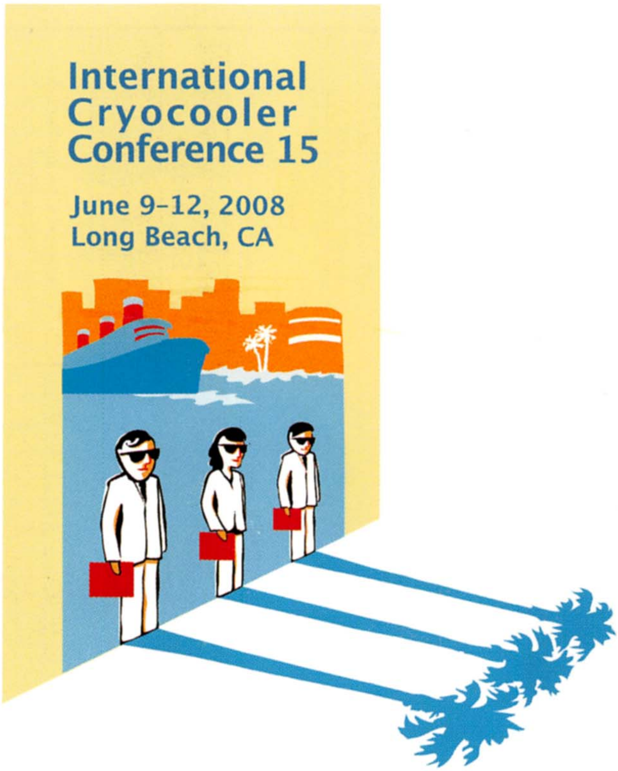
International Cryocooler Conference 15

June 9 – 12, 2008
Long Beach, California



Final Program

With Complete Technical Abstracts

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CONFERENCE COMMITTEE

CONFERENCE CHAIR

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WELCOME

We are happy to welcome you to the 15th International Cryocooler Conference (ICC15) being held June 9-12, 2008 in Long Beach, California, USA. The ICC, held every other year, has emerged as the preeminent international conference on the development and usage of cryocoolers. This meeting attracts participants from the Americas, Europe, and Asia representing academia, government laboratories, and industry.

In this meeting you will have the opportunity to learn of the latest developments in cryocooler technology and will be able to discuss these developments with authors from around the world. To make certain that you will not miss any of the presentations the program has been arranged so that there are no parallel sessions. As a participant you will receive a copy of Cryocoolers 15 approximately six months after the conference that includes copies of the papers presented at ICC15, following a peer review process instituted to assure the quality of the printed proceedings.

Based upon past years, attendees at ICC15 will include:

- Cryocooler users, including commercial and military;
- Mechanical, electrical, and software engineers engaged in cryocooler design;
- System engineers responsible for selecting and/or integrating cryocoolers;
- Educators, particularly those interested in cryogenics and/or thermal management;
- Cryogenic component manufacturers and suppliers.

We are very pleased to be hosting the event in such an exciting location! Shopping, dining, and entertainment options abound within walking distance of the beautiful Hyatt Regency Hotel, with vista overlooks of the Queen Mary and Long Beach Harbor. With ready access to the vast array of Los Angeles and Orange County attractions, you might find it difficult to find time for the exciting Technical Program we are putting together! Our theme in 2008 is "Reaching Out," and we are doing so both with respect to people and ideas. We have built on our traditionally strong program in cryocoolers of all types and for many applications by broadening into some areas we feel have been under represented in the past, like cryocooler electronics and cryocooler-enabled systems.

The ICC15 conference banquet will be a "Surf Party" at the Aquarium of the Pacific, which will be held Wednesday evening of the Conference. This will be a great event you won't want to miss!

Welcome to Long Beach and ICC15!

Carl S. Kirkconnell
General Chair

Mark V. Zagarola
Program Chair

GENERAL INFORMATION

ICC15 will be held at the Hyatt Regency Hotel in Long Beach, CA on the waterfront in downtown Long Beach. The Conference will begin with a Welcome Reception in the Hyatt Beacon Ballroom on Monday evening, with the Technical Program commencing at 8:00AM Tuesday, June 9. Roughly 120 papers will be presented in both oral and poster formats during the ensuing three days, concluding on Thursday, June 12 at 5:15PM. A very full Social Program including the aforementioned Welcome Reception, a Vendor-Sponsored Reception on June 10, and a "Surf Party" at the Aquarium of the Pacific on June 11 will complement the Technical Program and provide plenty of opportunities for seeing old friends and making new ones. A complete overview of the Conference Schedule is provided on the back of the front cover and on the website for your convenience.

REGISTRATION

All attendees must register. The onsite registration fee is $625, which includes attendance at the Technical Program, all of the Social Program events and provided meals, conference materials, and a hardcopy of the Conference Proceedings, which will be mailed to each participant approximately 6 months after the event. Companion tickets to the Surf Party at the Aquarium of the Pacific are available for an additional fee ($85).

Payments to the ICC must be in U.S. currency. Purchase orders will not be accepted. Registration is available online at www.cryocooler.org and onsite at the Conference at the Registration desk. Onsite registration hours are as follows:

Monday, June 9:	12:00N – 5:00PM
Tuesday, June 10:	6:30AM – 5:00PM
Wednesday, June 11:	7:00AM – 5:00PM
Thursday, June 12:	7:00AM – 12:00N

CONFERENCE BANQUET

This year's conference banquet will be a Southern California Surf Party. Entertainment will be provided by a famous local surf band, the Insect Surfers. The event will be held at the beautiful Long Beach Aquarium of the Pacific. Guests will have full access to the Aquarium's majestic displays of local and far flung aquatic wildlife throughout the evening. The party, which includes a full banquet dinner, will run from 7:00PM to 11:00PM. The Aquarium is a pleasant 10 minute walk from the Hyatt. Shuttle buses will be provided to and from the Aquarium for the convenience of those who would prefer not to walk.

Your ICC registration package includes one "ticket" to the Surf Party. Additional guest tickets are available for $85/each. These must be purchased prior to the Surf Party, either online or at the onsite registration desk. Each "ticket" includes a full dinner and two drink tickets; additional bar refreshments will be available on a cash basis.

VENDOR RECEPTION

For the first time since the inception of the ICC, a Vendor Reception is being hosted as an additional means by which the Conference can help facilitate the types of contacts which spawn new friendships and new ideas. The Vendor Reception will begin at 5:45PM on Tuesday, June 10, immediately after the conclusion of the Technical Program for the day. The Vendor Reception will be in the same location as the Welcome Reception, the Hyatt Beacon Ballroom.

This event has been made possible through the generous sponsorship of the following companies:

- **AIM INFRAROT-MODULE GmbH**
- **Air Liquide – Advanced Technology Division**
- **Cryogenic Control Systems, Inc.**
- **Cryomech, Inc.**
- **L-3 Communications Cincinnati Electronics**
- **Lake Shore Cryotronics, Inc.**
- **Raytheon Space and Airborne Systems**
- **Ricor - Cryogenic & Vacuum Systems**
- **SunpowerCryo**
- **THALES Cryogenics B.V.**

MEALS

Your registration includes breakfast every morning before the Technical Program (Tuesday through Thursday) at 7:00AM. Additionally, hors d'oeuvres will be provided at the evening receptions on June 9 and 10, and a full dinner will be provided at the June 11 conference banquet. We encourage you to enjoy the many local restaurants within walking distance of the hotel for lunches, and the conference organizers have provided ample time for participants to do so. Gladstone's, one of the area's top seafood restaurants and conveniently located across the street from the hotel, will generously provide a 10% discount on all food items to ICC attendees. Just present your badge to the server to receive your discount.

(Thank you, Gladstone's!)

GLADSTONE'S Long Beach

LONG BEACH, CALIFORNIA

Long Beach is where the action begins and the fun never ends. From the regal Queen Mary and spectacular Aquarium of the Pacific to stirring Broadway shows, live music venues and hundreds of exclusive dining destinations--all centrally located. Airport-close, a brief and pleasant cruise away from Catalina Island and a short distance from Disneyland, Universal Studios Hollywood and everything Southern California has to offer--Long Beach is the perfect destination!

The weather is mild in Long Beach year round. The average high and low temperatures for June are 78°F (26°C) and 62°F (17°C), and the average precipitation in June is essentially nil.

For more information, please visit http://www.visitlongbeach.com.

CONFERENCE HOTEL - THE HYATT REGENCY LONG BEACH

The beautiful Hyatt Regency on the Long Beach Waterfront will be the focal point of all the conference-related activities. In additional to providing preferred lodging arrangements for all ICC 15 attendees, the Hyatt will also be the site of the Welcome Reception, the Vendor Reception, the Technical Program, and the Cryogenic Society of America (CSA) Cryocooler Course. The Hyatt is across the street from a large number of excellent restaurants, and it is also just a short walk from the Aquarium of the Pacific, the site of the conference banquet.

TRANSPORTATION TO HYATT – AIR TRAVEL

To/From Long Beach Airport:
Yellow Cab offers a flat rate of $21 each way to the hotel. Guests MUST tell the cab driver they want the $21 flat fee, otherwise they will be charged at a normal fee. Yellow Cabs are available at the airport. Super Shuttle is available with advance reservations only. Please call (310) 782-6600 or 1-800 Blue Van for information and rates.

To/From LAX Airport:
Super Shuttle runs 24 hours a day. Reservations are not needed or taken. Vans are located outside on the lower level of the baggage claim area. Cross over to the center island and look for the orange sign. Shuttles pick up approximately every 10 minutes. A Super Shuttle attendant will be available to assist passengers. Cost is $17/person. Wheelchair transportation is available from LAX to the hotel through Super Shuttle. Advance reservations are required. Please call (310) 782-6600 for reservations and information. A taxi will cost between $50 and $60.

To/From Orange County Airport (John Wayne Airport):
Super Shuttle is available at transportation center across the street. Look for the 3rd Island marked *Van Shuttle Service*. Reservations are suggested but not required. Cost is $34 each way for one person and $9 each way for

each additional person. Please call (714) 517-6600 or 1-800-862-7771 for reservations. The approximate taxi fare from John Wayne is $60.

To/From Ontario Airport:
Shuttle transportation is approximately $60 each way, per person. Shuttles are available at the Ground Transportation area of the airport.

To/From Burbank Airport:
Shuttle transportation is approximately $40 each way, per person. Shuttles are available at the Ground Transportation area of the airport.

TRANSPORTATION TO HYATT – DRIVING

From 405 South and Los Angeles International Airport (approximately 22 miles):
Take the San Diego Freeway (405) South to the Long Beach Freeway (710) South toward Long Beach. At the Freeway split, take the LEFT LANES for Downtown Long Beach/Convention Center. Stay on Shoreline Drive, (DO NOT TAKE Broadway/Civic Center/Pine Avenue exit) follow the signs to: Aquarium/Convention Center/ Pine Avenue. TURN LEFT on Pine Avenue (4th stop light). The hotel is on the corner of Shoreline Drive and Pine Avenue.

From 405 North, John Wayne Airport / Orange County (approximately 24 miles) and Long Beach Airport (approximately 6 miles):
Take the San Diego Freeway (405) NORTH to the Long Beach Freeway (710) South toward Long Beach. At the Freeway split, take the LEFT LANES for Downtown Long Beach/Convention Center. Stay on Shoreline Drive, (DO NOT TAKE Broadway/Civic Center/Pine Avenue exit) follow the signs to: Aquarium/Convention Center/ Pine Avenue. TURN LEFT on Pine Avenue (4th stop light). The hotel is on the corner of Shoreline Drive and Pine Avenue.

TECHNICAL PROGRAM SUMMARY

The Technical Program for the 15th ICC is organized into 18 sessions containing 116 papers. The technical sessions will begin at 8:15AM on Tuesday, June 10 immediately following a fifteen-minute introduction by the ICC15 Organizing Committee, and will begin promptly at 8:00AM on Wednesday and Thursday. The conference ends at 5:15 PM on Thursday.

The entire conference will be held at the Hyatt Regency Hotel, Long Beach, CA. All oral technical sessions will be held in the Regency Ballroom. The four poster sessions will be held in the Regency Foyer, which will provide an excellent opportunity for close personal interaction with authors of specialized topical subjects. The morning poster sessions will be held all three days of the conference and are scheduled to coincide with mid-morning breaks. An afternoon poster session will be held on Wednesday coincident with the afternoon break. Light refreshments will be served during the poster sessions.

Authors and presenters should submit their manuscripts and presentations to conference staff in the Publications Room, located in the Pacific Room on the lower level of the conference area. Presentations will be loaded on a laptop for use during the conference presentations. Technical papers will be distributed by the publications staff for peer review prior to publication in the conference proceedings (Cryocoolers 15).

AUTHOR / PRESENTER INFORMATION

INSTRUCTIONS FOR POSTER PRESENTERS

Poster sessions will be held each day of the conference in the morning at approximately 10:00AM and also on Wednesday afternoon. The exact times are listed in the program. Presenters are expected to attend to their poster during their respective session only. We encourage all poster session papers to be posted by 9:00AM of the day of the session and request that they be removed by 5:00PM. Papers not removed in a timely manner will be discarded.

Each poster presenter will be provided with a poster mounting area 48" (1.22 m) wide by 48" (1.22 m) tall. The poster boards are a foam core surface and papers must be affixed with pushpins, which will be provided. Only **pushpins** may be used to attach materials to the poster boards.

Poster material must be readable from a distance of six feet (2 meters). Lettering in text and figures should be at least 0.25" (6 mm) high; the poster title should be in letters at least 1" (25 mm) high. The poster paper number will be mounted by Conference personnel at the top of each poster board, outside of your mounting area.

INSTRUCTIONS FOR ORAL PRESENTERS

Each oral presenter is permitted 15 minutes. You should arrange your talk so that your presentation lasts 12-13 minutes, with 2-3 minutes available for questions. You are expected to notify the session chair of your presence 10 minutes before the start of the session so that he/she knows you are present. There will be no rearrangement of papers within an oral session to accommodate absences or cancellations, so the time you have been assigned within the oral session is fixed. Please inform your session chair if you must withdraw your paper from the program on site at the conference.

All oral presenters are required to submit an electronic version of their presentation by 5:00PM of **the day prior** to their presentation. **Presentations must be submitted in Microsoft Power Point format** (but may be saved as a PDF) and should be turned in to the Publication Room at the conference (lower level, Pacific Room). It is strongly recommended that presenters save their Power Point presentations with True Type fonts attached. Acceptable media include CD and USB flashdrive. All presentations will be scanned for any viruses and subsequently loaded on an appropriate computer for the following day's presentations. All sessions will be equipped with an LCD projector, a computer, and a screen. Presenters are not allowed to use their own personal laptops. The laptops are not equipped to accommodate audio sound.

Mac computers will NOT be available in any of the sessions. Authors using a Mac platform will need to ensure that their files operate compatibly in the PC environment.

Authors are strongly encouraged to bring to their session an additional electronic copy for added security against unanticipated software/hardware anomalies.

If a presenter has failed to submit his/her presentation by 5:00PM of the day prior to their presentation, they may be required to present their paper without an accompanying presentation.

SESSION 1: Space Cryocooler Applications & Overview
Tuesday, June 10, 2008 8:15 – 10:00 AM

Co-Chairs: Franklin Miller, NASA Goddard Space Flight Center
Melora Larson, Jet Propulsion Laboratory
Jeff Feller, NASA Ames Research Center

8:15 **MSL/CheMin Cryocooler System Requirements and Characterization Tests** [1-17]
D. Johnson, B. Carroll, R. Leland, Jet Propulsion Laboratory, Pasadena, CA

8:30 **Thermal Model for a Mars Instrument with Thermo-Electric Cooled Focal Plane: CCD Subsystem with Heat Switch** [1-73]
D. Ladner, J. Martin, N-Science Corporation, Arvada, CO

8:45 **AIRS Pulse Tube Coolers Performance Update – Six Years in Space** [1-18]
D. Johnson, R. Ross, Jr., D. Elliott, Jet Propulsion Laboratory, Pasadena, CA

9:00 **Performance Characterization of the ABI Cryocooler** [1-44]
P. Ramsey, S. Clark, ITT Space Systems Division, Fort Wayne, IN; A. Chuchra, R. Boyle, D. Early, NASA Goddard Space Flight Center, Greenbelt, MD; and R. Colbert, Northrop Grumman Space Technology, Redondo Beach, CA

9:15 **USAF Cryogenic Thermal Management System Needs** [1-53]
T. Roberts, F. Roush, Air Force Research Laboratory, Kirtland AFB, NM

9:30 **Development of Advanced Two-stage Stirling Cryocooler for Next Space Missions** [1-30]
Y. Sato, H. Sugita, K. Komatsu, R. Shimizu, H. Uchida, T. Nakagawa, H. Murakami, K. Mitsuda, Japan Aerospace Exploration Agency, Japan; M. Murakami, University of Tsukuba, Ibaraki, Japan; I. Iwata, S. Tsuneta, National Astronomical Observatory of Japan, Tokyo, Japan; S. Tsunematsu, K. Kanao, K. Ootsuka, M. Hirabayashi, Sumitomo Heavy Industries, Ltd., Niihama, Ehime, Japan

9:45 **Space Cryocooler Survey 2007** [1-57]
J. Cha, S. Yuan, D. Curran, The Aerospace Corporation, El Segundo, CA

SESSION 2: Pulse–Tube/Stirling Cryocoolers (Single & Multistage) [POSTER SESSION]
Tuesday, June 10, 2008   10:00 – 11:00 AM

Co-Chairs: Ray Radebaugh, Nat'l Institute of Standards & Technology
Ted Nast, Lockheed Martin Space Systems
Ken Price, The Aerospace Corporation

Experimental Investigation on Single Stage Inline Stirling Type Pulse Tube Refrigerator [2-10]
L. Mohanta, M. Atrey, Indian Institute of Technology Bombay, Mumbai, Maharastra, India

Research of Separated Pulse Tube Coolers Driven by One Single Compressor [2-20]
X. Chang, L. Yang, J. Liang, J. Cai, G. Hong, Technical Institute of Physics and Chemistry of CAS, Beijing, China; Graduate University of Chinese Academy of Sciences, Beijing, China

Performance Comparison of Stirling Type Single Stage Pulse Tube Refrigerator for Inline and "U" Configurations [2-11]
M. Tendolkar, M. Atrey, Indian Institute of Technology Bombay, Maharastra, Mumbai, India; K. Narayankhedkar, Veermata Jijabai Technological Institute, Maharastra, Mumbai, India

Theoretical and Experiment Study on a Single Stage Pulse Tube Cryocoolers Driven with a Linear Compressor [2-113]
Q. Cao, G. Liu, Z. Li, L. Qiu, Z. Gan, Cryogenics Lab., Zhejiang University, Hanghzou, China

10K Pulse Tube Cooler Performance Data [2-108]
C. Jaco, T. Nguyen, J. Raab, Northrop Grumman Space Technology, Redondo Beach, CA

Raytheon Stirling Pulse / Tube Cryocooler Maturation Programs [2-8]
C. Kirkconnell, R. Hon, Raytheon Space and Airborne Systems, El Segundo, CA; T. Roberts, Air Force Research Laboratory, Kirtland AFB, NM

Development of a Two Stage High Temperature Pulse Tube Cooler for Space Applications [2-16]
I. Charles, A. Coynel, J.M. Duval, CEA/DSM/INAC/SBT, Grenoble, France; C. Daniel, R. Briet, CNES, Toulouse, France

SESSION 2: continued

Multistage Pulse Tube Refrigeration Characterization of the Lockheed-Martin RAMOS Cryocooler [2-52]
T. Roberts, E. Pettyjohn, W. Scheirer, Air Force Research Laboratory, Kirtland AFB, NM

Two-Stage Pulse Tube Refrigerator with 2nd Stage Recuperator [2-90]
J. Jung, S. Jeong, G. Hwang, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

SESSION 3: Tactical & Military Cryocoolers
Tuesday, June 10, 2008 11:00 AM – 12:15 PM

Co-Chairs: Frank Roush, Air Force Research Laboratory
Dean Johnson, Jet Propulsion Laboratory

11:00 Development of a High Capacity Cryocooler [3-27]
J. Tanchon, T. Trollier, A. Ravex, Air Liquide Advanced Technology, AL/DTA, Sassenage, France; A. Caughley, Industrial Research Ltd., Christchurch, New Zealand

11:15 Acoustic-Stirling 55 gal/day Oxygen Liquefier for Use on Aircraft Carriers [3-98]
P. Spoor, J. Corey, CFIC-Qdrive, Troy, NY

11:30 Development of the Miniature Flexure Bearing Cryocooler SF070 [3-74]
M. Mai, I. Ruehlich, C. Rosenhagen, Th. Wiedmann, AIM Infrarot-Module GmbH, Heilbronn, Germany

11:45 Pulse Tube Cryocooler for Rapid Cooldown of a Superconducting Magnet [3-99]
M. Lewis, P. Bradley, I. Garaway, R. Radebaugh, National Institute of Standards and Technology, Boulder, CO; R. Taylor, University of Wisconsin-Madison, Madison, WI

12:00 Integrated Testing of a Complete Low Cost Space Cryocooler System [3-9]
R. Hon, G. Hartley, D. Sigurdson, C. Kesler, Raytheon Space and Airborne Systems, El Segundo, CA; Raytheon Vision Systems, Goleta, CA

SESSION 4: Cryogenic Integration Technologies
Tuesday, June 10, 2008   1:45 – 2:45 PM

Co-Chairs: Mike Barr, Raytheon Space & Airborne Systems
Sidney Yuan, The Aerospace Corporation

1:45 **Design of Aural Undetectable Cryogenically Cooled Infrared Imagers** [4-40]
A. Veprik, H. Vilenchik, R. Broyde, N. Pundak, Ricor Cryogenic & Vacuum Systems, En Harod Ihud, Israel

2:00 **A Thermomechanical Heat Switch** [4-39]
L. Duband, CEA/INAC/Service des Basses Temperatures, Grenoble, France

2:15 **A Cryogenic Heat Transport System for Space-Borne Gimbaled Instruments** [4-101]
M. Zagarola, J. Sanders, Creare Inc., Hanover, NH; C.S. Kirkconnell, Raytheon Space & Airborne Systems, El Segundo, CA

2:30 **Low Vibration, Low Thermal Fluctuation System for Pulse Tube and GM Cryocoolers** [4-68]
L. Mauritsen, D. Snow, A. Woidtke, M. Chase, I. Henslee, S2 Corporation, Bozeman, MT

SESSION 5: Low-Temperature Cryocoolers
Tuesday, June 10, 2008 2:45 – 3:45 PM

Co-Chairs: Peter Shirron, NASA Goddard Space Flight Center
Johannes Burger, University of Twente

2:45 **50 mK Continuous Cooling with ADRs Coupled to Helium3 Sorption Cooler** [5-65]
J.M. Duval, N. Luchier, L. Duband, CEA/SBT, Grenoble, France;
A. Sirbi, ESA/ESTEC, Noordwijk, The Netherlands

3:00 **Development of Low Magnetic Field ADR for Transition Edge Sensors** [5-104]
T. Nast, D. Martinez-Galarce, S. Deiker, J. R. Olson, E. Roth, J. Mix, Lockheed Martin, Palo Alto, CA

3:15 **A Superfluid Pulse Tube Driven by a Thermodynamically Reversible Magnetic Pump** [5-122]
F. Miller, NASA Goddard Space Flight Center, Greenbelt, MD;
J. Brisson, Massachusetts Institute of Technology, Cambridge, MA

3:30 **Pocket Dilution Cooler** [5-37]
T. Prouve, N. Luchier, L. Duband, CEA-Grenoble, Service des Basses Temperatures, Grenoble, France

SESSION 6: Commercial & Industrial Cryocoolers & Applications
Tuesday, June 10, 2008 4:00 – 5:45 PM

Co-Chairs: Lionel Duband, CEA-Grenoble, France
Toru Kuriyama, Toshiba, Power & Industrial Systems
Klaus Timmerhaus, University of Colorado – Boulder

4:00 **Initial Evaluation and Application Potential of a 4-Kelvin 4-Stage Pulse Tube Cryocooler** [6-110]
R. Webber, V. Dotsenko, J. Delmas, A. Kadin, E. Track, HYPRES, Inc., Elmsford, NY

4:15 **Development of a Diaphragm Pressure Wave Generator for Cryocoolers** [6-64]
Alan Caughley, Industrial Research, Ltd., Christchurch, New Zealand; C. Wang, Cryomech, Inc., Syracuse, NY

4:30 **Development of the Active Magnetic Regeneration (AMR) Refrigerator Using a Permanent Magnet** [6-77]
H. Nakagome, S. Uchimoto, K. Kamiya, S. Kito, Chiba University, Chiba, Japan; A. Saito, S. Kaji, T. Kobayashi, Toshiba Corporation, Kawasaki, Japan

4:45 **Intermediate Cooling in 4 K Pulse Tube Cryocoolers** [6-100]
C. Wang, Cryomech, Inc., Syracuse, NY

5:00 **Low Vibration 1W4K Two-Stage Pulse Tube Cryocooler** [6-80]
M. Xu, M. Saito, H. Takayama, Sumitomo Heavy Industries, Ltd., Tokyo, Japan

5:15 **Dilution Refrigerator with Direct Pulse Tube Precooling** [6-23]
Kurt Uhlig, Walther Meissner Institute, Garching, Germany

5:30 **Complex Approach to Ultra-Low Vibration Control of a Linear Split Stirling Cryogenic Refrigerator** [6-117]
A. Veprik, S. Riabzev, H. Vilenchik, N. Pundak, Ricor Cryogenic and Vacuum Systems, En Harod Ihud, Israel; E. Castiel, National Instruments, Tel Aviv, Israel

SESSION 7: Recuperators & Micro-JT Cryocoolers
Wednesday, June 11, 2008 8:00 – 9:45 AM

Co-Chairs: Weibo Chen, Creare Inc.
Alain Ravex, Air Liquide, France
Peter Kittel, Palo Alto, CA

8:00 **Micro Channel Recuperator for a Reverse Brayton Cycle Cryocooler** [7-61]
C. Becnel, J. Lagrone, K. Kelly, Mezzo Technologies, Baton Rouge, LA

8:15 **Performance Results of Microplate Heat Exchangers** [7-94]
E. Marquardt, Ball Aerospace & Technologies Corp., Boulder, CO

8:30 **Performance of a MEMS Heat Exchanger for a Cryosurgical Probe** [7-13]
M. White, G. Nellis, S. Klein, University of Wisconsin-Madison, Madison, WI; W. Zhu, Y. Gianchandani, University of Michigan-Ann Arbor, Ann Arbor, MI

8:45 **Modeling and Experimental Verification of a Cascaded Mixed Gas Joule Thomson Cryoprobe** [7-109]
H. Skye, G. Nellis, S. Klein, University of Wisconsin – Madison, Madison, WI

9:00 **On-Chip Detector Cooling For Space Applications** [7-12]
J. Derking, H. ter Brake, H. Rogalla, University of Twente, Enschede, The Netherlands; A. Sirbi, European Space Agency, ESTEC, Noordwijk, The Netherlands

9:15 **Development of a Mixed-Refrigerant Joule-Thomson Microcryocooler** [7-105]
P. Bradley, R. Radebaugh, M. Huber, National Institute of Standards and Technology, Boulder, CO; M.-H. Lin, Y. Lee, V. Bright, University of Colorado, Boulder, CO

9:30 **Development of a Piezoelectric Microcompressor for a Joule-Thomson Microcryocooler** [7-107]
M. Simon, C. Deluca, Y. Lee, V. Bright, University of Colorado at Boulder, Boulder, CO; P. Bradley, R. Radebaugh, National Institute of Standards and Technology, Boulder, CO

SESSION 8: Modeling of Pulse-Tube/Stirling Cryocoolers [POSTER SESSION]
Wednesday, June 11, 2008   9:45 – 10:45 AM

Co-Chairs: Mostafa Ghiaasiaan, Georgia Institute of Technology
Chris Dodson, Air Force Research Laboratory

Theoretical Design and Analysis of 1 W @ 80 K Pulse Tube Cryocooler Required for Space Related Applications [8-38]
S. Chikurde, MMCOE, Pune, Maharashatra, India

A Model for Exergy Analysis and Performance Evaluation of Regenerators [8-42]
C. Dodson, A. Razani, T. Roberts, Air Force Research Laboratory, Kirtland AFB, NM; A. Razani, The University of New Mexico, Kirtland AFB, NM

Investigation of 300 Hz Pulse Tube Cryocoolers [8-21]
H. Cai, J. Yang, L. Yang, J. Liang, Y. Zhou, University of Chinese Academy of Sciences, Beijing, China

A New Concept on Multi-Stage Stirling Refrigerators [8-49]
S. Yuan, D. Curran, Aerospace Corp., El Segundo, CA

Anisotropic Hydrodynamic Parameters of Regenerator Materials Relevant to Miniature Cryocoolers [8-70]
T. Conrad, E. Landrum, S.M. Ghiaasiaan, Georgia Institute of Technology, Atlanta, GA; C.S. Kirkconnell, Raytheon Space and Airborne Systems, El Segundo, CA; T. Crittenden, S. Yorish, Virtual AeroSurface Technologies, Atlanta, GA

Numerical Simulation of Oscillating Fluid Flow in Inertance Tubes [8-43]
C. Dodson, A. Razani, T. Roberts, Air Force Research Laboratory, Kirtland AFB, NM; A. Razani, The University of New Mexico, Kirtland AFB, NM

Effect of Geometric Configuration on the Dynamic Behavior of Linear Compressor and Cooling Performance in Stirling-type Pulse Tube Refrigerator [8-14]
J. Ko, S. Jeong, Korea Advanced Institute of Science and Technology, Daejeon, Korea

Numerical Simulation of Orifice Pulse Tube Cryocooler [8-2]
S. Krasae-in, Ph.D. Student, University of Science & Technology, Trondheim, Norway

SESSION 8: continued

Comparative Numerical Study of Pulse Tube Refrigerators [8-78]
T. Ashwin, S. Jacob, G. Narasimham, Indian Institute of Science, Bangalore, Karnataka, India

Cryocooler Particle Image Velocimetry [8-119]
E. Pettyjohn, J. Arnold, Air Force Research Laboratory, Kirtland AFB, NM; M. Martin, T. Fraser, Applied Technology Associates, Albuquerque, NM

Theoretical Investigation of Thermoacoustic Effect [8-121]
W. Jangsawang, S. Supprem, Phranakhon Rajabhat University, Bangkok, Thailand

SESSION 9: Two-Stage Pulse-Tube/Stirling Cryocoolers
Wednesday, June 11, 2008 10:45 – 11:45 AM

Co-Chairs: Jeff Olsen, Lockheed Martin Space Systems
Tanh Nguyen, Northrop Grumman Space Technology

10:45 **Experimental Results of 20 K Pulse Tube Cold Fingers for Space Applications** [9-22]
J. Duval, I. Charles, A. Gauthier, CEA/SBT, Grenoble, France;
T. Trollier, J. Tanchon, Air Liquide / DTA, Sassenage, France;
M. Linder ESA/ESTEC, Noordwijk, The Netherlands; R. Briet, CNES, Toulouse, France

11:00 **Raytheon Compact-Inline RSP2 Cryocooler** [9-48]
R. Hon, C. Kirkconnell, D. Wolfe, Raytheon, El Segundo, CA

11:15 **ABI Cooler System Protoflight Performance** [9-45]
R. Colbert, G. Pruitt, T. Nguyen, J. Raab, Northrop Grumman Space Technology, Redondo Beach, CA

11:30 **Investigation of Thermally Coupled Two-Stage Pulse Tube Cooler** [9-19]
L. Yang, Technical Institute of Physics and Chemistry, CAS, Beijing, China; Institute of Applied Physics, University of Giessen, Germany

SESSION 10: Laboratory Cryocooler Applications
Wednesday, June 11, 2008 1:15 – 2:15 PM

Co-Chairs: Chris Paine, Jet Propulsion Laboratory
Rob Boyle, NASA Goddard Space Flight Center

1:15 **Cold-Head Vibrations on a Two-Stage Coaxial Pulse Tube Refrigerator** [10-56]
T. Koettig, CERN, Geneva, Switzerland; F. Richter, C. Schwarz, R. Nawrodt, M. Thuerk, P. Seidel, Friedrich-Schiller-University Jena, Jena, Germany

1:30 **Ground Testing of a Space Infrared Sensor Using a G-M Type Cryocooler** [10-76]
C. Kesler, T. Matsuoka, J. Zimmerman, C. Kirkconnell, D. La Komski, Raytheon Space and Airborne Systems, El Segundo, CA

1:45 **Cryocoolers for Scientific Research at a Neutron Scattering Facility** [10-29]
B. Hill, L. Santodonato, Oak Ridge National Laboratory, Oak Ridge, TN

2:00 **Integration and Application of Cryocoolers for Advanced Characterization of High Temperature Superconducting Power System Components** [10-66]
S. Pamidi, H. Rodrigo, D. Knoll, D. Crook, S. Ranner, S. Dale, Center for Advanced Power Systems, Florida State University, Tallahassee, FL

SESSION 11: Cryocooler Integration Technologies & Components [POSTER SESSION]

Wednesday, June 11, 2008   2:15 – 3:15 PM

Co-Chairs: Mark Zagarola, Creare Inc.
Chao Wang, Cryomech, Inc.
Peter Bradley, Nat'l Institute of Standards and Technology

Effect of Pressure on Regenerator Hydrodynamic Parameters in Axial Steady Flow [11-71]
E. Landrum, T. Conrad, S. Ghiaasiaan, C. Kirkconnell, Georgia Institute of Technology, Atlanta, GA; C. Kirkconnell, Raytheon Space and Airborne Systems, El Segundo, CA

A Numerical Study on the Performance of the Heat Exchanger for the Miniature Joule Thomson Refrigerator [11-89]
Y-J Hong, S-J Park, Korea Institute of Machinery & Materials, Daejeon, Korea; Y-D Choi, Korea University, Seoul, Korea

Distributed Cooling Techniques for Space Applications [11-92]
J. Feller, L. Salerno, NASA-Ames Research Center, Moffett Field, CA; J. Maddocks, B. Helvensteijn, A. Kashani, Atlas Scientific, San Jose, CA; G. Nellis, University of Wisconsin-Madison, Madison, WI; Y. Gianchandani, University of Michigan-Ann Arbor, Ann Arbor, MI

Remote Cooling with the Coaxial HEC Cooler [11-106]
T. Nguyen, M. Michaelian, M. Petach, J. Raab, Northrop Grumman Space Technology, Redondo Beach, CA

Hydrogen and Neon Gas-Gap Heat Switch [11-112]
I. Catarino, G. Bonfait, CEFITEC, Caparica, Portugal; L. Duband, CEA/INAC, Grenoble, France

Investigation of Cryogenic Cooling Systems Activated by Piezoelectric Elements [11-60]
S. Sobol, G. Grossman, Technion, Israel Institute of Technology, Haifa, Israel

Nitrogen Cryogenic Loop Heat Pipe: Results of a First Prototype [11-28]
P. Gully, P. Seyfert, P. Thibault, L. Guillemet, CEA-Grenoble/SBT, Grenoble, France; M. Qing, CAS/TIPC Cryogenic Laboratory, Beijing, China

SESSION 11: Cryocooler Integration Technologies & Components [POSTER SESSION]

Wednesday, June 11, 2008 2:15 – 3:15 PM

SESSION 11: continued

Prognostic Health Management System for Cryocooling Systems [11-75]
A. Shah, B. Penswick, E. Sandt, Sest, Inc., Middleburg Heights, OH;
C. Dodson, T. Roberts, Air Force Research Laboratory, Kirtland AFB, NM

Development of a Continuous ADR System for Weak Gravity Missions [11-124]
T. Numazawa, K. Kamiya, K. Takahashi, National Institute for Materials Science, Tsukuba, Japan; M. Mitsuda, JAXA/ISAS, Sagamihara, Japan; Y. Ishisaki, Tokyo Metropolitan University, Tokyo, Japan; R. Fujimoto, Kanazawa University, Kanazawa, Japan; P. Shirron, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Experimental Study on Preliminary AMR Apparatus for Magnetic Hydrogen Refrigerator [11-125]
T. Numazawa, K. Kamiya, S. Yoshioka, National Institute for Materials Science, Tsukuba, Japan; K. Matsumoto, T. Kondo, Kanazawa University, Kanazawa, Japan; T. Nakagome, Chiba University, Chiba, Japan

SESSION 12: Distributed Cryocoolers & Modeling
Wednesday, June 11, 2008 3:15 – 5:15 PM

Co-Chairs: Rod Oonk, Ball Aerospace and Technologies Corp.
Mike Superczynski, Chesapeake Cryogenics, Inc.
Gershon Grossman, Technion, Israel Institute of Technology

3:15 **Compact Cryocooler for 10 K Operation** [12-36]
W. Gully, P. Hendershott, D. Glaister, E. Marquardt, Ball Aerospace and Technologies Corporation, Boulder, CO

3:30 **Initial Test Results for a 35 K** [12-41]
W. Gully, D. Glaister, P. Hendershott, E. Marquardt, J. Lester, R. Levenduski, Ball Aerospace and Technologies Corporation, Boulder, CO; Redstone Engineering, Longmont, CO

3:45 **Further Developments on a Vibration-free Helium-Hydrogen Sorption Cooler** [12-35]
J. Burger, H. Holland, R. Meijer, H.J.M. ter Brake, University of Twente, Enschede, The Netherlands; J. Doornink, Dutch Space, Leiden, The Netherlands; A.Sirbi, ESA-ESTEC, Noordwijk, The Netherlands

4:00 **Vibration-Free Joule-Thomson Cryocoolers for Distributed Microcooling** [12-103]
W. Chen, M. Zagarola, Creare Inc., Hanover, NH

4:15 **Second-Law Analysis of a Hybrid Reverse Brayton-Stirling Cryocooler** [12-55]
A. Nieuwkoop, T. Roberts, A. Razani, C. Dodson, Air Force Research Laboratory, Kirtland AFB, NM

4:30 **Demonstration of a Two-Stage Turbo-Brayton Cryocooler for Space Applications** [12-102]
M. Zagarola, J. Breedlove, Creare Inc., Hanover, NH; C. Kirkconnell, J. Russo, T. Chiang, Raytheon Space & Airborne Systems, El Segundo, CA

4:45 **On the Lowest Attainable Temperature by a Reverse Brayton Cryocooler According to the Second Law of the Thermodynamics** [12-46]
B. Maytal, Rafael, Ltd., Haifa, Israel

SESSION 12: continued

5:00 **Mid InfraRed Instrument (MIRI) Cooler Subsystem Design** [12-123]
D. Durand, D. Adachi, D. Harvey C. Jaco, M. Michaelian, T. Nguyen, M. Petach, J. Raab, Northrop Grumman Space Technology, Redondo Beach, CA

SESSION 13: Cryocooler Electronics
Thursday, June 12, 2008 8:00 – 9:00 AM

Co-Chairs: Eric Marquardt, Ball Aerospace and Technologies Corp.
Robert Hon, Raytheon Space and Airborne Systems

8:00 **Universal Drive for Tactical Cryocoolers** [13-96]
B. Pilvelait, R. Kline-Schoder, Creare Inc., Hanover, NH

8:15 **21st Century Cryocooler Electronics** [13-116]
M. Jackson, M. Kieffer, J. Ortiz, F. Wang, J. Hylander, A. Tran, N. Kiani, J. Herschberg, R.C. Hon, Raytheon Space and Airbourne Systems, El Segundo, CA

8:30 **Compact, Lightweight Electronics for Space-Borne Turbo-Brayton Cryocoolers** [13-97]
B. Pilvelait, J. McCormick, M. Zagarola, Creare Inc., Hanover, NH

8:45 **Control and Power Electronics for a Two-Stage Turbo-Brayton Cryocooler for Space Applications** [13-115]
J. Becker, B. Dull, R. Van Shoubrouek, Raytheon Company, El Segundo, CA; J. McCormick, Creare Inc., Hanover, NH; E. Cheung, W. Clement, Jackson & Tull, Greenbelt, MD; J. Murphy, J B Murphy Consulting, Culver City, CA

SESSION 14: Thermoacoustic Cryocoolers
Thursday, June 12, 2008 9:00 – 9:45 AM

Co-Chairs: John Brisson, Massachusetts Institute of Technology
Marcel Ter Brake, University of Twente

9:00 **A 47K Thermoacoustically Driven Pulse Tube Cooler** [14-7]
J. Hu, E. Luo, G. Yu, W. Dai, Chinese Academy of Sciences, Beijing, China

9:15 **Numerical Study of Thermoacoustically-driven Pulse Tube Cooler With Spring-Mass Resonators** [14-6]
W. Dai, G. Yu, X. Wang, E. Luo, Chinese Academy of Sciences, Beijing, China

9:30 **Advance in 300Hz Thermoacoustically Driven Pulse Tube Cryocoolers** [14-33]
E. Luo, W. Dai, G. Yu, S. Zhu, X. Zhang, Chinese Academy of Sciences, Beijing, China

SESSION 15: Ground & Airborne Cryocoolers [POSTER SESSION]
Thursday, June 12, 2008 9:45 – 10:45 AM

Co-Chairs: Dave Glaister, Ball Aerospace and Technologies Corp.
Isaac Garaway, Nat'l Institute of Standards & Technology
Gerry Pruitt, Northrop Grumman Space Technology

Stirling Cryocooler for 3rd Generation IR Platforms [15-84]
M. Squires, L. Dicken, Carleton Life Support Systems, Davenport, Iowa

Model of a Twin-Screw Extruder Operating with a Gifford-McMahon Cryocooler for the Solidification of Deuterium [15-87]
J. Leachman, J. Pfotenhauer, G. Nellis, University of Wisconsin-Madison, Madison, WI

Performance Characteristics and Life of L-3 CE Re-optimized 0.6-Watt Linear Cooler [15-79]
Q. Phan, D. Kuo, R. Estrada, A. Loc, L-3 Communications – Cincinnati Electronics, Pasadena, CA

Development of a Stirling-type Pulse Tube Cryocooler of 2.5W at 65K for Telecommunication Applications [15-88]
N. Matsumoto, Y. Yasukawa, K. Ohshima, M. Yoshida, T. Takeuchi, T. Matsushita, Y. Mizoguchi, Fuji Electric Systems Co., Ltd., Tokyo, Japan

Cryocooled Cooling System for Superconducting Magnet [15-47]
Y. Choi, D. Kim, H. Yang, B. Lee, W. Jung, Korea Basic Science Institute, Daejeon, Korea

Reliability Growth of Stirling-Cycle Coolers at L-3 CE [15-50]
R. Estrada, D. Kuo, Q. Phan, A. Loc, L-3 Communications, Pasadena, CA

Effect of Regenerator Material Configuration on 4K-GM Cryocooler Performance [15-67]
T. Kuriyama, H. Tachibana, K. Sagawa, Toshiba Power and Industrial Systems R&D Center, Tokyo, Japan; T. Okamura, Tokyo Institute of Technology, Ykohama, Japan

Wide-Temperature Range Sample Stage for 6-Circle Diffractometer in X-ray Scattering Experiments Based on Stirling Cooler [15-58]
V. Borzenets, B. Johnson, M. Toney, Stanford Linear Accelerator Center, Menlo Park, CA

SESSION 15: continued

Upgrading the GM Type Pulse Tube Cryocooler Served as a Power Lead Unit [15-86]
R. Maekawa, S. Takami, National Institute for Fusion Science, Toki Gifu, Japan; Y. Matsubara, Cryogenic Consultant, Chiba, Japan

Novel Concept for Driving Micro Miniature Linear Cryogenic Cooler in Battery Powered Infrared Imagers [15-120]
V. Maron, L. Finkelstein, I. Ziv, Soreq NRC, Yavne, Israel; A.Veprik, H. Vilenchik, N. Pundak, Ricor, En Harod Ihud, Israel

SESSION 16: Cryocooler Components
Thursday, June 12, 2008 10:45 AM – 12:00 Noon

Co-Chairs: Willie Gully, Ball Aerospace and Technologies Corp.
Dave Curran, The Aerospace Corporation

10:45 Characterization on Dynamic and Time-averaged Heat Transfer of Oscillating-Flow Parallel-Plate Heat Exchangers [16-32]
B. Gao, E.C. Luo, Chinese Academy of Sciences, Beijing, China

11:00 Miniature PCHE-Type Recuperator with Transverse Bypass [16-91]
J. Jung, S. Jeong, Korea Advanced Institute of Science and Technology, Daejeon, Korea

11:15 Cooling Performance of Miniaturized Thermoacoustic Expanders Operated at 133 K [16-69]
Z. Hu, CryoWave Advanced Technology, Inc., Pawtucket, RI

11:30 Proton Conductive Membrane Compressor-Driven Pulse Tube Cryocooler [16-63]
J. Muller, Johnson Research & Development, Atlanta, GA;
C. Kirkconnell, L. Johnson, Raytheon SAS, El Segundo, CA

11:45 Calculated Performance of Low-Porosity Regenerators at 4 K with Helium-4 and Helium-3 [16-93]
R. Radebaugh, A. O'Gallagher, J. Gary, National Institute of Standards and Technology, Boulder, CO; Y. Huang, Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, China

SESSION 17: Modeling & Testing of Stirling/Pulse-Tube Cryocoolers
Thursday, June 12, 2008 1:30 – 3:30 PM

Co-Chairs: Tom Roberts, Air Force Research Laboratory
Jeff Cha, The Aerospace Corporation
Paul Bailey, Oxford University

1:30 **Infrared Imaging as a Means of Characterizing Flow and Temperature Instabilities within Pulse Tube Cryocoolers** [17-118]
I. Garaway, P. Bradley, R. Taylor, M. Lewis, R. Radebaugh, National Institute of Standards and Technology, Boulder, CO; I. Garaway, Technion – Israel Institute of Technology, Haifa, Israel; R. Taylor, University of Wisconsin-Madison, Madison, WI

1:45 **Design of an Experimental Test Facility for Direct Measurement of Pulse-Tube Energy Flows** [17-95]
R. Taylor, G. Nellis, S. Klein. University of Wisconsin-Madison; R. Taylor, M. Lewis, P. Bradley, R. Radebaugh, National Institute of Standards and Technology

2:00 **The Analysis of Free Piston Free Displacer Stirling Cryocooler from Design Point of View** [17-114]
T. Jindal, Punjab Engineering College, Chandigarh, India

2:15 **The Role of Thermoconductivity in Pulse Tube Cryocoolers** [17-3]
Peter Kittel, Consultant, Palo Alto, CA

2:30 **Continued Study on Universal Scaling Law of Inertance Tube Phase Shifter for Pulse Tube Cryocoolers** [17-34]
S. Zhu, E. Luo, Z. Wu, W. Dai, J. Hu, Chinese Academy of Sciences, Beijing, China; S. Zhu, Graduate University of Chinese Academy of Sciences, Beijing, China

2:45 **CFD Modeling of Pulsating Flow Around a Bend With and Without Flow Straighteners as Applicable to Pulse Tube Cryocoolers** [17-83]
I. Nachman, Ricor, En Harod Ihud, Israel; G. Grossman, Technion, Israel Institute of Technology, Haifa, Israel

SESSION 17: continued

3:00 **Dynamic Grid Coarsening and Efficient Simulation of Fluid Flow and Energy Transfer in Pulse Tubes** [17-62]
M. Reza Rasaei, M. Sahimil, University of Southern California, Los Angeles, CA; C. Kirkconnell, Raytheon Space and Airborne Systems, El Segundo, CA

3:15 **CFD Modeling of Meso-Scale and Micro-Scale Pulse Tube Refrigerators** [17-72]
T. Conrad, E. Landrum, S. Ghiaasiaan, S. Mostafa, T. Crittenden, Georgia Institute of Technology, Atlanta, GA; C. Kirkconnell, Raytheon Space and Airborne Systems, El Segundo, CA; S. Yorish, Virtual AeroSurface Technologies, Atlanta, GA

SESSION 18: Single-Stage Stirling/Pulse-Tube Cryocoolers
Thursday, June 12, 2008 3:45 – 5:15 PM

Co-Chairs: Jeff Raab, Northrop Grumman space Technology
Iran Spradley, Lockheed Martin Space Systems

3:45 **Very High Capacity Aerospace Cryocooler** [18-111]
J. Olson, P. Champagne, E. Roth, B. Evtimov, J. Mix, T. Nast, Lockheed Martin Advanced Technology Center, Palo Alto, CA; D. Clark, Lockheed Martin Advanced Technology Center, Denver, CO

4:00 **Development of a 15W Coaxial Pulse Tube Cooler** [18-25]
W. van de Groep, J. Mullie, D. Willems, T. Benschop, Thales Cryogenics, Eindhoven, The Netherlands

4:15 **Status of Air Liquide Space Pulse Tube Cryocoolers** [18-15]
T. Trollier, J. Tanchon, J. Buquet, A. Ravex, Air Liquide Advanced Technology Division, Sassenage, France

4:30 **Development of a Miniature 150 Hz Pulse Tube Cryocooler** [18-85]
I. Garaway, P. Bradley, R. Radebaugh, National Institute of Standards and Technology, Boulder, CO; Z. Gan, Cryogenics Laboratory, Zhejiang University, Zhejiang, China; I. Garaway, Technion – Israel Institute of Technology, Haifa, Israel; A. Veprik, RICOR Cryogenic & Vacuum Systems, En Harod Ihud, Israel

4:45 **High Frequency Coaxial Pulse Tube Microcooler for Space Applications** [18-82]
M. Petach, M. Waterman, E. Tward, Northrop Grumman Space Technology, Redondo Beach, CA

5:00 **Performance Realization of Single Stage Stirling Cryocooler at ISRO** [18-31]
A. Ramasamy, Padmanabhan, C. Gurudath, Thermal Systems Group, Bangalore, India

PROGRAM ABSTRACTS

The following pages contain abstracts for the papers and posters to be presented at the Conferences. They appear in the same order as they are listed in the Technical Program.

MSL/CheMin Cryocooler System Requirements and Characterization Tests [1-17]

D. Johnson, B. Carroll, R. Leland
Jet Propulsion Laboratory, Pasadena, CA, USA

The Chemistry Mineralogy (CheMin) instrument is being built for use on the Mars Science Laboratory (MSL) to make precision measurements of mineral constituents of Mars rocks and soil. The instrument uses a commercially available Ricor K508 Stirling cycle cryocooler to cool a CCD to 173K to make X-ray diffraction spectroscopy measurements. The Mars surface environment provides a unique and challenging thermal environment for the instrument and the cooler. The primary atmospheric constituent is carbon dioxide, which adds a conductive/convective load on the cooler, and which will freeze out on the cooler and detector if operating too cold. The MSL rover provides a thermal surround for the payload instruments that maintains the thermal environment between -40°C and +50°C. The CheMin instrument will operate during the Mars evening when the ambient temperatures are minimum; and for a limited number of hours each evening due to the energy limits on the science instruments. The cooler therefore will be subjected to many power cycles during the mission. The Ricor K508 cooler has been flown on several space flight missions in the past, however the present CheMin version of the cooler drive electronics has not. CheMin plans to fly the cooler and its electronics as built; it therefore requires ample testing of the cooler to verify the robustness of the mechanical cooler and the electronics. This paper presents the CheMin instrument cryogenic design and the extensive cryocooler characterization and qualification test program to validate the cooler design and reliability to satisfy the instrument and MSL reliability requirements.

Thermal Model for a Mars Instrument with Thermo-Electric Cooled Focal Plane: CCD Subsystem with Heat Switch [1-73]

D. Ladner, J. Martin
N-Science Corporation, Arvada, CO, USA

The Mineral Identification and Composition Analyzer (MICA) is a miniature instrument that employs X-ray scattering and visual imaging to determine nondestructively the mineralogy of a rock sample in-situ. The X-ray CCD subsystem comprises the CCD focal plane, thermoelectric cooler (TEC), TEC heat sink, passive heat switch, and subsystem radiator. The TEC is used to hold the CCD focal plane at or below 208K during instrument operation to eliminate thermal dark current. Inclusion of the heat switch and TEC significantly extend instrument observation times and enable schedule flexibility during extreme Martian diurnal temperature excursions of atmosphere (175 - 255K) and sky (130 - 200K). The CCD Subsystem Model includes all parasitic and dissipative heat sources. The model incorporates logic that simulates heat switch operation to provide heat sink cool-down by night and isolation by day if a sufficient temperature difference exists between the radiator and the sink; the sink temperature must not exceed 258K. Model parameter variation allows the instrument designer to optimize the subsystem thermal parameters to minimize input power to the TEC and maximize instrument observation periods. This paper extends previous results to include all combinations of heat switch status, TEC status, and ambient environmental conditions. Recent X-ray diffraction and fluorescence test results of the MICA prototype instrument are discussed.

AIRS Pulse Tube Coolers Performance Update – Six Years in Space [1-18]

D. Johnson, R. Ross, Jr., D. Elliott
Jet Propulsion Laboratory, Pasadena, CA, USA

The Atmospheric Infrared Sounder (AIRS) instrument pulse tube cryocoolers began operation 39 days after May 4, 2002 launch of the NASA EOS/AQUA spacecraft. Designed with redundant cryocoolers (a primary and a backup), the AIRS instrument began operation using a single cooler to bear the load of both the detector and the non-operating, backup cooler. During the early months of the mission, contamination of the cryogenic surfaces led to increased cryocooler loads and the need for several decontamination cycles. A change in operating strategy was made in November 2002 to run both coolers simultaneously to both overcome the increased cryogenic contamination load and to allow operation at a much reduced compressor stroke level. This change led to the successful continuous operation of the coolers since November 2002 and the non-interruption of science data collection from the AIRS instrument. After a brief review of the AIRS instrument cryogenic design, this paper presents detailed data on the highly successful continuous operation of the AIRS pulse tube cryocoolers and instrument thermal design over the past six years since the original turn-on in 2002. The data show that the cryogenic contamination reached an equilibrium level after a year of space operation and the cooler stroke required for constant-temperature operation has only increased by 2% since that time. This high level of operational stability not only indicates that the cooler contamination load has not increased, but also that the cryocoolers have maintained near-constant efficiency and that the instrument's thermal design has presented a near-constant heat rejection and parasitic-load environment. At this time AIRS continues continuous operation in space providing important scientific data on Earth's atmospheric parameters.

Performance Characterization of the ABI Cryocooler [1-44]

P. Ramsey, S. Clark
ITT Space Systems Division, Fort Wayne, IN, USA

A. Chuchra, R. Boyle, D. Early
NASA Goddard Space Flight Center, Greenbelt, MD, USA

R. Colbert
Northrop Grumman Space Technology, Redondo Beach, CA, USA

Performance measurements were made on the cryocooler that will be used for the GOES-R imager, also known as the Advanced Baseline Imager (ABI). The cryocooler, based on the NGST HEC design, is a hybrid two-stage cooler providing cooling at two temperatures. The main (integral) cooler uses a linear pulse tube. The compressor drive level is determined by a feed-back loop that controls the integral cold tip temperature to a specified level. An external tube transfers some fraction of the compressor work to the remote cooler, which contains a co-axial pulse tube. In the ABI instrument, the integral cooler controls the temperature of a housing that supports medium and long wave IR detectors. The remote cooler cools a second housing that supports visible/near IR detectors, as well as shielding the colder housing from the instrument environment. The goal of this investigation was to characterize the cooler over a relevant range of operating conditions so that instrument level performance can be predicted and optimized. Besides the obvious effects of cryogenic load and compressor drive level, there are effects of orientation with respect to gravity. Natural convection in the pulse tube affects the capacity of the operating cooler as well as the heat leak through a non-operating redundant cooler. Predicting the zero-g performance of the cooler is a major consideration. Demonstration of system level margins will be made with the cooler operating in an adverse orientation, to control the heat leak from the redundant cooler. A third orientation of the cooler will be used for instrument system-level testing. ABI is a NOAA funded, NASA administered instrument contract.

USAF Cryogenic Thermal Management System Needs [1-53]

T. Roberts, F. Roush
Air Force Research Laboratory, Kirtland AFB, NM, USA

The Air Force Research Laboratory (AFRL) Space Vehicles Directorate pursues cryogenic refrigeration system and system integration technology research in support of the research needs of the Air Force (USAF), Missile Defense Agency (MDA), and Department of Defense (DoD). This effort derives requirements from multiple programs and develops general solutions to the cryogenic needs for general space missions as well as specific solutions for individual mission applications. The general thermal management needs of missions supporting Air Force space operations are supported by modeling payload interactions with their cryogenic components. Specific strengths and weaknesses of the current state of technology are also compared to these needs.

Space Cryocooler Survey 2007 [1-57]

J. Cha, S. Yuan, D. Curran
The Aerospace Corporation, El Segundo, CA, USA

A synopsis of a long-life cryocooler survey conducted in 2007 by The Aerospace Corporation is presented. This survey summarizes the available and those under development mechanical cryocoolers for space applications. More than 30 long-life units have been identified from this survey. Cryocooler types include Stirling, Pulse Tube, reverse Brayton, and Joule-Thomson as well as component configurations such as split, integral, multi-stage, and hybrid covering the 4-20K, 35-60K, 50-95K, and above 100K temperature ranges. Results of the survey provide a hardware summary and performance comparison for potential application on cryogenic payloads by the user community. Empirical models of the specific power and the specific mass are also presented as derived from vendor performance data. The models use a power law curve fit analysis expressed as a function of cooler cold tip temperature (for multi-stage coolers the model is expressed as last-stage cold tip temperature). The model involves only coefficients representing either cooler mass or power input to the compressor. These empirical relations allow the user to estimate cooler performance characteristics for a unit to fit a particular design need

Development of Advanced Two-stage Stirling Cryocooler for Next Space Missions [1-30]

Y. Sato, H. Sugita, K. Komatsu, R. Shimizu, H. Uchida, T. Nakagawa, H. Murakami, K. Mitsuda
Japan Aerospace Exploration Agency, Japan

M. Murakami
University of Tsukuba, Ibaraki, Japan

I. Iwata, S. Tsuneta
National Astronomical Observatory of Japan, Tokyo, Japan

S. Tsunematsu, K. Kanao, K. Ootsuka, M. Hirabayashi
Sumitomo Heavy Industries, Ltd., Niihama, Ehime, Japan

The advanced two-stage stirling cryocooler has been developed for the cryogenic system of next astronomical missions, Spectrum-RG(2011), ASTRO-G(2012), NEXT(2013), SPICA(2017) proposed to JAXA. Especially, SPICA mission is the second Japanese infrared space telescope with the primary mirror of 3.5 m diameter and the optical bench, which is required to be maintained at 4.5K during over 5 years with the innovative cooling system. The technical feasibility of the effective radiant cooling system with advanced mechanical cryocoolers has been investigated to meet thermal and structure vibrational requirements for high spatial accuracy and resolution of SPICA mission optical observation devices. The temperature of 4.5K is obtained by the JT(Joule-Thomson) circuit, combined with the two-stage Stirling cryocooler for precooling to 15-20K. The advanced two-stage Stirling cryocooler has been modified and developed for higher mechanical reliability over 5-year operational lifetime and higher cooling capacity of 200mW at 16K, based on the existing two-stage Stirling cryocooler with a cooling capacity of 200mW at 20K developed for the first Japanese infrared astronomical satellite AKARI(ASTRO-F) to be operated for more than 1.5 year. Several technical approaches are investigated for improvement of higher mechanical reliability and cooling performance of advanced two-stage Stirling cryocooler, for instance, modification of flexure spring supported displacer for mechanical attrition reduction, optimization of cooler driving conditions and active control operation for low mechanical vibration. This paper describes the development status of advanced two-stage Stirling cooler as one of key technologies for next space missions.

SESSION 2: Pulse–Tube/Stirling Cryocoolers (Single & Multistage) [POSTER SESSION]

Tuesday, June 10, 2008 10:00 – 11:00 AM

Experimental Investigation on Single Stage Inline Stirling Type Pulse Tube Refrigerator [2-10]

L. Mohanta, M. Atrey
Indian Institute of Technology Bombay, Mumbai, Maharastra, India

The salient features of Stirling type Pulse Tube Refrigerator (PTR) are its compactness, low vibration, high frequency of operation and longevity. The flow in the pulse tube is complex because of oscillatory nature. The flow pattern plays an important role in the performance of the pulse tube. Various design parameters like dimensions of pulse tube, regenerator and operating parameters like pressure and frequency affect the pulse tube performance. The cold end heat exchanger forms the most important components of the PTR as the cooling effect is distributed from this component. The present paper evaluates the experimental performance of the PTR for different configuration of cold end heat exchanger in terms of cool down curve, lowest temperature reached and wattage study at 80K. The performance of the PTR is studied using a stack of coarse copper meshes in the cold heat exchanger. Similar investigation is carried out by replacing the meshes with a tapered finned copper block in order to get better heat transfer at the cold end. The results showed substantial improvement in the performance of the PTR. It is also found that the optimum frequency gets affected by such changes. In another system, the study is further extended to investigate the effect of taper of cold end heat exchanger using coarse copper meshes. The included taper angle is varied and its effect on the performance of the PTR is studied.

SESSION 2: Pulse–Tube/Stirling Cryocoolers (Single & Multistage) [POSTER SESSION]

Tuesday, June 10, 2008 10:00 – 11:00 AM

Research of Separated Pulse Tube Coolers Driven by One Single Compressor [2-20]

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There is no moving part at cold tip of the pulse tube, this unique feature results the merit of long life and PTC will not be broken generally. For this reason, we could duplicate the compressor only to prolong the lifetime of the system. We are developing duplicate compressor technology. Generally pulse tube cooler system includes one cold head. Certainly, there is the case for multi-stage cooler which has multi-cold head. For some cases, there is the need of different position cooling and different refrigeration temperature, for example, 0.5W/80K and 0.5W/60K at two position of distance of 0.5m. Two PTCs are needed for this case. For these two PTCs, if the compressor needs to be duplicated, there will be four compressors, and this will be a complex system. There is the method whether we could use one compressor to driven two PTCs at the same time, and this will simplify the system design and decrease the system weight evidently. For such case, there is the question of cooperation of the PTCs and the compressor. This paper introduces such a research work. First the program is developed to simulate the characteristics of two cold heads driven by one compressor. Then a experimental system is set up, which includes one compressor and two different PTC. The effects of average pressure, frequency, input power are revealed. Further, the connection tube length of PTCs to compressor is changed to investigate the effect. Both experiments and simulation are coinciding generally. Detail results will be introduced.

Performance Comparison of Stirling Type Single Stage Pulse Tube Refrigerator for Inline and "U" Configurations [2-11]

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K. Narayankhedkar
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Pulse Tube Refrigerators (PTR) have become highly popular due to their inherent advantages like absence of moving parts at the cold end, reduced vibrations, high reliability, light weight and simple construction. There are various configurations possible in PTRs like inline, U-type, co-axial and annular. Also, different phase shifting mechanisms like orifice valve, double inlet valve, Inertance tube, etc. are in practice. The present work aims to study and compare the performance of the inline and the U-type configuration of the PTR developed in the laboratory, keeping the same dimensions of the pulse tube and the regenerator. The inline configuration reached minimum temperature of 48.2K; while the PTR with the U-type configuration reached about 70K till date; for the same pulse tube and regenerator dimensions. The "U" configuration is further studied to understand the performance dependence on the connecting tube diameter and length. Investigations are further carried out to study and compare the performance of these PTRs for different operating parameters like charging pressure, frequency of operation, etc. and design parameters like length of Inertance tube; for both inline and U-type configurations. The comparison is carried out in terms of cool down time, minimum temperature reached and cooling effect.

Theoretical and Experiment Study on a Single Stage Pulse Tube Cryocoolers Driven with a Linear Compressor [2-113]

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After successful visiting from Ray Radebaugh's group at National Institute of Standards and Technologies (NIST), Boulder, CO, we have built a single-stage Stirling-type pulse tube cryocoolers (PTC) recently. The NIST numerical model known as REGEN 3.2, which is based on finite difference equations for the conservation equations, was used for optimization of the regenerator which operating at charging pressure 2.0-2.5MPa and frequency at 60Hz. According to REGEN3.2 calculation, the regenerator geometry is 45mm long and inside diameter 15mm for cooling power above 5W. Two-sectional inertance tube was used to regulate the right phase between pressure and mass flow rate at the hot end of the pulse tube based on INERTANCE developed by Ray Radebaugh. A setup of a single stage pulse tube cryocoolers was built according to the above calculation. When the charging pressure is 2.5MPa and operating at 60Hz, it could reach the lowest temperature 57.0K, and the cooling capacity was 5.0W at 79.1K initially. Further improvement is needed. It indicated that the experimental results are quite agreeable with the design.

This work is supported by National Natural Science Foundation (50676081) and Science and Technology Department of Zhejiang Province (2007C30063).

SESSION 2: Pulse–Tube/Stirling Cryocoolers (Single & Multistage) [POSTER SESSION]

Tuesday, June 10, 2008   10:00 – 11:00 AM

10K Pulse Tube Cooler Performance Data [2-108]

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The 10K EM Pulse Tube cooler is a three-stage pulse tube cooler for space applications. The staged cooler uses the same compressor and parallel staging configuration for the 1st and 2nd stages previously employed in NGST's Flight Qualified High Capacity Cryocooler (HCC Qual). Addition of the third stage extends the performance of this cooler to operating temperatures below 10K. The cooler performance has been mapped under a wide range of operating conditions. This paper presents the test data collected with the cooler at different input power levels, heat rejection temperatures and cooling conditions.

SESSION 2: Pulse–Tube/Stirling Cryocoolers (Single & Multistage) [POSTER SESSION]

Tuesday, June 10, 2008 10:00 – 11:00 AM

Raytheon Stirling Pulse / Tube Cryocooler Maturation Programs [2-8]

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T. Roberts
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Raytheon has continued to advance the maturity of the Stirling / pulse tube two-stage cryocooler technology. Two versions of this cryocooler are currently in test. The first one has been developed on an Air Force Research Laboratory (AFRL) program to cool large long wave infrared (LWIR) sensors. This cryocooler, called the High Capacity Raytheon Stirling / Pulse Tube Two-Stage (HC-RSP2), delivered 2.6 W at 35K simultaneously with 16.2W at 85K for 513W cryocooler input power during thermal vacuum testing. A second version called the Mid Capacity (MC) RSP2 delivered 2.4W at 58K simultaneously with 6.1W at 110K for 166W cryocooler input power during bench top testing. These and additional test results are discussed. Lessons learned during the build and test of these two cryocoolers and the efforts underway to apply those lessons learned to the development of a second generation, improved RSP2 Cryocooler are presented.

Development of a Two Stage High Temperature Pulse Tube Cooler for Space Applications [2-16]

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C. Daniel, R. Briet
CNES, Toulouse, France

In the framework of a Research and Technology program co-funded by the French space agency (CNES), CEA/SBT is developing a high frequency two stage pulse cold finger able to provide 2W at 70K on the second stage and simultaneously 6W at 140K on the first stage. This cooler should address the cooling needs of detectors for low orbit earth observation missions. In order to capitalize European effort in the cryocooler fields, this cold finger is designed to operate with the compressor developed in the framework of ESA LPTC project. This compressor is able to provide around 120W of PV power. A modular prototype of the pulse tube cold finger has been built. The design of this prototype will be presented as well as the first experimental results. The constraints associated to the design of a cold finger matching the parameters of an existing compressor will be discussed. Effect of input power, frequency and filling pressure is also studied.

Multistage Pulse Tube Refrigeration Characterization of the Lockheed-Martin RAMOS Cryocooler [2-52]

T. Roberts, E. Pettyjohn, W. Scheirer
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The performance mapping of a multistage pulse tube refrigeration system has been performed on the Lockheed Martin RAMOS cryocooler by the Air Force Research Laboratory. The results are presented in terms of primitive variables such as temperature, work inputs, and cooling load supported. It is then restated in terms of composite variables such as available work (exergy) inputs, the individual and composite exergies of the cooling loads supported, and system efficiency. Additional data from the heat rejection interfaces of this refrigeration system are presented, including the temperature variations over the extended compressor-expander section transfer line. The data presented shows both the application envelope of this refrigerator and how it interacts with its application environment.

Two-Stage Pulse Tube Refrigerator with 2nd Stage Recuperator [2-90]

J. Jung, S. Jeong, G. Hwang
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We have been developing a recuperative two-stage pulse tube refrigerator. As a part of the development, two subjects were investigated. The first one was an equipment for generating two pulsating pressures of opposite phases, and the second one was a high-effectiveness miniature recuperator which could replace the 2nd stage regenerator. As a result of the investigation on the first subject, a tandem rotary valve was devised and experimentally verified a few years ago. For the second subject, we recently made remarkable progress. A PCHE(Printed Circuit Heat Exchanger)-type recuperator which has hydraulic diameter as small as 0.05 mm was built. With the prepared items, a recuperative two-stage pulse tube refrigerator was constructed. In detail, a pair of pulse tube refrigerators were combined in the 2nd stage by the recuperator, and the tandem rotary valve drove the assembled system. In the system, no gas reservoir was used, but the hot ends of the pulse tubes were joined instead. The total system finally has 12 adjustable valves and 6 possible DC-flow loops. The valve tuning is far more complicated than in a conventional pulse tube refrigerator. With the valves carefully tuned, the system reached approximately 45K at the 1st stage and approximately 8K at the 2nd stage. This result was below our expectation. The pressure drop at the recuperator was larger in actual operating condition, and the helium line between the helium compressor and the rotary valve produced unnecessary pressure drop.

Development of a High Capacity Cryocooler [3-27]

J. Tanchon, T. Trollier, A. Ravex
Air Liquid Advanced Technology, AL/DTA, Sassenage, France

A. Caughley
Industrial Research Ltd., Christchurch, New Zealand

A few years ago, AL/DTA initiated, in the framework of a DOE contract, the development of a Very Large Pulse Tube Cooler (VLPTC) for HTS devices. This cooler is in the 250W@65K range when connected to a 8kW flexure bearing compressor making it potentially suitable for HTS refrigeration or gas liquefaction. In parallel to this development, AL/DTA developed a larger cooler at 120K for cryo-trapping on-board submarine. Those two coolers are currently at development model and are not mature enough for a large scale industrialization due to high costs. The main limitation of these kind of coolers is the compressor cost. For laboratory or industrial applications the use of large flexure bearing compressor seems not to be realistic. In partnership with Industrial Research and HTS-110, AL/DTA is working on the development of an evolution of these coolers based on a low cost pressure wave generators using metallic diaphragm. The status of this development is presented and the current performances will be discussed for various cold finger configurations.

Acoustic-Stirling 55 gal/day Oxygen Liquefier for Use on Aircraft Carriers [3-98]

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For the next generation of aircraft carriers, the U. S. Navy has specified that acoustic-Stirling ("pulse-tube") refrigeration is the preferred technology for liquefying oxygen. This paper will describe the modeling and design of the first prototype liquefier, built for a Navy subcontractor. The performance requirement for these first prototypes is 55 gallons per day of oxygen, or a gross cooling power of >1000W at the liquefaction point (90K at 0psig). To be confident of hitting or exceeding the performance target, we have chosen to build this liquefier around our largest pressure-wave generator, which is capable of delivering as much as 20kW of acoustic power at 60 Hz. To simplify the interface between the cold zone and the process gas, we have chosen a coaxial cold-head design with a salient cold tip. Each liquefier will have three heads on one acoustic drive, thus each head must have over 300W of cooling capacity in this configuration. This may make these the highest-capacity coaxial high- frequency cold heads ever built. Performance tradeoffs relating to the coaxial configuration versus the in-line configuration will be discussed. Performance sensitivity to process gas pressure and process gas purity will also be discussed. Test results will be shown if available by the conference date.

Development of the Miniature Flexure Bearing Cryocooler SF070 [3-74]

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Enhancement of reliability is still a major goal for today's development of tactical cryocoolers. For linear coolers the introduction of the Flexure Bearing technology enables MTTF lives of 20000h and more. This shall result in a significant reduction of the total cost of ownership for the IR devices. Recently AIM has introduced the flexure bearing cooler SF100 with full Flexure Bearing suspension on both ends of the driving mechanism and Moving Magnet driving mechanism in the one watt class. This solution meets performance data, environmental specification and even form factor requirements of the current standard linear cooler. The transfer of the above mentioned technologies to the entire range of linear coolers at AIM is in progress. Typically, such transfer to devices with smaller form factor is more demanding compared to devices with less stringent form factor requirements. The paper reports on the development of a compact 3/4W Flexure Bearing Moving Magnet cooler SF070. This Paper gives an overview on the design consideration in order to achieve highest compactness and presents performance data of the cryocooler when being operated with a 8mm Stirling coldfinger in sleeve design. The cooler is characterized for ambient temperatures ranging from -40 to 71°C with coldtip temperatures from 67 to 90K.

Pulse Tube Cryocooler for Rapid Cooldown of a Superconducting Magnet [3-99]

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R. Taylor
University of Wisconsin-Madison, Madison, WI, USA

A single-stage pulse tube cryocooler was designed to provide rapid cooldown of a high temperature superconducting (HTS) magnet that is part of a gyrotron required for the generation of high-power mm-wave (95GHz) beams. These beams are used in the nonlethal weapons systems known as the Active Denial System. The optimized cryocooler is designed to provide 50W of net refrigeration power at 50K and is driven by a pressure oscillator that can produce up to 2.8kW of acoustic power at 60Hz. The rapid cooling technique makes use of a resonant phenomenon in the inertance tube and reservoir system to decrease the flow impedance and thereby increase the acoustic power through the system when the cold end is near room temperature. We use three different reservoir volumes at the end of the inertance tube with ball valves to select the optimum reservoir for any particular cold-end temperature. With the optimum reservoir connected, the cooler impedance at any temperature is better matched to that of the pressure oscillator, which allows for a greater input power and faster cooldown without hitting the end stops in the pressure oscillator. This paper discusses the construction and performance of the cryocooler. Initial measurements showed the presence of serious flow nonuniformities inside the pulse tube that led to poor performance. The steps taken to eliminate the nonuniformities and their effect on the cooler performance are discussed. The cooling rates for different reservoir volumes with a 20kg copper mass attached, which simulates a HTS magnet, are compared and discussed. Funding from Cryomagnetics and the U.S. Air Force is acknowledged.

Integrated Testing of a Complete Low Cost Space Cryocooler System [3-9]

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Raytheon Vision Systems, Goleta, CA, USA

Significant progress has been made on the Raytheon Low Cost Space Cryocooler (LCSC), also called the Dual Use Cryocooler (DUC) because of its applicability to space and terrestrial applications. Most notably, the LCSC has been integrated and tested with an engineering model LCSC Electronics (LCSCE) module. Just as the LCSC combines features from traditional tactical and space cryocoolers to achieve the required long-life operation at substantially lower cost than typical space cryocoolers, the LCSCE also embodies features from both the tactical and space cryocooler product lines. The LCSCE unit tested was fabricated from all military grade, high reliability components. Every component is either radiation hard to 300 krad total ionizing dose (TID) or replaceable with a functionally equivalent component that is. The LCSCE was shown to efficiently drive and control the LCSC without complication. The integrated test results of the LCSC with the LSCSE are presented.

Design of Aural Undetectable Cryogenically Cooled Infrared Imagers [4-40]

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For the sake of weight and compactness, the enclosures of the modern portable cryogenically cooled infrared imagers are made in the form of a light metal (aluminum, magnesium) thin-walled shell, serving as an optical bench, accommodating a telescope, an optical train and an Infrared Detector Dewar Cooler Assembly (IDDCA). Such IDDCAs normally rely on miniature rotary Stirling cryogenic coolers, which are known as powerful sources of wideband vibration export giving rise to the inherently lightly damped structural resonances in the imager enclosure thus causing strong structure-borne noise. This normally leads to an increased range for aural detectability of forward observers who must remain undetected, potentially for long periods of time. Consequently, the aural nondetectability distance becomes one of the crucial figures of merit (along with the overall weight, battery life, imagery quality, etc.) characterizing the modem portable infrared imager. In the novel approach, the IDDCA is mounted within the enclosure using a special silencing pad, effectively attenuating vibration export over the typical high frequency range that contains the relevant structural resonances of the enclosure. The residual noise radiation from the imager enclosure is then attenuated practically to a background level by reshaping the radiation modes thus canceling the overall volume velocity. This is achieved by finding the "critical point" and affixing there the optimally sized correction mass. The authors report on a successful attempt to develop a cooled imager that is inaudible at greater than 10 meters (even during the cool down phase) per MIL-STD-1774D (Level II).

A Thermomechanical Heat Switch [4-39]

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CEA/INAC/Service des Basses Temperatures, Grenoble, France

Cryogenic heat switches are one of the key technologies in many space cryogenic systems. To the exception of the ultra low temperature range for which specific techniques must be employed, two types of switches are mostly used. The mechanical switches whereby the thermal conductance is directly linked to the quality of contact between two surfaces, and the gas gap heat switch whereby the conductance is due to the absence or presence of gas between two interlocked parts. In most cases, particularly at liquid helium temperature, the gas gap heat switch is selected for its high reliability (no moving parts) and excellent ON thermal conductance. However its characteristics require to take precaution during integration and the mechanical constraints on the switch free end must be limited. To improve these aspects a new design is proposed. In addition this design allows for a control of the ON conductance and extremely fast switching time. A first prototype has been build and tested, and the concept has been experimentally demonstrated. The design has been further improved and several new prototypes are currently being assembled. The general design along with the results obtained will be discussed at the conference.

A Cryogenic Heat Transport System for Space-Borne Gimbaled Instruments [4-101]

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A key technical challenge facing future space-based target acquisition and tracking systems is the cooling of detectors and associated components mounted on a gimbal. A critical trade must be performed at the spacecraft-level to determine whether to place the cryocooler on or off the gimbal. The off-gimbal approach requires a cryogenic heat transport system to exchange heat from on-gimbal components to the cryocooler. This approach has the advantage of removing the mass of the cryocooler and ambient-temperature heat rejection system from the gimbal, but requires the use of either (1) a cryogenic heat transport system or (2) a continuous flow cryocooler. Creare and Raytheon are currently developing a cryogenic heat transport system that uses a single phase gaseous flow loop. The flow loop consists of: ultra-flexible tubing to impart minimal torque to the gimbal motors; a miniature cryogenic circulator to pump the cycle gas with minimal input power; and thermally effective heat exchangers to transport heat with high conductance. The heat transport system has heritage in the NICMOS heat transport system developed by Creare and operational since 2002 on the Hubble Space Telescope. This paper describes: the component technologies; the test results from cryogenic life and reliability tests on the system components; the measurements of tubing flexibility at cryogenic temperatures; and our progress towards a demonstration of a two-stage cryogenic heat transport system.

Low Vibration, Low Thermal Fluctuation System for Pulse Tube and GM Cryocoolers [4-68]

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As a result of a multi-year engineering effort to enable S2 Corporation's new optical processing and programmable stable laser technologies, a compact integrated vibration isolation system for pulse tube and GM cryocoolers which provides vibration reduction to less than 10 nanometers, thermal fluctuation reduction to less than 10mK, easy sample access, and a base temperature of 2.7K - 3K was developed. Cryogenic cooling can be enabling for many new technologies, but the integration of cryocoolers with cooled components is fraught with challenges that hinder system performance and technology advancement. S2 Corporation's technology is one such example where enabling cryogenic technology has advanced an optical processing technology to a fully functioning prototype which has recently been successfully demonstrated on US military radar assets. Data will be presented which shows the vibration and thermal performance of the vibration isolation system as well as a description of how the results were obtained. Also, an overview of S2 Corporation's cryogenic-enabled technologies will be given which includes radar, spectral monitoring, communications, and programmable frequency stable lasers. Additional technologies that may benefit from this enabling cryogenic technology include quantum computing, superconducting electronics and basic research where a stable cryocooled environment is required.

50 mK Continuous Cooling with ADRs Coupled to Helium3 Sorption Cooler [5-65]

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A. Sirbi
ESA/ESTEC, Noordwijk, The Netherlands

CEA/SBT has a well established knowledge and a recognized experience in sorption coolers reaching 200 to 300mK. The association of this technique with Adiabatic Demagnetization Refrigerators gives the possibility to reach temperature below 50mK with limited mass budget (less than 5kg for a 1uW cooler). In the framework of an ESA contract we are developing such a cooler for continuous cooling at 50mK based on this technology. The cycle chosen is described and discussed. Mass and efficiency optimization is being done and a trade-off is presented. Experimental results on a one shot cooling system reaching temperature of 30mK are also shown.

Development of Low Magnetic Field ADR for Transition Edge Sensors [5-104]

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Trends in remote sensing/space-based photon detectors are to operate at temperatures < 100mK. One of the leading techniques for achieving these temperatures is with the Adiabatic Demagnetization Refrigerator (ADR). We are developing an ADR system leveraging on earlier work done by the University of Wisconsin. Our design is compatible with the next generation microcalorimeter sensors (i.e. transition edge sensors operating at <100mK) which require very low magnetic fields. The system is compatible with sounding rocket flight loads with a liquid helium guard tank. There was a focused effort to reduce the magnetic field to allowable values (50 mGauss at full magnet current of 8.5 A) and several shielding approaches were considered before the final selection. In addition, extensions of this technology utilizing a Lockheed Martin 4-5K pulse tube cryocooler as the guard for long life missions is under study.

This paper will present data on the operation of the system and results of magnetic field measurements and attenuation from the superconducting magnet.

A Superfluid Pulse Tube Driven by a Thermodynamically Reversible Magnetic Pump [5-122]

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J. Brisson
Massachusetts Institute of Technology, Cambridge, MA, USA

A concept for superfluid pulse tube refrigerator that has no moving parts and uses a 3He-4He mixture as the working fluid is described. The pulse tube refrigerator is driven by a novel, thermodynamically reversible, magnetic pump. A model used to predict the performance of the pulse tube refrigerator is presented. This model is used to develop a design for the magnetic pump and as a system level design tool for the refrigerator.

Pocket Dilution Cooler [5-37]

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We have developed a compact, self-contained dilution cooler that can be operated from a 2.5K or lower heat sink. The system comprises a helium sorption cooler coupled to a closed loop in which the helium mixture is circulated. The dilution loop operates continuously and is only limited by the autonomy of the sorption unit which needs to be recycled on a regular basis. This first prototype has been designed to provide temperatures below 100mK for a typical day work. The system is an energy device and can be scaled up within certain limits. Temperature down to 67mK and typical cooling power of 10 microwatts at 100mK have already been achieved. Modifications are being made to reach 50mK. The system is gravity driven and could be used to test detectors or as a cooling solution onboard balloon flown experiments. The design and performance achieved will be discussed.

Initial Evaluation and Application Potential of a 4-Kelvin 4-Stage Pulse Tube Cryocooler [6-110]

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The deployment of high performance superconducting electronics in many applications requires the integration of a robust, long life, highly efficient 4K cryocooler with an equally robust cryopackage including superconducting Integrated Circuits (ICs). HYPRES has focused on the field of wireless communications, with the goal of producing self-contained receivers and/or transceivers for both the military and commercial markets. A first laboratory prototype for such a cryocooler was recently developed by Lockheed Martin and delivered to HYPRES. This 4-stage Stirling-type pulse tube with up to 40 mW of heat lift at the fourth stage (4.5K) has been described earlier by Lockheed Martin at the 2007 CEC/ICMC conference. We report on our initial evaluation of this prototype, including (a) the thermodynamic performance, (b) the results of cryopackaging and testing a superconducting IC on the cryocooler, and (c) the determination of the desired changes to graduate from a laboratory prototype to a field prototype. Our thermodynamic results agree with those obtained by Lockheed Martin prior to delivery of the system, and the superconducting IC has been operated successfully. A set of future improvements has been identified and will be discussed, pertaining to thermodynamic performance, external packaging, EMI shielding, and volume manufacturing.

Development of a Diaphragm Pressure Wave Generator for Cryocoolers [6-64]

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C. Wang
Cryomech, Inc., Syracuse, NY, USA

This paper describes the development and testing of a low-cost, industrial-style pressure wave generator which employs metal diaphragms. The use of diaphragms removes the need for rubbing or clearance seals whilst maintaining a hermetic seal between the cryocooler gas circuit and the lubricated driving mechanism. This allows a conventional low-cost electric motor to be used as the power input device. A first prototype of the diaphragm pressure wave generator produced 3.3kW of PV power with a measured electro-acoustic efficiency of 69%. The diaphragm pressure wave generator has successfully driven a number of pulse tubes including one developed by Cryomech that achieved over 100W cooling at 80K. The prototype has now been operated more than 2,000 hours without failure. Accelerated testing predicts a diaphragm lifetime in excess of 40,000 hours. In order to reduce size, cost and mechanical noise from the linkage driving the diaphragms, an alternative form of force amplifier is under test for driving the diaphragms. Test results of the new driving mechanism for the diaphragm compressor will be presented in this paper.

Development of the Active Magnetic Regeneration (AMR) Refrigerator Using a Permanent Magnet [6-77]

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A. Saito, S. Kaji, T. Kobayashi
Toshiba Corporation, Kawasaki, Japan

The problem of global warming and ozone layer depletion is actualizing. Promotion of the research and development about alternative energy or energy saving is desired strongly from now on. In such a situation, the magnetic refrigeration method will become still more important. As for a magnetic refrigeration method, application to liquefaction of the helium or hydrogen in a cryogenic temperature region is expected. On the other hand, the application to an air conditioner or a refrigerator can be considered in a normal temperature region. We are studying the active magnetic regenerative (AMR) refrigerator, which used gadolinium and gadolinium alloys for magnetic working material. Experiments were conducted changing parameters, such as a kind of magnetic material, particle diameter, cycle speed, and environmental temperature. By optimization of the parameter, it succeeded in building a not less than 40K difference of temperature using the permanent magnet of the magnetic field intensity of 1T. Furthermore, the simulation about the AMR cycle was performed and it asked for the relation of the refrigerating capacity and the coefficient of performance to the difference of temperature between high temperature end and low temperature end. By carrying out comparison of the obtained experimental results at simulation results, understanding of cycle operation of magnetic refrigeration was able to be deepened.

Intermediate Cooling in 4 K Pulse Tube Cryocoolers [6-100]

C. Wang
Cryomech, Inc., Syracuse, NY, USA

This paper introduces intermediate cooling from the 2nd stage pulse tube and regenerator in 4K pulse tube cryocoolers. Two intermediate heat exchangers have been installed on the 2nd stage pulse tube and regenerator separately in a 4K pulse tube cryocooler for studying the performance and behavior of the intermediate cooling. Due to the large enthalpy flow in the 2nd stage pulse tube and regenerator, both intermediate heat exchangers on the pulse tube and regenerator can provide cooling capacities in the temperature range of 5-15K without or with minor effect on the performance of the 4K stage. Extracting cooling capacity from the 2nd stage pulse tube or regenerator does reduce the 1st stage cooling performance in the present study. A joint intermediate heat exchanger which thermally anchored on the 2nd stage pulse tube and regenerator has been tested and demonstrated better cooling performances at different temperatures of the first stage.

Low Vibration 1W4K Two-Stage Pulse Tube Cryocooler [6-80]

M. Xu, M. Saito, H. Takayama
Sumitomo Heavy Industries, Ltd., Tokyo, Japan

Sumitomo Heavy Industries, Ltd. (SHI) has been developing 4K pulse tube cryocoolers for cooling MRI Magnet Systems, Small Superconducting Magnets, SQUIDs, X-ray detectors, etc. A typical vibration displacement of less than 3 μm has been achieved on SHI 0.5W4K pulse tube cryocooler with minor impact on performance. The valve unit of the cryocoolers is separated from the cold head by a self-sealed coupling. With this configuration, the maintenance for the valve unit becomes much easier and faster than that with a unified one since it is not necessary to warm up the cold head and cool down again. The vibration from the compressor and valve unit can be reduced by this configuration with some simple techniques. The vibration displacement has been reduced by optimizing the wall thickness of regenerators and pulse tubes. Recently, these techniques have been applied on SHI 1W4K pulse tube cryocoolers. The typical vibration displacement is less than 8 μm with minimum impact on performance. The cooling capacity is over 40W at 45K on the first stage and 1.0W at 4.2K on the second stage. When the compressor is operated at 60Hz, the input power is less than 8kW at normal steady state with 40W heat load on the first stage and 1.0W on the second stage. Experimental data are reported in this paper.

Dilution Refrigerator with Direct Pulse Tube Precooling [6-23]

Kurt Uhlig
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Helium-3,4 dilution refrigerators (DR) are the workhorses for researchers doing experiments at sub-Kelvin temperatures. DRs with pulse tube (PTR) precooling are especially convenient to operate and usually more economical than those with liquid helium precooling. So far, in most dry DRs the Helium-3 is condensed in an "integrated" JT-circuit; after the Helium-3 gas is precooled by a two-stage PTR, it is further precooled and (partially) liquefied in a heat exchanger which is part of a JT stage, before it is run to the dilution refrigeration unit. This heat exchanger is cooled by the Helium-3 return gas pumped from the still. In the new DR, the Helium-3 is precooled by the PTR in three heat exchangers (first stage, regenerator of second stage, second stage) to a temperature of about 2.5K, and then directly run to the impedance of the dilution unit without further precooling. An important feature of the PTR is utilized, namely that it has excess refrigeration capacity at its second stage regenerator, which can be used without impairing the cooling capacity and the base temperature of the second stage. The precooling temperature of 2.5K is low enough to operate a DR. Temperature sensors are placed in all critical locations of the cryostat. In our presentation, we give details on the temperature profile of the cryostat; the characteristics of the temperature profile are shown in an enthalpy diagram. Cooling capacity data of the DR are also presented. The new condensation system allows for a very short and compact layout of the dilution cryostat.

Complex Approach to Ultra-Low Vibration Control of a Linear Split Stirling Cryogenic Refrigerator [6-117]

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E. Castiel
National Instruments, Tel Aviv, Israel

Wide use of so called "dry-cooling" technology, eventually replacing the LN2 cooling approach in vibration-sensitive instrumentation, such as Scanning Electronic Microscopes, Helium Ion Microscopes, Superconductive Quantum Interference Devices, etc., motivates further quieting of appropriate cryogenic refrigerators. Linear Stirling cryogenic refrigerators are known to be a major source of harmful vibration export compromising the overall performance of vibration-sensitive equipment. The dual-piston approach to a design of a linear compressor yields inherently low vibration export and, therefore, is widely accepted across the industry. However, the residual vibration disturbance originated even from the technological tolerances, natural wear and contamination cannot be completely eliminated. Moreover, a vibration disturbance produced by a pneumatically driven cold head is much more powerful as compared to this of a compressor. The authors successfully redesigned the existing Ricor model K535 Stirling cryogenic refrigerator for use in vibration sensitive electro-optical instrumentation, where the imagery accuracy is specified in angstroms. The objective was achieved by passive mechanical counterbalancing of the expander portion of the refrigerator, in a combination with an active two-axis control of residual vibrations, relying on National Instruments CompactRIO hardware, incorporating a real-time processor and reconfigurable FPGA for reliable stand-alone embedded application, developed using LabVIEW graphical programming tools. The attainable performance of the Ultra-Low Vibration linear Stirling cryogenic refrigerator RICOR model K535-ULV was evaluated through the full-scale experimentation.

Micro Channel Recuperator for a Reverse Brayton Cycle Cryocooler [7-61]

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Missile Defense Agency SBIR funding is supporting an effort to design, fabricate and test a recuperator that is compact, light weight, durable, and provides extremely high effectiveness. The recuperator is designed to be installed in a reverse Brayton cycle cryocooler that will operate between 300K and 60K, providing 300mW of cooling. The effectiveness of the recuperator must equal or exceed 99.6%. The specifications of the system are as follows: the working fluid is helium, the mass flow rate of the working fluid is 0.56 grams/sec, and the absolute pressures of the two flow streams are 2.3 and 1.6 atmospheres. The allowable fractional pressure drop of the recuperator was specified to be no more than 2%. Additional specifications included acceptable leakage rates, burst pressure, g-loading, etc. Mezzo has spent the last year designing and fabricating a recuperator that will meet performance specifications while providing substantial weight savings (less than one third the weight) and volume savings (less than half the volume) over the current recuperator design. The progress associated with that effort will be presented. Specifically, the micro channel recuperator design will be described along with the modeling approach that was used to predict performance. In addition, the test facility used to quantify the recuperator thermal performance will be presented along with test results.

Performance Results of Microplate Heat Exchangers [7-94]

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High effectiveness heat exchangers are required for recuperative cycles such as Brayton and Joule-Thomson cryocoolers as well as precooled hybrid coolers. System efficiency is greatly improved by higher exchanger effectiveness. An improvement of the effectiveness from 98% to 99% can reduce the input power by 24% for a typical Brayton cryocooler. The microplate heat exchangers tested use a parallel plate geometry. A new manufacturing method has been developed allowing higher performance in a parallel plate geometry reducing the perform degradation caused by flow maldistribution. We have manufactured and tested the performance of several heat exchangers. The heat exchanger effectiveness has been measured and these experimental results will be presented. Effectiveness values of 98.7% have been measured. While there is still much to be learned to be able to reliably design and build these exchangers, this work shows important improvements in performance. With the lessons learned here we expect the next generation of heat exchangers to perform above 99% effectiveness.

Performance of a MEMS Heat Exchanger for a Cryosurgical Probe [7-13]

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W. Zhu, Y. Gianchandani
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This paper presents the experimental results of a 2nd generation Micro-Electro-Mechanical Systems (MEMS) heat exchanger that is a composite of silicon plates with micromachined flow passages interleaved with glass spacers. The MEMS heat exchanger was designed for use as the recuperative heat exchanger within the Joule-Thomson cycle used to energize a cryosurgical probe. The experimental measurements are compared with the numerical predictions from a design model and also with experimental results obtained from a 1st generation MEMS heat exchanger. The 1st generation heat exchanger was unable to withstand the high pressure differences (1400kPa) required by a J-T cryosurgical probe. The 2nd generation heat exchanger addresses these design deficiencies and exhibits superior thermal performance. Several prototypes of the 2nd generation heat exchanger have been manufactured and tested over a range of conditions.

Modeling and Experimental Verification of a Cascaded Mixed Gas Joule Thomson Cryoprobe [7-109]

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Cryosurgery is a technique for destroying undesirable tissue, such as cancers, using a freezing process. A vacuum insulated experimental test facility is used to quantify the performance of a commercial two-stage Mixed Gas Joule Thomson (MGJT) cryoprobe system in which the evaporator of a conventional vapor compression (VC) cycle using a pure refrigerant pre-cools the MGJT cycle that provides refrigeration at the cryoprobe tip. The cryoprobe refrigeration, cryoprobe tip temperature and the thermodynamic state and flow rate of each of the streams entering and leaving the cryoprobe are measured. The performance of the system with various mixtures comprised of argon, nitrogen and synthetic refrigerants (R134a, R23, R22) is studied. Additionally, the cryoprobe refrigeration with varied precooling evaporator temperatures is studied experimentally and analytically. The selection of refrigerant mixture for the experiments is guided using a thermodynamic modeling tool that was developed for the two stage MGJT cryoprobe. The model is integrated with an optimization routine in order to investigate the optimal mixture composition that provides maximum refrigeration for different cryoprobe tip temperatures and precooling temperatures. The predicted and measured system performances are compared to validate the thermal model of the cryosurgery system and demonstrate the model's usefulness as a tool for selecting optimal mixtures and operating conditions for a two stage cryosurgical system.

On-Chip Detector Cooling For Space Applications [7-12]

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A. Sirbi
European Space Agency, ESTEC, Noordwijk, The Netherlands

Miniature Joule-Thomson (JT) coolers have a high potential for space applications in cooling small detector systems for future earth observation and science missions. Both, cooler and detector can be integrated on a single chip by means of MEMS technology. One of the advantages of JT cooling is that multiple cold tips can be driven by a single compressor. In this way several cold tips can be distributed over the spacecraft to cool multiple detectors, remote from the compressor. This allows maximum flexibility in spacecraft design. If a sorption compressor is used, the cycle is closed without moving parts. This means that the cooling system is vibration free, and has the potential of a long life time. For future space missions, the European Space Agency is interested in on-chip detector cooling for the temperature range 70K – 250K. Within this temperature range, the best working gas was selected on basis of the coefficient of performance (COP) of the cold stage. This COP is determined as the available cooling power divided by the input Gibbs free energy. In addition, a figure of merit of the heat exchange in the counterflow heat exchanger was evaluated. This figure of merit is based on the thermal conductivity and specific heat of the gas. The results of the optimization will be presented. To simulate the performance of a JT cooler integrated with a detector system in different thermal environments, a thermal mathematical model is built in the software program ESATAN. The cooler is modeled as an area with a fixed cooling power and surrounded by a vacuum chamber of constant temperature. Radiation is taken into account as well as losses due to cabling and heat transfer through the cooler-detector interface. The results of these simulations will also be presented.

Development of a Mixed-Refrigerant Joule-Thomson Microcryocooler [7-105]

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M.-H. Lin, Y. Lee, V. Bright
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We discuss in this paper the development of a mixed-refrigerant Joule-Thomson microcryocooler (MCC) to support on-chip cooling of high temperature superconducting electronics that require less than 5mW of net refrigeration at about 80K. Some applications include the cooling of infrared and terahertz imaging sensors that operate at about 77K. Terahertz sensors can be used for the imaging of concealed nonmetallic weapons as well as the spectroscopic identification of chemical and biological material. The MCC is designed to deliver approximately 9 mW gross refrigeration, which yields about 3mW of net refrigeration once losses due to the heat exchanger, conduction, radiation, and pressure drop are subtracted. The MCC utilizes a 2-cm long heat exchanger made with six small glass capillaries inside a 0.613mm OD glass capillary. The manifolds at each end are fabricated using MEMS techniques, and the cold manifold, which contains a micro-expansion valve, is about 2 mm square by 1.3mm thick. The cryocooler utilizes a multi-component gas mixture that is precooled to 240K by a thermoelectric cooler. Precooling the gas mixture significantly increases the minimum isothermal enthalpy difference, which is the gross refrigeration power per unit flow. For a pressure ratio of 16:1 this enthalpy difference is about 1.43kJ/mol for the mixed refrigerant compared with 0.15 kJ/mol for pure nitrogen. The MCC has been designed to operate at pressure ratios of 16:1 to 25:1 for a flow rate of about 6 μmol/s (~ 0.15std. cm^3/s). We discuss the cold head design with measured pressures, flow rates, and lowest temperatures achieved to date. Funding from the DARPA Microcryocooler Program is acknowledged.

Development of a Piezoelectric Microcompressor for a Joule-Thomson Microcryocooler [7-107]

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In this paper we discuss the development of a microcompressor capable of delivering pressure ratios from 16:1 to 25:1 for design flow rates of about 0.15 std. cm^3/s intended to provide flow for a mixed refrigerant Joule-Thomson (JT) microcryocooler. The JT microcryocooler supports on-chip cooling applications, such as terahertz and infrared imaging sensors operating at about 77K that require less than 5 mW of net refrigeration. The high pressure ratio of the compressor is enabled by minimizing dead volume and using a 10 mm diameter metallized polyimide membrane that is actuated by a zirconium titanate piezoelectric (PZT) stack. With a stroke of about 28 μm and a swept volume of about $2mm^3$, the design flow rate could be achieve with a frequency of about 100Hz. The entire microcryocooler, compressor module, sensor, and thermal integration module are expected to occupy less than 10 cm^3 volume. At present the compressor module demonstrates a pressure ratio of 21:1 when blanked off and has a volume less than $2cm^3$. We discuss numerous design iterations for achieving the 21:1 ratio as well as studies comparing stroke and volume vs. frequency to achieve design flow rates. We present design alternatives for the valves in the compressor head, including passive MEMS and active PZT, with their measured pressure ratios and flow rates. Funding from the DARPA Microcryocooler Program is acknowledged.

Theoretical Design and Analysis of 1 W @ 80 K Pulse Tube Cryocooler Required for Space Related Applications [8-38]

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The extension of the human exploration of space from low earth orbit into the solar system is one of NASA's challenges for the next millennium. NASA planned first cargo mission to Mars in 2011 and the first piloted human exploration in 2014. Without safe and efficient cryogen storage, economically feasible human Mars missions will not be possible. Significant launch mass reductions and consequent cost savings can be achieved by improving storage and production technology. A combination of both active and passive technologies is being proposed to address this problem. In Mars mission the key cryogenic technology areas to be considered are long term, propellant storage, cryogenic refrigeration, cryo liquefaction. long term storage for the thermal control of cryogenic propellant is best accomplished with a mixture of passive and active technologies. Passive technology such as advanced MLI concepts will be combined with the development of active coolers, e.g., stirling, pulse tube, etc. The integration of passive and active technologies will form a hybrid system optimized to minimize the launch mass while preserving the cryogenic propellants. These types of cryocoolers are used in thermal imaging camera, astronautical instruments, satellite cooling applications and also for production of LN2, LHe, etc.

A Model for Exergy Analysis and Performance Evaluation of Regenerators [8-42]

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A. Razani
The University of New Mexico, Kirtland AFB, NM, USA

One of the major losses in Stirling-Type Cryogenic Refrigerators (STCRs) is due to heat transfer and fluid flow irreversibility in the regenerative heat exchanger. Accurate numerical modeling of these losses requires extensive numerical simulation of coupled mass, energy and momentum conservation equations. In this study, a first order model is presented relating the mass flow rate and pressure at the hot and cold sides of the regenerator. Heat transfer and pressure drop in the regenerator is obtained assuming reasonable correlations for fluid friction and heat transfer in the regenerator. Therefore, exergy analysis of the regenerator can be performed and the exergy at the cold and hot sides of the regenerator can be related. A performance criteria based on exergetic efficiency of the regenerator is defined and evaluated. The performance of the regenerator and its optimization, based on the exergetic efficiency, is evaluated. The exergy destruction due to heat transfer and pressure drop is determined and discussed. The effect of important parameters on the exergetic efficiency of the regenerator is presented and discussed.

Investigation of 300 Hz Pulse Tube Cryocoolers [8-21]

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Adopting higher operating frequencies will reduce the size of the pressure oscillator and the pulse tube cryocooler (PTC) so as to meet the vaster and more advanced need nowadays. This work is the preliminary investigation on PTC operating at 300Hz that aims at getting a lower temperature with a lower input power. The pressure oscillator is a thermoacoustic driver, provided by Luo E. C., which has advantages over the liner compressor that it has no moving part and can extend the life of the cooler. Two kinds of pulse tube cooler are used: U-shaped and coaxial. Unlike the conventional orifice valve, the fixed bypassed and double inlet nozzles are used to shift the phase, as well as the inertance tube. This paper will research on the oscillating flow in the pulse tube and the phase between the flow and the pressure. The attention is also paid on the regenerator and the inertance tube. At the high working frequencies, the flow speed will increase, resulting in the loss of the regenerator increasing greatly. Therefore, it makes great sense on the study of the flow and the heat transfer in the regenerator. The inertance tube at this frequency is the main phase shifter of the cooler. The length and the radius have been tested. Both analysis and tested results are introduced.

SESSION 8: Modeling of Pulse-Tube/Stirling Cryocoolers [POSTER SESSION]

Wednesday, June 11, 2008 9:45 – 10:45 AM

A New Concept on Multi-Stage Stirling Refrigerators [8-49]

S. Yuan, D. Curran
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A new concept on multi-stage Stirling refrigerators will be presented which allows phase shifting among stages, and it also enhances the performance of the cooler. Predicted performance of this new concept will also be shown.

Anisotropic Hydrodynamic Parameters of Regenerator Materials Relevant to Miniature Cryocoolers [8-70]

T. Conrad, E. Landrum, S.M. Ghiaasiaan
Georgia Institute of Technology, Atlanta, GA, USA

C.S. Kirkconnell
Raytheon Space and Airborne Systems, El Segundo, CA, USA

T. Crittenden, S. Yorish
Virtual AeroSurface Technologies, Atlanta, GA, USA

Recent successful CFD models of cryocooler systems have shown that such models can provide very useful performance predictions for cryocoolers. For miniature cryocoolers, CFD modeling is likely the best technique available as models developed for larger systems may not accurately represent phenomena which become important as the device scale is reduced. Accurate CFD modeling of Stirling and pulse tube refrigerators requires realistic closure relations, particularly with respect to the hydrodynamic and thermal transport processes for the porous media which make up their heat exchangers and regenerators. Generally, these porous media are morphologically anisotropic, and thus the parameters which characterize them are anisotropic as well. Measurement of the hydrodynamic parameters in at least two dimensions is therefore preferred.

Miniature regenerative cryocoolers will require porous regenerator and heat exchanger fillers with considerably smaller characteristic pore sizes than those commonly used in larger scale devices. This paper describes measurements of the hydrodynamic parameters of stacked discs of 635 mesh stainless steel and 325 mesh phosphor bronze using a CFD-assisted methodology. These materials are among the finest commercially available structures that are suitable for use as miniature regenerator and heat exchanger fillers. Measurements were made in the axial and radial directions for both steady and oscillatory flow. Higher frequency operation is preferred for miniature cryocoolers, therefore a frequency range between 50 and 200Hz was investigated for the oscillatory flow cases. The test setups for steady flow incorporated static pressure transducers and a mass flow rate meter; for oscillatory flow, the apparatus included dynamic pressure transducers and hot wire probes for CFD model verification. These test setups were each modeled using the Fluent CFD code. The directional permeability and Forchheimer coefficients were obtained based on iterative comparisons between experimental measurements and CFD simulation results.

Numerical Simulation of Oscillating Fluid Flow in Inertance Tubes [8-43]

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A. Razani
The University of New Mexico, Kirtland AFB, NM, USA

Inertance tubes are used in Pulse Tube Refrigerators (PTRs) to control the phase shift between the mass flow and pressure to increase performance of the refrigerator. Computational Fluid Dynamics (CFD) simulation of the oscillating fluid flow in the inertance tube for different tube geometries is presented in this study. Commercial CFD code FLUENT is used to carry out the simulations. The results of CFD simulations are compared to the available experimental results. In addition, the results of grid convergence studies, important in any numerical simulation, are presented and discussed. A numerical model is developed by dividing the inertance tube into sections where the conventional first order model is used in each section. The resulting simultaneous non-linear Ordinary Differential Equations (ODEs) are solved numerically to determine the input acoustic power and the phase shift between mass flow and pressure at the inlet of the inertance tube. The results of the first order model and CFD simulation are compared and discussed.

Effect of Geometric Configuration on the Dynamic Behavior of Linear Compressor and Cooling Performance in Stirling-type Pulse Tube Refrigerator [8-14]

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For a given linear compressor, the geometric configuration of the PTR affects on the dynamic behavior of a linear compressor as well as the cooling performance of the PTR (pulse tube refrigerator). The geometric configuration of each component determines the flow impedance which contains the flow resistance, the inertance effect and the compliance effect. In this paper, several simulation sets are performed with the analysis code in consideration of the dynamics of a linear compressor and the thermal losses. For the same magnitude of input current, the swept volume and the resonant frequency of a linear compressor vary with the geometric configuration of the PTR, because the flow impedance determines the amount of the gas spring effect and the gas damping effect to the piston. For a linear compressor, the larger swept volume of the piston generally results in the higher acceptance of the input power and the better compression efficiency. But, the higher compression power and compression efficiency of a linear compressor do not always guarantee the better cooling performance of the PTR. The simulation results show the existence of the optimum geometric configuration of the PTR for the given linear compressor. The underlying physical reasons are explained with the power transfer from the input power to the cooling capacity.

Numerical Simulation of Orifice Pulse Tube Cryocooler [8-2]

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This paper presents a simple one-dimensional numerical model of low frequency oscillating gas 4He flow inside the Single-Stage Orifice Pulse Tube refrigerator in every component of the cooler: aftercooler, regenerator, cold end heat exchanger, pulse tube, hot end heat exchanger and reservoir. The continuity, the momentum, the energy and the state equations together with the real gas properties are used to analyze the heat transfer and the refrigeration mechanism. From the experimental data, the sizes of the main components, the wall temperatures at aftercoolers, hot end heat exchangers, the cold end heat exchangers, and the pressure profiles in pulse tubes and reservoirs are input into the program. In the pulse tubes, the comparisons are mainly focused on the cooling power, the gas temperature profiles, the gas velocity profiles and the gas displacements. For the other components, the results of simulation data are shown. In the pulse tubes, the predictions of the simulation data compared with the experimental data give good results, that can prove the validity of the model that again can predict the fluid mechanisms of the other parts especially inside the regenerator. It takes a few minutes to run the program. The model is the fundamental concept and easy to understand; however, there is lot of development for future work to improve the model to get a perfect tool to describe the cooling machine.

Comparative Numerical Study of Pulse Tube Refrigerators [8-78]

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The focus of this work is the modeling and performance comparison of different models of pulse tube refrigerators, namely, the Basic Pulse Tube Refrigerator (BPTR), Orifice Pulse Tube Refrigerator (OPTR) and the Inertance-tube Pulse Tube Refrigerator (IPTR) with both in-line as well as co-axial configurations. A detailed analysis of the flow and heat transfer in various components of the aforementioned models under oscillating flow conditions is carried out using the CFD package FLUENT. The components of the BPTR are the compressor, transfer line, after cooler, regenerator, cold heat exchanger, pulse tube and the hot heat exchanger. The phase angle between pressure and temperature in the pulse tube is a crucial parameter affecting the overall performance as reported in several sources of literature. The integrated model of IPTR requires modeling of additional components like inertance tube and the buffer volume to improve the phase angle between mass flow rate and pressure. The modeling of OPTR is done by replacing the inertance tube with a needle valve to control the working gas flow to buffer. The phase angle can be modulated to the optimum value by controlling the valve opening. This facilitates attainment of lower temperatures without redesigning the geometry. The modeling of the geometry and meshing of the various parts are done with GAMBIT. The regenerator and heat exchangers are modeled using porous approximation with thermal equilibrium. Dynamic meshing is used to model the compressor part where the volume of the domain changes with time. A user-defined function is written to track and properly guide the motion of the compressor piston with respect to time. The charge pressure is 25 bar and the working frequency is 50 Hz. The working fluid is helium and is treated as an ideal gas. The thermophysical properties are considered temperature-dependent. For the chosen geometrical parameters, the IPTR needs typically 500 seconds of real time to reach a periodic state with a time step advancement of 0.7 milliseconds. The effect of axial conduction on performance of pulse tube refrigerator is also analyzed by introducing the wall thickness to all components except compressor. For the geometric and other parameters chosen in this study, the IPTR is found to reach 90K without wall thickness and 130 K with wall thickness under no-load condition.

Cryocooler Particle Image Velocimetry [8-119]

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Pulse Tube fluid flow interactions are not well understood in cryocoolers. Cooling is achieved in a cryocooler by a phase shift that occurs between the mass flow rate and pressure waves inside the pulse tube. The overall objective is to study internal fluid flow characteristics in pulse tubes, and understand how the necessary phase shift occurs to create a pulsed flow and ultimately cryogenic cooling. This will be done by measuring velocity vectors in a seeded gas environment (pulse tube) at cryogenic temperatures in and out of a vacuum. Discussions will include challenges of experiment, goals, and data analysis as well as a comparison to the Computational Fluid Dynamics work previously presented by AFRL for model validation.

Theoretical Investigation of Thermoacoustic Effect [8-121]

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The study on thermoacoustic effect in Thailand is quite new to date. Design and development of thermoacoustic devices required well understanding of theoretical background and scientific behide. Thermoacoustic refrigerator is an environmentally friendly device because it is totally eliminates the use of refrigerants. There are two types of the principle parameters involving in thermoacoustic refrigerator design; operation parameter and design parameters. To gain more insight understanding, theoretical investigation in the principle parameters is crucial need before designing and developing of the devices. The present study used the simulation code developed at Los Alamos National Laboratory, DeltaEC, as a tool for theoretical investigation. The simulation results was studied and compared with the design criteria recommended from the previous study.

Experimental Results of 20 K Pulse Tube Cold Fingers for Space Applications [9-22]

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R. Briet
CNES, Toulouse, France

Pulse tube cooler is an appropriate technology for providing cooling power of several hundreds of milliwatts at 20K for space application. In the framework of an ESA contract (ESA/ESTEC n0 20497/0/NL/PA-20-50K Pulse tube cooler), we developed single and double stage cold fingers in this temperature range. A single stage pulse tube has been designed to work with a heat interceptor at about 80K. Cooling power higher than 300 mW at 20K has been achieved. We designed and tested a double stage pulse tube for second stage cooling at 30K with a first stage temperature of 120K. PV power for these pulse tubes is ranging from 100 to 120W PV. Experimental results on these 2 kinds of cold finger will be presented. These different designs and their measured performances are compared.

Raytheon Compact-Inline RSP2 Cryocooler [9-48]

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Closed-cycle mechanical cryogenic refrigerators, or cryocoolers, are an enabling technology for next generation infrared (IR) sensors. Of particular interest are the linear Stirling and pulse-tube type cryocoolers that have been used successfully in a variety of applications. The strengths of pulse-tube cryocoolers centrally concern their high efficiency at temperatures above ~60K, in combination with the mechanical simplicity and low system mass associated with their lack of moving elements in the cold head. Stirling cryocoolers exhibit relatively high efficiency at temperatures below ~50K, in addition to a higher degree of operational flexibility that is afforded by their actively-drive expansion mechanism. Linear Stirling cryocoolers are, however, often physically larger and higher in mass than their pulse-tube counterparts. In an effort to combine the strengths of the two linear cryocooler architectures, Raytheon Space and Airborne Systems has developed a next-generation Stirling cryocooler that achieves reductions of mass and package volume through combination of the typically-separate expander and compressor modules into a single volume. In addition to these benefits, the selected architecture provides electromechanical, thermodynamic and exported disturbance performance advantages in comparison to typical two-module designs. A comprehensive redesign of the compressor and Stirling displacer drive mechanisms has been performed in order to fully realize the benefits associated with the concept, while the cold-end design of the cryocooler is largely a reuse of the existing Raytheon Stirling Pulse-Tube 2-stage (RSP2) hybrid design. The baseline design can be easily scaled to operate over a wide range of temperatures and heat loads, and the RSP2 cold head can be reconfigured to operate as a single stage machine if desired. The name of the system is the Compact-Inline RSP2. This paper will provide a general description of the Compact Inline RSP2, including expected package dimensions, mass, and performance parameters. Development status will be presented, as well as a discussion of the remaining steps required to mature the concept.

ABI Cooler System Protoflight Performance [9-45]

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The Advanced Baseline Imager (ABI) Pulse Tube Cooler System is a two-stage pulse tube cooler for space applications. The cooler incorporates an integral HEC pulse tube cooler and a remote coaxial cold head. The two-stage cold head was designed to provide simultaneous large cooling power at 53K and 183K. This paper presents the data collected on the two protoflight module (PFM-1 and PFM-2) coolers during acceptance testing. Tests conducted on the PFM coolers included applied vibration, survival at non-operational temperature extremes, thermal performance measurements over a range of operational temperatures and temperature stability tests. Designed for a 10-year life, the ABI coolers are required to provide 2.27W of cooling at 53K and 5.14W of cooling at 183K while rejecting to 300K with less than 186W input power to the cooler control electronics. The ABI PFM-1 and PFM-2 coolers met the cooling requirements at 53K and 183K at input power levels of 162 and 170W respectively. Both coolers demonstrated short and long term temperature stability of less than 60mKp-p vs. requirements of 100mKp-p and 500mKp-p respectively. These protoflight module coolers represent the first flight set of coolers delivered to the ABI Program. "Northrop Grumman Space Technology is part of the ITT Advanced Baseline Imager (ABI) team. ITT leads the team as the prime contractor and has overall responsibility for the program development effort. ABI is a NOAA funded, NASA administered contract."

Investigation of Thermally Coupled Two-Stage Pulse Tube Cooler [9-19]

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Multi-stage PTCs, which are capable of achieving lower cooling temperatures and which meet the cooling requirements at different temperature levels, have been researched and developed since the invention of the pulse tube cooling concept. A two-stage Stirling-type pulse tube cryocooler with thermally coupled stages has been designed and established two years ago and some results have been published. In order to study the effect of first stage precooling temperature, related characteristics on performance are experimentally investigated. It shows that for high input power, when the precooling temperature is lower than 110K, its effect on second stage temperature is quite small. There is also the evident effect of precooling temperature on pulse tube temperature distribution; this is for the first time that author notice the phenomenon. The mean working pressure is investigated in order to reach a low refrigeration temperature and the 12.8K lowest temperature with 500W input power and 1.2MPa average pressure have been gained, this shows the benefit of low average pressure. Beside the precooling temperature, the relation of first stage and second stage is investigated through the change of first stage inertance tube, the most important phase shifter of first stage. Tests have shown that through adjustment, the gas distribution could be changed and the performance will be changed. Such optimization has the limited function and the initial design is of most importance.

Cold-Head Vibrations on a Two-Stage Coaxial Pulse Tube Refrigerator [10-56]

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We report the measurements of mechanical vibrations at a two-stage pulse tube refrigerator. With the idea of building a compact cold head, we have developed a prototype of a two-staged GM-type pulse tube refrigerator, which prominent feature is a totally coaxial cold finger. The refrigerator uses an active type of phase shifting. One rotary valve unit controls the entire fluid dynamics in both stages. Novel lead coated screens build-up the inhomogeneous regenerator matrix of the low-temperature regenerator. Without using rare-earth regenerator-materials the cryocooler reaches a no-load temperature well below 6K and provides 5W @ 18K at the second stage cold head, while the first stage achieves 34W @ 80K at an electrical input power to the compressor unit of 6kW. The vibration measurements were done with a Michelson-Interferometer. The mechanical oscillations of the three Cartesian coordinates were measured and a frequency spectrum of each of them will be presented at various cooling temperatures (300K and 10K). The vibration amplitude is smaller than 9 micrometers parallel to the cold finger axis. Perpendicular to the cold finger axis the vibration amplitude is smaller than 1.5 micrometers.

Ground Testing of a Space Infrared Sensor Using a G-M Type Cryocooler [10-76]

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A G-M type cryocooler was successfully used as a low cost, low risk cryogenic cooling solution for the ground demonstration of a space infrared sensor. The program desired a cryocooler that could provide more than 50 W at 100 K to ensure that the ability to collect sensor performance data would not be jeopardized by a lack of cooling capacity. In addition, aggressive cost and schedule constraints were placed on the cryogenic cooling system. Several methods for providing cryogenic cooling were considered. A summary of this trade study is presented in the paper. The mechanical integration of the G-M type cryocooler is also presented. Because of the sensor's vulnerability to jitter, a vibration output test was done with the cold head of the G-M cryocooler. In addition, the rotary valve and its drive motor were removed from the cold head and placed in a remote motor housing in order to mitigate the amount of vibration imparted to the system by the cryocooler. Finally, a description of the cryogenic cooling system test set-up and performance data for the G-M cryocooler is presented. A conduction bar was calibrated using the G-M cryocooler, and was used as a "Q-meter" to determine the sensor waste heat. Heaters and feedback control temperature sensors were placed on both ends of the conduction bar, and were used to control the temperature at locations of interest inside the sensor.

Cryocoolers for Scientific Research at a Neutron Scattering Facility [10-29]

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Material scientists often need to perform measurements while a specimen is cooled within a carefully regulated "sample environment" chamber. At scientific user facilities such as the Spallation Neutron Source (SNS) at Oak Ridge National Lab, technical support teams are constantly finding ways to adapt and integrate off-the-shelf cryocoolers into customized measurement systems. Given here is an overview of several cryocooler-based systems that are in use and under development at the SNS. The functional requirements of these systems often go far beyond sample cooling, and may require additional environmental controls such as magnetic field and pressure, and automation capabilities such as sample manipulation and exchange. But even in the case of a "standard" temperature environment for materials research, the scientist expects more than just cooling. Temperature control and uniformity throughout the sample region are crucial factors that can make or break an experiment. And many experiments call for a temperature range that extends above and below room temperature. Finally, every sample environment must be compatible with the neutron beam environment. All of the above requirements point toward a modular design strategy where the cryocooler is but one drop-in component. The overall system will be frequently tested, reconfigured, and upgraded. In this fashion, the equipment inventory is continually under development, and the capabilities ever improving.

Integration and Application of Cryocoolers for Advanced Characterization of High Temperature Superconducting Power System Components [10-66]

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At the Florida State University Center for Advanced Power Systems, cryocoolers are being used in providing cryogenic environment in several novel experimental facilities for advanced characterization of materials and components high temperature superconducting power systems. Specifically, the facilities involve variable temperature measurements of dielectric properties, variable temperature measurements of total ac loss, and calorimetric measurements of heat load in superconducting coils under a variety of operating conditions. The facilities involve novel and unique designs to accomplish large volume of stable and uniform temperatures that can be controlled. The paper will present details of experimental designs, results and recent results.

Effect of Pressure on Regenerator Hydrodynamic Parameters in Axial Steady Flow [11-71]

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An experimental investigation was carried out to measure the effect of average pressure on the hydrodynamic porous media closure relations relevant to steady axial flow through several regenerator fillers. Using room temperature helium as the working fluid, pressure drops occurring across a test section that contained various regenerator filler materials were measured. The test apparatus allowed for the adjustment of the mean pressure in the test section. The tested regenerator samples included loose stacked screens of 325 stainless steel mesh and 400 stainless steel mesh, screens of 400 stainless steel mesh stacked and sintered together, and a stainless steel metal foam. The helium superficial velocity (Darcy velocity) through the porous samples covered a range from 0.2 to 19 m/s. The test section and its vicinity were then modeled as a porous structure using the Fluent CFD code, and the model porous media hydrodynamic parameters were iteratively adjusted to match the model predictions to the experimental results. Using this methodology, it was possible to determine axial viscous and inertial resistances related to the Darcy permeability and Forchheimer inertial coefficient, respectively, for all the porous samples. The results are tabulated for the investigated porous media and indicate that the axial hydrodynamic parameters are independent of test section average pressure, provided that the maximum pressure drop through the porous sample is limited to about 0.7 MPa.

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A Numerical Study on the Performance of the Heat Exchanger for the Miniature Joule Thomson Refrigerator [11-89]

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Miniature Joule-Thomson refrigerators have been widely used for rapid cooling of infrared detectors, probes of cryosurgery, thermal cameras, missile homing head and guidance system, due to their special features of simple configuration, compact structure and rapid cool-down characteristics. The cool-down time, the temperature at the cold end, the running time and the gas consumption are the important indicators of the performance of the Joule-Thomson refrigerator. Limited experimental and theoretical studies on the performance of the refrigerator were performed due to the complexity of the geometry of the recuperative heat exchanger of the Joule-Thomson refrigerator. In this study, effectiveness-NTU approach was adopted to predict the thermodynamic behaviors of the heat exchanger for the Joule-Thomson refrigerator. The thermodynamic properties from the REFPROP were used to account the real gas effects of the gas. The results show the effect of the operating conditions on the performance of the heat exchanger and refrigerator for the given heat exchanger. The influences of mass flow rate and the supply pressure on the effectiveness of heat exchanger and the refrigeration power are discussed in details.

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Distributed Cooling Techniques for Space Applications [11-92]

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Future Exploration Missions are considering Zero Boil-Off (ZBO) cryogenic systems that require active cooling of large cryogenic tanks. There are numerous issues associated with the interface between distributed loads and their requisite cryogenic systems. It is often envisioned that distributed loads will be cooled by a single cryocooler such as a pulse tube refrigerator (PTR). Because all regenerative type coolers are oscillating flow devices, they typically have small cold heads to which heat loads must currently be coupled conductively which is far from ideal. To distribute the cooling from the cold head of a PTR to the distributed load, a circulating flow loop (CFL) is required. The CFL consists of a circulator that circulates gaseous helium cooled by the cryocooler to the distributed load via a flow loop with an actively controlled throttle valve. Both a warm circulator and a cold circulator are under consideration. The warm circulator consists of a helium linear pressure wave generator, a warm flow rectifier and a heat exchanger. The rectifier, a set of check valves and buffer volumes, rectifies and flattens the oscillating flow generated by the compressor. The cold circulator consists of a rectifier, integrated into the cold heat exchanger of a PTR. The rectifier splits off part of the oscillating flow as it passes through the cold heat exchanger, rectifying and smoothing it. The cold gas is then delivered to the load via the flow loop. Of critical importance to the cooling loop in either approach is a small, lightweight, actively controlled throttle valve. We are developing a micro-scale control valve, using MEMS fabrication techniques, which can be used, in conjunction with the loop, to cool an arbitrary thermal load. The use of multiple micro-valve platforms will allow integration of distributed loads with a single cryogenic system.

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Remote Cooling with the Coaxial HEC Cooler [11-106]

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This paper presents the test data for remote cooling using NGST's HEC cooler. The remote cooling technology enables the pulse tube cryocooler to be located remotely from the cooled items and use cooled gas to cool the object. In our design, a single compressor provides gas flow to both the pulse tube cooler and the remote cooling loop. This configuration is mechanically simple with excellent reliability. After Helium is split from the compressor, it is precooled to the design temperature before flowing to the object to be cooled. The cooled object can be located meters away from the mechanical cooler. Test data will be presented and an energy balance analysis will be presented to identify the parameters which can be optimized to increase the efficiency of the system.

Hydrogen and Neon Gas-Gap Heat Switch [11-112]

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Heat switches are important devices in many cryogenic setups, especially in space applications and many systems have been used to allow a good ability to make or break a thermal contact. Among them, the so-called gas gap heat switches, in which the pressure is managed thanks to a small cryopump, are known to be very reliable and simple, principally due to the nonexistence of moving parts. However, in such switches, the gas characteristics and its adsorption properties have to be taken into account to determine their functioning temperature ranges. In this communication, a gas gap heat switch, with a charcoal adsorption pump, tested with Neon and Hydrogen as conducting gas is described and the simple thermal model used to calculate its characteristics as well as the experimental results are presented. Avoiding the gas condensation , limiting the OFF conductance and reaching a viscous regime in the ON state lead to an operational temperature window for the sorption pump that depends of the amount of gas. For Neon, the minimum temperature to actuate our switch ranges from 17 K to 40 K; for Hydrogen, this temperature range goes from 9 K up to 55 K. Such switches offer an extension to the well-studied helium gas gap heat switch which is limited to temperatures up to 15 K. Measured values for the thermal ON conductance (74 mW/K at 20 K for Neon, 120 mW/K at 11 K for H_2) compare very well with the results expected from gas conductivity properties found in literature. For Neon an ON/OFF conductance ratio about 220 is obtained at 20K, whereas, for H_2, a ratio up around 530 was measured at 11K.

Investigation of Cryogenic Cooling Systems Activated by Piezoelectric Elements [11-60]

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Most cryocoolers are based on thermodynamic cycles which normally employ mechanical compressors producing an oscillating pressure in a gas. The main disadvantage of the mechanical compressors is their limited life span, caused by mechanical friction and wear. Additional disadvantages are size, induced vibrations, heat generation, noise and contamination of the working gas by wear products. For improved reliability it has been proposed to replace the conventional mechanical compressor by a device activated by piezoelectric elements, which are frictionless, have a high volumetric power density and a long life span. The major problem in employing the piezo actuators is an extremely small elongation of the piezo materials, which is about 0.1% of the total actuator length, and is on the order of microns in standard piezo actuators. For the cooling cycle it is required to produce cooling gas motion amplitude on the order of millimeters and to apply on the gas pressures on the order of atmospheres. The main goal of this research has been to develop an efficient motion amplification and transfer of force from a piezo actuator to the cooling gas. A compressor for a cryocooler based on a new concept employing a piezo actuator with mechanical amplification was developed theoretically and was built practically during this research. The compressor development includes modeling, calculations, optimization and dynamic simulations of the entire system involving the ANSYS finite elements software. An approximate linear analytical model of the compressor was also developed. The analytical model confirms the numerical results and enables some parametric analysis for static and harmonic system responses. The entire compressor system has been manufactured, assembled, and tested in the laboratory. The paper will describe the results of the theoretical analyses and the test results.

Nitrogen Cryogenic Loop Heat Pipe: Results of a First Prototype [11-28]

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Efficient thermal links are needed to ease the distribution of the cooling power in satellites. Loop heat pipes are currently used at room temperature as passive thermal links based on a two-phase flow generated by capillary forces. Transportation of the cooling power at cryogenic temperatures requires a specific design. In addition to the main loop, the cryogenic loop heat pipe (CLHP) features a hot reservoir and a secondary circuit which allow to cool down the loop from room temperature conditions. A first prototype of CLHP working with nitrogen around 80K has been developed at CEA-SBT and tested in collaboration with the CAS/TIPC. The general design, the instrumentation and the performance results are presented. The effects of mass inventory, condensation temperature and the influence of the secondary circuit are presented and discussed. It is shown that, thanks to an appropriate design of the prototype, a cooling power of 19W with a limited temperature difference of 3K is obtained over a 0.46m distance.

Prognostic Health Management System for Cryocooling Systems [11-75]

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Various high performance sensors and superconducting devices are playing an increasingly important role in medical, scientific, industrial, and US government applications particularly in DoD related activities. For these devices to operate properly they must be cooled to very low (cryogenic) temperatures. A healthy and reliable mechanical refrigeration system (cryocooler) is critical for reliable performance of these sensors. The ability to accurately predict the "health" or remaining useful life of the cryocooler has significant benefits from the viewpoint of insuring and meeting the mission objectives with a high probability of success. The proposed paper provides an overview and approaches used for the development of a Cryocooler Prognostic Health Management System capable of assessing the cryocooler "health" from the viewpoint of the level of performance degradation and/or the potential for near term failure. Additionally, it quantifies the reliable remaining useful life of the cryocooler. While the proposed system is focused on the specific application to linear drive cryocoolers, especially for DoD, many of the attributes of the system can be applied to other specialized system hardware in both commercial and U.S. Government agency for situations where it is critical that all aspects of the hardware ôhealthö and ôremaining useful lifeö be fully understood. Several benefits of the health monitoring system are also described in the paper.

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Development of a Continuous ADR System for Weak Gravity Missions [11-124]

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Low temperature environments are essential for advanced space science missions such as X-ray astronomy or microgravity physics. Adiabatic Demagnetization Refrigeration (ADR) does not use working fluids such as 4He or 3He and this is a dominant advantage for space applications under the weak gravity condition. In this study, we have develop a new continuous ADR system to provide the cooling temperatures around 100mK. The system consists of 4 stages of magnetic materials and magnets cascaded with heat switches for each temperature range. This ADR cooler has been tested to confirm the ability of the continuous ADR system for the future space applications under the micro-gravity condition using an airplane. Typical experimental results for 1G and micro-gravity will be shown. This study is done through the collaborative works with NASA Goddard Space Flight Center and JAXA ISAS group.

Experimental Study on Preliminary AMR Apparatus for Magnetic Hydrogen Refrigerator [11-125]

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Hydrogen energy is considered as an alternative for fossil fuels, which produce a huge amount of green-house gases. For efficient, economic transport and storage, liquid hydrogen should be used because of its high density. Magnetic refrigeration which is based on the magnetocaloric effect of solids has the potential to achieve high thermal efficiency for hydrogen liquefaction. We have been developing a magnetic refrigerator for hydrogen liquefaction which cools down hydrogen gas from liquid nitrogen temperature and liquefy at 20 K. The magnetic liquefaction system consists of two magnetic refrigerators. The liquefaction stage made use of Carnot cycle and has succeeded in liquefying hydrogen around 20 K. Above liquefaction temperature, a regenerative refrigeration cycle should be necessary to precool hydrogen gas because adiabatic temperature change reduced by a large lattice specific heat of magnetic materials. We have constructed a preliminary experimental apparatus to study AMR cycle between 20 K and 30 K. The test apparatus is a very simple system where magnetic material reciprocally moves through magnetic field and heat exchange gas. We tested several kinds of materials such as Gd-Dy-Al garnet and observed AMR effect in 20 K region. Experimental details and analysis using simulation will be shown.

Compact Cryocooler for 10 K Operation [12-36]

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Ball Aerospace has designed, built, and characterized a compact refrigeration system for cooling very low temperature infrared detectors. The system is robust, will be integrated into a mobile application, and can also be used in space environments. The system is a hybrid of complementary Stirling and Joule Thomson (J.T.) cycle cryocoolers. The Stirling is a version of our standard two stage SB235E cryocooler, with its second stage optimized for cooling to 15K. The J.T., which provides the refrigeration at 10K, uses a reed valve equipped Oxford style compressor to drive a compact cold head which is precooled by the Stirling cooler. The cold head consists of three counter flow heat exchangers, a bypass valve, and an expansion valve packaged on a small diameter, mechanically robust cryostat. The cryocooler provides over 100mW of cooling at 10K for the focal plane, 100 mW at 16K for intercepting system parasitics, and over 4 watts at 70K for cooling the system optics. The 70K interface consists of a pair of copper braids for carrying the high loads. The 16 and 10K interfaces use the circulating J.T. fluid to transfer cooling to the load. The fluid interfaces are quite flexible, can be remotely located, and are mechanically and electrically isolating. The system includes a set of electronics that provide power conversion and autonomous control of the entire system. The cryocooler has undergone its initial system tests. Recent characterizations of the individual components, and of the system as a whole, will be presented.

Initial Test Results for a 35 K [12-41]

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Ball Aerospace and Redstone Engineering together have designed, built, and characterized a hybrid cryocooler tailored for cooling infrared imaging systems that have variable loads. The system is a hybrid of complementary Stirling and Joule Thomson (JT) cycle cryocoolers. It is based on Ball's efficient two stage Stirling cycle cryocooler, the SB235E, which provides the bulk of the refrigeration. It supplies in excess of 8 watts at 80K for optics cooling and 2 watts at 35K in addition to intercepting the parasitic loads associated with the JT cryostat. The JT system uses a custom "Oxford" style linear compressor equipped with reed valves to circulate neon through a compact cold head. The cold head consists of high efficiency counter flow heat exchangers, heat sinks, and a very special internal thermal storage unit (ITSU) mounted in a rigid support structure. The ITSU, basically a tank for holding liquid neon, provides the system's load leveling capability. During the low load part of the focal plane's operational cycle, liquid neon condenses in the ITSU. During the high load part of the cycle, the JT compressor speeds up to increase the circulation rate of the coolant to the 35K interface, depleting the stored neon in the process. In this way it can provide multiples of the steady state cooling rate of the precooler. Results will be presented for the various qualification tests, especially the 35K load leveling capability.

Further Developments on a Vibration-free Helium-Hydrogen Sorption Cooler [12-35]

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A.Sirbi
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The University of Twente is working in a continuous effort on the development of a passively precooled two-stage 4.5K / 14.5K helium-hydrogen sorption cooler. This cooler has no moving parts and is, therefore, essentially vibration-free. It is a favorite option for space missions such as ESA's Darwin and Xeus missions, which require long-life and vibration-free cooling to low temperatures. We have developed and built a demonstrator of the helium stage under an ESA-TRP contract. The design of this cooler, together with detailed experiments, was presented at the ICC in 2006. Since then, we have monitored a number of aspects that may effect the long-term operation of this cooler, such as contamination issues, check valve operation and gas-gap heat switch performance. These aspects will be discussed. We have replaced the four sorption cells with new cells that contain a new high-density activated carbon, which results in an efficiency improvement with a factor of about 1.5. Measurements with these new cells will be presented. In addition, experiments will be presented that illustrate the ability of this cooler to reduce the low temperature to about 3K. Furthermore, we will present the design of an integrated compact cooler chain that consists of a Thales 50K Stirling cooler and the helium-hydrogen sorption cooler. The total package, including compact vacuum chamber and electronic controller, has a mass of less than 20kg, requires less than 150W input power, and may be used to test this cooler chain in space. Finally, we will summarize the current development activities on the hydrogen sorption cooler, which are carried out in a new recently started ESA-TRP study.

Vibration-Free Joule-Thomson Cryocoolers for Distributed Microcooling [12-103]

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This paper reports on an innovative concept for a Joule- Thomson (J-T) cryocooler that utilizes a continuous flow compressor to provide cooling at multiple miniature cold heads. The heat transport to each cooling site is accomplished at ambient temperature, allowing large separation distances between cryocooler components and cooling sites with minimal performance impact. The compressor uses non- contacting, gas-lubricated bearings and is a derivative of TRL 9 technology that has demonstrated long life and high reliability. The concept addresses the limitations on life and reliability normally associated with JT cryocoolers. The key technical challenge is the development of a Low-Specific-Speed (LSS) compressor impeller to match the operating conditions of the J-T cycle. Cycle analysis was carried out to identify the optimum system operating conditions as well as the optimum composition of the cycle gas. A LSS compressor and a compact coldhead were designed, and their performance, mass, and size were estimated. The cryocooler was designed to provide 10 mW of cooling at 150K to each of multiple coldhead. The performance of LSS impellers was measured, and results were used to correlate the LSS compressor performance model. The results of the study and tests demonstrated that a J-T cryocooler with a LSS centrifugal compressor can be developed that is lightweight, compact, reliable, vibration-free, and efficient at extremely low cooling capacities. The design of the cryocooler, optimization of the cycle gas composition, and the results of tests performed with a LSS compressor impeller are the focus of this paper.

Second-Law Analysis of a Hybrid Reverse Brayton-Stirling Cryocooler [12-55]

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Multi-stage cryocoolers are often used to cool infrared sensors for space applications. Using a Reverse Brayton cryocooler for the lower stage ensures low vibration due to only high frequency moving parts and allows for remote cooling separated from the compressor and Stirling upper stage. A second-law analysis of a Reverse Brayton cryocooler as the lowest stage in a multi-stage cryocooler is presented. Parametric studies were done on the losses in the lower stage. Parametric studies were also done on variations of the supported cooling load. The effects on hybrid system performance of variations in the operation of the Stirling cycle upper stage were modeled. Finally, losses due to the upper stage are studied.

Demonstration of a Two-Stage Turbo-Brayton Cryocooler for Space Applications [12-102]

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Turbo-Brayton cryocoolers have inherent technical advantages for many space applications because of their extremely low emitted vibration and simplicity of integration with payloads and spacecraft heat rejection systems. The technology was first demonstrated in space in March 2002 when the NICMOS Cryocooler was installed on the Hubble Space Telescope. The NICMOS Cryocooler is a single-stage unit that supplies 7W of refrigeration at 70K, and has recently exceeded 6 years of space operations without degradation or malfunction. The need for efficient cooling at multiple temperatures has driven the development of a two-stage turbo-Brayton cryocooler. This paper focuses on the design, development history, and performance of a recently demonstrated two-stage turbo-Brayton cryocooler.

On the Lowest Attainable Temperature by a Reverse Brayton Cryocooler According to the Second Law of the Thermodynamics [12-46]

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There are two categories of cryocoolers (and a combination of these) that employ continuous flow recuperation: the Linde-Hampson (or Joule-Thomson) and reverse Brayton. The performance of a Joule-Thomson cryocooler depends on real gas properties and by its nature, the lowest attainable temperature is the boiling point of the applied coolant. In contrast, the performance of a reverse Brayton cryocooler may be formulated by ideal gas properties and its temperature of cryocooling is a function of the performance of its two main components: the efficiency of the expander and the effectiveness of the recuperator. The common approach estimates these parameters for any desirable temperature of operation. The purpose of the present study would be to determine the lowest attainable temperature of a reverse Brayton cryocooler. The effectiveness of the recuperator and the efficiency of the expander would not suffice for this purpose since one has to satisfy as well the second law of the thermodynamics. On this basis the lowest attainable temperature is derived as function of the expanded pressure ratio, the effectiveness of the recuperator, and the kind of coolant, while accounting for the generated entropy. Another result of this analysis is the lowest efficiency of the expander for each pressure ratio in order to enable any cryocooling.

Mid InfraRed Instrument (MIRI) Cooler Subsystem Design [12-123]

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The Cooler Subsystem for the Mid InfRared Instrument (MIRI) of the James Webb Space Telescope (JWST) features a 6 Kelvin Joule-Thomson (JT) cooler pre-cooled by a three-stage Pulse Tube (PT) cryocooler to provide 65 mW of cooling at the instrument's Optical Bench Assembly (OBA). Having demonstrated Technology Readiness Level 6 (TRL 6) in early 2007, the focus shifted to the flight cooler subsystem design. This paper describes the overall flight cooler subsystem design and performance estimate. Performance characterization of key subassemblies; including the pulse tube pre-cooler, the JT cooler, and Cryocooler Control Electronics units (CCEs). The pulse tube pre-cooler is characterized as a stand-alone subassembly in terms of its efficiency over the range of operating conditions required by the overall cooler subsystem design. The JT cooler characterization is closely related to the MIRI Cooler Subsystem performance model, anchored in end-to-end testing. The pulse tube pre-cooler and JT cooler compressors are each driven by an independent CCE unit. The CCE for JT compressor drive is closely based on our standard Advanced Cryocooler Electronics (ACE) design, nominally rated at 180 W compressor drive. The CCE for pulse tube pre-cooler drive has twice the drive capability, 360W compressor drive. The performance of the CCE units is characterized in terms of unit level efficiency over the range of drive levels. The MIRI Cooler performance model combines the characterized performance of the subassemblies to produce the total cooler integrated performance.

Universal Drive for Tactical Cryocoolers [13-96]

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Superconducting Electronics (SCE) systems are becoming commonplace due to their substantial benefits in performance and cost when compared to traditional, semiconductor-based components. For example, HYPRES is presently developing novel superconducting digital-RF technologies which enable highly efficient multi-carrier, broadband systems for military and commercial communications and other RF applications. To achieve widespread adoption of SCE systems, low-cost and rugged cryocoolers and associated drives are needed. In cooperation with HYPRES, Creare is developing a universal Tactical Cryocooler Drive (TCD) for Stirling and Pulse tube-class cryocoolers. Our TCD provides dual, independent drives, which can be customized for each application with only software changes. In this paper we describe the results of a comprehensive design study and brassboard demonstration where the electronics simultaneously and independently controlled dual cryocooler compressors with input power up to 270W and efficiencies as high as 96%. The technology is scalable up to power levels of 1,500W per channel. We have demonstrated through brassboard tests: (1) a 20KHz Pulse Width Modulation (PWM) control strategy which results in minimal ripple currents; (2) a custom, programmable waveform generation method based on a Graphical User Interface (GUI); (3) thermal control where we were able to maintain temperature at 66K in the presence of thermal loads up to 2.5W; and (4) a control strategy that minimizes the exported vibration from the dual-compressor apparatus by independently controlling drive amplitude and phase relationships. This paper describes the results of these demonstrations and our plans for building and demonstrating a prototype with the form, fit, and function of the final product.

21st Century Cryocooler Electronics [13-116]

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Significant progress has been made on the development of Cryocooler Control Electronics (CCE) to support the unique capabilities of the Raytheon Stirling / Pulse Tube Two-Stage (HC-RSP2). Design capabilities of the CCE feature two stage temperature control and vibration control down to 20 mNewtons. The CCE will complete an overall system capable of delivering 2.6W at 35K simultaneously with 16.2W at 85K for 513W cryocooler input power which was demonstrated during thermal vacuum testing with lab electronics. Active line filtering will be incorporated to reduce the conducted emissions by >30 db at >90% efficiency. The result will be a complete Electro-Optic cooling system with one main 300kRad total ionizing dose (TID) capable electronics box and one cryocooler, greatly reducing system complexity and improving operational performance.

Compact, Lightweight Electronics for Space-Borne Turbo-Brayton Cryocoolers [13-97]

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Turbo-Brayton cryocoolers are attractive options for a variety of space applications because they have demonstrated long-life, produce no deleterious vibrations, and simplify integration with payloads and spacecraft systems. In 2002, the first turbo-Brayton cryocooler was qualified and installed on the Hubble Space Telescope. This cryocooler uses a high-frequency centrifugal compressor operating between 0 and 7500 rev/sec driven by a power inverter that converts the variable DC bus voltage to a regulated three-phase AC voltage. The inverter uses pulse-width-modulated circuitry to provide the necessary power and control to the compressor. It also incorporates special features to adjust the power factor to the motor and to reduce EMI. Creare is currently pursuing multiple pathways toward electronics for future turbo-Brayton space cryocoolers. In this paper, we describe our effort to establish a standard line of electronic modules that can be easily combined and scaled as necessary to dramatically reduce development time and costs for future cryocooler programs. This topology uses standardized hybrid electronic modules that can be built-to-print and a transformer module that can be easily scaled depending on mission dependent voltage and power requirements. We have designed the hybrid modules for output power levels up to 800W, eliminating the need for future custom designs and costly radiation and environmental qualification tests for most space missions. The drive has been designed to withstand a Total Ionizing Dose (TID) of at least 300 krad as well as Single Event Upset (SEU) requirements typical for space applications. The use of hybrid microelectronics circuits offers dramatic reductions in size and mass relative to discrete electronics. This paper describes the design and scalability of the electronics, and presents results from performance and environmental tests on the compressor drive electronics.

Control and Power Electronics for a Two-Stage Turbo-Brayton Cryocooler for Space Applications [13-115]

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Last year saw the successful demonstration of an autonomously controlled two-stage turbo-Brayton cooler. The electronics developed for this demonstration were evolved from the seminal work of the NICMOS cryocooler, the first flight qualified turbo-Brayton cooler. Two key features of the electronics are the ability to control temperature without the use of trim heaters and the ability to recover expander energy back to the main power bus. The development of the control and power electronics for this two-stage cooler was the first step toward a space qualifiable design. The technical challenges, solutions and performance of the electronics developed for the two-stage turbo-Brayton cooler are presented.

A 47K Thermoacoustically Driven Pulse Tube Cooler [14-7]

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A thermoacoustically driven pulse tube cooler mainly consists of a thermoacoustic engine and a pulse tube cooler. Due to its structural simplicity, environmental friendliness, and high reliability, this cooler has attracted much attention in recent years. In order to obtain lower cooling temperature, the pressure ratio of the thermoacoustic engine and the performance of the pulse tube cooler must be improved. In this paper, we will introduce a new thermoacoustically driven pulse tube cooler with two great improvements compared with our previous one. One improvement is the pressure ratio. A larger tapered resonator was used to match the loop of the traveling wave TE, and an acoustic amplifier was employed to couple the TE and the PTC. Thus, the pressure ratio at the inlet of the PTC reached 1.36. The other improvement is the phase shifter. Inertance tubes utilize the inertia of the oscillating flow to bring about a proper shift in the phase between the flow and the pressure in pulse tubes, but for some small pulse tube coolers, the phase shift may be only a few degrees which is far less that the PTCs need. So in our experimental setup, a double-inlet valve with a DC flow suppresser was employed as a secondary phase shifter. Because of the two improvements, the cooling temperature of our TAD-PTC last reached 47K which obtained a temperature reduction of more than 18K.

Numerical Study of Thermoacoustically-driven Pulse Tube Cooler With Spring-Mass Resonators [14-6]

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Thermoacoustically-driven pulse tube cooler could be heat-driven and offer the advantages of being simple and highly reliable. Normal thermoacoustic engines with a long resonance tube to control the frequency face the problems of large thermoviscous dissipation, oversize and structural vibrations, etc., which is not good for practical small-scale applications. One solution is using spring-mass resonator to replace the resonance tube, which could ensure the compact size, low vibration and remains to be simple on structure. This article uses the linear thermoacoustic theory to simulate such a configuration, which aims at small-scale cryogenic applications. The influences of spring-mass resonator parameters, operating conditions, coupling configurations and other factors are studied. Experiments have also been done to verify this idea.

Advance in 300Hz Thermoacoustically Driven Pulse Tube Cryocoolers [14-33]

E. Luo, W. Dai, G. Yu, S. Zhu, X. Zhang
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A thermoacoustically-driven pulse tube cooler (TADPTC) has the advantage of structure simplicity with no moving mechanical components and thus promises a potential with long life time. High frequency operation of such a system can lead to a much reduced size, which is very attractive in small-scale cryogenic applications. This article introduces our recent experimental advances on a 300Hz pulse tube cooler driven by a thermoacoustic standing-wave engine. By using photochemical etching process instead of Electrical Discharge Machining (EDM) process, better stacks are fabricated and tested in the standing-wave thermoacoustic engine. Consequently, the engine performance is significantly improved which leads to a better cooling performance compared with that in our previous work. Cooling powers of the pulse tube cooler with different operating conditions have been measured in detail. So far, a lowest no-load temperature of 68K, cooling powers of 1.2W at 80K and 3.8W at 120K are obtained with a mean pressure of 4.1MPa and a heating power of 1000W. Furthermore, by optimizing the lengths of the stack and hot buffer, a no-load temperature of 76.9K and a cooling power of 0.2W at 80K are achieved with only 500W heating power.

Stirling Cryocooler for 3rd Generation IR Platforms [15-84]

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The new cryocooler aims to fulfill the requirements of new forward looking infrared systems. The new cryocooler has the cooling capacity of a 1.5W tactical cooler in a smaller package. The new cryocooler uses a 1.75 inch diameter compressor from the CLSS LC1062 cryocooler with an entirely new coldfinger and expander. The cryocooler design benefits from system and component level simulation using commercially available software such as Sage and ANSYS. The cryocooler can hold a 1.5W heat load at less than 77K with less than 50W electrical input power at an ambient temperature of 23°C. Cooldown time from 300K to 77K with a 19.1 g copper mass is 6.3 minutes. At an elevated temperature of 71°C, the cooler can hold a 1 W load at less than 77K with less than 50W electrical input power, and will cool a 19.1 g mass to 77K in 7.2 minutes.

Model of a Twin-Screw Extruder Operating with a Gifford-McMahon Cryocooler for the Solidification of Deuterium [15-87]

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This paper discusses the modeling of a Gifford-McMahon cryocooler with a twin-screw extruder for the generation of solid deuterium pellets. A numerical model of the extruder is developed in order to simulate the solidification of deuterium over a range of operating conditions and extruder design parameters. The numerical model integrates a set of conservation equations in the flow direction and includes variations in the thermodynamic and transport properties of the deuterium and extruder material as well as the effect of viscous energy dissipation and the latent heat of solidification. The model is used to evaluate the most important parameters that govern the process in order to guide experimental efforts. Recommendations are made regarding the cryocooler power and maximum extruder operation speed.

SESSION 15: Ground & Airborne Cryocoolers
[POSTER SESSION]
Thursday, June 12, 2008 9:45 – 10:45 AM

Performance Characteristics and Life of L-3 CE Re-optimized 0.6-Watt Linear Cooler [15-79]

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L-3 CE has re-optimized the design of its 0.6-Watt cooler model B600 to provide twice the refrigeration lift without significant changes to weight and size. This paper presents the latest performance characteristics and the life test data of the re-optimized cooler model B610.

Development of a Stirling-type Pulse Tube Cryocooler of 2.5W at 65K for Telecommunication Applications [15-88]

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Fuji Electric Group has developed high-reliability technologies for various types of Stirling cryocoolers for space satellite systems. For commercial applications, we also have developed and marketed a miniature pulse-tube cryocooler providing 2W to 3W of refrigeration at 70K with 100W of electric power input. To improve efficiency and power density, we have developed a new moving-magnet linear motor to replace the moving-coil motor (which has only 70% efficiency) and have adopted a coaxial pulse-tube expander. This development is for cooling a high-temperature superconductive (HTS) device in a wireless telecommunication system. The cryocooler requires a cooling power of 2.5W at 65K, COP 2.5% and a lifetime longer than 50,000 hours. This development is supported by the Ministry of Internal Affairs and Communications in Japan. At this point, the preliminary testing of each part of the moving magnet linear motor and the coaxial pulse tube has been completed. For the next phase, we constructed a first stage prototype compressor using the new linear motor, and tested the new machine. This paper describes the test results for the pulse tube cryocooler.

Cryocooled Cooling System for Superconducting Magnet [15-47]

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The cryogenic cooling system using a two-stage cryocooler for superconducting magnet is designed, fabricated and tested. The superconducting magnet is composed of the NbTi solenoid coils with the effective warm bore of 52mm and the maximum central field of 3T. The NbTi solenoid coils are wound around the copper form which is thermally connected to the second stage coldhead of a cryocooler through the cooling medium. The temperature distributions along the cooling medium are calculated by the relevant thermal analysis during cool-down process as well as in steady state and compared with the results from the measurements. The effect of thermal radiation, contact resistance and cooling capacity of cryocooler are also discussed.

SESSION 15: Ground & Airborne Cryocoolers [POSTER SESSION]

Thursday, June 12, 2008 9:45 – 10:45 AM

Reliability Growth of Stirling-Cycle Coolers at L-3 CE [15-50]

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The key objective of this paper is to update the L-3 CE life testing for the 0.6-Watt Cooler (Model B600C) and the 1.5-Watt Cooler (Model B1500E). Acceptance testing is performed at 500-hour intervals and the accumulated life test data is used to formulate sets of empirical constants for life prediction for any operating condition using the Watt-Hour approach [1]. Results are presented in graph form and depict performance characteristics such as cooldown time, refrigeration capacity and input power. The data presented here extends the boundary of life data in previous paper from the authors.

Effect of Regenerator Material Configuration on 4K-GM Cryocooler Performance [15-67]

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This paper describes experimental results and calculation analysis of 4K-GM cryocooler. A configuration of the regenerator material is one of the important parameters for the improvement of a 4K-GM refrigerator. The effect of the configuration, such as the material diameter and porosity, on the performance has been investigated. Firstly, the cooling capacity around 6K was measured varying the diameters of lead (Pb) spheres from 0.06 mm to 1.18 mm. Because of larger heat transfer area and higher coefficient of heat transfer, smaller spheres show higher NTU, which improves an efficiency of a regenerator. But, smaller spheres also make higher pressure drop in the regenerator and it reduces an expansion work at the cold end. Then, it is confirmed that the optimal diameter exists when the porosity of the Pb spheres is kept constant. Secondly, the effect of the porosity on the cooling capacity was also measured by mixing two different diameters of Pb spheres. The lower porosity regenerators showed an improvement of cooling capacity in some conditions. Lastly, by using experimental results of Pb regenerators, the 4K level cooling capacity was investigated by using $HoCu_2$ magnetic regenerator material. The porosity of $HoCu_2$ spheres was also changed by mixing different diameters of spheres. The cooling capacity increased about 18% when the porosity was increased from 66% to 73%.

Wide-Temperature Range Sample Stage for 6-Circle Diffractometer in X-ray Scattering Experiments Based on Stirling Cooler [15-58]

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Some x-ray scattering experiments using focused synchrotron x -ray beams require changing the sample temperature from cryogenic to room temperatures and above during data collection. Covering such a wide range of temperatures typically requires different sample stages for the regions below and above room temperature and, consequently, time consuming realignment of the sample. We propose a wide- temperature range (40K-573K) sample holder concept for use in x-ray scattering experiments that will completely cover this sample temperature range without stage realignment. This will result in the ability to collect data through the entire required sample temperature range without the need to changes stages and realign samples. That is, the user will have more time to measure samples and will not have the problem of fitting results from different temperature ranges together. This design also reduces the size, power consumption and servicing time of the sample cryo/heater-stage. Conceptually, collecting data across this wide temperature range will be achieved by having the cryo-cooler and heater connected to the same sample stage through a mechanical thermal switch in a dual-can vacuum space. Cooling will be achieved by using a one-stage Stirling cooler. The thermal contact for the low- temperature stages of the cryo-cooler with the sample package will be achieved via properly matched conical thermal metal-to-metal contacts. The cryogenic and heater interface packages will require good thermal insulation, and will be mechanically well matched to each other to achieve good heat flow, and minimized thermal expansion and energy loss.

Upgrading the GM Type Pulse Tube Cryocooler Served as a Power Lead Unit [15-86]

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Utilization of GM type pulse tube cryocooler to the power lead unit has been developed to validate its high technical applicability. The first prototype unit demonstrated 2100A operation with solenoid valves served as a phase shift system in 2005. To upgrade the first prototype unit, the design has been reviewed to increase the rated current of up to 3000A. At the same time, the rotary valve unit has been designed based on the numerical model. Fabrication of a pair of power lead unit as well as the rotary valve unit are being conducted to demonstrate its validity. The optimization processes of the power lead operation is discussed in detail. The alternative phase shift technique is also presented.

Novel Concept for Driving Micro Miniature Linear Cryogenic Cooler in Battery Powered Infrared Imagers [15-120]

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Battery-powered portable, aural undetectable, low power consuming and long life cooled infrared imagers became crucial for delivering day/night capability for carrying out special operations. This calls for a development of a new generation of microminiature linear split Stirling cryogenic engines, the performance of which depends strongly on the performance of their drivers. In traditional approach, they rely on the PWM power supplies producing the fixed frequency sine voltage, the magnitude of which varies as to maintain the desired focal plane array temperature. Typical is that the power/current delivered by the battery oscillate with the double frequency, giving rise, therefore, to the elevated peak and RMS levels of power/current producing harmful EMI and shortening time between battery charges. Resulting from this is a need for bulky low frequency filters and more capacitive battery being capable of producing more peak power/current and compensating for corresponding power losses caused by the elevated RMS currents. The authors present the outcomes of the feasibility study towards development of the novel (patent pending) driver consuming essentially constant instant battery power/current. In one of the possible implementation, this approach relies on using the regulation stage incorporating the buck-boost converter operating in the instant battery power/current control mode. From experimentation, in spite of the essential departure of the motor current shape from a sinusoidal one, the net power consumption by the linear compressor operating in the closed loop mode was not compromised at all. Further, such a driver produced exceptionally high coefficient of performance and short cool down times over the entire range of the battery voltages. Additional advantages are: absence of heavy low frequency filters, reduced weight and better temperature mode of battery pack, reduced weight of the driver power conversion stage due to excluding of electrical power peak during operation period, enhanced time between battery charges.

Characterization on Dynamic and Time-averaged Heat Transfer of Oscillating-Flow Parallel-Plate Heat Exchangers [16-32]

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In regenerative or thermoacoustic engines (including prime movers and refrigerators), the oscillating flow heat exchangers play an important role in transport heat with external high and low temperature sinks. Physically, heat transfer mechanism in the heat exchangers is more complex than that in the regenerators. Unlike the regenerators, there are both oscillating heat exchange flux (first order) and non-zero time-averaged heat exchange flux (second order) in the hot and cold end heat exchangers of thermoacoustic systems. The non-zero time-averaged heat flux just reflects the net heat exchange between the working substance and external heat sinks, which is more important and interesting for design. In this paper, the physical mechanism of oscillating flow heat exchanger is first analyzed. Based on an understanding of the heat transfer mechanism, the theoretical model for characterizing the dynamic and time-averaged heat transfer of parallel-plate heat exchangers is then developed. For the dynamic heat transfer, it is found that gas compressibility makes predominant contribution. For small kinematical Reynolds number region, the dynamic Nusselt number is approximately equal to 12. For the time-averaged heat transfer, the key of the problem is to obtain transversal distribution of the second order time-averaged temperature, T20(y). After obtaining the T20(y), an analytical expression about the Nusselt number describing the time-average heat transfer under the assumption of fully developed oscillating laminar flow can be given. It is found that the Nusselt number may go down to zero when the kinematical Reynolds number goes to zero, and go to constant in between 12 to 14 if the kinematical Reynolds number goes to infinite; in addition, there is maximum value for the Nusselt number of the time-averaged heat transfer. At present, such a unique feature about the time-averaged heat transfer is still not understood, which needs further study in the future.

Miniature PCHE-Type Recuperator with Transverse Bypass [16-91]

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A high-effectiveness multi-channel heat exchanger has flow distribution problem. Even slightly mal-distributed flow in such a heat exchanger causes severe thermal-performance reduction, but what is worse is that complete elimination of flow mal-distribution is practically impossible. No matter how good the design or the manufacture of the heat exchanger would be, the flow is slightly mal-distributed (the only way of avoiding it is to make a single-channel heat exchanger). Several methods were proposed conceptually to resolve the problem so far. Those methods can be classified into two categories. The first category handles the flow itself (flow regulation or flow re-distribution) to minimize performance reduction, and the second one makes a heat exchanger resistant to flow mal-distribution (small performance reduction even under large flow mal-distribution). However, those methods are hardly applicable to practical heat exchangers because they deteriorate manufacturability. Investigating a miniature PCHE(Printed Circuit Heat Exchanger)-type recuperator, we experienced performance reduction and found that one of the methods needs to be adapted. We combined transverse bypass structure with a conventional PCHE. In a conventional PCHE, hot stream layer and cold stream layer alternate with the fluid in each layer completely separated. However, in a transverse bypass PCHE, hot or cold stream layers are joined together through the transverse bypass. Hence, internal flow re-distribution and partial flow mixing are allowed. The performance reduction which was observed in the conventional PCHE could be weakened in the transverse bypass PCHE.

Cooling Performance of Miniaturized Thermoacoustic Expanders Operated at 133 K [16-69]

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The recuperative cryocoolers that have less or no moving parts at the cold stage can satisfy the long term mission targets and possess a compelling advantage for many applications that require reliability, vibration free, deliver cooling over distance, and efficient operation. A new type of thermoacoustic expander that were developed by the author will meet the challenges for recuperative coolers used in future space-borne telescopes and infrared instruments. The recent progresses in miniaturizing thermoacoustic expenders for low-cooling power recuperative coolers were made through the research funded by DoD SBIR program and reported in this paper. A thermoacoustic expander was miniaturized and tested at cryogenic temperature with helium gases to verify the feasibility of this technology. Initial cooling experiments of the miniaturized thermoacoustic expander (MTAE) showed that significant temperature drop was generated in the inverse temperature range of helium gases, and demonstrated that MTAE enables to enhance the cooling power of recuperative cryocooler in a broad temperature range by directly removing heat from the cold-stage without sacrificing reliability and simplicity. The experimental results also exhibited the significant cooling performance of MTAE vs. JT expanders at the tested cryogenic temperature, and proven the feasibility of this technology applied in miniature cryocooler systems. The MTAE also operated continuously in variable conditions and provided the stable cooling performance in the temperature range with the ratio 2.26. The cooling performance experiments demonstrated that the MTAE as a cryogenic expansion device enables to stably run through the start-up stage at ambient and down to cryogenic temperature.

Proton Conductive Membrane Compressor-Driven Pulse Tube Cryocooler [16-63]

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Johnson Research & Development (JRD) and Raytheon are collaboratively developing a pulse tube cryocooler based on a novel solid-state proton conductive membrane compressor (PCMC). This approach improves upon the current state of the art, in which positive-displacement compressors using linear motors are used as the pressure wave generator, by eliminating all moving parts from the system. Cryocooler system performance predictions based upon recent proton conductive membrane (PCM) experimental measurements reveal that the PCMC is not only competitive efficiency-wise with existing compressor technology, but it also has significant advantages for advanced cryocooler systems including: (1) All solid state system, (2) Extremely low vibration, (3) Flexible form factor, (4) Low cost electronics and control systems, (5) High reliability, (6) Scalable designs, and (7) Potential elimination of cryocooler redundancy requirement for space-based systems. This system holds great promise for achieving a low cost, high efficiency, and high reliability system. The cryocooler is generally considered one of the highest risk components in a space IR sensor, so reliability enhancements at the cryocooler component level are well-leveraged risk reduction measures at the sensor level. The stressing lifetime and reliability requirements typical of space surveillance missions result in tight tolerances, labor-intensive assembly procedures, and costly materials. The vibration output requirement also contributes to the design complexity of the cryocooler and necessitates expensive control electronics that mitigate the vibration output through closed-loop control of the input current waveform. Terrestrial applications such as High Temperature Superconductors (HTS) for power transmission will also benefit from this high reliability system.

Calculated Performance of Low-Porosity Regenerators at 4 K with Helium-4 and Helium-3 [16-93]

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Previously we have shown that the lower volumetric heat capacity and more ideal behavior of helium-3 compared with helium-4 at 4K results in an improved performance for packed sphere regenerators operating with helium-3 between 4K and about 35K. In this paper we use REGEN3.3 to calculate the regenerator loss and the coefficient of performance (COP) of 4K regenerators with porosities between 0.1 and 0.38 for parallel holes in a rare-earth matrix operating at 30Hz frequency using either helium-3 or helium-4. A comparison is made with packed spheres at a porosity of 0.38. Calculations were made for average pressures ranging from 0.3MPa to 1.5MPa, mostly with a pressure ratio of 1.5. The results show that the regenerator loss decreases and the COP increases as the porosity decreases for all average pressures. For helium-3 the regenerator performance is improved for pressures below 1MPa, whereas the lower pressures do not benefit helium-4 regenerators. The COP of a helium-3 regenerator with 0.2 porosity operating at 30Hz and 0.5MPa average pressure is about 3.4 times higher than a helium-4 regenerator using packed spheres with 0.38 porosity. The effect of regenerator matrix material and the temperature of the heat capacity peak are also investigated. Funding from the Office of Naval Research is acknowledged.

Infrared Imaging as a Means of Characterizing Flow and Temperature Instabilities within Pulse Tube Cryocoolers [17-118]

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Infrared (IR), or thermo-graphic imaging, has long been used in general industry as a means of troubleshooting thermal, mechanical, and electrical systems. As IR imaging constructs a temperature map based on the infra-red radiation a body is emitting, it is very useful at showing such things as friction points, heat leaks, electrical shorts, and at quickly performing such diagnostics that classical sensors have difficulty doing. In this paper we show how infrared imaging can also be used as a diagnostic tool in characterizing the flows and instabilities within pulse tube cryocoolers. While classical temperature sensors, such as thermocouples or diodes, may be indicative of the temperature at a specific point, they are quite limited in mapping a fully dynamic temperature profile resulting from some flow instability within the cryocooler. It is for such cases that IR imaging is quite helpful. IR imaging devices however do have limitations when employed in conjunction with cryocoolers, namely they are limited to imaging relatively high temperatures (those of 230 K and above) nevertheless they can still be a powerful diagnostic tool if used correctly. This paper will discuss some of the methods and points by which an IR camera can still be well utilized and will also present some actual examples where IR imaging was used successfully as a diagnostic tool for quickly determining the source of detrimental flow nonuniformities in pulse tubes.

Design of an Experimental Test Facility for Direct Measurement of Pulse-Tube Energy Flows [17-95]

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In recent years, much effort has been directed at optimal design of Pulse-Tube Cryocooler (PTC) systems via the use of advanced modeling techniques such as computational fluid dynamics (CFD). These models have been shown to qualitatively predict the processes that one would expect in a PTC. However, for these models to become useful and accepted as design tools, precise experimental data from actual PTC systems are required that can be utilized for validation. More specifically, detailed knowledge of the regenerator loss, acoustic power flow at the cold end, cooling power, phase angles and the instantaneous pressure and mass flows are required to thoroughly validate an advanced CFD model. This paper discusses the design and construction of an experimental test facility capable of directly measuring the aforementioned quantities. The purpose of the test facility is to facilitate validation of advanced PTC CFD models as well as sophisticated regenerator models. Therefore, the test facility has been designed so that the regenerator loss is decoupled and measured independent of the pulse-tube component. Subsequently, the use of a custom designed mass flow meter and pressure sensors allows the mass flow and pressure at the cold end to be measured to determine the acoustic power flow entering the pulse-tube component. The acoustic power measurement, coupled with measurement of the gross cooling power and the regenerator loss allows the loss in the pulse-tube component to be directly determined. These quantities provide validation for CFD models which predict the efficiency of the pulse-tube component with respect to converting acoustic power into useful cooling. Initial measurements of the pulse-tube loss and efficiency are presented for different geometric designs of the pulse-tube and flow transition components. This work is supported by the Office of Naval Research under contract N00014-06-1-0007, the Wisconsin Space Grant Consortium, and the CEC Timmerhaus Scholarship.

The Analysis of Free Piston Free Displacer Stirling Cryocooler from Design Point of View [17-114]

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Free piston free displacer cryocoolers of small capacity have been used for cooling infrared sensors of missiles, night vision equipments and for space borne applications. Despite the fact that there are a number of mathematical models available for cryocoolers, very few models are available for such type of cryocoolers. Moreover, the models available do not even represent the complete dynamics of the cryocoolers from the design point of view. In the present paper the mathematical modeling for simulating one of such cryocooler is given. The mathematical model prepared predicts the performance parameters of a linear motor operated free piston free displacer Stirling cryocooler. The complete dynamics and thermodynamics of the cryocooler is presented including the pressure loss due to the flow through the regenerator and the bounce space effect as well. The cryocooler characteristic variables are divided in two parts viz. Internal variable named as design variables and external operating variables which affect the performance of the cryocoolers. The design variables are the motor parameters and the cylinder, piston dimensions. The operating variables, which have an effect on the performance of the cryocooler, are the phase difference between the piston and the displacer motor, frequency of operation, charge pressure and impressed voltage of the piston motor. The performance parameters are identified as the cooling power and the coefficient of performance. The performance curves drawn for the analysis show the effect of operating frequency, impressed voltage and charge pressure on the performance parameters of the cryocooler. The analysis of the performance is done by taking the effect of the operating parameters one by one, starting from the effect of phase angle on the performance parameters. The design of the cryocooler can be based on the performance curves.

SESSION 17: Modeling & Testing of Stirling/Pulse-Tube Cryocoolers

Thursday, June 12, 2008   1:30 – 3:30 PM

The Role of Thermoconductivity in Pulse Tube Cryocoolers [17-3]

Peter Kittel
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Descriptions of the thermodynamics of pulse tube cryocoolers usually concentrate on the roles of entropy, enthalpy, pressure, and mass flow. Thermoconductivity is often considered as a source of parasitic losses. This paper reviews the role thermoconductivity plays in determining not only the temperature profiles in the regenerator and pulse tube but also the interaction between thermal conductivity and real gas effects and in determining the behavior at the transitions between components.

Continued Study on Universal Scaling Law of Inertance Tube Phase Shifter for Pulse Tube Cryocoolers [17-34]

S. Zhu, E. Luo, Z. Wu, W. Dai, J. Hu
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S. Zhu
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An inertance tube is a long thin tube subjected to oscillating flow, which can be used as an efficient phase shifter for pulse tube coolers. Normally, the phase shifting features is characterized by the inlet phase angle and acoustical power of the inertance tube. The proper inlet phase angle can improve the efficiency of the pulse tube cooler, while the inlet acoustical power reflects the gross cooling power of the pulse tube cooler. In our previous work, we developed a simplified turbulent-flow model for characterizing the phase shifting features of inertance tubes, and provided a series of universal charts to guide choosing appropriate inertance tubes by means of using dimensionless parameters. Due to adopting inappropriate dimensionless acoustic power, we found it not straightforward to determine the length and diameter of the inertance tube phase shifter because the inertance tube diameter in the dimensionless acoustical power is unknown. Therefore, determination of the inertance tube needs many iteration steps with the previous scaling law. In this paper, we have made continued study on the universal scaling law by introducing a new dimensionless acoustical power. Because the viscous penetration depth in the new dimensionless is known if the operating parameters including operating frequency, temperature and pressure, it will be straightforward and easy to determine the length and diameter of the inertance tube. In particular, using the dimensionless acoustical power more clearly reflects the physical feature of power dissipation along the inertance tube. In addition, a more reasonable model for correcting the turbulent-flow heat transfer effect on the influence of the inertance tube is developed, which leads a better agreement with reported experiment data. It is expected that the new developed scaling law may provide more useful and more accurate guidance for designers of inertance tube pulse tube cryocoolers.

CFD Modeling of Pulsating Flow Around a Bend With and Without Flow Straighteners as Applicable to Pulse Tube Cryocoolers [17-83]

I. Nachman
Ricor, En Harod Ihud, Israel

G. Grossman
Technion, Israel Institute of Technology, Haifa, Israel

Coaxial and U-shaped Pulse Tube cryocoolers involve a change in the direction of the flow as it proceeds from the regenerator through the cold heat exchanger to the (buffer) pulse tube. This rather sharp U-turn in the flow causes non-uniformities over the cross section which may have an adverse effect particularly in the buffer tube – creating eddies leading to undesirable mixing. Flow straighteners are sometimes introduced in order to deal with this phenomenon. This study is concerned with a CFD model of the reciprocating flow around a 180° bend, as applicable to U-shaped Pulse Tube cryocoolers. Cases with and without flow straighteners have been considered. Special attention is paid to the role of flow straighteners in terms of convective heat loss and pressure loss. It is shown that the flow characteristic in the cold head of the pulse tube cryocooler is critical, and is of greater significance in miniature cryocoolers. The pressure drop in the flow around a sharp bend vs. the one in a straight tube is studied. Both the pressure drop and the convective heat transfer are affected by the Valensi and Reynolds numbers characterizing the pulsating flow. The CFD software makes is possible to visualize the flow and map out the temperature and velocity fields as they vary in time, as well as to observe local phenomena such as vortices and flow reversal.

Dynamic Grid Coarsening and Efficient Simulation of Fluid Flow and Energy Transfer in Pulse Tubes [17-62]

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C. Kirkconnell
Raytheon Space and Airborne Systems, El Segundo, CA, USA

We develop a new approach to numerical simulation of fluid flow and energy transfer in pulse tubes, based on a novel method that combines a multiresolution wavelet transformation (WT), dynamic restructuring of the computational grid, and the finite-volume method. The strategy is based on identifying, at each time step, those parts of the system in which important phenomena are occurring using the WT. These include the "hot spots" in the system, and/or those parts in which the flow velocities change significantly over a small length. Then, the WT coarsens the computational grid in those parts of the system in which there are not large temperature and/or velocity gradients, and preserves the fine structure of the grid where complex and important phenomena are occurring. This results in reducing the number of equations, resulting from the discretization of the momentum and energy equations, to be solved at each time step by orders of magnitude, without loss of accuracy. To verify the accuracy and efficiency of the simulator, the simulation results are tested against the results obtained with uniform and highly resolved computational grids. The method is then utilized for investigating the effect of various physical factors on the performance of a pulse tube, and optimizing its operation. It is also used to simulate the phenomena in pulse tubes with decreasing sizes, in order to determine the length scale at which the classical hydrodynamics may not a priori be valid. We identify the critical length scale.

CFD Modeling of Meso-Scale and Micro-Scale Pulse Tube Refrigerators [17-72]

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C. Kirkconnell
Raytheon Space and Airborne Systems, El Segundo, CA, USA

S. Yorish
Virtual AeroSurface Technologies, Atlanta, GA, USA

For miniature cryocoolers, CFD modeling is likely the best technique available as dedicated models developed for larger systems may not accurately represent phenomena which become important as the device scale is reduced. However, the increased detail provided by CFD models is paid for with greatly increased computational time, and thus performing extensive parametric studies with CFD may be prohibitively time consuming. In this paper, system-level CFD modeling and optimization of miniature pulse tube refrigerators were performed using Fluent, following a preliminary scaling study done with the Sage PTR modeling program. Using Fluent and Sage together in this manner allowed for fast initial model development using Sage, the results of which could then be authenticated and extended in Fluent.

Several different meso-scale and micro-scale models having respective total volumes of 3-4 cm^3 and approximately 1 cm3, excluding the compressor, were constructed and optimized in Sage. These provided initial geometry and operating conditions to similarly scaled Fluent models. In order to produce meaningful results, the Fluent models also required accurate closure relations for their porous segments, which were made up of stacked 635 mesh stainless steel and 325 mesh phosphor-bronze screens. Therefore, experimentally measured hydrodynamic parameters for these porous fillers were incorporated into the Fluent models.

Thus constructed, the Fluent models were iterated to find their periodic steady-state solutions, at which point they were parametrically optimized. Timely optimization in Fluent was facilitated by a technique of initializing the PTR models with an assumed cold temperature and linear temperature gradients in the regenerator and pulse tube. The predicted performance of these Fluent-optimized models is presented, along with the initial Sage-based Fluent models and the predictions of Sage itself. These results show that the aforementioned miniature PTRs suitable for staged application are feasible.

Very High Capacity Aerospace Cryocooler [18-111]

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D. Clark
Lockheed Martin Advanced Technology Center, Denver, CO, USA

Lockheed Martin's Advanced Technology Center has developed a new aerospace cryocooler with very high cooling capacity. This robust U-tube pulse tube cryocooler is designed to provide 40W of cooling at 95K while rejecting heat at 300K. The pulse tube is driven by our new M5Midi compressor which is capable of very high power density. The input electrical power into the compressor can exceed 600W, and the mass of the pulse tube cryocooler and compressor is just 8kg. The motivation for such high cooling capacities is oxygen liquefaction and storage, both for propellant generation and human breathing supply. However, the large cooling capability could also be used to cool optical structures or other devices with high heat loads. Test data will be presented, mapping the cryocooler performance across a broad range of operating conditions.

Development of a 15W Coaxial Pulse Tube Cooler [18-25]

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In the recent years Thales Cryogenics has achieved good cryogenic performance results with its one- and four-watt pulse tube coolers operating around 80K, which are currently in full serial production. These coolers consist of compressors that are based on well-proven and highly reliable flexure bearing technology, and pulse-tube cold fingers that are based on a CEA/SBT design. This design has been further optimized by Thales. In 2007 Thales has developed and tested the even more powerful LPT9710 coaxial pulse tube cooler that has proven to produce a cooling power of at least 15W at 80K. Advantage of a pulse-tube cooler in this cooling range is the absence of a relative high moving mass, present in a Stirling cooler with similar performance. This moving mass results in high forces and consequently high induced-vibration levels at the cold-finger position and has a negative impact on cooler reliability. The LPT9710 is a cost-effective, low-vibration, and very high-efficiency pulse-tube cooler that is able to reach high cooling powers and low temperatures with a single-stage cooler. Temperatures down to 40K have been measured, without optimization for this temperature range. This paper describes the trade-offs that have been considered in the design phases of the compressor and the pulse tube. Design optimizations of the complete pulse-tube cooler will be presented as well. An overview of the test results, the status of the qualification program and the resulting specification of this pulse-tube cooler will be given. The high cooler efficiency will be outlined in more detail and will be compared to other split-Stirling and coaxial pulse-tube coolers. Finally, future development areas that have been made available by this new compressor and pulse tube will be discussed.

Status of Air Liquide Space Pulse Tube Cryocoolers [18-15]

T. Trollier, J. Tanchon, J. Buquet, A. Ravex
Air Liquide Advanced Technology Division, Sassenage, France

Air Liquide Advanced Technology Division (AL/DTA) proposes two Pulse Tube cooler systems in the 40-80K temperature range. The Miniature and the Large Pulse Tube Cooler (respectively MPTC and LPTC) qualification and production status are presented. The integration of such Pulse Tube cooler systems in coming Earth Observation missions such as Meteosat Third Generation, Sentinel 3, etc., is discussed. The associated Cooler Drive Electronics is also an important aspect specifically regarding the active control of the cryocooler during the launch phase and the active reduction of the vibrations induced by the compressor. The CDE status will also be presented and discussed.

Development of a Miniature 150 Hz Pulse Tube Cryocooler [18-85]

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Z. Gan
Cryogenics Laboratory, Zhejiang University, Zhejiang, China

I. Garaway
Technion – Israel Institute of Technology, Haifa, Israel

A. Veprik
RICOR Cryogenic & Vacuum Systems, En Harod Ihud, Israel

A miniature, high energy density, pulse tube cryocooler has been developed to provide appropriate cooling for size-limited cryogenic applications demanding fast cool down. This cryocooler design was optimized using REGEN3.2 for an operating frequency of 150Hz and an average pressure of 5.0MPa in order to maintain high cooling power and high efficiency in a very compact package. The regenerator has dimensions of 4.4mm inside diameter by 27 mm long and is filled with #635 mesh stainless steel screen. A net refrigeration power of about 0.5 W at 80K is calculated for this miniature pulse tube cryocooler. Various design features, such as the use of compact heat exchangers and a miniature linear compressor relying on a resonant "moving magnet" actuator and having a swept volume of 0.5cm^3, resulted in a remarkably compact pulse tube cryocooler. In this study we present the important design parameters of this particular cryocooler and the testing procedures incorporated to characterize the cryocooler. The effect of fill pressure and operating frequency on cryocooler performance are presented along with the optimized cryocooler cool down characteristics. Additional modifications allowing further volume reduction such as replacing the inertance tube and reservoir with an appropriately sized phase shifting component are discussed.

High Frequency Coaxial Pulse Tube Microcooler for Space Applications [18-82]

M. Petach, M. Waterman, E. Tward
Northrop Grumman Space Technology, Redondo Beach, CA, USA

This paper describes a coaxial pulsetube cold head designed for higher operating frequencies than previous coaxial cold heads. This high frequency design results in a small, low mass, fast cool down pulse tube cryocooler. The coaxial pulse tube coldhead was optimized to utilize the small swept volume of a scaled down version of Northrop Grumman Space Technology's existing line of flight qualified compressors with a mass of 600 grams. It was also thermodynamically and mechanically optimized for rapid cool down, and it has a very low inherent thermal mass at the cold end. At 298K reject, this cooler can lift 1.1W at 77K. This paper describes this cooler performance over a range of frequencies up to 145Hz and discusses the estimated losses in both the coldhead and the compressor.

Performance Realization of Single Stage Stirling Cryocooler at ISRO [18-31]

A. Ramasamy, Padmanabhan, C. Gurudath
Thermal Systems Group, Bangalore, India

Cryogenic cooling to low temperature of around 80K with 1W load is required with minimum input power for certain space applications such as instruments for scientific and earth observation. Stirling cycle cryocooler is one of the cooling devices, which can meet the above requirement. Hence the development of Stirling cycle cryocooler was taken up at ISRO Satellite Centre.

Split Stirling cryocooler with compressor mounted head to head and single stage expander was developed to meet the above requirement. A development model was fabricated, assembled and tested. Initial thermal performance studies indicated that this unit can provide the required cooling for an input power of 48watts.

To achieve the required performance with an input power of 30watts or less, further studies were conducted and certain modifications such as achieving close clearance seal between piston and cylinder, displacer and cryocylinder and re-sizing of regenerator were incorporated. With these modifications, the required performance as per specification has been achieved for an input power of 25watts. The efficiency of the cryocooler at 80K with 1watt load is 11% at ambient heat rejection temperature of 300K. This unit also provides 1W cooling at 60K for an input power of 43W. This paper gives the overall system configuration, thermal performance, development status, future plan and conclusions.

15th International Cryocooler Conference - Preliminary Schedule

Monday, June 9	Tuesday, June 10	Wednesday, June 11	Thursday, June 12
Foundations of Cryocoolers 2008 Short Course (Shoreline A) 8:00AM - 5:00 PM	***Breakfast (Regency Foyer) 7:00 - 8:00 AM***	***Breakfast (Regency Foyer) 7:00 - 8:00 AM***	***Breakfast (Regency Foyer) 7:00 - 8:00 AM***
On Site Registration (Harbor) 1:00 - 5:00 PM	Introduction 8:00 - 8:15 AM	Recuperators & Micro - JT Cryocoolers 8:00 - 9:45 AM	Cryocooler Electronics 8:00 - 9:00 AM
Welcome Reception (Beacon Ballroom) 6:00 - 9:00 PM	Space Cryocooler Applications & Overview 8:15 - 10:00 AM	Modeling of Pulse-Tube/ Stirling Cryocoolers (Poster) 9:45 - 10:45 AM	Thermoacoustic Cryocoolers 9:00 - 10:00 AM
	Pulse-Tube/Stirling Cryocoolers (Poster) 10:00 - 11:00 AM	Two-Stage Pulse-Tube/ Stirling Cryocoolers 10:45 - 11:45 AM	Ground & Airborne Cryocoolers (Poster) 10:00 - 11:00 AM
	Tactical & Military Cryocoolers 11:00 - 12:15 PM	***Lunch 11:45 - 1:15 PM***	Cryocooler Components 11:00 - 12:15 PM
	Lunch 12:15 - 1:45 PM	Laboratory Cryocooler Applications 1:15 - 2:15 PM	***Lunch 12:15 - 1:45 PM***
	Cryogenic Integration Technologies 1:45 - 2:45 PM	Cryocooler Integration Technologies & Components (Poster) 2:15 - 3:15 PM	Modeling & Testing of Stirling/ Pulse-Tube Cryocoolers 1:45 - 3:45 PM
	Low-Temperature Cryocoolers 2:45 - 3:45 PM	Distributed Cryocoolers & Modeling 3:15 - 5:15 PM	***Break 3:45 - 4:00 PM***
	Break 3:45 - 4:00 PM	Conference "Surf Party" (Aquarium of the Pacific) 7:00 - 11:00 PM	Single-Stage Stirling/Pulse-Tube Cryocoolers 4:00 - 5:30 PM
	Commercial & Industrial Cryocoolers & Applications 4:00 - 5:45 PM		***End of Conference***
	Vendor Reception (Beacon Ballroom) 5:45 - 7:30 PM		

11:00 PM