up to the patient in the clinic. Goal is to fully replace liquid nitrogen in the cryogenic cold chain. The system is powered entirely by electricity, which brings the temperature down to liquid nitrogen levels (~ 83 K) and maintains it below (153 K) for up to about five days by use of closed cycle cryocooler. The shipper can be kept 'on charge', docked with a cryocooler, for an extended period. Cryogenic temperatures are maintained the whole time, which represents good news for patients.Removing the need for liquid nitrogen reduces the burden on training and safety procedures. It also simplifies the cryogenic logistics workflow. The shipper can have more days of hold time at cryogenic temperature, which accommodates most scenarios where delays might occur.

Commercial and Laboratory Applications, Paper No. 11.6

Closed Cycle Cryocoolers in Low Temperature Silicon Analysis

D. Dutta, Bhabha Atomic Research Centre, Dept. of Atomic Energy, India

Sensitive analysis of solar grade silicon material requires sample cooling to very low temperature.Closed cycle cooling that requires no cryogenic liquids allows very low detection limits to be achieved. Quantification of group III and V shallow impurities in single silicon crystal down to the low ppta range, substitutional carbon in poiysilicon or single crystal silicon down to the low ppba range and also of interstitial oxygen in polysilicon or single crystal silicon down to the low ppba range is made possible by application of closed cycle cryo cooling. Very low detection limits are achievable. For single crystal material at liquid helium temperatures, detection limits as low as parts per trillion atoms(ppta 10-12) can be achieved for some impurities. Combination of a high performance FTIR interferometer with closed cycle cryo cooling that does not require any liquid nitrogen or liquid helium has enabled low temperature impurity analysis and quality control of solar grade silicon crystals that conforms to international ASTM/SEMI standards. The closed cycle cryo cooling technology frees from the need to use expensive and potentially hazardous cryogenic liquids. Solar power is a smart way to reduce carbon emissions. (advise an emphasis on closed vs. open cycle cooling OR CEC)

Gas Liquefaction Applications, Paper No. 11.7

Development and Validation of a Small-Scale Hydrogen Liquefier Using a Modified Linde-Hampton Cycle

S.Y.Kim and J. Lee, Hylium Industries, Korea; S.W. Park, Korean Inst. of Science and Tech., Korea

Recent trends are towards the use of renewable energy and hydrogen is seen as a key fuel source for the future. In terms of overall efficiency existing analysis show liquid hydrogen as the most efficient method of transportation for hydrogen fuel; however, liquefaction plants are far and few. To promote the hydrogen infrastructure, Korea Institute of Science and Technology (KIST) and Hylium Industries, Inc. will develop the first small-scale commercial hydrogen liquefier for Korea's Gangwon province. A 30 Kg/day liquefaction rate, direct-cooling type hydrogen liquefier using a modified Linde-Hampton Cycle has been designed and fabricated. The liquefaction cycle in respective order consists of a compressor, liquid nitrogen precooler, single-stage G-M cycle cryocooler, JT-expansion nozzle, two single-stage series G-M cryocoolers, and a vacuum jacketed internal storage tank. The liquefier was specially fabricated to minimize heat leak while maximizing overall cycle and storage efficiency. A detailed overview of component fabrication and experimental procedure and validation are discussed in this paper.

Gas Liquefaction Applications, Paper No. 11.8

The Modified Linde-Hampson Cycles with GM-JT Refrigeration for Small-Scale Hydrogen Liquefaction Processes

J. Park, S.W. Karng, Korea Inst. of Sci. and Tech., Seoul, Korea; H. Lim, G.W. Kim, G.H. Rhee, Univ. of Seoul, Seoul, Korea; S.Y. Kim, Hylium Industries, Seongnam, Korea

The Linde-Hampson cycle with a GM cryocooler was proposed to improve low efficiencies of small-scale hydrogen liquefaction processes. Normal Linde-Hampson processes consist of a compressor, a precooler using LN2, a JT (Joule-Thomson) valve and a heat exchanger (HEX) between GH2 around 80K after the LN2 precooler and GH2 around 20K returning from the liquefier. The HEX is required to be designed to cool additionally GH2 down at least 49K due to JT inversion. It is very important that the temperature of GH2 was cooled to the range 47~49K by the HEX since the liquefaction rate rapidly increases only under the prefer temperature drops of GH2. In other words, cooling GH2 below 47K increases the efficiency of JT expansion, but is not good for the liquefaction rate as the ratio of gas to liquid decreases, resulting in a lack of GH2 around 20K to cool GH2 around 80K. The simulations of processes were carried out by ASPEN HYSYS V11 and NIST REFPROP 10.0. As results, the maximum liquefaction rate was 195 kg/day, consuming the lowest electricity of 25 kWh/kg_LH2 at 47K of GH2 before the JT expansion and under 8 MPa of working pressure. This energy consumption is only 36% of the theoretical Linde-Hampson cycle (around 70 kWh/kg_LH2).

Cryocooler Integration Technologies, Paper No. 12.1

Study for Continuity of Cooling Operation of SPICA Cryogenic System by Adding Refrigerant Circulation System

K. Narasaki, Sumitomo Heavy Industries, Ltd., Japan

SPICA (Space Infrared Telescope for Cosmology and Astrophysics) is a pre-project mission of JAXA to launch a large infrared observatory to the second Sun-Earth Lagrangian liberation point (L2) in the 2020s. A unique feature of SPICA cryogenic system is a warm launch system using radiative cooling and a large number of mechanical coolers in orbit to cool 2.5m-class large IR telescope below 8K and its detectors in sub kelvin. The latest concept of SPICA uses a sub-Kelvin cooler consists of an adiabatic demagnetization refrigerator (ADR) and a sorption cooler, two sets of 1K-class Joule-Thomson coolers (1K-JT cooler) and two sets of 4K-class Joule-Thomson coolers (4K-JT cooler) with three sets of two-stage Stirling (2ST) coolers used as pre-coolers respectively for redundancy and reliability. Additionally, two 2ST coolers are used to cool the telescope shields. The pre-coolers for 1K-JT cooler should be separated from 4K-JT cooler because of the influence of the pre-cooler's failure as well as a required pre-cooling temperature for 1K-JT cooler lower than that for 4K-JT cooler. This paper proposes an improvement for continuity of cooling operation of SPICA cryogenic system by adding refrigerant circulation system. The added refrigerant circulation system are increased the redundancy and reliability of SPICA cryogenic system that if a pre-cooler or a JT compressor is stopped. As additional effects, number of the pre-coolers are decreased to two from three and the arrangement limitation of thermal link and heat exchanger assemblies are also degreased. This paper describes theoretical analysis based on enthalpy to understand design method for the refrigerant circulation system. Results of the heat balance analysis using several parameters are demonstrated.

Cryocooler Integration Technologies, Paper No. 12.2

Space Cryogenic Circulator

D. Frank, J.R. Olson, V. Mistry, E. Roth, A.D. Ruiz, Lockheed Martin Space, ATC, Palo Alto, CA

Circulation of cryogenic fluid is a critical technology for cryogenic propellent storage, where it is important to cool the large surface area of the cryogenic storage tank. Furthermore, cryogenic circulation can enable remote cooling of sensitive instruments with low exported vibration by isolating the instrument from the cryocooler with flexible coolant lines. Lockheed Martin Space has developed a 1.4 kg cryogenic circulator based on a modified pulse tube cryocooler compressor. Lockheed Martin pulse tube compressors have previously operated at cryogenic temperatures as low as 125 K. With Lockheed Martin internal research and development funding, a TRL 6 mini compressor was retrofitted with newly designed check valves which rectify the oscillating flow. This circulator was tested at ambient temperature, and the measured flow is equal to the piston swept volume times the drive frequency, as expected. The measured flow exceeded 3 standard liters per second helium flow with 90% motor efficiency. Testing at cryogenic temperature was also performed, and the circulator performed without problem at 90 K. Quantitative testing was not possible because neither the flow meter nor the piston position sensors work at cryogenic temperatures, but some results will be presented. These results indicate this cryogenic circulator has sufficient flow to provide 50 W of remote cooling at 90 K with reasonably small thermal gradients

Cryocooler Integration Technologies, Paper No. 12.3

Cryocooler with Novel Circulator Providing Broad Area Cooling at 90K for Spaceflight Applications

M. Petach, L. Amouzegar, Northrop Grumman AS, Redondo Beach, CA

This paper describes the conceptual design of a space flight cryocooler system for Broad Area Cooling of radiant shields and remote heat intercepts. This cooler system which provides cryogenic circulating gas sufficient to lift 150W of heat from a customer specified remote distributed load at 90 Kelvin. The cryocooler uses a novel design for the cryogenic gas circulation pump that utilize a thermal buffer tube (also known as a pulse tube) to thermally isolate the cryogenic gas loop from an ambient temperature linear flexure bearing compressor. The predicted performance characteristics of this cooler system are presented.

Cryocooler Integration Technologies, Paper No. 12.4

High Performance Thermal Straps for a Full Range of Application Temperatures

M. Ralphs, M. Sinfield, and M. Felt, Space Dynamics Lab, Logan, UT

Thermal straps are an essential component when using vibration sensitive instruments and cryocoolers in close proximity. Thermal straps conduct heat from the instrument to the cryocooler while limiting the amount of mechanical vibration the cryocooler transfers back to the instrument. Thermal straps are made from flexible, thermally conductive materials. Traditionally, they are made of metal – aluminum or copper, mostly – that has been formed into thin foils, wires, or braids to provide greater flexibility while still providing satisfactory thermal conductivity. These metallic straps provide superior thermal performance at cryogenic temperatures (< 50 K) where their thermal conductivities peak to extraordinary levels. Pyrolytic Graphite Sheet (PGS) thermal straps have a thermal conductance that peaks at higher temperatures – 160 K – and provide much higher mass-specific thermal conductance at temperatures above 60 K. This paper discusses the pros and cons of aluminum, copper, and PGS thermal straps along with various techniques to model and test their thermal performance.

Experimental Study on Response of Split Stirling Cryocooler to Mechanical Conditions under Non-Rigid Contact Conditions

Z. Wang, J. Chen, C.L Yin, Y.D. Lu, Y. Gao, The Provincial Key Laboratory of Cryogenic Tech., Hefei, China

In mechanical experiments, the stirling cryocooler is often rigidly contacted with the fixture, and mechanical condition applied on the cooler is the same as that generated by the shaking table. In some special cases, flexible design is needed between the cryocooler and the fixture, and the relative position between them will change during the vibration process. Then, the mechanical condition on the cooler is quite different from that generated by the shaking table. In order to obtain the response of the cryocooler to mechanical condition under non-rigid contact conditions, a split Stirling cryocooler is selected in this paper. A gap is designed between the cooler and the fixture. The response of the cryocooler to different mechanical conditions is tested, and the response spectrum is obtained. This study is helpful to further understand the response characteristics of split stirling cryocoolers to mechanical conditions, and also has certain contribution to the application expansion of stirling cryocoolers.

Cryocooler Integration Technologies, Paper No. 12.6

Vibration Reduction of Pulse Tube Cryocooler for High Purity Germanium Detector

H.Y. Wei, Y.Q. Xun, C.Z. Shi, L.Y. Wang , J.H. Cai, Key Lab of Space Energy Conv. Tech., Tech. Inst. of Physics and Chemistry, CAS, Beijing, China

HPGe detectors require cooling to cryogenic temperatures (<100 K) to operate as gamma-ray detectors, which is a vibration-sensitive high-resolution detector. The widening use of mechanically cooled technology is replacing the traditional use of liquid nitrogen for cooling a HPGe detector. Thus, vibration reduction of mechanical cooler is vital for HPGe detectors. Low-vibration pulse tube cooler is selected. The authors incorporate active vibration control in addition to passive isolation from mounting structures. The vibration amplitude is reduced dramatically. The vibration or microphone noise created in HPGe detector is reduced dramatically by vibration reduction.

Cryocooler Drive Electronics, Paper No. 13.1

Specifying Cryocooler Electronics for Space Based Missions

K.D Frohling, Iris Technology, Irvine, CA

Specifying cryocooler electronics (CCE) for space based missions is often a perplexing exercise for system integrators. In this presentation, Iris Technology will explain the basic architecture of space based CCEs and how to decide which features are necessary to drive the selected cryocooler in the mission environment. The configuration of the CCE will be defined by the cryocooler, the spacecraft bus, and the flight environment. Primary considerations are the power bus interface, the data interface, the sensors being used, and the form of power required by the cryocooler. In addition to selecting the performance requirements of the CCE, specifying the class of parts acceptable for the mission may have a significant effect on the cost and delivery schedule for the CCE.

Cryocooler Drive Electronics, Paper No. 13.2

Linear Cryocooler Electronics for Tactical Space Missions

B.R. Pilvelait, C.B. Cameron, R.W. Kaszeta, M.V. Zagarola, Creare LLC, Hanover, NH; and M. Martin, N. Hudson, C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

Many future space science and military missions will utilize small spacecraft, and many of these missions will require cryocoolers for cooling electro-optical payloads. For Class C and D missions, the cryocooler technical requirements for performance, size, and mass, coupled with the programmatic requirements for minimal cost and development time, are extremely challenging. Flight ready cryocoolers and associated control electronics developed for traditional satellites do not meet these technical, cost, or schedule requirements for future small space platforms. Creare with our partners from West Coast Solutions have recently developed and qualified low cost cryocooler control electronics for linear cryocoolers. These electronics leverage technologies and capabilities that were demonstrated on prior programs. This paper provides an overview of the design, qualification results and initial performance testing with tactical cryocoolers.

Cryocooler Drive Electronics, Paper No. 13.3

Reduced-Size Cryocooler Electronics for Space

K.D Frohling, Iris Technology, Irvine, CA

Iris Technology has developed a set of GaN FET based dual piston cryocooler electronics (CCE) that provide a significant size advantage over MOSFET based electronics with similar performance. This CCE also provides additional features such as the capability of operating the CCEs in a master/slave configuration and adaptive vibration control not available on the MOSFET version. In addition to GaN FET technology, this CCE incorporates a radiation tolerant microcontroller. This facilitates personality driven configurations that can be applied without any changes to the hardware design. The design and testing of this CCE will be discussed along with potential next step developments to support SmallSat deployments.