# ICC 16

## International Cryocooler Conference

Atlanta, Georgia
May 17 - 20, 2010

# International Cryocooler Conference 16

## May 17 – 20, 2010

### Atlanta, Georgia

## Final Program With Complete Technical Abstracts

**Cosponsored by**

**The George W. Woodruff School of Mechanical Engineering**

## 16th Annual International Cryocooler Conference - Preliminary Schedule

| Monday, May 17 | Tuesday, May 18 | Wednesday, May 19 | Thursday May, 20 |
|---|---|---|---|
| Foundations of 2009 Short Course 8:00 AM -5:00 PM | **Breakfast/Session Chair Meeting 7:00 AM -8:00 AM** | **Breakfast 7:00 AM -8:00 AM** | **Breakfast 7:00 AM -8:00 AM** |
| **On Site Registration 1:00 PM -5:00PM** | Introduction 8:00 AM - 8:15 AM | Oral Session WO1 8:00 AM -9:30 AM | Oral Session THO1 8:00 AM -9:45 AM |
| **Welcome Reception 6:00 PM -9:00 PM** | Oral Session TO1 8:15 AM - 9:45 AM | Poster Session WP2 9:30 AM -10:30 AM | **Break 9:45 AM -10:15 AM** |
| | Poster Session TP2 9:45 AM -10:45 AM | Oral Session WO3 10:30 AM -12:00 PM | Oral Session THO2 10:15 AM - 11:30 AM |
| | Oral Session TO3 10:45 AM - 12:00 PM | **Lunch Break 12:00 PM -1:30PM** | **Lunch Break 11:30 AM -1:00 PM** |
| | **Lunch Break 12:00 PM -1:30PM** | Oral Session WO4 1:30 PM - 3:00PM | Oral Session THO3 1:00 PM -2:15 PM |
| | Oral Session TO4 1:30 PM - 3:00PM | Poster Session WP5 3:00 PM -4:00 PM | **Break 2:15 PM -2:45** |
| | Poster Session TP5 3:00 PM -4:00 PM | Oral Session WO6 4:00 PM -5:30 PM | Oral Session THO4 2:45 PM -4:15 PM |
| | Oral Session TO6 4:00 PM -5:45 PM | **Conference Party at Stone Mountain 5:45 PM -10:30 PM** | End of Conference |

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# CONFERENCE COMMITTEES

## CONFERENCE CHAIRMAN

S. Mostafa Ghiaasiaan
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## PROGRAM CO-CHAIRS

Sidney W.K. Yuan, Aerospace Corp.
Jeesung (Jeff) Cha, Aerospace Corp.

## TREASURER

Ray Radebaugh, NIST

## CONFERENCE PROCEEDINGS CO-EDITORS

Saul Miller, Aerospace Corp.
Ron Ross, Jet Propulsion Laboratory

## PROGRAM COMMITTEE

Peter Bradley, NIST
John Brisson, MIT
Weibo Chen, Creare
Lionel Duband, CEA
Sangkwon Jeong, KAIST
Ali Kashani, Atlas Scientific
Carl Kirkconnell, Iris Technology
Eric Marquardt, Ball Aerospace
Erin Pettyjohn, AFRL/RVSS
Jeff Raab, NGAS
Frank Roush, AFRL/RVSS
Mark Zagarola, Creare

## ORGANIZING COMMITTEE

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John Brisson, MIT
Jeesung (Jeff) Cha, Aerospace Corporation
Weibo Chen, Creare
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John Hendricks, Alabama Cryogenics
Sangkwon Jeong, KAIST
Carl Kirkconnell, Iris Technology
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Eric Marquardt, Ball Aerospace
Saul Miller, Aerospace Corporation
Alain Ravex, Air Liquide
Ron Ross, Jet Propulsion Laboratory
Frank Roush, AFRL/RVSS
Ingo Ruehlich, AIM
Michael Superczynski, Chesapeake Cryogenics
Chao Wang, Cryomech
Sidney Yuan, Aerospace Corporation
Mark Zagarola, Creare

# WELCOME

On behalf of the ICC16 Organizing and Program Committees, we would like to welcome you to the 16th International Cryocooler Conference (ICC16) being held May 17-20, 2010 in Atlanta, Georgia, USA. The ICC, which is held every other year, is now the preeminent international conference for the dissemination of novel ideas and experiences on the development and application of cryocoolers. ICC16 is attended by scientists and engineers representing academic, research and industrial institutions in Americas, Europe, Asia, and Africa.

ICC16 program has been arranged so that there will be no parallel sessions, to ensure that you will not miss any presentation. The proceedings of the conference, furthermore, will be published in a bound volume titled Cryocooler 16. The papers presented or posted in the conference will be documented in Cryocooler 16 after passing through a peer review process. Each participant in the conference will receive a copy of Cryocooler 16 approximately six months after the conference.

It is our pleasure to host ICC16 in Mid-Town Atlanta, where shopping, dining, sightseeing, and entertainment options are abundant.

The ICC16 conference banquet will be an exciting visit to the Georgia Stone Mountain Park. The participants will be transported by bus to the Memorial Hall Terrace in Stone Mountain, where they will enjoy spectacular scenery and a barbeque buffet dinner. They will then be transported back to the Georgia Tech Hotel and Conference Center by buses.

**Welcome to Atlanta and ICC16!**

**S. Mostafa Ghiaasiaan**
*General Chair*

**Sidney W.K. Yuan**
**Jeesung Cha**
*Program Co-Chairs*

# GENERAL INFORMATION

The ICC 16 conference will take place at the Georgia Tech Hotel and Conference Center (GTHCC) in Midtown Atlanta, Georgia. The Conference will begin with a Welcome Reception in GTHCC Ballroom on the evening of Monday May 17th, 2010. The Technical Program will commence at 8:00 AM on Tuesday, May 18th, 2010. Approximately 130 papers will be presented in both oral and poster formats during the following three days. The Conference will conclude on Thursday, May 20, 2010, at 4:15 PM. The Conference social programs that complement the Technical Program will include the aforementioned Welcome Ceremony and a Conference Banquet on the terrace of the Memorial Hall at Georgia Stone Mountain.

A complete overview of the Conference Schedule is provided on the back of the front cover and on the website of the Conference.

## REGISTRATION

All Conference attendees must register. The onsite registration fee is $665, which includes attendance at the Technical Program, all of the Social Program events and provided meals, conference materials, and a hard copy of the Conference Proceedings, which will be mailed to each participant approximately six months after the event. Companion tickets to the Conference Party at Georgia Stone Mountain are available for an additional fee of $70.

Payments to the ICC 16 Conference must be in US dollars. Purchase orders will not be accepted. Registration is available online at www.cryocooler.org and onsite at the Conference Registration Desk. Onsite registration hours are as follows:

| | |
|---|---|
| **Monday, May 17:** | **5:30 PM – 7:30 PM** |
| **Tuesday, May 18:** | **7:00 AM – 5:00 PM** |
| **Wednesday, May 19:** | **7:00 AM – 5:00 PM** |
| **Thursday, May 20:** | **7:00 AM – 12:00 N** |

## CONFERENCE PARTY

The conference banquet will take place at the Memorial Hall Terrace at Georgia Stone Mountain Park, on the evening of Wednesday, May 19th, 2010.

Participants will travel by bus from the Georgia Tech Hotel and Conference Center to Stone Mountain Park. The buses leave GTHCC at approximately 5:45 p.m. Participants will ride the buses back to GTHCC after the party.

Georgia Stone Mountain is the 9th most popular tourist attraction in the US. It is located on 3,200 acres of incredible natural beauty, and provides a second-to-non spring time landscape.

The Memorial Hall Terrace at Georgia Stone Mountain Park overlooks the Stone Mountain rock carvings. Participants will be treated to the Stone Mountain Fireworks and Laser Show. Dinner will consist of a supreme barbecue buffet.

All registered conference attendees can participate in the conference party free of charge. Conference attendees bringing companions must pay $70 for each additional guest. The additional companion tickets for the Conference Party must be purchased prior to the Conference Party, either online or at the registration desk.

## MEALS

Your registration includes continental breakfast every morning before the Technical Program (Tuesday, May 18, though Thursday, May 20), starting at 7:00 AM. Hors d'oeuvres will be provided at the Welcome reception on the evening of Monday, May 17th, and a full dinner will be provided at the May 19th Conference Party at Georgia Stone Mountain Park. The conference organizers have provided ample time for the participants to enjoy the many local restaurants within walking distance of the hotel for lunches, and for dinner on Tuesday, May 18th.

## MIDTOWN ATLANTA, GEORGIA

The Conference will take place at Georgia Tech Hotel and Conference Center, located on the corner of Spring Street and 5th Street in the revitalized Midtown Atlanta neighborhood. Midtown Atlanta is the second largest financial district in the city of Atlanta, Georgia, and contains about one-third of the city's high-rises. The vibrant live-work-play area is located close to nearby Atlanta landmarks including the corporate headquarters of Coca-Cola, BellSouth and Bank of America. The Midtown Atlanta district is the epicenter of Atlanta's music and artistic scene that includes the Fabulous Fox Theatre, Woodruff Arts Center, the High Museum of Art, Atlanta Symphony Orchestra, and the 14th Street Playhouse.

# CONFERENCE HOTEL – THE GEORGIA TECH HOTEL AND CONFERENCE CENTER

The Georgia Tech Hotel and Conference Center (GTHCC) will be the focal point of all the ICC 16 conference activities. In addition to providing the preferred lodging arrangements for the Conference attendees, GTHCC will also be the site of the Conference Welcome Reception, the Technical Program, and the Cryogenic Society of America (CSA) Foundations of Cryocoolers short course.

GTHCC is located on the new Technology Square complex (commonly called Tech Square) encompassing three blocks in the heart of midtown Atlanta. In addition to GTHCC, the Technology Square includes the Georgia Tech Global Learning Center, Georgia Tech College of Management, the Economic Development Institute, the Georgia Tech Bookstore, and a vast array of retail stores and restaurants.

Getting round the city of Atlanta is easy; the conference site is within walking distance from the North Avenue and Midtown Metro Atlanta Rapid Transport Agency (MARTA) transit stations, which provide a comfortable and efficient gateway to Buckhead, the Atlanta downtown business district, and the Hartsfield-Jackson Atlanta International Airport. GTHCC is also within easy access to Interstate 75/85. Some of the nearby attractions are as follows:

- Fabulous Fox Theatre - ½ mile
- Underground Atlanta - 1 mile
- World of Coca-Cola - 1 mile
- Georgia Aquarium - 1.1 mile
- Atlanta Civic Center - 1.2 miles
- High Museum of Art - 1.3 miles
- CNN Center - 1.5 miles
- Centennial Olympic Park - 1.5 miles
- Philips Arena (Atlanta Hawks & Thrashers) - 1.6 miles
- Atlantic Station – 1.6 miles Piedmont Park - 2.5 miles
- Atlanta Botanical Gardens - 2.3 miles
- Georgia Dome (Atlanta Falcons) - 2.3 miles
- Georgia World Congress Center - 2.4 miles
- Martin Luther King Center - 2.5 miles
- Carter Center - 3 miles
- Fernbank Museum of Natural History - 4 miles
- Turner Field (Atlanta Braves) - 4 miles
- Buckhead/Lenox Mall - 5 miles

# TRANSPORTATION TO GTHCC – FROM HARTSFIELD-JACKSON ATLANTA INTERNATIONAL AIRPORT

## Driving

- Head west on South Terminal Pkwy
- Make a slight right onto Airport Blvd.
- Take the I-75/I-85/I-20/GA-403/Camp Creek Pkwy ramp to Atlanta
- Keep left at the fork and continue toward GA-403 North/I-85 North
- Keep left at the fork and follow signs for I-85/GA-403
- Merge onto GA-403 North/I-85 North
- Take Exit 250 toward 10th Street/14th Street
- Merge onto Williams Street NW
- Turn right at 10th Street NW
- Turn right at Spring Street NW
- Hotel is on the right at 800 Spring Street NW

## Using MARTA

Take a train to the Midtown MARTA station. Then catch the free Tech Trolley on the Peachtree Place station exit. Take off at the first stop before the trolley enters the main Georgia Tech campus. Cross the street and you will find the hotel. The trolley runs every twenty minutes from 7:30 AM until 7 PM Monday through Friday during summer semesters.

From the North Avenue MARTA station: Head north on West Peachtree Street until you reach Fifth Street. Turn left onto Fifth Street and go one block. Cross Spring Street at the pedestrian crossing, and find the Georgia Tech Hotel and Conference Center.

# TECHNICAL PROGRAM SUMMARY

The ICC 16 Technical Program is organized into 16 sessions, containing 133 papers. The technical sessions will begin at 8:15 AM on Tuesday, May 18th, immediately following a 15 – minute introduction by the ICC 16 Organizing Committee. The Technical Sessions will begin promptly a 8:00 AM on Wednesday, May 19th, and Thursday, May 20th. The conference will be adjourned at 4:15 PM on Tuesday, May 20th.

The entire conference will take place at Georgia Tech Hotel and Conference Center, in Atlanta, Georgia. All oral sessions will be held in Salons 1-4 at GTHCC. The four poster sessions will be held in the Salon 1-4 Foyer and will provide an excellent opportunity for personal interaction among the authors and conference attendees. The morning and afternoon poster sessions have been scheduled to coincide with mid-morning and mid-afternoon breaks, respectively. Light refreshment will be provided throughout the conference hours, including the poster sessions.

Authors and presenters should submit their manuscripts and presentations to the conference staff in the Publications Room, located in Conference Room 9, on the same level as the conference area. Presentations will be loaded on a laptop for use during the oral sessions. The technical papers will be distributed among peer reviewers by the publications staff prior to publication in the conference proceedings (Cryocoolers 16).

# AUTHOR/PRESENTER INFORMATION

## Instructions for Poster Presenters

Poster sessions will be held at the designated time periods that can be found in the Conference Schedule shown on the inside of the cover sheet of this document. Presenters are expected to attend to their posters during the respective session only. The presenters of poster papers in morning are encouraged to post their papers at least half an hour prior to the beginning of their sessions, and remove them shortly after the end of their sessions.

Each poster presenter will be provided with a four feet by 5 feet (120 cm by 150 cm) poster mounting board.

Poster material must be legible from a distance of about six feet (about 2 meters). Lettering in text and figures should be at least 0.25" (6 mm) in height, and the poster titles should be in letters at least 1" ( 25 mm) high. The poster paper number will be mounted by Conference personnel on the top of poster boards.

## Instructions for Oral Presenters

Each oral presentation must be limited to 15 minutes. The oral presenters should arrange their presentations so that their presentation would take 12 – 13 minutes, leaving 2 – 3 minutes for questions. You are expected to notify the chair of your session of your presence 10 minutes before the start of the session so that the session chair knows that you are available. There will be no re-arrangement of papers within an oral session to accommodate absences or cancellations, therefore the time you have been assigned within the oral session is fixed. In case you must withdraw your paper from the program, please inform your session chair or one of the program chairs on site in the conference.

All oral presenters are required to submit an electronic version of their presentation by 5:00 PM 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 (Conference Room 9, on the same level as the Conference site). Acceptable media include CD and USB flashdrives. All presentations will be scanned for viruses before they are loaded on an computer for the following day's presentation. The meeting room where sessions take place will be equipped with an LCD projector, a computer and a screen. Presenters will not be allowed to use their own personal laptops. The laptops are not equipped to accommodate audio sounds.

Mac computers will NOT be available in any of the sessions. Authors using a Mac platform must ensure that their files are compatible with the PC environment.

Authors are strongly encouraged to bring to their session an additional electronic copy of their presentations (on a CD or USB flashdrive) for added security against any unanticipated software or hardware malfunctions.

A presenter who has failed to submit his/her presentation to the Publication Room by 5:00 PM of the day prior to his/her session may be required to present his/her paper without an accompanying presentation.

## Instructions for Paper Submission

Complete technical papers are due by 5 p.m. on the first full day of the conference, May 17th, in the Publication Room. Please bring the following:

- An electronic version on a CD or flash drive
- One print –ready hard copy
- Three additional hard copies for use by the technical reviewers

All papers will be peer reviewed for format and technical content prior to selection for publication in the conference proceedings, Cryocooler 16. Strict Adherence to the established format is required for consideration. In addition, ICC copyright Release Form must be completed, signed, and accompany your submitted manuscript for publication in the Proceedings of the International Cryocooler Conference. Copyright Form can be found through link below:

http://www.cryocooler.org/papers/index.php

# Session [T01]: Space Cryocooler Applications Tuesday, May 18, 2010 – Oral Session: 8:15 AM - 9:45 AM

**Co-Chairs:** **Jennifer Marquardt**, Ball Aerospace
**Paul Whitehouse**, NASA Goddard

**8:15 AM** **Cryocoolers for Microsatellite Military Applications [T01-A025]**
E. Pettyjohn
Air Force Research Laboratory, Albuquerque, NM, USA

**8:30 AM** **In Flight Performance of the Herschel Sorption Cooler – One Year of Operation [T01-A083]**
L. Duband, E. Ercolani, L. Guillement, M. Sauvage*, J. Martignac*, B. Swinyard†, D. Griffin†, C. Jewell‡, B. Collaudin**
CEA/INAC/Service des Basses Températures, Grenoble FR, *CEA/IRFU/Service d'Astrophysique, Saclay FR, †Rutherford Appleton Laboratory, STFC, Chilton, UK
‡ESA / ESTEC, Noordjwick, NL, **THALES Alenia Space, Cannes FR

**8:45 AM** **SPICA/SAFARI Subkelvin Cryogenic Chain [T01-A137]**
L. Duband, J. Duval*, N. Luchier*, S. d'Escrivant†
SBT CEA-GRENOBLE
*CEA/INAC/Service des Basses Températures, Grenoble FR
†CNES, Toulouse FR

**9:00 AM** **Progress in the development of the IXO 50 mK Sorption-ADR stage [T01-A143]**
J. Duval, N. Luchier, L. Duband, T. Tirolien*
CEA Grenoble, FR
*ESA, NL

**9:15 AM** **Multi-stage ADRs for Current and Future Astronomy Missions: Performance and Requirements for Cryogen-Free Operation [T01-A147]**
P. Shirron, M. Kimball, K. Vlahacos
NASA/GSFC, USA

**9:30 AM** **Design of the Cryogenic Sub-System for the LDCM Thermal Infrared Sensor [T01-A197]**
P. Whitehouse, V. Otero, M. Fetzer*, N. Clemons†, D. Neuberger‡, C. Henry†
NASA Goddard Space Flight Center, USA
*Bastion Technologies, USA, †Orbital Sciences Corporation, USA
‡Edge Space Systems, USA

# Session [TP2]: Terrestrial Cryocoolers
# Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

Co-Chairs: **Frank Miller**, NASA Goddard
**Greg Swift**, Los Alamos National Laboratory

9:45 AM **Development of re-condensing cryostat for PAMELA [TP2-A045]**
S. Pattalwar, T. Jones*, J. Strachan*, H. Witte†, N. Bliss*
ASTeC, STFC Daresbury Laboratory, UK
*STFC Daresbury Laboratory, UK
†John Adams Institute for Accelerator Science, Oxford, UK

9:45 AM **Performance Degradation of Cryocooler for Superconducting Magnet [TP2-A056]**
D. Dutta
Nuclear Physics Division, BARC,Mumbai-400085, India

9:45 AM **6 K Solid State Energy Storage and 60K Triple Point Energy Storage Unit [TP2-A077]**
R. Patricio, I. Catarino*, G. Bonfait*
Active Space Technologies
*FCT-University of Lisbon

9:45 AM **Low Vibration Cold-finger Stage for Pulse Tube and Gifford-McMahon [TP2-A121]**
M. Chase, A. Woidtke, I. Henslee
S2 Corporation, USA

9:45 AM **Experimental Study for Hydrogen AMR Cycle [TP2-A196]**
T. Numazawa, Y. Hirano*, H. Hattori*, M. Sobue†, K. Asamoto†, H. Nakagome‡, K. Matsumoto†
National Institute for Materials Science
*NIMS, Japan
†Kanazawa University, Japan
‡Chiba University, Japan

9:45 AM **Cryocooler Prognostic Health Management Systems (CPHMS) [TP2-A205]**
E. Sandt, B. Penswick, A. Shah, C. Dodson*, T. Roberts*
Sest, Inc., USA
*U. S. Air Force Research Laboratory

# Session [TP2]: Cryocooler Electronics
# Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

| | |
|---|---|
| Co-Chairs: | **Eric Marquardt**, Ball Aerospace<br>**Dave Harvey**, Northrop Grumman Aerospace Systems |
| 9:45 AM | **Drive Electronics for Moving Magnet Type Linear Motor Compressor [TP2-A040]**<br>R. Karunanithi, S. Jacob, A. Gour<br>Indian Institute of Science, Bangalore, India |
| 9:45 AM | **Automated Cryocooler Monitor and Control System [TP2-A048]**<br>M. Britcliffe<br>Jet Propulsion Lab, USA |
| 9:45 AM | **The Advantages of using a Digital Temperature Controller in a Miniature Stirling Cryogenic Refrigerator [TP2-A086]**<br>S. Ninbourg<br>Ricor Inc., Israel |
| 9:45 AM | **Self-Induced Vibration of NGAS Space Pulse Tube Coolers [TP2-A103]**<br>R. Colbert, T. Nguyen, J. Raab, E. Tward<br>Northrop Grumman, USA |
| 9:45 AM | **Design and Analysis of Power Controller for Moving Magnet Linear Motor Compressor [TP2-A141]**<br>S. Jacob, V. Ramanarayanan, R. Karunanithi, S. Prabhu<br>Indian Institute of Science, India |
| 9:45 AM | **Cryocooler Control Module for Next Generation IR Platforms [TP2-A162]**<br>J. Fessel<br>Cobham Mission Systems, USA |
| 9:45 AM | **Modular Linear-Drive Cryocooler Electronics [TP2-A202]**<br>C. Kirkconnell, J.Freeman<br>Iris Technology Corporation |

# Session [TO3]: Cryocooler Fundamentals
# Tuesday, May 18, 2010 – Oral Session: 10:45 AM- 12:00 PM

**Co-Chairs:** **Marcel ter Brake**, University of Twente
**Gershon Grossman**, Technion - Israel Institute of Technology

**10:45 AM** **Are P-V and T-S Diagrams Meaningful for Regenerative Cryocoolers? [T03-A046]**
P. Kittel
Consultant, USA

**11:00 AM** **Why High-Frequency Pulse Tubes Can Be Tipped [T03-A075]**
G. Swift, S. Backhaus
Los Alamos National Laboratory, USA

**11:15 AM** **Some Insights Into Stirling Machine Behavior [T03-A122]**
A. Tucker, M. Gschwendtner*, D. Haywood†
University of Canterbury, NZ
*TS-dot Engineering, NZ
†Avon River Engineering, NZ

**11:30 AM** **Cryocooler Performance and Mass vs. Operational Temperature: a Survey of the Open Literature for Pulse Tube and Stirling [T03-A165]**
D. Ladner
N-Science Corporation USA

**11:45 AM** **Study on minor Losses in Thermoacoustic Engines [T03-A131]**
Y. Chen*†, Y. Zhang†, W. Dai, E. Luo†
*Institute of Mechanics, China
†Chinese Academy of Sciences, China

# Session [T04]: JT Crycoolers
# Tuesday, May 18, 2010 – Oral Session: 1:30 PM - 3:00 PM

**Co-Chairs:** **Weibo Chen**, Creare Inc.
**John Brisson**, Massachusetts Institute of Technology

**1:30 PM** **Open Cycle Joule-Thomson Cryocooling by Mixed Coolants [T04-P035]**
B. Maytal
Rafael, Ltd., Israel

**1:45 PM** **Cooling Load Estimation for 80 K Mixed Refrigerant Joule-Thomson (MR J-T) Cooler [T04-P063]**
N. Walimbe, K. Narayankhedkar*, M. Atrey
Indian Institute of Technology Bombay, Mumbai, India, *VJTI Mumbai, India

**2:00 PM** **Progress in Joule-Thomson Microcooling at the University of Twente [T04-P094]**
M. ter Brake, P. Lerou*, H. Cao, H. Holland, D. Zalewski, A. Mudaliar, H. Derking, M. Garcia
University of Twente, NL, *Kryoz Technologies, NL

**2:15 PM** **35 K Variable Load Space Cryocooler Performance and Acceptance Testing [T04-P126]**
D. Glaister, W. Gully, P. Hendershot, C. Wilson, R. Levenduski*, J. Lester, E. Marquardt
Ball Aerospace, Boulder, CO, USA
*Redstone Engineering, USA

**2:30 PM** **14.5 K Hydrogen-Based Sorption Cooler: Design and Breadboard Tests [T04-P148]**
J. Burger, M. ter Brake, H. Holland, R. Meijer, D. Zalewski, A. Mudaliar, M. Linder*
University of Twente, NL
*European Space Agency, NL

**2:45 PM** **Modeling and Experimentation with a Pre-Cooled Mixed Gas Joule Thomson Cycle for Cryosurgery [T04-P163]**
H. Skye, S. Klein, G. Nellis
University of Wisconsin – Madison, USA

# Session [TP5]: Cryocooler Components & Integration Technologies
## Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

**Co-Chairs:** **Susan Breon**, NASA Goddard
**Jean-Marc Duval**, CEA Grenoble
**Sidney Yuan**, Aerospace Corp
**Ted Conrad**, Georgia Institute of Technology

**3:00 PM** **Pressure Drop Characteristics of Steady and Oscillating Flow in a Slit-type Heat Exchanger [TP5-P052]**
T. Ki, S. Jeong, M. Seo
Korea Advanced Institute of Science and Technology, Republic of Korea

**3:00 PM** **Theoretical and Experimental Investigation of Flow Straightners in U-type Pulse Tube Cryocooler [TP5-P058]**
A. Badgujar, M. Atrey
Indian Institute of Technology Bombay, Mumbai, India

**3:00 PM** **Effects of Heat Exchanger Configuration on Performances of the Joule-Thomson Refrigerator [TP5-P064]**
Y. Hong, S. Park, Y. Choi*
Korea Institute of Machinery and Materials, S. Korea
*Korea University, S. Korea

**3:00 PM** **CFD Simulation and Experimental Validation of a Diaphragm Pressure Wave Generator [TP5-P101]**
T. Huang, A. Caughley*, R. Young*
HTS-110 Ltd, NZ
*Industrial Research Ltd, NZ

**3:00 PM** **Low Temperature Adsorption Versus Pore Size in Activated Carbons [TP5-P142]**
D. Martins, I. Catarino, D. Lopes, I. Esteves,
J. Mota, G. Bonfait
Faculdade de Ciências e Tecnologia, UNL, Portugal

3:00 PM **Development of Moving Magnet Linear Motor Pressure Wave Generator for Pulse Tube Refrigerator [TP5-P153]**
S. Jacob, V. Ramanarayanan, R. Karunanithi, Damu C, Jagadish G, M. Achanur, Manjunatha R, S. Prabhu, A. Gaunekar*
Indian Institute of Science, India
*ASM Technology Singapore pte ltd, Singapore

3:00 PM **Continuously Variable Inertance Tubes [TP5-P166]**
J. Pfotenhauer, T. Steiner
University of Wisconsin – Madison, USA

3:00 PM **An Advanced Compressor for Turbo-Brayton Cryocoolers [TP5-P172]**
R. Hill, J. Hilderbrand, M. Zagarola
Creare Inc., USA

3:00 PM **Enhanced Helium Compressor Operation for Sensitive Measuring Instrumentation [TP5-P177]**
S. Spagna, T. Sayles, D. Martien, J. Diederichs, N. Manivannan, J. Sloan
Quantum Design, USA

3:00 PM **Study on 35K Regenerator Performance Operating at High Frequency [TP5-P184]**
Z. Gan
Zhejiang University, Hangzhou, China

3:00 PM **Low-Power 4 K Pulse Tube Cryocooler for Operation at Tilt Angles of up to 45" [TP5-P066]**
K. Allweins, W. Dong*, G. Thummes
TransMIT-Center for Adaptive Cryotechnology and Sensors, Germany
*Zhejiang University, Hangzhou, China

3:00 PM **Performance Test of Pulse Tube Cooler with Integrated Circulator [TP5-P124]**
J. Maddocks, P. Maddocks, A. Kashani
Atlas Scientific, USA

3:00 PM **Thermal Storage Unit Using the Triple Point of Hydrogen [TP5-P157]**
I. Charles, A. Coynel, C. Daniel*
CEA/DSM/INAC/SBT, France
*CNES, France

# Session [T06]: Cryocooler Modeling and Performance Investigation
# Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

**Co-Chairs:** **Ray Radebaugh**, NIST
**Alain Ravex**, Air Liquide

**4:00 PM** **Heat Transfer during Laminar Pulsating Flow in Porous Media [T06-P129]**
M. Pathak, S. Ghiaasiaan
Georgia Institute of Technology, USA

**4:15 PM** **Numerical Modeling on a Reciprocating Active Magnetic Regenerator Refrigeration [T06-P136]**
Jing LI*†, Takenori Numazawa*, Hideki Nakagome†, Koichi Matsumoto**
*National Institute for Materials Science, Japan
†Chiba University, Japan
**Kanazawa University, Japan

**4:30 PM** **Clearance loss analysis in linear compressor with CFD method [T06-P144]**
W. Zhou, Z. Gan, X. Zhang, L. Qiu
Zhejiang University, Hangzhou, China

**4:45 PM** **Measured and Calculated Performance of a High Frequency, 4 K Stage, He-3 Regenerator [T06-P150]**
I. Garaway, M. Lewis, P. Bradley, R. Radebaugh
National Institute of Standards and Technology, USA

**5:00 PM** **Regenerator Friction Factor and Nusselt Number Information Derived from CFD Analysis [T06-P173]**
M. Cheadle, G. Nellis, S. Klein
University of Wisconsin – Madison, USA

**5:15 PM** **Secondary Pulse Tubes and Regenerators for Coupling to Room-Temperature Phase Shifters in Multistage Pulse Tube Cryocoolers [T06-P182]**
R. Radebaugh, A. O'Gallagher, J. Gary
National Institute of Standards and Technology, USA

**5:30 PM** **Measurement and Correlation of Regenerator Hydraulic Resistance at Cryogenic Temperature [T06-P210]**
J. Cha, J. Harvey*
Aerospace Corp., USA
*Consultant, Houston TX, USA

# Session [WO1]: Cryocooler Integration Technologies
# Wednesday, May 19, 2010 – Oral Session: 8:00 AM – 9:30 AM

| | |
|---|---|
| Co-Chairs: | **David Glaister**, Ball Aerospace<br>**Mark Zagarola**, Creare Inc. |
| 8:00 AM | **Cryogenic Boil-Off Reduction System Test [W01-A118]**<br>D. Plachta, J. Feller, G. Mills*, C. Mclean*,<br>NASA Glen Research Center, Cleveland OH, USA<br>*Ball Aerospace Technologies & Corporation, Boulder CO, USA |
| 8:15 AM | **NASA TIRS Cryocooler Induced Vibration and Heat Rejection Mounting System [W01-A127]**<br>D. Glaister, W. Gully, P. Hendershot, C. Wilson, P. Whitehouse*<br>Ball Aerospace Technologies & Corporation, Boulder CO, USA<br>*NASA Goddard Space Flight Center, Greenbelt MD, USA |
| 8:30 AM | **Thermal Switching Cryogenic Heat Pipe [W01-A186]**<br>D. Bugby, ATK, Beltsville MD, USA |
| 8:45 AM | **Liquid Nitrogen Energy Storage Units [W01-A074]**<br>J. Afonso, I. Catarino, D. Martins, R. Patrício*, L. Duband**, G.Bonfait,<br>Faculdade de Ciências eTecnologia – UNL, Portugal<br>*Active Space Technologies, Portugal<br>**SBT-INAC-CEA, France |
| 9:00 AM | **Pulse Tube Cooler with Remote Cooling [W01-A115]**<br>J. Raab, J. Maddocks* T. Nguyen, G. Toma, R. Colbert<br>Northrop Grumman Aerospace Systems, Redondo Beach CA, USA<br>*Atlas Scientific, Palo Alto CA, USA |
| 9:15 AM | **A 2-K Active Magnetic Cooler for Remote Cooling of Space Instruments [W01-A169]**<br>W. Chen, J. McCormick, M. Zagarola<br>Creare Inc., Hanover NH, USA |

# Session [WP2]: Commercial Cryocoolers
# Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

**Co-Chairs:** **Ravi Bains**, Advanced Research Systems
**Richard Dausman**, Cryomech

**9: 30 AM** **Development of 2 stage GM-type pulse tube refrigerator for cryopump [WP2-A110]**
J. Ko, D. Koh, H. Kim, Y. Hong, H. Yeom, S. Park
Korea Institute of Machinery and Materials, Republic Of Korea

**9: 30 AM** **Analysis Of A Supercritical Hydrogen Liquefaction Cycle [WP2-A211]**
W. Staats, J. Brisson
Massachusetts Institute of Technology, Boston MA, USA

**9: 30 AM** **Concept of a powerful cryogen-free dilution refrigerator with separate 1K stage [WP2-A033]**
K. Uhlig
Walther-Meißner-Institute, Germany

# Session [WP2]: Small Scale Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

**Co-Chairs:** **Peter Bradley**, National Institute of Standards and Technology
**Chris Dodson**, Air Force Research Laboratory (AFRL/RVSS)

**9: 30 AM** **Development of a Miniature Fast Cool-Down JT Cryocooler [WP2-A082]**
N. Tzabar, I. Lifshits
Rafael Ltd., Israel

**9: 30 AM** **Analysis of multi-stage Joule-Thomson microcoolers [WP2-A151]**
H. Cao, P. Lerou*, A. Mudaliar, H. Holland, H. Derking, D. Zalewski, M. ter Brake
University of Twente, Netherlands
Kryoz Technologies, Netherlands

**9: 30 AM** **A STUDY OF A MINIATURE IN-LINE PULSE TUBE CRYOCOOLER [WP2-A097]**
S. Sobol, Y. Katz, G. Grossman
Technion - Israel Institute of Technology, Israel

**9: 30 AM** **Impact of Small Regenerator Structural Flaws on the Performance of Miniature Pulse Tube Cryocoolers [WP2-A199]**
T. Conrad, S. Ghiaasiaan, C. Kirkconnell*
Georgia Institute of Technology, Atlanta GA, USA
*Iris Technology Corporation, Irvine CA, USA

**9: 30 AM** **The Effect of Component Junction Tapering on Miniature Cryocooler Performance [WP2-A200]**
T. Conrad, S. Ghiaasiaan, C. Kirkconnell*
Georgia Institute of Technology, Atlanta GA, USA
*Iris Technology Corporation, Irvine CA, USA

# Session [WP2]: Space Cryocooler Applications
# Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

**Co-Chairs:** **Lionel Duband**, CEA-Grenoble
**Peter Shirron**, National Aeronautics and Space Administration (NASA)

**9:30 AM** **Wide-Field Infrared Survey Explorer Solid Hydrogen Cryogenic Support System [WP2-A189]**
B. Lloyd, S. Schick*
Space Dynamics Laboratory, North Logan UT, USA
*Practical Technology Solutions, Inc. North Logan UT, USA

**9:30 AM** **RESPONSIVE SPACE CRYOCOOLER CONSIDERATIONS [WP2-A026]**
E. Pettyjohn, T. Fraser
Air Force Research Laboratory AFRL/RVSS, Kirtland NM, USA

**9:30 AM** **Developments of 1-4K class space mechanical coolers for new generation satellite missions in JAXA [WP2-A155]**
K. Shinozaki, H. Sugita, Y. Satoh, K. Mitsuda, T. Nakagawa, R. Fujimoto*, K. Narasaki**, K. Kanao**, S. Tsunematsu**, K. Otsuka**
Japan Aerospace Exploration Agency, Japan
*Kanazawa University, Japan
**Sumitomo Heavy Industries Ltd., Japan

**9:30 AM** **Modified Methodology for Technology Forecasting: case study of cryocooler efficiency and induced vibration [WP2-A209]**
D. Webb, J. Cha, S. Yuan
The Aerospace Corporation, Los Angeles CA, USA

**9:30 AM** **Flight Hardware of the Cryogenic System for the Micro-X Sounding Rocket Telescope [WP2-A159]**
P. Wikus, J. Adams*, S. Bandler**, W. Doriese**, M. Eckart*, E. Figueroa-Feliciano, R. Kelley*, C. Kilbourne*, S. Leman, D. McCammon***, F. Porter*, J. Rutherford, S. Trowbridge
Massachusetts Institute of Technology, Boston MA, USA
*NASA Goddard Spaceflight Center, Greenbelt MD, USA
**National Institute of Science and Technology, Boulder CO, USA
***University of Wisconsin, Madison WI, USA

**9:30 AM Problems and general structure of cooling system of space cryotelescope Millimetron [WP2-A193]**

V. Vdovin, E. Baranov*, A. Baryshev**, I. Charles***, Y. Golovanov****, V. Il`in*, N. Kardashev, N. Myshonkova, O. Shilkin****, V. Troitsky*****, I. Vinogradov
ASC Lebedev PI RAS, IAP RAS, Russian Federation
*Scientific and technical complex "Cryogenic Technique" Ltd., Russian Federation
**SRON, Groningen, IRE RAS, Netherlands
***CEA, France
****JSC "Reshetnev" Information Satellite Systems", Russian Federation
*****Lebedev Physical Institute RAS, Russian Federation

# Session [WO3]: Tactical Cryocoolers
# Wednesday, May 19, 2010 – Oral Session: 10:30 AM – 12:00 PM

**Co-Chairs:** **Ted Nast**, Lockheed Martin Space Systems
**Alexander Veprik**, Ricor

**10:30 AM** **10 K Airborne Cryocooler and High Efficiency Heat Exchangers [W03-A125]**
D. Glaister, W. Gully, P. Hendershot, C. Wilson, E. Marquardt
Ball Aerospace Technologies & Corporation, Boulder CO, USA

**10:45 AM** **Life Testing of L-3 1.0-Watt Tactical Stirling Cryocooler for redundant space cooling application [W03-A179]**
M. Barr
Raytheon Space and Airborne Systems, El Segundo CA, USA

**11:00 AM** **THE DEVELOPMENT OF A NEW GENERATION OF MINIATURE LONG LIFE LINEAR COOLERS [W03-A022]**
W. Groep
Thales Cryogenics, Netherlands

**11:15 AM** **Reduction of Self Induced Vibration of Rotary Stirling Coolers [W03-A024]**
U. Binnun
FLIR Systems Inc., Boston MA, USA

**11:30 AM** **Methods for Reducing Self Induced Vibration in Rotary Stirling Tactical Coolers [W03-A047]**
U. Binnun
FLIR Systems Inc., Boston MA, USA

**11:45 AM** **STIRLING-CYCLE COOLER RELIABILITY GROWTH AT L-3 CE [W03-A123]**
D. Arndt, Q. Phan, D. Kuo
L-3 Communications, Pasadena CA, USA

# Session[W04]: Miniature Cryocoolers and Technologies
# Wednesday, May 19, 2010 – Oral Session: 1:30 PM – 3:00 PM

| | | |
|---|---|---|
| **Co-Chairs:** | **Isaac Garaway**, National Institute of Standards and Technology<br>**Robert Hon**, Raytheon Space and Airborne Systems | |
| **1:30 PM** | **Space Micro Pulse Tube Cooler [W04-P104]**<br>T. Nguyen, M. Petach, M. Michaelian, J. Raab<br>Northrop Grumman Aerospace Systems<br>Redondo Beach CA, USA | |
| **1:45 PM** | **Heat Rejection Capacity in Miniature Thermoacoustic Expanders (MTAEs) at Cryogenic Temperatures [W04-P050]**<br>Z. Hu, T. Roberts*<br>Cryowave Advanced Technology, Pawtucket, RI, USA<br>*Air Force Research Laboratory AFRL/RVSS, Kirtland NM, USA | |
| **2:00 PM** | **Miniature pulse tube cooler at 100Hz [W04-P112]**<br>H. Chen, N. Xu, L. Yang, J. Cai, J. Liang<br>Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, P.R. China | |
| **2:15 PM** | **Simulation of Boundary Layer Effects in the Pulse Tube of a Miniature Cryocooler [W04-P198]**<br>T. Conrad, S. Ghiaasiaan, C. Kirkconnell*<br>Georgia Institute of Technology, Atlanta GA, USA<br>*Iris Technology Corporation, Irvine CA, USA | |
| **2:30 PM** | **Compact linear split Stirling cryogenic cooler for high temperature infrared imagers [W04-P113]**<br>A. Veprik, S. Zehtzer, N. Pundak<br>Ricor, Cryogenic and Vacuum Systems, Israel | |

# Session [WP5]: Pulse Tube Cryocoolers & Thermoacoustic Coolers
# Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

**Co-Chairs:** **Sangkwon Jeong**, Korea Advanced Institute of Science and Technology (KAIST)
**Dean Johnson**, Jet Propulsion Laboratory (JPL)

**3: 00 PM** **SITP's Miniature Coaxial Pulse Tube Cryocooler [WP5-P069]**
H. Dang, L. Wang, Y. Wu
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, P.R. China

**3: 00 PM** **Investigation of Multi-bypass Pulse Tube Cryocooler with Precooling [WP5-P128]**
Y. Liu, L. Yang
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, P.R. China

**3: 00 PM** **Progress in the Development and Performance of a High Frequency 4 K Stirling-Type Pulse Tube Cryocooler. [WP5-P180]**
P. Bradley, R. Radebaugh, E. Gerecht
National Institute of Science and Technology, Boulder CO, USA

**3: 00 PM** **Influence of Ratio of Specific Heats on Thermoacoustic Performance [WP5-P039]**
H. Kang
Beijing Institute of Technology, China

**3: 00 PM** **Investigations on a Standing Wave Thermoacoustic Refrigerator [WP5-P060]**
R. Dhuley, M. Atrey
Indian Institute of Technology Bombay, Mumbai, India

**3:00 PM** **Design Of Standing Wave Type Thermoacoustic Prime Mover For 300 Hz Operating Frequency [WP5-P134]**
S. Mehta, K. Desai*, H. Naik*, M. Atrey**
Mech. Eng. Dept., L .D. College Of Engineering, Ahmedabad, Gujarat, India
*Mech. Eng. Dept., S. V. National Institute of Technology, Surat, India
**Indian Institute of Technology Bombay, Mumbai, India

**3:00 PM** **Improvements on a thermoacoustically-driven pulse tube cooler operating at 300 Hz [WP5-P139]**

G. Yu, X. Wang, W. Dai, E. Lou
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, P.R. China

# Session [WP5]: Cryocooler Modeling
# Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

**Co-Chairs:** **Peter Kittel**, Consultant
**Tanh Nyugen**, Northrop Grumman Aerospace Systems (NGAS)
**Ryan Taylor**, Virginia Military Institute (VMI)

**3:00 PM** **PHASOR ANALYSIS OF PULSE TUBE REFRIGERATOR [WP5-P061]**
M. Lokanath, M. Atrey
Indian Institute of Technology Bombay, Mumbai, India

**3:00 PM** **THEORETICAL AND EXPERIMENTAL INVESTIGATION OF 30 K SINGLE STAGE G-M TYPE PULSE TUBE CRYOCOOLER [WP5-P080]**
S. Desai, K. Desai*, H. Naik*, M. Atrey**
Mech. Eng. Dept., C. K. Pithawala College of Engineering, Surat, Gujarat, India
*Mech. Eng. Dept., S. V. National Institute of Technology, Surat, Gujarat, India
**Mech. Eng. Dept., Indian Institute of Technology Bombay, Mumbai, India

**3:00 PM** **Theoretical and experimental investigation on the temperature mismatch and its optimization of coaxial inertance pulse ? tube cryocoolers [WP5-P090]**
L. Wang, H. Dang, Y. Wu, S. Li, K. Yang, C. Xiong
Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

**3:00 PM** **CFD Simulation of Natural Convection in a Pulse Tube Cryocooler [WP5-P145]**
J. Ren, J. Hu, L. Zhang, E. Lou, Y. Huang
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, China

**3:00 PM** **Inertance Tube and Reservoir Modeling – Meshing, Convergence and Friction Factors for Oscillating Flow [WP5-P188]**
C. Dodson, A. Razani*, T. Roberts
Air Force Research Laboratory AFRL/RVSS, Kirtland NM, USA
*University of New Mexico, Albuquerque NM, USA

**3:00 PM** **Thermodynamic comparison of two-stage pulse tube refrigerators for two different configurations[WP5-P201]**
A. Razani, T. Fraser*, C. Dodson*, T. Roberts*
University of New Mexico, Albuquerque NM, USA
*Air Force Research Laboratory AFRL/RVSS, Kirtland NM, USA

**3:00 PM** **Effect of Frequency on Hydrodynamic Parameters of Mesh Fillers in Oscillatory Flow [WP5-P130]**

E. Landrum, T. Conrad, M. Pathak, S. Ghiaasiaan, C. Kirkconnell*, T. Crittenden**, S. Yorish**
Georgia Institute of Technology, Atlanta GA, USA
*Iris Technology Corporation, Irvine CA, USA
**Virtual AeroSurface Technologies, Atlanta, GA, USA

**3:00 PM** **Oscillating Flow and Heat Transfer in Porous Structure Regenerator in Pulse Tube Cryocooler [WP5-P140]**

X. Chang
Technical Institute of Physics and Chemistry, CAS, China

**3:00 PM** **Comparison of Thermoelectric and Stirling Type Cryocoolers Using Control Thermodynamic Model [WP5-P072]**

A. Razani, C. Dodson*, T. Roberts*
University of New Mexico, Albuquerque NM, USA
*Air Force Research Laboratory AFRL/RVSS, Kirtland NM, USA

**3:00 PM** **A study of temperature gradient inside the AMR bed at room temperature [WP5-P156]**

H. SAKAMOTO, S. UCHIMOTO, H. NAKAGOME, T. KOBAYASHI*, S. KAJI*, A. SAITO*
Chiba University, Japan
*Toshiba Corporation, Japan

**3:00 PM** **Investigation on the Phase Characteristics of High Frequency Inertance Pulse Tube Cryocoolers above 50 K [WP5-P087]**

S. Li, H. Dang, Y. Wu, L. Wang, K. Yang
Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

# Session [WO6]: Pulse Tube Cryocooler Analysis and Experiments Wednesday, May 19, 2010 – Oral Session: 4:00 PM – 5:30 PM

**Co-Chairs:** **Frank Roush**, Air Force Research Laboratory/RVSS
**Jeff Olson**, Lockheed Martin Space Systems

**4:00 PM** **Flow and Heat Transfer Processes in an Orifice type Pulse Tube Refrigerator [W06-P174]**
D. Antao, B. Farouk
Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia PA, USA

**4:15 PM** **EFFECT OF COMPONENT GEOMETRY ON FLOW NONUNIFORMITIES IN A LARGE PULSE TUBE CRYOCOOLER [W06-P175]**
M. Lewis, R. Taylor*, P. Bradley, R. Radebaugh
National Institute of Standards and Technology, Boulder CO, USA
*Virginia Military Institute, Lexington VA, USA

**4:30 PM** **Two-Dimensional Analysis and Optimization of an Inertance Tube Pulse Tube Refrigerator [W06-P095]**
R. Jahanbakhshi, M. Saidi, F. Roshanghalb
Sharif University of Technology, Tehran, Islamic Republic of Iran

**4:45 PM** **Second Law Based Analysis of High Frequency Two-Stage Pulse Tube Cryocoolers [W06-P119]**
A. Ghahremani, M. Saidi, A. Jafarian*
Sharif University of Technology, Tehran, Islamic Republic of Iran
*Tarbiat Modares University, Islamic Republic of Iran

**5:00 PM** **Performance Analysis of a Contoured Pulse Tube Refrigerator [W06-P167]**
M. Gholamrezaei,
Sharif University of Technology, Tehran, Islamic Republic of Iran

**5:15 PM** **Numerical Simulation of Heat and Fluid Interactionof a Contoured Pulse Tube Refrigerator [W06-P168]**
M. Gholamrezaei,
Sharif University of Technology, Tehran, Islamic Republic of Iran

# Session [THO1]: Single Stage Stirling/ Pulse Tube Cryocoolers
# Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

Co-Chairs: **Jeff Raab**, Northrop Grumman Aerospace Systems (NGAS)
**John Pfotenhauer**, University of Wisconsin
**Ercang Lou**, Technical Institute of Physics and Chemistry

8:00 AM **Performance Investigation on SITP's 60K High Frequency Single-stage Coaxial Pulse Tube Cryocoolers [TH01-A068]**
H. Dang, L. Wang, Y. Wu, S. Li, K. Yang
Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

8:15 AM **HEC Pulse Tube Coaxial Cold Head Coolers [TH01-A114]**
T. Nguyen, G. Toma, C. Jaco, M. Michaelian, J. Raab,
Northrop Grumman Aerospace Systems, Redondo Beach CA, USA

8:30 AM **Single-Stage Large Pulse-Tube Cooler for 50K, with Tapered Buffer Tube [TH01-A170]**
P. Spoor
CFIC Inc., Troy NY, USA

8:45 AM **Development of SITP's Large Capacity High Frequency Coaxial Inertance Pulse Tube Cryocoolers [TH01-A070]**
H. Dang, Y. Wu, L. Wang, S. Li, K. Yang
Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

9:00 AM **A 100 Hz pulse tube cryocooler working at liquid nitrogen temperature [TH01-A78]**
J. Hu, X. Wang, L. Zhang, W. Dai, E. Luo
Technical Institute of Physics and Chemistry, CAS, China

9:15 AM **Performance of a Stirling-type Pulse Tube Cooler for high efficiency operation at 100Hz [TH01-A138]**
X. Wang, W. Dai, J. Hu, E. Luo, Y. Zhou
Technical Institute of Physics and Chemistry, CAS, China

9:30 AM **Experimental Investigation on a Single-stage Stirling-type Pulse Tube Cryocooler Working around 30 K [TH01-A183]**
J. Ren, W. Dai, E. Luo, J. Hu, X. Wang
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, China

# Session [THO2]: Single Commercial Industrial Cryocooler and Applications Thursday, May 20, 2010 – Oral Session: 10:15 AM – 11:30 AM

**Co-Chairs:** **Ali Kashani**, Atlas Scientific
**Paul Bailey**, University of Oxford

**10:15 AM** **Development of High Efficiency 4K Two-Stage Pulse Tube Cryocooler [THO2-A030]**
M. Xu, H. Takayama, K. Nakano
Sumitomo Heavy Industries Ltd., Japan

**10:30 AM** **An oil-free DC compressor for GM type cold heads [THO2-A043]**
A. Caughley
Industrial Research Ltd., New Zealand

**10:45 AM** **Experimental study of Active Magnetic Regenerator (AMR) composed of spherical GdN [THO2-A195]**
Y. Hirayama, H. Okada, T. Nakagawa, T. Yamamoto, T. Kusunose, T. Numazawa*, M. Koichi**, T. Irie***, E. Nakamura***
Osaka University, Japan
*National Institute for Materials Science, Japan
**Kanazawa University, Japan
*** SANTOKU Corporation, Japan

**11:00 AM** **Development of a High Frequency Pulse Tube for an HTS Magnet [THO2-A133]**
N. Emery, A. Caughley, N. Glasson, A. Tucker*, M. Gschwendtner**
Industrial Research Ltd, New Zealand
*University of Canterbury, New Zealand
**TS-dot Engineering Ltd, New Zealand

**11:15 AM** **Dynamic operation of 4 K pulse tube cryocooler with an inverter driven compressor [THO2-A116]**
C. Wang
Cryomech, Syracuse NY, USA

# Session [THO3]: Multi-stage Stirling and Pulse Tube Cryocoolers
# Thursday, May 20, 2010 – Oral Session: 1:00 PM - 2:15 PM

**Co-Chairs:** **Willy Gully**, Ball Aerospace
**Chao Wang**, Cryomech, Inc.

**1:00 PM** **Application of New Figures Of Merit for Multi-Stage Cryocoolers [TH03-P120]**
J. DELMAS, A. Kadin, R. Webber, E. Track
Hypres Inc., USA

**1:15 PM** **A Three-stage Stirling Pulse Tube Cryocooler Approaching 4 K [TH03-P146]**
Q. Cao, L.M. Qiu, Z.H. Gan, Y.B. Yu
Zhejiang University, Hangzhou, China

**1:30 PM** **Vibration-Free, Hybrid Cryocooler for 4 K Space Applications [TH03-P171]**
M. Zagarola, W. Chen
Creare Inc., USA

**1:45 PM** **Performance of the 4 K Stage in a High Frequency, Pulse Tube Cryocooler Incorporating a Room Temperature Phase Shifter [TH03-P178]**
P. Bradley, M. Lewis, I. Garaway, R. Radebaugh
National Institute of Standards and Technology, USA

**2:00 PM** **Experimental Investigations on 20 K Stirling–type Two–Stage Pulse Tube Cryocooler with Inline Configuration [TH03-P062]**
M. Tendolkar, K. Narayankhedkar*, M. Atrey
Indian Institute of Technology Bombay, Mumbai, India
*VJTI Mumbai, India

# Session [TH04]: Space Cryocoolers
# Thursday, May 20, 2010 – Oral Session: 2:45PM - 4:15 PM

**Co-Chairs:** **Carl Kirkconnell**, Iris Technology
**Erin Pettyjohn**, Air Force Research Laboratory/RVSS

**2:45 PM** **Pulse Tube Cryocoolers Development and Qualification for Space Applications [TH04-P117]**
A. Ravex
Air Liquide, France

**3:00 PM** **Experimental Results of 15 K Pulse Tube Cold Fingers for Space Applications [TH04-P154]**
J. Duval, I. Charles, A. Coynel, A. Gauthier
CEA Grenoble, France

**3:15 PM** **MIRI Cooler System Design Update [TH04-P181]**
J. Lin, D. Durand, M. Petach, M. Michaelian
Northrop Grumman, USA

**3:30 PM** **Raytheon Low-Temperature RSP2 Cryocooler Design, Fabrication and Test [TH04-P185]**
R. Hon, J. Shrago, M. Ellis, B. Schaefer
Raytheon Space and Airborne Systems, USA

**3:45 PM** **Very High Capacity Aerospace Cryocooler [TH04-P190]**
J. Olson, P. Champagne, E. Roth, J. Mix, T. Nast
Lockheed Martin Space Systems Company, USA

**4:00 PM** **AIM Space Cryocooler Programs [TH04-P206]**
M. Mai
AIM Space Cryocooler Programs, Germany

# SESSION- TO1 [Oral]: Space Cryocooler Applications Tuesday, May 18, 2010 – Oral Session: 8:15 AM- 9:45 AM

## [TO1-A025]

## Cryocoolers for Microsatellite Military Applications

E. Pettyjohn
Air Force Research Laboratory, Albuquerque, NM, USA

Space qualified cryocoolers have beevively developed for large military and commercial satellite electro-optical (EO) infrared (IR) missions, but not so for microsatellites due to the complexity of the thermodynamics and fluid mechanics of the mechanical refrigeration system. The trend in military responsive space programs is leaning towards microsatellites that are cheaper and faster to build and launch. No longer can cryocoolers take 3-5 years to develop at a cost of millions. Therefore solutions to the cryogenic needs for microsatellites are presented through research into the thermodynamic processes. Discussions will include efficiency improvements to reduce the size, weight and power constraints of space qualified cryocoolers, as well as current state-of-the-art cryocoolers that meet the needs of military microsatellites.

# SESSION- TO1 [Oral]: Space Cryocooler Applications Tuesday, May 18, 2010 – Oral Session: 8:15 AM- 9:45 AM

## [TO1-A083]

## In Flight Performance of the Herschel Sorption Cooler – One Year of Operation

L. Duband, E. Ercolani, L. Guillement, M. Sauvage*, J. Martignac*, B. Swinyard†, D. Griffin†, C. Jewell‡, B. Collaudin**
CEA/INAC/Service des Basses Températures, Grenoble FR
*CEA/IRFU/Service d'Astrophysique, Saclay FR
†Rutherford Appleton Laboratory, STFC, Chilton, UK
‡ESA / ESTEC, Noordjwick, NL **THALES Alenia Space, Cannes FR

Herschel, the fourth 'cornerstone' mission in the ESA science programme, was launched on 14 May 2009 from Kourou French Guyana. With a 3.5 m Cassegrain telescope it is the largest space telescope ever launched. Herschel is performing photometry and spectroscopy in the range of approximately 55-672 µm. This bridges the gap between earlier infrared space missions and ground-based facilities. Herschel's payload consists of three instruments built by international scientific consortia: HIFI (Heterodyne Instrument for the Far Infrared), PACS (Photoconductor Array Camera & Spectrometer) and SPIRE (Spectral and Photometric Imaging REceiver). Two of these instruments, SPIRE and PACS, use bolometric detectors cooled to 300 mK. The Herschel cryogenic sub-system relies on passive cooling for both the cryostat & telescope down to liquid nitrogen temperatures, and features a 2367 liters superfluid helium tank venting to space which provides the instruments with 4 interface temperatures between 15K and 1.6 K. Two dedicated sorption coolers are then used to lower the PACS and SPIRE bolometer temperatures to below 300 mK. These units are single shot devices and need to be recycled on a regular basis. Their typical hold time is over 48 hours for less than 2 hours recycling. Over 50 re-cycles have already been successfully performed and the performance of the coolers are stable and fully in line with predictions. At the time of the conference these systems will have been in operation for approximately a year. The paper will describe the cooler operations, performances, and the interfaces with the Herschel cryogenic sub-system.

# SESSION- TO1 [Oral]: Space Cryocooler Applications Tuesday, May 18, 2010 – Oral Session: 8:15 AM- 9:45 AM

## [TO1-A137]

## SPICA/SAFARI Sub-kelvin Cryogenic Chain

L. Duband, J. Duval*, N. Luchier*, S. d'Escrivant†
SBT CEA-GRENOBLE
*CEA/INAC/Service des Basses Températures, Grenoble FR
†CNES, Toulouse FR

SPICA, a Japanese led mission, is part of the JAXA future science program and is planned for launch in 2018. SPICA will perform imaging and spectroscopic observations in the 5 to 210 mm waveband. The SPICA payload features three instruments, one of which SAFARI is developed by a European based consortium.SPICA's distinctive feature is to use an actively cooled telescope down to 4K. In addition SPICA is a liquid cryogen free satellite and all the cooling will be provided by radiative cooling (L2 orbit) down to 30 K and by mechanical coolers for lower temperatures.The satellite will be launch warm and slowly bring to its operating temperatures once in orbit. This warm launch approach allows to suppress any large liquid cryogen tank and to use the mass saved to launch a large diameter telescope (3.5 meters). This 4K cooled telescope allows to significantly reduce its own thermal radiation, offering superior sensitivity in the infrared region.The cryogenic system that enables this warm launch/ cooled telescope concept is a key issue of the mission. This cryogenic chain features a number of cooling stages comprising passive radiators, Stirling coolers and several Joule Thomson loops, offering cooling powers at typically 20, 4.5, 2.5 and 1.7 K.The SAFARI detectors require cooling to temperatures as low as 50 mK and thus the SAFARI instrument cooler will be operated from these heat sinks. It is composed of a small demagnetization refrigerator (ADR) pre cooled by a sorption cooler. This hybrid architecture allows to design a low weight cooler able to reach 50 mK. Because the sorption cooler is probably the lightest solution to produce sub-Kelvin temperatures, it allows the stringent SAFARI mass budget to be met. This paper discusses this concept and present preliminary results.

# SESSION- TO1 [Oral]: Space Cryocooler Applications Tuesday, May 18, 2010 – Oral Session: 8:15 AM- 9:45 AM

## [TO1-A143]

## Progress in the development of the IXO 50 mK Sorption-ADR stage

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The nominal temperature of the new generations of detectors for the next space mission IXO is expected to be around 50 mK. The coupling of a helium 3 cooler with an ADR provides an elegant cooler in this temperature range with low mass and few interfaces. As part of an ESA contract to develop such a solution, we designed an efficient assembly based on two thermal interfaces at 15 K and at 2.5 K. The cooler is sized to provide simultaneously net heat lifts of 1 μW at 50 mK and 10 μW at 300 mK for an autonomy exceeding 24 hours. The design of an engineering model is presented, as well as experimental results showing the cooling capacity at 50 mK with an ultimate temperature of 20 mK. The influence of the interface parameters are discussed together with different cycling scenario possibility.

# SESSION- TO1 [Oral]: Space Cryocooler Applications Tuesday, May 18, 2010 – Oral Session: 8:15 AM- 9:45 AM

## [TO1-A147]

## Multi-stage ADRs for Current and Future Astronomy Missions: Performance and Requirements for Cryogen-Free Operation

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The cooling requirements for current (e.g. Astro-H) and future (e.g. IXO and ASP) astronomy missions pose significant challenges for the sub-Kelvin cooler. In particular, the use of large detector arrays increases the cooling power needed, and the variety of cryocoolers that can be used for pre-cooling greatly expands the range of temperatures at which the sub-Kelvin cooler can be designed to reject heat. In most cases, there is also a need for a stable higher temperature stage for cooling amplifiers or telescope components. NASA/GSFC is currently building a 3-stage ADR for the Astro-H mission, and is developing a 5-stage ADR suitable for IXO and ASP, as well as many other missions in the early planning stages. The architecture of these ADRs allows them to be adapted rather easily for different cooling requirements and to accommodate different cryocooler capabilities (operating temperature and cooling power). This paper will discuss the performance of these ADRs, which operate in both continuous and single-shot cooling modes, and the minimum cryocooler capabilities needed to meet the requirements of future missions.

# SESSION- T01 [Oral]: Space Cryocooler Applications Tuesday, May 18, 2010 – Oral Session: 8:15 AM- 9:45 AM

## [T01-A197]

## Design of the Cryogenic Sub-System for the LDCM Thermal Infrared Sensor

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The Thermal Infrared Sensor (TIRS) is a thermal imager to provide two-channel thermal band data for the Landsat Data Continuity Mission (LDCM). Three QWIP arrays on the Focal Plane Assembly (FPA) are cooled below 43 K by the cold stage of a Ball Aerospace SB-235E two-stage Stirling cryocooler. The mid-stage of the cryocooler is used to cool an inner radiation shield and also provides a heat sink for the FPA isolation support system and signal harness. A description is given of the Cryogenic Sub-System (CSS) being designed at the Goddard Space Flight Center to control the cryogenic and contamination environment of the FPA.

# SESSION- TP2 [Poster]: Terrestrial Cryocoolers Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A045]

## Development of re-condensing cryostat for PAMELA

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PAMELA is a compact proton accelerator proposed for the development of cancer therapy using proton and carbon beams. The accelerator utilises FFAG technique using specific combination of superconducting magnets which form dipoles, quadrupoles, sextupoles and octupoles for steering the ion beam. PAMELA will consist of 12 cryostats, each with three sets of the superconducting magnets, having large bore of 246 mm. We propose to develop these cryostats using the re-condensing technology with the help of closed cycle cryocoolers. Several issues arise, mainly due to the complex combination of superconducting magnets and associated current leads. In this paper we address some of the key cryogenic issues and our approach to design an appropriate cryostat.

# SESSION- TP2 [Poster]: Terrestrial Cryocoolers
# Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A056]

## Performance Degradation of Cryocooler for Superconducting Magnet

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Quench is a phenomenon often seen in superconductors used for making superconducting magnets, superconducting cavities and other devices using superconductivity. Once initiated, quench may propagate and may result in helium dry-out when LHe is the cooling medium. Besides having the advantages of simplicity, compactness and efficiency, cryogenic liquid free cryocooler cooled superconducting magnets find wider acceptance as such system does not suffer from the said phenomena of `quench' that may result in helium dry-out if early detection is absent. It has been observed that the cooling capacity of closed cycle cryocoolers gets degraded in presence of magnetic field. This is mainly due to (a) regenerator not performing well in presence of magnetic field and (b) performance of electric motor driving the cryocooler is affected in presence of magnetic field. These aspects are required to be looked after when cryocoolers are preferred for applications like superconducting magnet cooling. The paper examines the degradation of cooling capacity of a two stage 4K cryocooler in presence of magnetic field.

# SESSION- TP2 [Poster]: Terrestrial Cryocoolers Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A077]

## 6 K Solid State Energy Storage and 60K Triple Point Energy Storage Unit

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Active Space Technologies
*FCT-University of Lisbon

A cryogen-free cold source for temperature below 6 K without mechanical, thermal and electromagnetic perturbations would be welcome in many sensitive applications. This article describes such a device (Energy Storage Unit-ESU) built to store 36 J between 3 K and 6 K. This ESU consists of a solid state enthalpy reservoir connected to a cryocooler by a heat switch. Its different parts as well as the experimental results are presented. The choice of Gd2O2S (GOS) as high specific heat solid material for the enthalpy reservoir is discussed. Tests in different conditions were performed. A very good agreement was found between the experimental data and those predicted using the heat switch characteristics and the specific heat measurements of the GOS used in this experimental set-up. A stable 6 K temperature was maintained during more than 50 minutes in a completely silent environment. A semi-continuous operation for this cold source was successfully tested during 2.5 hours. Further, we experimentally demonstrate a system storing energy between 60 K and 80 K using N2 as working fluid. The inconvenient of such a system is its temperature drift. The use of a liquid-gas system maintaining a constant temperature by pressure control presents some advantages: the constraint to work at the triple point disappears and then the working temperature can be a priori chosen.

# SESSION- TP2 [Poster]: Terrestrial Cryocoolers Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A121]

## Low Vibration Cold-finger Stage for Pulse Tube and Gifford-McMahon

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A vibration isolation system for either Pulse Tube or Gifford-McMahon closed-cycle cryocoolers has been developed and improved upon. The cold-finger mounted stage provides vibration reduction, to levels less than 70 nanometers over 1Hz – 10kHz frequency range, with a base temperature of ~3.0K. The device offers sample access via removal of two easily accessible plates. 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. Vibration and thermal data have been collected on both the Sumitomo SHI RDK-101D and a Cryomech PT-405. The robust vibration isolation module has been designed to fit most commercial cryocoolers and can be operated outside of lab environments; expanding the applications and capabilities of current systems. This device is a result of a multi-year engineering effort to enable S2 Corporation's photonic signal processing technology, with other applications of superconducting electronics, quantum computing, and spectroscopic research, where a low vibration environment is required.

# SESSION- TP2 [Poster]: Terrestrial Cryocoolers Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A196]

## Experimental Study for Hydrogen AMR Cycle

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Magnetic refrigeration based on the magnetocaloric effect of solid materials has the potential to achieve high thermal efficiency. We have been developing a magnetic refrigerator for hydrogen liquefaction, which cools down hydrogen gas from liquid nitrogen temperature and liquefies at 20 K. This system consists of two magnetic refrigerators; the liquefaction stage with a high efficient Carnot cycle and an active magnetic regenerator (AMR) device that should be used to pre-cool the hydrogen gas. In this study, we will show the experimental results for AMR cycle for higher temperatures typically 30-70 K. For the AMR stage, rare earth intermetallic compounds RT2 (R: rare earth; T: Al, Ni, Co) have been investigated. The experimental apparatus consists of a magnetic refrigerant, superconducting magnet with a maximum field of 4 T and 300 mm bore cooled by mechanical cooler, two electric motors that give field change to magnetic refrigerant and gas flow independently. This test machine operated the AMR cycle with the temperature span higher than 10 deg. We also have conducted numerical cycle analysis of the multilayered AMR bed and multistage AMR cycle will be analyzed.

# SESSION- TP2 [Poster]: Terrestrial Cryocoolers Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A205]

## Cryocooler Prognostic Health Management Systems (CPHMS)

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*U. S. Air Force Research Laboratory

The use of cooled sensors in ever more complex, integrated applications has made determination of the cryocooler and related component "health or remaining reliable useful life" a critical factor in successfully meeting mission requirements. Sest Inc. has been actively developing a Cryocooler Prognostic Health Management System (CPHMS) under US Air Force sponsor ship to address this issue. Using non-invasive means to measure performance of cryocooler with limited data availability, a variety of failure mechanisms have been evaluated based on a combination of "physics of failure" assessments as well as the results of extensive cryocooler testing carried out on "healthy" and selectively "degraded" cryocoolers. Used in conjunction simple models of the fundamental dynamic behavior of linear drive free-piston systems it is possible to identify the presence and type of potential degradation mechanisms. For a diagnostic system, identifying that a problem exists is half the battle. In the CPHMS with the results from the earlier diagnostic evaluation available, it is possible to carry out prognostic estimation of estimating the remaining life via the use of Bayesian statistics. The latter are used to continuously improve the estimations of reliable remaining useful life for the cryocooler under various failure modes. While the CPHMS is focused on "tactical" class cryocooler the basic approach is easily adapted to other cryocooler types as well as more complex integrated systems.

# SESSION- TP2 [Poster]: Cryocooler Electronics Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A040]

## Drive Electronics for Moving Magnet Type Linear Motor Compressor

R. Karunanithi, S. Jacob, A. Gour
Indian Institute of Science, Bangalore, India

An inexpensive drive circuit to operate a moving magnet type linear motor compressor up to 100 W power is described in this paper. It is a PWM based circuit with provisions to adjust the frequency and modulation index of the sine wave, frequency of the carrier wave, etc. It is a simple circuit without any need for software development as discrete electronic components are used in the circuit without the use of any microcontroller. Power MOSFETs are used in the H bridge circuit for driving the linear motor with opto-coupler isolation to eliminate the EMI interference from the motor to the gate circuit. The required logic states are generated using flip-flop and the PWM wave form is generated using off-the-shelf operational amplifiers. The circuit is designed to operate with D.C. power supplies of ±5V and +12V. Hence, it can be conveniently operated with the SMPS of Pentium IV computer. This way, the need for developing specialized D.C. power supply for the electronics is avoided. The developed circuit is capable of providing up to 100 W power to drive a single compressor. With suitable modifications, it can be adapted to operate dual opposing compressors of each 100W. The circuit design, schematic, working principle of the circuit and the performance are discussed in this paper.

# SESSION- TP2 [Poster]: Cryocooler Electronics Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A048]

## Automated Cryocooler Monitor and Control System

M. Britcliffe
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This article describes an automated cryogenic control system developed to monitor and control the operation of small-scale crycoolers. The system was designed to automate cryogenically cooled low-noise-amplifier systems used in the NASA Deep Space Network (DSN). It automates the entire operation of the system including cool down, warm-up and performance monitoring. The system is based on a single board computer with custom software and hardware to monitor and control the cryogenic operation of the system. The system provides local display and control and can be operated remotely with a web interface. The system utilized in the DSN reduces the mean time to return to service by a factor of two. The system can be used for many other small scale cryogenic cooler application including electronic cooling, medical imaging and cryopumps.

# SESSION- TP2 [Poster]: Cryocooler Electronics Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A086]

## The Advantages of using a Digital Temperature Controller in a Miniature Stirling Cryogenic Refrigerator

S. Ninbourg
Ricor Inc., Israel

Modern Infra-Red (IR) night-vision thermal imagers for reconnaissance, surveillance, recognition and targeting rely mostly on Stirling-cycle cryogenic refrigerators thanks to their high thermodynamic efficiency. Traditionally, linear cryogenic refrigerators comprised analog temperature controllers for controlling the cold-tip temperature and controlling the desire frequency. These controllers usually consist operational amplifiers, comparators, resistors and capacitors. The fine-tuning of the pre-set cold-tip temperature and the desire cooler frequency where achieved by setting potentiometers to a certain resistance. It is known that potentiometers are affected by environmental temperature variations, continuous exposure to extreme temperatures, and aging. Another aspect of using a potentiometer is the difficulty for the customer to change the pre-set cold tip temperature and frequency. Using potentiometer to reach wide operation set point temperature means potentiometer with high resistance with less accuracy, means less accuracy set point. Even without the use of potentiometers, the accuracy and stability of the analog components are not sufficient for the increasing requirements of advanced IR detectors at various environmental temperatures, loads, and input voltages. Moreover, manufacturers of cryogenic refrigerators could improve the reliability and traceability of their products by adding various functions to the controllers. A digital temperature controller that is based on a highly integrated flash MCU could serve both goals: improve the accuracy of the cold-tip temperature and accuracy of the desire frequency, and provide with extra features aimed at improving the functionality and reliability of the refrigerators. This paper describes the various functions and advantages of the K527 Sine digital temperature controller that was developed in RICOR Vacuum and Cryogenic Systems.

# SESSION- TP2 [Poster]: Cryocooler Electronics Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A103]

## Self-Induced Vibration of NGAS Space Pulse Tube Coolers

R. Colbert, T. Nguyen, J. Raab, E. Tward
Northrop Grumman Aerospace Systems, USA

Space cryocoolers are often used to cool the focal planes and optics of telescopes. Since telescope and focal plane jitter can affect the clarity of the image, space cryocoolers are designed for inherent low vibration. For very sensitive applications, many cryocooler systems incorporate active vibration control in addition to passive isolation from their mounting structures. The sole moving parts in all the NGAS pulse tube coolers, whether one, two or three stage, are the moving compressor pistons and their flexure supports that are inherently balanced in a back to back configuration. To further reduce the vibration below this already very low level, all the cooler systems are provided with single axis active control on the drive axis of the compressor that contains the moving piston masses. The cryocooler control electronics takes a signal from an accelerometer mounted parallel to the drive axis and feeds it back to the compressor motor drive signals to further reduce the vibration by >40dB. In this paper we present the self-induced vibration measurements made on a number of NGAS flight coolers including the single stage HEC cooler with either linear or coaxial cold heads, a micro cooler and the much larger capacity HCC cooler. We also present self-induced vibration measurements for the simultaneous operation of two HEC coolers mounted to the same platform.

# SESSION- TP2 [Poster]: Cryocooler Electronics Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A141]

## Design and Analysis of Power Controller for Moving Magnet Linear Motor Compressor

S. Jacob, V. Ramanarayanan, R. Karunanithi, S. Prabhu
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Permanent magnet linear motors (PMLM) are widely used in the manufacturing of pulse tube refrigerators. In this paper, we discuss the design and analysis of power controller used to drive the twin moving magnet linear motors used in the pulse tube refrigerator. The microcontroller dsPIC6010A drives two single phase H-bridge inverters which are used to drive the twin motors. Pulse width modulated (PWM) technique is implemented to drive the inverter circuit. By varying the duty cycle of the PWM wave the voltage amplitude can be varied and the output frequency of the inverter can be varies by varying the carrier frequency of the PWM modulator. The phase difference between the two inverters can also be varied. This is used to synchronize the twin motors and overcome any existing phase difference between the mechanical outputs. Variation in performance of the PMLM caused by the variation in the applied voltage and frequency is illustrated. Simple PWM modulation, trapezoidal PWM modulation and sine-triangle PWM modulation techniques are implemented by controller programming. Motor performances for these modulation techniques are discussed. It is also shown that the current wave form contains fewer harmonic in case of sine-triangular modulation.

# SESSION- TP2 [Poster]: Cryocooler Electronics Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A162]

## Cryocooler Control Module for Next Generation IR Platforms

J. Fessel
Cobham Mission Systems, USA

This paper describes the development and performance of a new tactical Cryocooler Control Module (CCM) at Carleton Life Support Systems, Inc. (CLSS) of Davenport, Iowa. The CCM aims to satisfy requirements of new Forward Looking Infrared (FLIR) systems. This next generation CCM builds upon existing CLSS technology and adds new digital control algorithms which allow for more accurate temperature control, more efficient power conversion, and adds provisions for system level communication and prognostic health monitoring. The CCM has improved the control for the Focal Plane Array (FPA) temperature and can regulate the temperature within ±0.1K. The CCM also introduces an option for an all digital control loop via the system RS422 communication bus in addition to the traditional current source feedback. The RS422 bus is also used to communicate many other parameters monitored by the CCM that can be used to track the health of the system. These parameters include expander temperature, compressor temperature, input voltage and current, output power and operation time. The CCM also adds reprogramming capabilities via the RS422 communication bus, which allows for software upgrades without requiring removal of the device from the system. The CCM is capable of outputting 75W of power and has a package size of 1.75"x2.00"x0.90".

# SESSION- TP2 [Poster]: Cryocooler Electronics Tuesday, May 18, 2010 – Poster Session: 9:45 AM- 10:45 AM

## [TP2-A202]

## Modular Linear-Drive Cryocooler Electronics

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Iris Technology Corporation

The Modular Advanced Cryocooler Electronics (MACE) system developed at Iris Technology Corporation combines configurable, high-power motor drives with precision telemetry capability in a design that is amenable to radiation hardening. A Telemetry Aggregation Unit (TAU) located near the cryocooler minimizes attenuation and contamination of sensitive cryocooler feedback by digitizing sensor data locally for transport back to the controller, while multiple 500W drive channels supply power waveforms at up to 96% efficiency. The modular design concept allows adding drive cards in the event that additional channels are required or removing drive cards to reduce size, weight, and power. The TAU incorporates up to 14 external sensors with an aggregate data rate of up to 800k samples per second, dynamically allocated to any combination of telemetry by the control software. A low cost version of the electronics can be realized by populating commercial components, or by utilizing an alternate control scheme to reduce the cost of radiation-hard controller components. A brassboard demonstration was performed at Raytheon in which the High Capacity RSP2 cryocooler was driven, with temperature and vibration control loops closed at high power and low cryogenic temperatures. This paper will discuss the MACE development, testing, and lessons learned.

# SESSION- TO3 [Oral]: Cryocooler Fundamentals Tuesday, May 18, 2010 – Oral Session: 10:45 AM- 12:00 PM

## [TO3-A046]

## Are P-V and T-S Diagrams Meaningful for Regenerative Cryocoolers?

P. Kittel
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P-V and T-S diagrams are a common tool used to illustrate thermodynamic cycles. For recuperative cycles, it is easy to idealize a cycle so that the history of a gas element can be traced on P-V and T-S diagrams as it flows around the machine. In such cycles, dead volumes such as accumulators, reservoirs, and head space in piston compressors and expanders are not fundamental to the operation. However, such dead volumes do have practical purposes in controlling pressure variations in recuperative coolers. Regenerative cryocoolers also have dead volumes, which include the void volumes in heat exchangers, regenerators, and pulse tubes. Because of these volumes, gas elements do not traverse all components of the cooler. Rather, it is possible that an element remain in a single component. For the Stirling cycle, P-V and T-S diagrams can be constructed if the void volumes are ignored. However, what happens in a pulse tube cooler where the volumes of the pulse tube, inertance tube, and reservoir are fundamental to the coolers operation? P-V and T-S diagrams can still be constructed if they are reinterpreted to represent the envelope of the motion of all possible gas elements. This approach will be explored here.

# SESSION- TO3 [Oral]: Cryocooler Fundamentals Tuesday, May 18, 2010 – Oral Session: 10:45 AM- 12:00 PM

## [TO3-A075]

## Why High-Frequency Pulse Tubes Can Be Tipped

G. Swift, S. Backhaus
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The typical low-frequency pulse-tube refrigerator loses significant cooling power when it is tipped with the pulse tube's cold end above its hot end, because natural convection in the pulse tube loads the cold heat exchanger. Yet most high-frequency pulse-tube refrigerators work well in any orientation with respect to gravity. In such a refrigerator, natural convection is suppressed by sufficiently fast velocity oscillations, via a nonlinear hydrodynamic effect that tends to align the density gradients in the pulse tube parallel to the oscillation direction. Since gravity's tendency to cause convection is only linear in the pulse tube's end-to-end temperature difference while the oscillation's tendency to align density gradients with oscillating velocity is nonlinear, it is easiest to suppress convection when the end-to-end temperature difference is largest. Simple experiments demonstrate this temperature dependence, the strong dependence on the oscillating velocity, and little dependence on the magnitude or phase of the oscillating pressure. In some circumstances in this apparatus, the suppression of convection is a hysteretic function of oscillating velocity. In some other circumstances, a time-dependent convective state seems more difficult to suppress.

# SESSION- TO3 [Oral]: Cryocooler Fundamentals Tuesday, May 18, 2010 – Oral Session: 10:45 AM- 12:00 PM

## [TO3-A122]

## Some Insights Into Stirling Machine Behavior

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*TS-dot Engineering, NZ
†Avon River Engineering, NZ

Almost all practical cryocoolers embody, directly or indirectly, at least some elements of the Stirling cycle in its reversed form. Through its involvement in the analysis, design and development of both Stirling engines and refrigerating applications, the Stirling Cycle Research Group at University of Canterbury has, over several years, encountered a number of aspects of the practical realization of the Stirling Cycle – and indeed some aspects of its ideal realization – which are, in our view, easily overlooked or misinterpreted. Being unaware of these aspects may possibly lead to less-than-optimal design of Stirling machines and/ or misinterpretation of modeling predictions and the performance data from actual machines. The points of interest and intended clarification are: • The misleading, or at best easily misinterpreted, typical textbook representations of the ideal Stirling cycle in both p-v and T-s property diagrams; • The clear difference between direct and reversed implementations of the Stirling cycle in terms of the role which the regenerator plays; • Even though the ideal Stirling and Carnot cycles are indistinguishable in terms of the nature of the interactions between the system and its external surroundings, there are some interesting differences in performance that emerge when one explores the concept of replacing the Stirling cycle's regenerator with an additional "Carnot piston" (to achieve the required externally adiabatic expansion and compression).

# SESSION TO3 [Oral]: Cryocooler Fundamentals
# Tuesday, May 18, 2010 – Oral Session: 10:45 AM- 12:00 PM

## [TO3-A165]
## Cryocooler Performance and Mass vs. Operational Temperature: a Survey of the Open Literature for Pulse Tube and Stirling

D. Ladner

N-Science Corporation USA

Pulse Tube and Stirling cryocooler data that were reported in the open literature during the past decade were analyzed to find mathematical scaling laws for estimating the required input power and mass, as functions of the operational temperature at a required capacity, for near ambient temperature heat rejection. It is found that the average fraction of Carnot efficiency, determined empirically from an abundance of performance data, follows a relatively smooth nonlinear curve when plotted against the cold head temperature. This result can be used to estimate the required input power for a given temperature and capacity requirement. Incorporating results from a previous survey that separately tabulated the cryocooler electronics and thermo-mechanical masses of many space cryocoolers, the cryocooler total mass can be estimated from the input power requirement using equations derived from the survey results.

# SESSION TO3 [Oral]: Cryocooler Fundamentals Tuesday, May 18, 2010 – Oral Session: 10:45 AM- 12:00 PM

## [TO3-A131]

## Study on Minor Losses in Thermoacoustic Engines

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Thermoacoustic engines are being in a stage of rapid development by reason of meeting the demand of being environmentally friendly and making use of renewable energy. As the development needs of high-power, high efficiency engines, oscillating flow conditions and energy conversion mechanism in the thermoacoustic engines where oscillating flow occur are even more complex and we still know little of the mechanism within. This paper concentrates on the minor losses at the interface of thermodynamic segments in thermoacoustic engines. An experimental system with wide frequency and driving power adjustment ability for the research on the nonlinear thermoacoustic effect and complex flow in oscillating flow has been built. Flow conditions and minor losses in the vicinity region where sudden changes and gradient changes in cross section, as well as the ends of porous media stacked segments are experimentally investigated. Velocity distributions are measured by phase locked particle image velocimetry with the assistance of hot wire anemometry while turbulence exists. The transition of flow pattern is visualized and analysed. Based on the pressure and the velocity measurement, the analyses on entry effect have been made. Empirical formulas of the entry effect length and the modified pressure equation and velocity equation based on thermoacoustic theory have been given. This work can give a deep insight into acoustical loss mechanism in thermoacoustic systems.

# SESSION- TO4 [Oral]: JT Crycoolers
# Tuesday, May 18, 2010 – Oral Session: 1:30 PM - 3:00 PM

## [TO4-P035]

## Open Cycle Joule-Thomson Cryocooling by Mixed Coolants

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Rafael, Ltd., Israel

Open cycle Joule-Thomson (JT) cryocoolers are fed by high pressure coolants, stored in a vessel. Elevating the charging pressure is essential for this mode of cryocooling since it is accompanied by two beneficial and independent effects: (a) enhancement of the JT effect, and, (b) storing more coolant in the vessel. It enables faster cooldown and prolongs the mission. Traditionally, are employed pure coolants as nitrogen and argon for the 80 K and 90 K range, correspondingly. Mixed coolants of nitrogen with higher boiling point components might be beneficial for open cycle applications.More commonly, mixed coolants are employed for the closed cycle JT mode of cryocooling. Here, the potential of mixtures is utilized for reducing the pressure of operation. On the one hand, numerous experimental and theoretical studies of closed cycles were reported. However, the preferred compositions for low pressure (closed cycle) are not the same as for elevated pressure (open cycle). On the other hand, the reported experience with open cycle mixed coolants is quite rare. The present study is an experimental demonstration of a mixed coolant open cycle performing at elevated pressures. This mixture combines the advantages of nitrogen and argon; it reaches the lower temperature of nitrogen but still cools down as fast as argon.The examined mixture includes more then 80% of nitrogen (by volume) and hydrocarbons.

# SESSION- T04 [Oral]: JT Crycoolers
# Tuesday, May 18, 2010 – Oral Session: 1:30 PM - 3:00 PM

## [T04-P063]

## Cooling Load Estimation for 80 K Mixed Refrigerant Joule-Thomson (MR J-T) Cooler

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In recent past, Mixed refrigerant Joule-Thomson (MR J-T) cryocoolers, working on closed cycle, have been used to provide cooling effect in the range of 75 -150 K. Estimation of cooling capacity at a desired temperature or in a desired temperature range for MR J-T coolers is crucial in the design procedure of the coolers. This task is more challenging for the MR J-T cooler, because total cooling effect is contributed by number of refrigerant components, which are either absorbing latent heat of vaporization (boiling) and / or absorbing sensible heat. For most of the period, both the modes of heat exchange takes place simultaneously. However, the major contribution to the cooling effect is due to boiling of the low boiling components. The present paper aims to estimate the total cooling effect that can be theoretically produced for a given working and operating conditions. The procedure of calculation of refrigerating effect is designed. The contributions due to latent and sensible part are also calculated for each component of mixture in a given temperature of range. Further comparison between the theoretically estimated and experimentally obtained cooling load is given for the range of 80 K - 105 K.

## SESSION- TO4 [Oral]: JT Crycoolers Tuesday, May 18, 2010 – Oral Session: 1:30 PM - 3:00 PM

### [TO4-P094]

# Progress in Joule-Thomson Microcooling at the University of Twente

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The development of micromachined Joule-Thomson (JT) coolers has been an ongoing research project at the University of Twente for many years. The cold stage of the cooler consists of a stack of three glass wafers. The high and low pressure lines are etched as rectangular channel with supporting pillars in the top and bottom wafer. The high pressure line ends in a flow restriction, which is connected to the evaporator. The evaporator is extended across the center wafer and is connected to the low pressure line, thereby forming a counter flow heat exchanger between high and the low pressure channel. After successful development of the single-stage JT microcoolers with a cooling capacity of around 10 mW at 100K, the current research is focused on developing micro-cooler with higher cooling power (up to 100 mW) and/or at lower temperatures down to about 30 K (using multi-stage coolers).The incorporation of sorption compressors is being explored as well as the utilization of microcoolers in pilot projects such as cooling of low-noise amplifiers or optical detectors. Also, the issue of clogging caused by tiny amounts of water is further investigated. In the paper, recent developments in the Twente microcooling research will be discussed.

# SESSION- TO4 [Oral]: JT Crycoolers
# Tuesday, May 18, 2010 – Oral Session: 1:30 PM - 3:00 PM

## [TO4-P126]

## 35 K Variable Load Space Cryocooler Performance and Acceptance Testing

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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, 2 watts at 35 K, and intercepts the parasitic loads associated with the J-T cryostat. The cooler uses am internal thermal storage unit (ITSU), which is a tank for holding liquid neon, to provide the system's load leveling capability. Results will be presented for the various performance and environmental tests, especially the 35 K load leveling capability.

# SESSION- TO4 [Oral]: JT Crycoolers
# Tuesday, May 18, 2010 – Oral Session: 1:30 PM - 3:00 PM

## [TO4-P148]

## 14.5 K Hydrogen-Based Sorption Cooler: Design and Breadboard Tests

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At the University of Twente, a 14.5 K hydrogen-based sorption cooler is under development. It can be used as a stand-alone cooler, or as a precooler e.g. in combination with a 4 K helium-based sorption cooler. The advantage of sorption coolers is the absence of moving parts and, as a result, their vibration-free operation and potentially very long life. We developed and built a 4.5 K helium stage under ESA-TRP contract and in 2008, we started a new ESA-sponsored project on a hydrogen cooler stage. A demonstrator cooler has been designed that is able to cool 40 mW at 14.5 K requiring an input of only 5.6 W as electric power fed into a sorption compressor that is heat sunk at a 90 K radiator. The required radiator area is 1.9 m2. The compressor contains two stages consisting of cells filled with activated carbon. The cells are thermally cycled between the heat-sink level of 90 K and about 210 K causing hydrogen to be periodically adsorbed and desorbed. As a result, hydrogen is pumped from a low-pressure buffer at 0.1 bar to a medium-pressure buffer at 4 bar, and subsequently to the high-pressure side of the cold stage at 50 bar. The flow direction in this process is controlled by passive valves. In the cold stage the working fluid is precooled by a 50 K radiator (0.1 m2). In the paper, the design of the hydrogen-based sorption cooler is discussed along with breadboard tests on system components.

# SESSION- TO4 [Oral]: JT Crycoolers
# Tuesday, May 18, 2010 – Oral Session: 1:30 PM - 3:00 PM

## [TO4-P163]

## Modeling and Experimentation with a Pre-Cooled Mixed Gas Joule Thomson Cycle for Cryosurgery

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Cryosurgery is a technique for destroying undesirable tissue such as cancer tumors using a freezing process. One method of providing the cooling is a Mixed Gas Joule-Thomson (MGJT) cycle. The next generation of MGJT cycles for cryosurgery operate using a pre-cooling stage that consists of a conventional Vapor Compression (VC) cycle. A thermodynamic model of this system has been developed and integrated with a genetic optimization algorithm in order to guide the selection of the optimal mixture compositions as well as other operating parameters. An experimental test facility has been designed and fabricated in order to test the performance of the Pre-Cooled MGJT system operating with the new, optimized mixtures. A commercially available cryoprobe system has been modified and extensively instrumented in order to provide precise measurements at key locations and therefore completely characterize the cryoprobe performance. Temperatures, pressures, and mass flows are measured at various locations in order to identify thermodynamic states and calculate heat and work transfer rates. Temperature measurements within the recuperator are used to determine the pinch point temperature difference and infer the conductance of the device under various operating conditions. The experimental data are compared with the model in order to tune and verify its predictive capabilities.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P052]

## Pressure Drop Characteristics of Steady and Oscillating Flow in a Slit-type Heat Exchanger

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A slit-type heat exchanger offers several advantages to the design of a cryocooler; it can have the diverse configuration (straight or tapered shape) and no thermal contact resistance problem usually encountered in a mesh-type one. The appropriate heat path of radial direction in a large scale and high-power cryocooler is especially attractive. In this paper, we focus on measurement and analysis of pressure drop characteristics in a slit-type heat exchanger. First, measurement and analysis are considered in conditions of steady and oscillating flow. Second, a variation in the configuration of a slit-type heat exchanger includes: 1) size of slit; 2) the number of slit; and 3) angle of slit. For the experimental comparison, the specified heat exchangers are fabricated and the general correlation of the pressure drop is carefully obtained. Analysis of pressure drop characteristics includes: 1) calibration of analysis process from the developed correlation; and 2) estimation of pressure drop characteristics for new configurations. Using the boundary conditions from the experiments, CFD (Computational Fluid Dynamics) is prepared to reproduce experimental data. By the CFD calculation, the entrance and exit loss of the pressure are examined. In the slit-type heat exchanger of the new configuration, pressure drop characteristics are finally estimated and confirmed using the CFD simulation and the experiment. From the comparison of these results, we can judge the accuracy and usefulness of the confirmed CFD process and the developed correlation. The result of this paper enables to design an optimum cryocooler with slit-type heat exchangers.

# SESSION-TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P058]

## Theoretical and Experimental Investigation of Flow Straightners in U-type Pulse Tube Cryocooler

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The U-type Pulse Tube Cryocoolers (PTC) involve a change in the direction of gas flow as it proceeds from the regenerator to the pulse tube through the cold end heat exchanger. The sharp U-turn causes turbulence in the flow of gas. This has an adverse effect on pulse tube cooling action due to formation of eddies and undesirable mixing in the cold end of the pulse tube. Flow straightners at the cold end play a very important role in overcoming such problem.The present work deals with experimentation and CFD modeling related to U-type PTC. Experimentation is carried out using copper mesh size of 100 as flow straightners. The optimum performance of the PTC in terms of low temperature is achieved with 18 numbers of flow straightners. The temperatures achieved at no load condition with and without flow straightners are 57.7 K and 88.8 K respectively, for the charging pressure of 16 bar. When the smooth 180 degree bend at the cold end is replaced by sharp 180 degree bend the no load temperature increases from 88.8 K to 137 K. In order to understand the role of flow straightners in PTC a CFD model is developed in FLUENT. The flow straightners and the hot end heat exchanger are modeled as homogeneous porous media. The results show that the flow straightners significantly affect the velocity patterns in the pulse tube. The optimum number of flow straightners improves the performance of pulse tube cryocooler.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P064]

## Effects of Heat Exchanger Configuration on Performances of the Joule-Thomson Refrigerator

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*Korea University, S. Korea

Typical Joule-Thomson refrigerator consists of a recuperative heat exchanger, a gas expansion nozzle, a mandrel and a compressed gas storage bottle. Thermodynamic performances of the J-T refrigerator highly depends on hydraulic and heat transfer characteristics of the recuperative heat exchanger. The typical recuperative heat exchanger of the J-T refrigerator has a double helical tube and fin configuration, but other heat exchanger configuration may be used, including two flow type helical tube and fins configuration, two stage heat exchanger configuration, a double helically wound tube circuit arranged in a spiral channel and etc. In this study, performances of the J-T refrigerators with single and two flow type recuperative heat exchanger were investigated. Effectiveness-NTU approach was adopted to predict the thermodynamic behaviors of the heat exchanger for the Joule-Thomson refrigerator. The results show the effect of the operating conditions on the performance of the heat exchanger and refrigerator for the 3 types of 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.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P101]

## CFD Simulation and Experimental Validation of a Diaphragm Pressure Wave Generator

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Industrial Research Ltd has been developing a low-cost diaphragm pressure wave generator for cryocoolers since 2005. Thermodynamic losses in the pressure wave generator can have a significant impact on the overall efficiency of a cryocooler. To help characterize the thermodynamic losses, a two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model was developed to simulate oscillating fluid flow and heat transfer in a diaphragm pressure wave generator. The ANSYS-CFX commercial code was utilized for the 2-D model. A series of validation experiments were conducted on an apparatus consisting of a diaphragm pressure wave generator respectively connected to four cylindrical spaces with the same volume but different diameters (40mm, 60mm, 80mm and 100mm). Volume and pressures at different locations were measured for both Helium gas and Nitrogen gas over a range of frequencies. Pressure and volume measurements were used to calculate hysteresis loss. Good agreement was achieved between the CFD simulations and the validation experiments. The model will be used to increase the efficiency and optimize the design parameters., Results obtained from CFD simulations and validation experiments are presented and discussed in this paper.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P142]

## Low Temperature Adsorption Versus Pore Size in Activated Carbons

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Activated carbons are used for a long time at low temperature for cryogenic applications and the physisorption properties depend on pore geometry and size: this feature can be used to optimize the carbon structure for a specific application. In this work, we report on the low-temperature adsorption properties of He, H2, and N2, on three coal-based activated carbons - a carbon monolith (sample A), a granular carbon (sample B) and a pelletized carbon (sample C)- with different pore size distributions. The sample A presents the highest total pore volume and BET surface area. Both the sample B and sample C are high density activated carbons; sample B has the lowest total pore volume and BET area, but is more microporous (< 20 Å) than sample C; the latter presents an intermediate total pore volume and BET area, exhibiting a significant porosity in the mesopore range (20–500 Å). The sample C, due to its pelletized structure, gives rise to a good packing density. Adsorption measurements were performed between 0.1 mbar and 1 bar and in the range 10-100 K for He, 15–300 K for H2, and 70–300 K for N2. The isosteric heat of adsorption was obtained: it increases with decreasing pore diameter, as expected from the enhanced solid-fluid interaction potential in smaller pores. The adsorption isosteres, i.e. P(T) at constant loading, were inter-compared in order to help choosing the correct porosity that meets the requirements (pressure, temperature) of a specific application.

## SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

### [TP5-P153]

# Development of Moving Magnet Linear Motor Pressure Wave Generator for Pulse Tube Refrigerator

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A moving magnet linear motor pressure wave generator of 2 cc swept volume has been designed and developed to operate an in-line pulse tube refrigerator of cooling capacity 0.5w@65K. It is of dual opposed piston configuration and the pistons are supported at the front and back by stacks spiral flexure bearings designed by FEM analysis. Radially magnetised NdFeB ring magnets are mounted on titanium magnet holders. Polyimide coated copper wires are used to form the coil. The motor is designed to deliver a Force of 15 N. The magnetic field distribution pattern along the length of the motor due to excitation of coil winding is discussed. Simple force measurement technique for linear motor is described and variation of no load force as a function of current is shown. The restoring force and the resultant force of the motor at various displacements are found and the generated force is calculated, which is nearly constant in its linear range of displacement. LVDT is used to measure the stroke of the piston. The operating characteristics of the pressure wave generator are discussed in the paper.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P166]

## Continuously Variable Inertance Tubes

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The efficiency and cooling power of pulse tube refrigerators are highly dependent on the phase angle between the mass flow and pressure waves used to produce cooling in the system, and inertance tubes are commonly used to set the phase angle for optimal efficiency. However, due to variations in fabrication or assembly, it is frequently unclear whether installed inertance tubes, with their fixed dimensions, produce the desired phase shift. A variable inertance tube allowing continuous adjustments to its geometry during operation has been constructed and mounted on a pulse tube, along with instrumentation to measure the pressure and mass flow oscillations and their relative phase at the interface between the inertance tube and pulse tube. A Lab-view based lock-in amplifier enables real time observation of the phase information. The variations in phase realized by changing the respective length and effective diameter of an inertance tube between 1.4 m to 1.7 m, and 6.4 mm to 7.7 mm, are compared to published models.

# SESSION-TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P172]

## An Advanced Compressor for Turbo-Brayton Cryocoolers

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Future space-borne infrared sensor missions will require reliable, efficient, and lightweight cryocoolers. Reverse turbo-Brayton cryocoolers have the inherent benefits of negligible vibration emittance and the ability to cool remote or distributed loads. In this paper we describe the results of our efforts to improve overall system efficiency with the development of a high performance permanent magnet motor compressor. A prototype 500 W-class compressor was fabricated and tested at prototypical operating conditions. The compressor utilizes gas bearings for zero-wear, negligible vibration, and high speed operation; and a miniature impeller for high performance at relatively low power levels. The impeller was manufactured using new fabrication processes that allow advanced blade geometries to be produced at a miniature scale. In addition, the new process is extremely precise, simplifies inspection, is readily scalable to different power levels and produces parts more quickly and at a lower cost than the heritage process. The compressor tests demonstrated a reduction in input power of up to 30% as compared to our induction-motor compressors. We expect further performance improvements as we add upgrades to the prototype.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

[TP5-P177]

## Enhanced Helium Compressor Operation for Sensitive Measuring Instrumentation

S. Spagna, T. Sayles, D. Martien, J. Diederichs,
N. Manivannan, J. Sloan

Quantum Design, USA

We describe recent advances in the design of a new class of "energy smart" helium compressors that reduce the operating cost of cryocooled based instrumentation. In these systems, the individual speed control of the compressor's capsule and cold head motor provide for "intelligent" oversight and budgeting of the cooling power delivered to the cryostat based on the user immediate measurement needs. In this report, we describe important elements of the system design, which increase operational life time, yield to power savings as well as providing for a low vibration environment in which sensitive measuring instrumentation such as a dilution refrigerator can operate without degrading its ultimate performance.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P184]

## Study on 35K Regenerator Performance Operating at High Frequency

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Making an option of regenerative materials on different temperature and working conditions is very critical for the regenerator performance. Considering material lead has larger volume heat capacity than stainless steel when temperature is lower than 67K, lead sphere is widely used in G-M cryocoolers and G-M type pulse tube cryocoolers for good regenerative performance. However, this approach could not be used for cryocoolers operating at high frequency. Yang L.W. found lead sphere as regenerator was not good in his Stirling type pulse tube cryocooler. The performance of stainless steel screen, ideal lead screen (commercial unavailable), lead sphere as regenerative material respectively at 35K based on a regenerator model known as REGEN3.2 was discussed in this paper. The results show that the performance of stainless steel screen is better than lead sphere, as good as ideal lead screen for the condition of 35K and 40Hz.The result is important for the research of high frequency cryocooler at 35K.

# SESSION-TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P066]

## Low-Power 4 K Pulse Tube Cryocooler for Operation at Tilt Angles of up to 45"

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4 K pulse tube cryocoolers (PTCs) are attractive for low-noise detector cooling in radio astronomy because of high reliability and low mechanical vibrations. Since in operation the receiving areal will be tilted by up to 90°, the cooling performance of the PTC should be nearly independent of tilting for angles in the range of ±45° from the vertical. Low-frequency PTCs exhibit a degradation of cooling performance upon tilting from vertical orientation, due to an enhanced heat transfer from gravity-induced convection of the helium gas in the tilted pulse tube. A higher operating frequency and a large length to diameter ratio of the pulse tube can restrain such convection losses. Here we report on a newly designed two-stage 4 K PTC that is operated on a GM-type 2 kW helium compressor. Compared to existing low-power TransMIT PTCs the length to diameter ratio of the 1st stage pulse tube was increased. In addition the new PTC is running at a higher frequency of 1.5 Hz. After optimization of the operating parameters in tilted position, the PTC reaches a base temperature below 2.8 K and provides a cooling power of 190 mW at 4.2 K in vertical position, while at tilt angles of ±45° a cooling power of 165 mW at 4.2 K is still available.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P124]

## Performance Test of Pulse Tube Cooler with Integrated Circulator

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To address the need for remote and broad area cooling using regenerative cryocoolers, Atlas Scientific is developing a lightweight, continuous-flow Integrated Circulator (IC) for installation on Pulse Tube Cryocoolers (PTCs). The basis of the IC is a rectifier that converts the oscillating flow of a regenerative cryocooler into a steady flow of cold gas that can readily be distributed over distances of several meters to multiple or broad area thermal loads. The Integrated Circulator has advantages over competing technologies, such as the use of a secondary mechanical or capillary pump dedicated to circulating cryogens through a cold heat exchanger conductively coupled to the coldhead of the cryocooler, in that it eliminates the pump, its potential reliability problems, its parasitic power consumption, and the additional temperature rise introduced by the presence of the conductively coupled heat exchanger at the PTC coldhead. Here, we report on PTC performance measurements made both with and without the presence of an Integrated Circulator. Such measurements are necessary in order to make quantitative comparisons of the IC to competing technologies. The results indicate that the IC is indeed a viable alternative.

# SESSION- TP5 [Poster]: Cryocooler Components & Integration Technologies Tuesday, May 18, 2010 – Poster Session: 3:00 PM - 4:00 PM

## [TP5-P157]

## Thermal Storage Unit Using the Triple Point of Hydrogen

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*CNES, France

In the framework of a Research and Technology program co-funded by the French space agency (CNES), CEA/SBT has developed a 14 K thermal storage unit using the triple point of hydrogen. The unit developed is able to store 10 J at 14 K. Various peak loads have been applied to the unit in order to validate the level of energy stored and to measure the temperature stability. This kind of thermal buffer could be used in satellite cryogenic chains subject to variable heat loads. The design of the unit will be described and the thermal results will be presented.

# SESSION- TO6 [Oral]: Cryocooler Modeling and Performance Investigation Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

## [TO6-P129]

## Heat Transfer during Laminar Pulsating Flow in Porous Media

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Solid-fluid thermal interactions during unsteady flow in porous media play an important role in the regenerators of pulse tube cryocoolers. Pore-level thermal processes in porous media under unsteady flow conditions are poorly understood. The objective of this investigation was to study the pore-level thermal phenomena during pulsating flow through a generic, two-dimensional porous medium by numerical analysis. Furthermore, an examination of the effects of flow pulsations on the thermal dispersion and heat transfer coefficient that are encountered in the standard, volume-average energy equations for porous media were carried out. Pulsating flow was chosen as an intermediate step towards the more difficult problem of periodic flow. The investigated porous media are periodic arrays of square cylinders. Detailed numerical data for the porosity range of 0.64 to 0.84, with flow pulsation frequencies of 10 - 64 Hz, were obtained. Based on these numerical data, the instantaneous as well as cycle-average thermal dispersion and heat transfer coefficients, to be used in the standard unsteady volume-average energy conservation equations for flow in porous media, were derived. Also, the adequacy of current applied cycle-average correlations for heat transfer coefficients and the inclusion of the thermal dispersion in the definition of an effective fluid thermal conductivity were investigated.

# SESSION- TO6 [Oral]: Cryocooler Modeling and Performance Investigation Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

## [TO6-P136]

## Numerical Modeling on a Reciprocating Active Magnetic Regenerator Refrigeration

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Active magnetic regenerative refrigeration (AMRR) which makes use of the magnetocaloric effect (MCE) is an environmentally attractive alternative to vapor compression refrigeration that does not use a fluorocarbon working fluid and has the potential to be more efficient. A one-dimensional porous media model for an active magnetic regenerator has been developed. It can be used to predicting the performance of AMRRs. The solid magnetic material and the regeneration fluid are separately modeled based on the determination of the convective heat transfer coefficient between solid and fluid. MCE is taken into account by the inclusion of a source term in the energy equation for the magnetic material. The adiabatic temperature change of the used magnetic material has been measured and is used as an alternative MCE than mean field modeling. The numerical discretization is based on the Finite Differential Method(FDM) and the temporal integration is marched fully explicit. The 1-D model has been validated by comparison with experimental AMRRs and used to optimize AMRRS by varying model inputs such as fluid mass flow rate, the ratio of fluid mass and magnetic material mass, cycle time.

# SESSION- TO6 [Oral]: Cryocooler Modeling and Performance Investigation
## Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

### [TO6-P144]

## Clearance loss analysis in linear compressor with CFD method

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Compressor is a key component to drive cryocooler working in a long life time process. For the traditional compressor, the piston moves back and forth in the cylinder freely to produce the pressure wave, providing power through the cryocooler that produces cooling capacity at the cold head, and the piston ring is used between the cylinder wall and the piston to seal the air gap. This kind of compressor has become an obstacle of long time operation of the whole cryocooler system because the lubricant may condense at the low temperature plugging the refrigerator. The non-contact seals technology, named clearance seals, used in the linear compressor is promise to be an excellent substitution for this problem. The present efforts aim to analyze the aerodynamics in the small clearance passage with the commercial CFD code Fluent. Three different types of the clearance seal shapes, the linear seal, the labyrinth seal, and the slope seal are modeled, and the general simulating results such as the pressure and temperature distribution are described. The clearance loss was quantitatively compared for all shapes by changing the piston style, inflation pressure, working fluid properties and operating frequency. A mathematical expression for the minimum clearance loss was also deduced based on the optimized gap thickness and piston length. The results can be used to optimize the design of the linear compressor in the future.

# SESSION-TO6 [Oral]: Cryocooler Modeling and Performance Investigation Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

## [TO6-P150]

## Measured and Calculated Performance of a High Frequency, 4 K Stage, He-3 Regenerator

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Efficiencies of small 4 K cryocoolers are less than 1% of Carnot, whereas 80 K cryocoolers achieve efficiencies of up to almost 20% of Carnot. The primary loss mechanisms in low temperature regenerative cryocoolers are caused by the non-ideal gas properties of the He-4 working fluid and the reduced volumetric heat capacity of the regenerator matrix compared with that of He-4 at these low temperatures. A recently developed model, REGEN3.3, which incorporates the thermodynamic and transport properties of He-3, shows that using He-3 should considerably improve the performance of 4 K regenerators. The model was used to design an optimized test apparatus to measure the performance of a He-3, 4 K regenerator with the warm end pre-cooled by a Gifford-McMahon cryocooler to about 35 K. The test regenerator is designed to operate at 30Hz and uses a layered matrix of gadolinium oxysulphate (GOS) spheres at the cold end and erbium-praseodymium (ErPr) spheres at the warm end. The experimental test apparatus, testing procedures and the results will be presented. In addition a novel method employed to improve the phase shifting at the warm end of the small He-3 cold-stage pulse tube will be presented along with its impact on the cycle performance.

# SESSION-TO6 [Oral]: Cryocooler Modeling and Performance Investigation Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

## [TO6-P173]

## Regenerator Friction Factor and Nusselt Number Information Derived from CFD Analysis

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Macroscopic models used in the design and development of pulse tube cryocooler regenerators do not explicitly consider the complex microscopic interaction of the working fluid as it flows through the interstitial passages formed by the solid matrix. Rather, governing equations for these models are typically formulated in terms of average macroscopic quantities (e.g., the bulk velocity and temperature within the interstitial passage) and require user input in the form of friction factor and Nusselt number to account for microscopic fluid-to-solid interactions. Traditionally, the friction factor and Nusselt number are correlated from steady flow experimental data, despite the oscillatory flow that exists within the regenerator. It is not clear how well this technique works and how much the failure to account for oscillating flow affects the performance predicted by a macroscopic model of a regenerator. In addition, correlations from steady flow are limited in terms of the matrix configuration and range of the conditions. This paper outlines the development of a design tool that is capable of deriving Nusselt number and friction factor correlations based on CFD analysis of a unit-cell model that considers the microscopic interactions of the fluid and solid matrix. The model explicitly includes the oscillating flow effects, can be applied to arbitrary matrix geometry, and can be used to provide information over the range of operating conditions typically encountered in a pulse tube cryocooler. This paper presents the details of the model and the data reduction process as well as preliminary results for a typical regenerator geometry.

# SESSION- T06 [Oral]: Cryocooler Modeling and Performance Investigation Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

## [T06-P182]

## Secondary Pulse Tubes and Regenerators for Coupling to Room-Temperature Phase Shifters in Multistage Pulse Tube Cryocoolers

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Multistage pulse tube cryocoolers require separate phase shifters for each stage. For sufficiently high frequency and acoustic power, the inertance tube is commonly used for such phase shifting. For Stirling-type, multistage pulse tube cryocoolers the warm end of the coldest pulse tube is often heat sunk to a warmer stage rather than at room temperature to improve the figure of merit for the pulse tube and/or to achieve a larger phase shift with a cold inertance tube. The use of a secondary pulse tube or regenerator between the main pulse tube and a phase shifter allows the phase shifter to operate at room temperature where space is more readily available. The secondary regenerator amplifies the acoustic power, so a room temperature inertance tube may perform as well as a cold one. A secondary pulse tube transfers acoustic power to room temperature without amplification, so a rather small warm expander or displacer can provide the optimum phase shift even in a low-power cryocooler. In this paper we model the behavior of these secondary pulse tubes and regenerators using REGEN3.3and present design graphs to assist in selecting the optimum geometry. We show that acoustic power flows from cold to hot can be modeled with REGEN3.3 by changing the flow phase by 180 degrees.

# SESSION- TO6 [Oral]: Cryocooler Modeling and Performance Investigation Tuesday, May 18, 2010 – Oral Session: 4:00 PM - 5:45 PM

## [TO6-P210]

## Measurement and Correlation of Hydraulic Resistance at Cryogenic Temperature

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The results of research program aimed at the measurement and correlation of hydrodynamic parameters of widely used pulse tube and Stirling cryocooler regenerator fillers are presented. Hydrodynamic parameters, namely, the permeability and inertial coefficients associated with axial periodic flow at cryogenic temperature are addressed. An experimental apparatus consisting of a cylindrical test section packed with regenerator fillers is used for the measurement. Regenerator fillers that are tested include stainless steel 635 mesh-screens, stainless steel 500 mesh-screens, stainless steel 400 mesh-screens, and stainless steel 325 mesh-screens. The test section is connected to a Stirling type BAE- compressor (provided by AFRL/RVSS) on one end and to a constant volume chamber on the other end. Cryogenic pressure transducers are used to measure local pressures at both ends of the test section. A CFD assisted methodology is then used for the analysis and interpretation of the measured data. In addition, one-dimensional semi-mechanistic model developed and derived from volume averaging theory will also be used to analyze and interpret the data. Hydrodynamic parameters obtained using both methods (CFD and one-dimensional semi-mechanistic method) will be presented.

# SESSION- WO1 [Oral]: Cryocooler Integration Technologies
# Wednesday, May 19, 2010 – Oral Session: 8:00 AM – 9:30 AM

## [WO1-A118]

## Cryogenic Boil-Off Reduction System Test

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Under NASA's Cryogenic Fluid Management project, which, as one of their goals, develops long-term cryogenic storage technologies in support of the Exploration Technology Development Program, NASA performed a test of a cooled shield imbedded within the radiation shield insulation of an LN2 dewar at Ball Aerospace facility. The dewar was inside a vacuum tank, which, through a side access port, coupled a cryocooler to the multi-layer insulation using a closed loop helium lines, which were affixed to a five mil aluminum shield approximately 40% through the insulation. The helium was compressed in the cryocooler and routed through the tubes and the insulation, along with the tank supports as well. Although the helium flow was lower than desired, which caused a longer delay until steady state was reached, the cryocooler removed heat as expected and the shield proved to be 74% efficient. This efficient and light weight cooling system test served to validate the boil off reduction system.

# SESSION- WO1 [Oral]: Cryocooler Integration Technologies Wednesday, May 19, 2010 – Oral Session: 8:00 AM – 9:30 AM

## [WO1-A127]

## NASA TIRS Cryocooler Induced Vibration and Heat Rejection Mounting System

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*NASA Goddard Space Flight Center, Greenbelt MD, USA

Ball Aerospace is providing the TIRS (Thermal Infra-Red Sensor) Flight Mission Cryocooler to NASA GSFC. NASA and Ball have developed a unique mounting system to both reject the heat dissipation of the cooler and minimize its induced vibration. This paper will describe that mounting system and the results from its testing.

# SESSION- WO1 [Oral]: Cryocooler Integration Technologies Wednesday, May 19, 2010 – Oral Session: 8:00 AM – 9:30 AM

## [WO1-A186]

## Thermal Switching Cryogenic Heat Pipe

D. Bugby

ATK, Beltsville MD, USA

This paper describes a thermal switching cryogenic heat pipe for an instrument on the NASA JPL SIM Lite telescope. The primary requirement is to transport 12 W from the 150 K instrument to a 140 K primary radiator 1.5 m away. The heat pipe is a 1.5 cm OD Al axial groove design with methane as the working fluid, which provides 75 W-m at 140 K. A secondary requirement is to periodically heat (decontaminate) the instrument to 293 K with minimal heater power. To meet the decontamination requirement, the heat pipe was modified to provide thermal switching by using small diameter SS tubing to connect it to a liquid trap cooled by a small secondary radiator thermally isolated from the primary radiator. The liquid trap is a scaled-up version of the liquid traps used on the CRISM flight system. During normal operation, a small heater keeps the liquid trap filled only with vapor. During decontamination, the liquid trap heater is turned OFF, the primary radiator is heated by the conductive heat leak down the heat pipe, the secondary radiator cooled liquid trap captures all the working fluid effectively turning the heat pipe OFF, and a small evaporator heater raises the instrument temperature to 293 K. When the liquid trap heater is re-enabled, the system returns to normal operation. This paper will describe the design, fabrication, and testing of this demonstration system. The tests described herein were conducted at the thermal vacuum chamber test facilities at ATK in Beltsville, MD.

# SESSION- WO1 [Oral]: Cryocooler Integration Technologies Wednesday, May 19, 2010 – Oral Session: 8:00 AM – 9:30 AM

## [WO1-A074]

## Liquid Nitrogen Energy Storage Units

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**SBT-INAC-CEA, France

These energy storage units (ESU) are to be attached on the cold finger of a cryocooler and aim for keeping the low temperature environment while momentarily stopping the cryocooler: a cryocooler equipped with an ESU allows measurements in a totally silent environment. This ESU consists of a nitrogen cell, coupled to a GM cryocooler by a gas-gap heat switch, and connected to an expansion volume at room temperature to limit the pressure increase. It was designed to store 3600 J between 63 K and 80 K. The nitrogen is firstly condensed into the liquid (solid) phase, and then for the silent measurements phase the cell is thermally decoupled from the cryocooler, the cryocooler is turned OFF and the liquid evaporation is used as energy absorbent. In this communication we present the tests performed using a cell of 35 cm3 and a 6 liters expansion volume filled with about half mole of nitrogen. Applying 1 W to the ESU, about 4 kJ were stored with a slow drift from 63.15 K up to 83 K. Modeling of the experiment agrees within 5% with the experimental results and a software for dimensioning such ESU (Stored energy, cell and expansion volumes, temperature drift, and cryogenic fluids) was written. While an ESU using the liquid-gas latent heat leads to a slow temperature drift in opposite to a triple point cell, it can absorb one order of magnitude more of energy for the same volume. A gravity insensitive ESU is under development.

# SESSION- WO1 [Oral]: Cryocooler Integration Technologies Wednesday, May 19, 2010 – Oral Session: 8:00 AM – 9:30 AM

## [WO1-A115]

## Pulse Tube Cooler with Remote Cooling

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Space pulse tube coolers are very efficient, but like all regenerative high frequency Stirling and pulse tube coolers, the cold head needs to be located near the compressor in order to minimize the input power to the cooler. For applications that require cooling some distance from the cooler or that require vibration isolation from the cooled object, the cooling can be effectively transferred with a fluid loop rather than with a higher mass conduction bar. This can greatly ease integration into a payload as well as readily transmit the cooling to multiple cooling points. In this paper we report on a proof of concept test in which we added cold reed valves to the pulse tube cold block of our flight proven high efficiency cooler (HEC) so that cold gas could be circulated without the need for an additional circulation pump and additional heat exchangers to cool the gas. In this test, the measured remote cooling and the parasitic heat loads were compared to our previously reported tests using warm reed valves. The two previous tests circulated gas from either a second circulator compressor or from the pulse tube compressor that also acted as a circulator and cooled the gas with a heat exchanger connected to the pulse tube cold head.

# SESSION- WO1 [Oral]: Cryocooler Integration Technologies Wednesday, May 19, 2010 – Oral Session: 8:00 AM – 9:30 AM

## [WO1-A169]

## A 2-K Active Magnetic Cooler for Remote Cooling of Space Instruments

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This paper reports on the development of an efficient, lightweight space magnetic cooler that can continuously provide remote/distributed cooling at temperatures in the range of 2 K with a heat sink at about 15 K. The magnetic cooler operates at a high cycle frequency to achieve a large cooling capacity. The cooler's ability to provide remote/distributed cooling not only allows flexible integration with payload(s) and spacecraft, but also reduces the mass of the magnetic shields needed. The technical challenges are the development of a reversible cryogenic circulator and highly effective magnetic regenerators. Research was carried out to determine the optimum magnetic field for the regenerator, analyze the performance of magnetic regenerators, optimize the system performance, and demonstrate the operation of critical components. The results of study show that a single-stage 2 K magnetic cooler can achieve a COP of about 35% of a Carnot cycle. The system can operate at a very short cycle period of 10 s. The magnetic cooler weighs only about 3 kg for a cooling power of nominally 60 mW. Preliminary test results confirm the stability of gas bearings in the reversible circulator under unique operating conditions. Ongoing fabrication and testing efforts for the cryogenic circulator and regenerators are also discussed.

# SESSION- WP2 [Poster]: Commercial Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A110]

## Development of 2 stage GM-type pulse tube refrigerator for cryopump

J. Ko, D. Koh, H. Kim, Y. Hong, H. Yeom, S. Park
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Pulse tube refrigerator is appropriate for the application to a cryopump due to its high reliability and low vibration. Generally, PTR for cryopump operates at 80 K (1st stage) and 20 K (2nd stage). This paper describes the development of 2 stage GM-type pulse tube refrigerator for cryopump. Especially, we concentrated on reducing unnecessary pressure loss through flow path between regenerator and pulse tube because pressure loss problem in PTR is more critical than GM cryocooler. We preceded the steady flow tests for several configurations of flow path before the fabrication of PTR. The cooling performance test was performed with the fabricated PTR. The experimental results are discussed with the measured pressure wave at each point.

# SESSION- WP2 [Poster]: Commercial Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A211]

## ANALYSIS OF A SUPERCRITICAL HYDROGEN LIQUEFACTION CYCLE

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If hydrogen is to be used as an energy carrier, the efficiency of liquefaction will become increasingly important. In this work, a supercritical hydrogen liquefaction cycle is proposed and analyzed numerically. By examining some difficulties of commonly used industrial liquefaction cycles, several changes were suggested and a readily scalable, supercritical, helium-cooled hydrogen liquefaction cycle was proposed. An overlap in the flow paths of the two coldest stages allowed the heat exchanger losses to be minimized and the use of a single-phase liquid expander eliminated the pressure reduction losses associated with a Joule-Thomson valve. A computational model was developed to investigate the effects on the cycle efficiency of altering component efficiencies and various system parameters. Furthermore, a heat exchanger simulation was developed to verify the feasibility of and estimate the approximate size of the heat exchangers in the cycle simulation. For a large, 50-ton-per-day plant with reasonable estimates of achievable component efficiencies, the proposed cycle offered a modest improvement in efficiency over the current state of the art. In comparison to the 30-40% Second Law efficiencies of today's most advanced industrial plants, efficiencies of 39-44% were predicted for the proposed cycle, depending on the heat exchange area employed.

# SESSION- WP2 [Poster]: Commercial Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A161]

## Effect of the charged pressure on the GM cryocooler performance

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* National Institute for Materials Science, Japan
**Oshima National College of Maritime Technology, Japan
***Sumitomo Heavy Industries, Ltd, Japan

This paper describes experimental results of the improvement effect of charged pressure on the refrigeration efficiency of the GM refrigerator. Recently, the progress of superconducting systems, such as Magnetic Resonance Imaging (MRI), silicon single crystal pull-up apparatus and cryopumping, has been remarkable and the GM cryocooler has an important role on refrigerating the systems because of their high reliability. From a viewpoint of the efficiency of the systems, improvements in the efficiency of the GM cryocooler are important. If a compression ratio of the GM cryocooler is lowered, the COP of the cryocooler come close to Carnot COP as the cryocooler is operated with the Simon expansion. Therefore, we investigated the effect of charged pressure of cryocooler and cycle frequency on the refrigeration efficiency. At first, we developed a GM cryocooler, which can be operated with various charged pressure and measured the efficiency of the cryocooler with various charged pressure and operation frequencies. Then, the experimental results were compared with numerical simulation results and an optimum charged pressure and an operation frequency were investigated.

# SESSION- WP2 [Poster]: Commercial Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A033]

## Concept of a powerful cryogen-free dilution refrigerator with separate 1K stage

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3He/4He dilution refrigerators (DR) are the workhorses for ultralow temperature scientists. DRs can be continuously operated for unlimited periods of time, and, compared to other cooling techniques, offer high cooling capacities. Base temperatures are well below 10 mK for well designed DRs. Cryogen-free (CF) DRs precooled by pulse tube refrigerators (PTR) have been become standard in recent years.In a typical CF-DR, the second stage of the PTR runs at temperatures between 3 K and 4 K. Its cooling capacity at 4 K is on the order of 1W. The next cooling stage is the still of the dilution unit with a typical temperature near 0.7 K. Its cooling capacity is proportional to the 3He flow and usually well below 20 mW. For many modern applications this is too little to cool and heat sink cold amplifiers, coax lines and electric cables. For these experiments an additional refrigeration stage at an intermediate temperature of about 1 K would be desirable. In our CF-DR, we plan to implement a continuous 4He refrigeration stage with a base temperature of 1.25 K. The cooling power of this stage is calculated to be 85 mW, whereas the cooling power of the still is 17 mW. The circulation rates of the DR and of the new 4He stage will be 1mmol/s (22 std. cm3/s) each. We present details of the planned CF-DR with 1 K stage.

# SESSION- WP2 [Poster]: Small Scale Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A082]

## Development of a Miniature Fast Cool-Down JT Cryocooler

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Rafael Ltd., Israel

One major advantage of joule-Thomson (JT) cryocoolers over other cryocoolers is the ability to achieve a very fast cool down, in the range of a few seconds only. The main fluid is chosen according to the desired cooling temperature and the fast cool down is usually obtained by allowing high flow rates during this transient process. A primary cooling stage may be added in order to cool the main fluid and reduce the cool down time, but it has a price of two pressure vessels and a more complex, and bigger, cryocooler. Fast cool down is usually required when the total cooling time is relatively short, few seconds up to few minutes, thus fixed orifice cryocoolers are preferable, according to manufacturing and reliability aspects. The flow rate of a fixed orifice cryocooler is strongly determined by the pressure at the vessel and since they both reduce rapidly during operation, the pressure in the evaporator significantly varies and thus the cooling temperature changes as well. In this case, a demand flow cryocooler is required in order to reduce the flow rate immediately when the desired cold temperature is achieved. In this paper we describe the development of a new flow valve, patent pending, for fast cool down cryocoolers that is a profit of practical considerations. The new valve is designed for miniature cryocoolers, has high reliability, is maintenance friendly, and provides fast reduction of the flow rate after cool down.

# SESSION- WP2 [Poster]: Small Scale Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A151]

## Analysis of multi-stage Joule-Thomson microcoolers

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Microcoolers machined from glass wafers, working on the basis of Joule-Thomson (JT) expansion have been investigated for many years at the University of Twente. After successful development of single-stage JT microcoolers with a cooling capacity of around 10 mW at 100K, the current research objective is to attain lower temperatures at about 30 K, using multi-stage coolers. As an initiative in this research effort, a dynamic model has been developed for analyzing the operation of these multi-stage microcoolers. A simplified model of a two-stage microcooler was developed using Matlab. The first stage operating with nitrogen, from 80 bar high pressure to 6 bar low pressure, is used to precool the second stage. The second stage operates with neon from high pressure of 40 bar to a low pressure of 1 bar. The model is composed of single lumped heat capacities at both evaporators and at the precooling stage. These capacities are linked via thermal resistances and are cooled by the evaporating fluids. The thermal resistances are based on dimensions of the counterflow heat exchangers. In the paper, the model will be described and some preliminary results will be discussed, as for instance the effects of the thermal resistances and the heat-exchanger efficiencies.

# SESSION- WP2 [Poster]:
# Small Scale Cryocoolers
# Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A097]

## A STUDY OF A MINIATURE IN-LINE PULSE TUBE CRYOCOOLER

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A miniature pulse tube cryocooler has been designed and tested in our laboratory. The main part of the cryocooler, consisting of an in-line assembly of aftercooler, regenerator, cold heat exchanger, buffer tube and hot heat exchanger has an overall length of 30 mm. The regenerator is filled with SS #635 mesh and has a length of 12 mm. Despite the miniature dimensions, all the aforementioned components of the cryocooler are connected by pressure-tight joints allowing easy disassembly and are easily replaceable. The modular arrangement allows an experimental optimization of the cryocooler. The oscillating pressure is supplied by an external compressor, and the entire assembly is fitted with an inertance tube and reservoir. A theoretical SAGE model estimated 240 mW of cooling at 110 K for operation at 100 Hz with filling pressure of 40 bars. As a result of the small dimensions the actual performance of the cryocooler is strongly dependent on the uniform passage of gas between the cooler components, and in most cases differs from the theoretical predictions.

# SESSION- WP2 [Poster]: Small Scale Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A199]

## Impact of Small Regenerator Structural Flaws on the Performance of Miniature Pulse Tube Cryocoolers

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Miniature cryocoolers are suitable for space applications and installation in portable devices. They can also be useful as final stages for applications where small cooling loads must be carried at temperatures lower than that required by the primary load. Strong regeneration, near plug-flow regime in the pulse tube and good flow control are essential for these cryocoolers to function. Miniature cryocoolers that use wire mesh as regenerator filler generally have a much larger ratio of regenerator filler pore size to regenerator diameter than their larger counterparts. For this reason, the significance of gaps existing between the porous regenerator filler and the interior wall of the regenerator shell will likely be greater for miniature cryocoolers. These gaps provide a low resistance flow path which may decrease the effectiveness of the regenerator. In this investigation the effects of such gaps on the performance of miniature pulse tube cryocoolers are examined using 2D and 3D CFD simulations. Miniature scale pulse tube cryocooler designs whose suitability for cryocooling under ideal conditions have been theoretically demonstrated are used as the bases for this study. The results confirm that extra precision and robustness are needed for miniature cryocoolers.

# SESSION- WP2 [Poster]: Small Scale Cryocoolers Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A200]

## The Effect of Component Junction Tapering on Miniature Cryocooler Performance

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Due to their relatively smaller volume and available cooling power, miniature cryocoolers are likely to be more sensitive to hydrodynamic losses than their full scale counterparts. Abrupt changes in diameter between cryocooler components are a possible source of such losses as flow separation and recirculation may occur at these points. Underutilization of regions of the regenerator and heat exchanger porous matrices may also occur due to jetting of fluid into these components. Eliminating such abrupt diameter changes by tapering or chamfering transitions between various miniature cryocooler components may therefore improve system performance. The effects of various tapers and chamfers applied at component interfaces on the overall performance of miniature pulse tube cryocoolers were investigated using system-level CFD models. A miniature scale pulse tube cryocooler design whose suitability for cryocooling under ideal conditions has been theoretically demonstrated was used as the basis for these models. Transitions between different combinations of open and porous regions were considered; tapers or chamfers representing various geometric profiles were applied to these component junctions and the performance predictions for the resulting systems were compared to those for a model with sharp component transitions. Visualizations of the predicted flow patterns were also used to determine the effects of the applied tapers on the flow within the pulse tube.

# SESSION- WP2 [Poster]:
# Space Cryocooler Applications
# Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A189]

## Wide-Field Infrared Survey Explorer Solid Hydrogen Cryogenic Support System

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The Wide-Field Infrared Survey Explorer (WISE) is a JPL managed MIDEX mission to perform an infrared all-sky survey. The WISE instrument, developed by the Space Dynamics Laboratory (SDL), is a 40-cm cryogenically-cooled telescope which includes a cryogenic scan mirror and four infrared focal planes (2-HgCdTe, 2-SiAs). Cooling of the instrument to the desired temperatures is accomplished by a two-stage, solid hydrogen cryostat, provided by Lockheed Martin Advanced Technology Center (LMATC). Required temperatures for the instrument optics and SiAs focal planes are <13 K and < 7.6 K respectively. To extend the cryogen lifetime, the vacuum shell is isolated from the spacecraft via composite struts and radiatively cooled to <200 K. The telescope aperture is protected from on-orbit environmental loads via a two-stage radiatively cooled aperture shade. WISE was successfully launched into a 530 km, polar orbit on Dec 14, 2009, beginning a 10-month mission to survey the entire sky in the infrared. This paper provides an overview of the cryogenic subsystem and initial on-orbit performance.

# SESSION- WP2 [Poster]: Space Cryocooler Applications Wednesday, May 19, 2010 – Poster Session: 9:30 AM– 10:30 AM

## [WP2-A026]

## RESPONSIVE SPACE CRYOCOOLER CONSIDERATIONS

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There is an increasing reliance on space in both the military and commercial sectors, and therefore space capabilities. Relying on exquisite satellite systems that take years to build and launch will not meet the needs of a rapid, flexible, and adaptable space arena. The solution is operationally responsive space, enabling space missions on tactically relevant timelines. This desire to rapidly augment or reconstitute space systems affects all satellite components, especially long lead items such as cryocoolers. This paper will discuss how space qualified cryocoolers need to be adapted in order to meet responsive space needs, including manufacturing time, modularity, etc

# SESSION- WP2 [Poster]: Space Cryocooler Applications Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A155]

## Developments of 1-4K class space mechanical coolers for new generation satellite missions in JAXA

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**Sumitomo Heavy Industries Ltd., Japan

Mechanical coolers are key technologies in order to utilize low temperature scientific instruments of new generation space science missions, such as the new X-ray astronomical satellite Astro-H, and the new infrared astronomical satellite SPICA. In particular, 1-4K class mechanical coolers are strongly required as a pre-cooler of low temperature detector's cooling system or to cool an space telescope with very low radiation background. In JAXA, two-stage Stirling coolers (2ST) for 20K and 4He JT coolers for 4.5K have been successfully developed and operated in space mission ('Akari' (Astro-F), 'JEM/SMILES'). Based on these heritages, 2ST coolers and 4He JT coolers have been modified and upgraded in reliability, cooling power, lower mechanical vibration, and longer life time. In the performance test of upgraded prototype mechanical coolers, these required cooling power of each coolers have been obtained. Then, the engineering model of 4K-class cooler which consists of two 2ST coolers and 4He JT cooler for the cooling system of Astro-H will be fabricated, and performance tests including a gravitational effect, level of vibration, and cooling behavior at the case of expected heat load in Astro-H will be verified. In this paper, these R&D status and performance test results of the 2ST coolers and 4He JT coolers will be reported. We will also report the development of 3He JT cooler for providing a 1.7K base temperature for detectors of SPICA.

# SESSION- WP2 [Poster]: Space Cryocooler Applications Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A209]

## Modified Methodology for Technology Forecasting: case study of cryocooler efficiency and induced vibration

D. Webb, J. Cha, S. Yuan

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

A methodology for forecasting cryocooler technology performance parameters will be presented. This presentation will show a step-by-step methodology for the analysis of historical trends in space capable cryocooler specific power and induced vibration. The analysis shown includes the data set from which the performance over time relationships were derived (adjusted to protect proprietary interests). Within the methodology are multiple technology improvement in space launch capability trends with time including temperature and the changes in efficiency including the approaching of the Carnot limit. A proposed method for the construction of a performance, by time and Technology Readiness Level (TRL) has also been derived and postulated.

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

# SESSION- WP2 [Poster]: Space Cryocooler Applications Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A159]

## Flight Hardware of the Cryogenic System for the Micro-X Sounding Rocket Telescope

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The Micro-X Imaging X-ray Spectrometer is a sounding rocket payload slated for launch in 2011. An array of Transition Edge Sensors, which requires cooling to 50 mK, will be used to obtain high resolution X-ray spectra of astronomical sources. An Adiabatic Demagnetization Refrigerator (ADR) forms the heart of the instrument's cryogenic system. It consists of a FAA salt pill in the bore of a low current 4 T superconducting magnet. The detector array is accommodated inside a magnesium housing which is thermally connected to the FAA salt. A bath of superfluid helium functions as a heat sink for the ADR. The helium tank is suspended inside a lightweight aluminum vacuum vessel by a set of re entrant G10 thrust tubes. The cryogenic system has been designed to withstand the extreme structural loads encountered in rocket flight, while at the same time providing hold-times sufficiently long to facilitate convenient operation during the launch campaign. Due to the short duration of a sounding rocket flight, the thermal time constant of the cold mass had to be kept on the order of only a few seconds. In addition, special attention has been paid to minimizing the heating of the cold stage due to the dissipation of vibration originating from the rocket motor. The assembly of the Micro-X cryogenic system has been completed, and performance tests have been carried out. We describe the design of the Micro-X cryogenic system and present the results of the performance tests.

# SESSION- WP2 [Poster]: Space Cryocooler Applications Wednesday, May 19, 2010 – Poster Session: 9:30 AM – 10:30 AM

## [WP2-A193]

## Problems and general structure of cooling system of space cryotelescope Millimetron

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Under a word wide cooperation have been started development of a space cryogenic 12 meter radiotelescope Millimetron [1,2,3]. The concept of cryogenic cooling of a telescope and cryocontainer with MM and SubMM wave receivers is presented. For cryogenic cooling have been designed a combination of passive and active systems based on radiating shields and cryorefrigerators. Refrigerators of Sub Kelvin level is planned for Sub MM receivers cooling.

References:

1.http://www.sron.rug.nl/millimetron/
2. http://www.asc.rssi.ru/millimetron/eng/millim_eng.htm
3. http://lerma7.obspm.fr/millimetron/Millimetron-Meeting/Welcome.html

# SESSION- WO3 [Oral]: Tactical Cryocoolers Wednesday, May 19, 2010 – Oral Session: 10:30 AM – 12:00 PM

## [WO3-A125]

## 10 K Airborne Cryocooler and High Efficiency Heat Exchangers

D. Glaister, W. Gully, P. Hendershot, C. Wilson, E. Marquardt

Ball Aerospace Technologies & Corporation, Boulder CO, USA

Ball Aerospace has designed, built, and characterized a compact refrigeration system for cooling very low temperature infrared imagers. The system is robust, will be integrated into an airborne application, and can also be used in space environments. This paper reviews the completed system testing and results as well as component testing of the high efficiency, micro-channel heat exchangers, which are an enabling technology for this cooler system. 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 15 K. 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.

# SESSION- WO3 [Oral]: Tactical Cryocoolers Wednesday, May 19, 2010 – Oral Session: 10:30 AM – 12:00 PM

## [WO3-A179]

## Life Testing of L-3 1.0-Watt Tactical Stirling Cryocooler for redundant space cooling application

M. Barr Raytheon Space and Airborne Systems, El Segundo CA, USA

This paper is a follow-up to one presented at the 2009 Space Cryogenics Workshop. Raytheon Space and Airborne Systems group works on programs that require vacuum maintenance up to and through launch environments. They have designed modules that accomplish this using ion pumps to remove air that leaks past seals. Ion Pumps, however, do not work well pumping water so there is a need for a cold trap upstream of the appendage ion pumps. To keep this trap cold up to and through launch, a high reliability, small, efficient and light-weight cryocooler system is needed. Raytheon chose the L-3 1.0-Watt Tactical Stirling Cryocooler System (cooler and drive electronics) for this mission. Some applications warrant redundancy for this function so a system has been designed with two Stirling coldfingers. They are attached to a common cold trap baffle such that either or both of them can maintain the temperature to colder than 90K. This insures that water is prevented from reaching the ion pumps so they can maintain system pressure below 1.0 E-4 torr. To accomplish this 'active redundancy,' certain control parameters had to be adjusted so that the coolers can 'share the load;' or either can assume the full load if necessary. Designs had to be set up to minimize side load on the coldfingers so the displacer motion within the Stirling coldfingers wasn't affected. Ten production cryocoolers and electronics were produced by L-3 and delivered to Raytheon. Of these, four were placed into production-like assemblies for life testing. Two life test set-ups used functional coolers paired with non-operational expanders to provide the simulated production side load environment. The third life test set-up used two functional coolers throughout the test. All three tests were run for six months with no cryocooler anomalies. Test results for L-3 acceptance testing and life test results are discussed. The remaining six cyrocoolers are slated for use on two production units (two cryocoolers each and two spares).

# SESSION- WO3 [Oral]: Tactical Cryocoolers Wednesday, May 19, 2010 – Oral Session: 10:30 AM - 12:00 PM

## [WO3-A022]

## The Development of a New Generation of Miniature Long Life Linear Coolers

W. Groep

Thales Cryogenics, Netherlands

Thales Cryogenics has an extensive background in delivering long life cryogenic coolers for military, civil and space programs. This cooler range is based on two main compressor concepts: close tolerance contact seals (UP) and flexure bearing (LSF/LPT) coolers. With both concepts Thales Cryogenics has achieved excellent lifetime results. New market developments require for more compact linear cryocoolers with long lifetimes. In this paper the development of two new compact linear cryocoolers will be outlined. Both coolers are initially designed for a ¼" IDCA cold finger and operation between 77K and 120K.The first cooler type, which is the UP8497, is a long life fully miniature close tolerance contact seal cooler with an expected lifetime of 15.000 hours. The second type, which is the LSF9997, is an extremely reliable cooler which is based on the well proven flexure bearing technology with an expected lifetime of well over 25.000 hours. The differences in cooler concepts will be described, including design and application trade-off's. Furthermore experimental results will be shown and discussed. Also the expected lifetimes of both concepts will be discussed and the roadmap towards even more improvements regarding the reliability of both concepts of Stirling coolers. Finally the development of miniature drive electronics suitable for this new generation of compact coolers will be presented.

# SESSION- WO3 [Oral]: Tactical Cryocoolers Wednesday, May 19, 2010 – Oral Session: 10:30 AM – 12:00 PM

## [WO3-A024]

## Reduction of Self Induced Vibration of Rotary Stirling Coolers

U. Binnun

FLIR Systems Inc., Boston MA, USA

An analytical method for calculating and modeling rotary stirling cooler self induced vibration is presented. We discuss in some details passive and active vibration reduction methods and ways to measure them. Actual data will be presented and compared with coolers before and after vibration reduction is implemented.

## SESSION- WO3 [Oral]: Tactical Cryocoolers Wednesday, May 19, 2010 – Oral Session: 10:30 AM – 12:00 PM

### [WO3-A047]

# Methods for Reducing Self Induced Vibration in Rotary Stirling Tactical Coolers

U. Binnun

FLIR Systems Inc., Boston MA, USA

FLIR Systems Inc. develops and applies tactical rotary stirling coolers in variety of IR military and commercial systems. It is well known that rotary coolers emit vibration levels large enough to cause significant degradation in system performance in terms of image quality, platform stabilization and audible noise. This paper describes in some detail methods and concepts used by FLIR'S development team to measure, model and engineer solutions to this problem. The paper present analytical models for predicting vibration emitions of dual piston crank mechanisms, brushless motor torsional vibration and more. Also, cooler vibration measurements methods and standards will be presented. The paper is concluded with actual test results and conclusions.

# SESSION- WO3 [Oral]: Tactical Cryocoolers Wednesday, May 19, 2010 – Oral Session: 10:30 AM – 12:00 PM

## [WO3-A123]

## STIRLING-CYCLE COOLER RELIABILITY GROWTH AT L-3 CE

D. Arndt, Q. Phan, D. Kuo

L-3 Communications, Pasadena CA, USA

L-3 CE has in place a continuous effort to evaluate and improve the lifetime of its cryocooler products. This effort includes analysis of both lab environment reliability tests and field data from production units. The purpose of this paper is to outline L-3 CE's life testing methodology and provide reliability data for L-3 CE cryocoolers, specifically for the 0.6-Watt Cooler (Model B602), 1.0-Watt Cooler (Model B610), and the 1.5-Watt Cooler (Model B1500). Cooler performance characteristics such as cooldown time, refrigeration capacity, and input power are monitored throughout the life of the cooler. The data presented here updates previously reported data.

# SESSION- WO4 [Oral]: Miniature Cryocoolers and Technologies Wednesday, May 19, 2010 – Oral Session: 1:30 PM – 3:00 PM

## [WO4-P104]

## Space Micro Pulse Tube Cooler

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Northrop Grumman Aerospace Systems
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The NGAS space micro pulse tube cooler (micro) is a split configuration cooler incorporating a coaxial cold head connected via a transfer line to a vibrationally balanced back to back linear compressor. The micro compressor is scaled from the flight proven high efficiency cooler (HEC) compressor and contains non-wearing pistons suspended on flexure bearings. Designed for > 10 year operation with no performance change, the 800 gram mechanical cooler can cool sensors and optics to temperatures <50K while rejecting heat to radiators over a wide range of reject temperatures. The very small, low vibration, high frequency cooler is designed to be readily integrated into space payloads. The coaxial cold head can also be integrated with custom focal planes into an integrated detector cooler assembly (IDCA) similar to those used with the shorter lived tactical coolers. This paper reports on the performance of this cooler.

# SESSION- WO4 [Oral]: Miniature Cryocoolers and Technologies Wednesday, May 19, 2010 – Oral Session: 1:30 PM – 3:00 PM

## [WO4-P050]

## Heat Rejection Capacity in Miniature Thermoacoustic Expanders (MTAEs) at Cryogenic Temperatures

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*Air Force Research Laboratory AFRL/RVSS, Kirtland NM, USA

Experiments have verified the feasibility of miniature thermo-acoustic expanders (MTAE) enabling heat remove from a cold stage expansion to a high-temperature reservoir (300K) in DC cold-stage flows. MTAEs feature to enhance cooling power output in recuperative type of cryocoolers without scarifying its reliability and simplicity in cold stage systems. Occurrences of the heat transport rely critically on the behavior of nonlinear wave systems created in miniature-scale channels (several hundred micron size) inside resonant-tube-bundles of MTAEs. This paper presents the experimental investigation of heat rejection capacity (the temperature span at which a heat flux occurs) and the influence of such a heat energy pumping on cooling performance of a MTAE operated in the cryogenic temperature between 133K and 77K so as to approach the limit of this technology's feasibility, both in the miniaturized design and the selected operating conditions. The characteristics of acoustic wave systems driven in the miniature channel with helium under different pressure and temperature conditions will be detected and reported. The observations and challenges of the thermo-acoustic streaming phenomenon and modeling in miniature or micron-scale channels will be discussed

# SESSION- WO4 [Oral]: Miniature Cryocoolers and Technologies Wednesday, May 19, 2010 – Oral Session: 1:30 PM – 3:00 PM

## [WO4-P112]

## Miniature pulse tube cooler at 100Hz

H. Chen, N. Xu, L. Yang, J. Cai, J. Liang

Technical Institute of Physics and Chemistry, CAS, China

Cryocoolers are often used in applications where small size and mass are needed. The diameter of regenerator can be decreased though the cooling capacity is decreased meanwhile. On the other hand, to diminish the PTC length, increasing the operating frequency is an effective method. At higher frequency the gas oscillates in less field, so the length requisite for regenerator can be reduced, as well as the pulse tube. However, high frequency leaves the working gas less time to transfer heat with the regenerator mesh.

In this paper, a prototype of 100Hz miniature pulse tube cooler is developed. The dimension of regenerator is optimized by REGEN3.3. Phase angle and mass flow rate expected at the cold end are gained by a well-designed inertance tube, which is optimized by DeltaEC. The phase shift angle and mass flow rate is also experimentally measured at the cold end of the pulse tube cooler.

An in-line prototype of miniature pulse tube cooler is manufactured firstly. The outer diameter of the regenerator is 7.8mm. The cooling capacity of 1W@80K is gained by about 30W PV power input. A coaxial prototype with a cold finger of 10mm diameter will be developed soon, whose length of pulse tube is even eliminated. Furthermore, coaxial type PTC is more comfortable for coupling with other apparatus.

# SESSION- WO4 [Oral]: Miniature Cryocoolers and Technologies Wednesday, May 19, 2010 – Oral Session: 1:30 PM – 3:00 PM

## [WO4-P198]

## Simulation of Boundary Layer Effects in the Pulse Tube of a Miniature Cryocooler

T. Conrad, S. Ghiaasiaan, C. Kirkconnell*
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*Iris Technology Corporation, Irvine CA, USA

As pulse tube cryocoolers are miniaturized, boundary layer effects in the pulse tube may become more important than they are for larger refrigerators. Nearly uniform flow in the pulse tube is believed necessary for efficient cryocooling, and this condition is compromised as the pulse tube diameter becomes smaller relative to the thermal and viscous boundary layer thicknesses. As a result, miniature pulse tube cryocoolers are likely to experience enhanced acoustic streaming losses compared to larger PTC's. This acoustic streaming results from thermal and viscous interactions between the working fluid and the pulse tube walls. The thermal and viscous penetration depths and their magnitudes relative to the pulse tube diameter and wall thickness are therefore important parameters for this phenomenon.

A parametric study of the effects of the pulse tube diameter and wall thickness, relative to the relevant boundary layer thicknesses, on acoustic streaming in the pulse tube was performed using CFD modeling. The effect of the operating frequency was also considered through the frequency dependence of the viscous and thermal penetration depths. Temperature dependant material properties were included in the CFD models because they play an important role in acoustic streaming. Results indicated that close attention must be given to the sizes of the boundary layers relative to the pulse tube physical dimensions when designing miniature pulse tube cryocoolers.

# SESSION- WO4 [Oral]: Miniature Cryocoolers and Technologies Wednesday, May 19, 2010 – Oral Session: 1:30 PM – 3:00 PM

## [WO4-P113]

## Compact linear split Stirling cryogenic cooler for high temperature infrared imagers

A. Veprik, S. Zehtzer, N. Pundak

Ricor, Cryogenic and Vacuum Systems, Israel

Split linear cryocoolers find use in a variety of high-resolution infrared imagers for using in airborne, heliborne, marine and vehicular platforms along with portable hand held and ground fixed applications. An upcoming generation of portable, high-definition night vision imagers will rely on the high temperature infrared detectors which are able to operate in the temperature range of 95 – 200K while showing the performance indices comparable with their traditional 77K rivals. Recent technological advances in industrial development of such high-temperature detectors initialized attempts for developing downsized split Stirling linear cryogenic coolers. Their known advantages, as compared to their rotary rivals, are superior flexibility in the system design, constant and high (circa 80Hz) driving frequency, lower wideband vibration export, unsurpassed reliability and aural stealth. The latest progress in designing highly efficient "moving magnet" resonant linear drives and accompanied electronics enable further essential reduction of the cooler size, weight and power consumption. The authors report on the successful development of a novel Ricor model K527 microminiature split Stirling linear cryogenic cooler successfully challenging integral rotary integral rivals also in terms of size, weight and electromechanical performances. Special attention is paid to resolving cooler induced vibration issues.

# SESSION- WP5 [Poster]: Pulse Tube Cryocoolers & Thermoacoustic Coolers Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P069]

## SITP's Miniature Coaxial Pulse Tube Cryocooler

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A single-stage miniature coaxial pulse tube cryocooler has been developed in Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SITP/CAS) to provide reliable low-noise cooling for a given infrared detector system. The designed cooling capacity is 1.2W@80K, and the more challenging work is the exacting requirement on its dimensions, which have to adapt to the given Dewar. The cold finger must be shorter than 50 mm and its outer diameter must not larger than 10 mm. The dimensions result in the insufficient regenerator potential and limit the phase-shifting ability of the system. A larger filling pressure of 3.6 Mpa and higher operating frequency of up to 70 Hz are adopted to increase the energy density, which will compensate for the decrease in working gas volume due to the miniature structure. The inertance tube consists of two parts with different inner diameter and length to achieve desirable phase relationship. A 1.5 kg dual opposed linear compressor is used to generate oscillating pressure wave, which is based on flexure bearing and moving magnet technology developed in the same group to realize light weight and low contamination. The design approach and trade-offs are discussed in detailed in this paper. The parametric studies and the performance characteristics are presented.

## [WP5-P128]

## Investigation of Multi-bypass Pulse Tube Cryocooler with Precooling


Y. Liu, L. Yang
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, P.R. China



A multi-bypass pulse tube cryocooler was designed and tested, and it could reach no load temperature of 23.1K with the input power of 200 W, the hot end of it was placed in room temperature. It is difficult to reach the temperature below 20K for single-stage Multi-bypass Pulse Tube Cryocooler. In order to gain lower temperature, multi-bypass pulse tube cryocooler with precooling is considered. Basing on previous high frequency multi-bypass pulse tube cryocooler which we have designed and tested, we design a multi-bypass pulse tube cryocooler with precooling. The hot end of the pulse tube cryocooler is placed at lower temperature. The system can reach no-load temperature of 17.03K with 80W input power, while the hot end around 80K. In this paper, the effect on the performance of pulse tube cryocooler of cold inertance tube, double inlet and multi-bypass in lower temperature are discussed. In the experiment, we also investigate the effect of the temperature of precooling stage, frequency, and average pressure.

# SESSION- WP5 [Poster]: Pulse Tube Cryocoolers & Thermoacoustic Coolers Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P180]

## Progress in the Development and Performance of a High Frequency 4 K Stirling-Type Pulse Tube Cryocooler.

P. Bradley, R. Radebaugh, E. Gerecht

National Institute of Science and Technology, Boulder CO, USA

Presently we are in the development process for a 4 K Stirling-type pulse tube cryocooler to support cooling requirements for a mobile THz detector system. In this paper we discuss the status of this development and the optimization methods for achieving 4 K with a three-stage hybrid design employing separate He-4 first and second stages that precool a He-3 third-stage. Acoustic power is provided by a linear compressor operating at 60 Hz and 2.5 MPa for the He-4 cryocoolers, whereas, a separate linear compressor operating at 30 Hz and 1.0 MPa provides acoustic power for the He-3 cryocooler. The first stage regenerator employs stainless steel mesh while the second stage regenerator employs erbium-praseodymium (ErPr). The third stage regenerator is layered with gadolinium oxysulphate (GOS) spheres at the cold end and erbium-praseodymium (ErPr) spheres at the warm end. This hybrid modular cryocooler design allows for a modular optimization approach for each cryocooler that mitigates time consuming redesign and fabrication of unaffected stages during the cryocooler development. Progress for each stage development and performance (goals and measured) optimization are presented.

## SESSION- WP5 [Poster]: Pulse Tube Cryocoolers & Thermoacoustic Coolers Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

### [WP5-P039]

# Influence of Ratio of Specific Heats on Thermoacoustic Performance

H. Kang
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Thermoacoustic researches have made great progress over decades, and benefited greatly from the publication of thermoacoustic conversion theory. However, a detail investigation of the effect of some important parameters on the behavior of the thermoacoustic performance is still lacking. One of these parameters is the ratio of specific heats. Thus, the influence of the ratio of specific heats on the thermoacoustic performance will be study in this paper. The result show that the optimal ratios of specific heats for the maximum acoustic power gain and efficiency are very different. With the increase of the ratio of specific heats, the acoustic power gain decreases while the thermoacoustic efficiency increases at first and then decreases. The best the ratio of specific heats for the thermoacoustic efficiency is not always the highest value. It is influenced by the parameters of the acoustic fields and the regenerator structure.

# SESSION- WP5 [Poster]: Pulse Tube Cryocoolers & Thermoacoustic Coolers Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P060]

## Investigations on a Standing Wave Thermoacoustic Refrigerator

R. Dhuley, M. Atrey
Indian Institute of Technology Bombay, Mumbai, India

Thermoacoustic Refrigerators (TARs) use acoustic energy to generate cooling. Development of TARs has gathered much attention due to their innate advantages like use of inert working fluids and minimal moving parts. The present work deals with experimental investigation on a Standing Wave TAR. A one-dimensional transient state model based on the linear theory, has been developed to predict the performance of TAR. Accordingly, a loudspeaker driven standing wave TAR with parallel plate Mylar stack, and a quarter and a half wavelength resonators has been constructed. The work aims to study the performance of the TAR when operated at different charging pressures, drive ratios and working gases like Helium and Nitrogen. The experimental results obtained are compared with those predicted by the developed model.

# SESSION- WP5 [Poster]: Pulse Tube Cryocoolers & Thermoacoustic Coolers Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P134]

## Design of Standing Wave Type Thermoacustic Prime Mover for 300 HZ Operating Frequency

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*Mech. Eng. Dept., S. V. National Institute of Technology, Surat, India
**Indian Institute of Technology Bombay, Mumbai, India

Thermoacoustically driven pulse tube cryocooler is gaining significant interest in the recent time due to its key advantage of complete absence of moving components from the entire system. Lot of literature regarding fundamentals of acoustic theory and design aspects are available. Devices, such as prime mover and refrigerator, based on the theory are gaining importance due to the advantages associated with them. The present work gives a simple design procedure for 300 Hz Standing Wave Type Thermoacoustic Prime mover having parallel plate type stack. The necessary code is written in MATLAB for solving the Rott's wave equation for this purpose. The code is validated by comparing the results with those available in the literature. The work further reports effect of operating and design parameters on the performance of the standing wave type thermoacoustic prime mover. The system performance, mainly in terms of acoustic power and pressure ratio, is significantly influenced by the operating and design parameters. The operating parameters are heat input, hot end temperature, frequency, filling pressure and design parameters are stack length, stack position, resonator length, dimensions of acoustic amplifier etc.

# SESSION- WP5 [Poster]: Pulse Tube Cryocoolers & Thermoacoustic Coolers Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P139]

## Improvements on a thermoacoustically-driven pulse tube cooler operating at 300 Hz

G. Yu, X. Wang, W. Dai, E. Luo
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High frequency thermoacoustically-driven pulse tube cooler has the advantages of high energy density, compact structure and high reliability. This article describes the performance of a high frequency standing wave thermoacoustic heat engine driven pulse tube cooler system working around 300 Hz. Through a series of improvements, the pulse tube cooler in our lab get four-fold increase in the cooling power than our last report. The influence of phase shifter and regenerator are investigated in detail, which is based on linear thermoacoustic theory. A cooling power of 1.04 W at 80 K and a no load temperature of 63 K are obtained with 508 W heating power.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P061]

## Phasor Analysis of Pulse Tube Refrigerator

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Phasor diagram for a pulse tube refrigerator (PTR) is a vectorial representation of mass flow rate, pressure and temperature at different locations as a function of time. With the help of phasor diagram, working of different types of pulse tube refrigerators can be well understood. The phasor analysis based on these diagrams gives an idea regarding underlying complex phenomena of the PTR. In the present work, a simplified model has been presented based on the assumption that there is no phase difference between temperature and pressure throughout the working space. The phasor analysis is extended to two stage Orifice Pulse Tube Refrigerator (OPTR) and Double Inlet PTR (DIPTR). The important contribution of the work is that it highlights the condition for which the DIPTR will work better than the OPTR.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P080]

## THEORETICAL AND EXPERIMENTAL INVESTIGATION OF 30 K SINGLE STAGE G-M TYPE PULSE TUBE CRYOCOOLER

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**Mech. Eng. Dept., Indian Institute of Technology Bombay, Mumbai, India

Theoretical modeling of pulse tube Cryocooler plays an important role in a design and development of Cryocooler. In the present work, a thermodynamic model of G-M type double inlet pulse tube Cryocooler has been developed. It includes calculation of ideal refrigeration power, various losses and hence net refrigeration power. An experimental setup was designed and fabricated to carry out experimental investigations on G-M type double-inlet pulse tube cryocooler. Experiments were conducted and results obtained were used for comparing the isothermal model developed in the present work. Effect of orifice valve opening, double inlet valve opening and frequency on the performance of cryocooler is studied in terms of net refrigeration power and no load temperature. A no load temperature of 28 K was recorded at an average pressure of 12 bar and operating frequency of 1.5 Hz. The net refrigeration power of 37 W was measured at 80 K for 16 bar average pressure and 1.5 Hz frequency.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 – 4:00 PM

## [WP5-P090]

## Theoretical and experimental investigation on the temperature mismatch and its optimization of coaxial inertance pulse tube cryocoolers

L. Wang, H. Dang, Y. Wu, S. Li, K. Yang, C. Xiong
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In a coaxial inertance pulse tube cryocooler (IPTC), the temperature mismatch between regenerator and pulse tube evidently influence the fluid dynamics and thermodynamics in the system, and then have a great effect on the cooler performance. In this paper, models about coaxial IPTC with or without radial conduction between regenerator and pulse tube are built, and dimensionless factors are used to analyze the loss mechanism. Several empirical coefficients considering these losses are theoretically analyzed, and the results provide the reference for optimizing general 1-D simulation models. Experiments aiming to find the most desirable matches are conducted systematically. Displacement transducers are used to analyze the pressure-flow phase angles in the practical system, which then compare with the simulated one and give the direction of optimization. Base on above studies, the initial experiments on designed a single-stage coaxial IPTC has achieved a COP of 2% at 60K and 4.3% at 80K with around 100 W of input electric power. The experimental performance is in general agreement with the simulation and verifies the design method.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 – 4:00 PM

## [WP5-P145]

## CFD Simulation of Natural Convection in a Pulse Tube Cryocooler

J. Ren, J. Hu, L. Zhang, E. Lou, Y. Huang

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

The pulse tube is an empty tube used to connect the hot and cold heat exchangers in a pulse tube cooler. If the cold end of the pulse tube is upward, the cooling performance of the pulse tube cooler will be severely deteriorated because of the natural convection inside the pulse tube. Due to the oscillating flow, the natural convection mechanism is quite different from steady flow systems. In this article, a three-dimensional computational fluid dynamics (CFD) simulation study of pulse tube cryocooler will be presented. The computations shows an increase of the dynamic pressure that can reduce the influence of gravity orientation effect, but cannot restrain it. When the pulse tube is added with a few parts of resistance (like cooper screens) in proportional spacing, the natural convection can be well suppressed. The present simulation just focuses on the pulse tube and phase shifter now, further research of entire cryocooler has in hand.

# SESSION-WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P188]

## Inertance Tube and Reservoir Modeling – Meshing, Convergence and Friction Factors for Oscillating Flow

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Pulse tube refrigerators (PTRs) have made dramatic improvements in reliability, efficiency and usage, with the addition of the inertance tube helping to create the improvements. The combination of the inertance tube and reservoir help to create a certain phase shift between mass flow rate and pressure that affects the fluid dynamics in the PTR. Current models are not adequate in accurately predicting the phase shifts in these oscillating refrigerators. Various modeling techniques have yet to address the issue of numerical solution convergence, especially with respect to the meshing and time step sizes when using Computational Fluid Dynamics (CFD) models. This study aims to address the issue based on comparisons to a set of experimental results. Along with the CFD correlation a comparison with a distributed inertance tube model based on new friction factors for oscillating flow will be reported.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P201]

## Thermodynamic comparison of two-stage pulse tube refrigerators for two different configurations

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Using exergy analysis, control thermodynamic models of two-stage Pulse Tube Refrigerators (PTRs) are developed for two different configurations. The models assume that phase shift controllers exist that control the phase shift between the mass flow and pressure in the pulse tubes. In one configuration, using thermally-coupled stages, separate gas circuits are used, thus requiring two compressors. This configuration provides flexibility for thermodynamic optimization. In another configuration, a conventional gas-coupled two-stage PTR is used where a constraint exists for mass flow allocations and the implementation of the phase shift control. The models include controllers for flow conductance, heat transfer effectiveness, and conduction heat transfer parameters in the regenerators in both stages for each configuration. The effects of the allocation of the values of flow conductance and ineffectiveness parameters in the regenerators, the mid-stage temperature, and the phase shift in each stage on the performance of the refrigerators are investigated. Important dimensionless parameters controlling the thermodynamic performance of the two-stage PTRs for each configuration is developed and discussed.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P130]

## Effect of Frequency on Hydrodynamic Parameters of Mesh Fillers in Oscillatory Flow

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An experimental investigation was carried out to determine the effect of frequency on the porous media hydrodynamic closure relations during steady periodic flow. Using room temperature helium as the working fluid, stacked discs of #635 stainless steel and #325 phosphor bronze wire meshes were subjected to an oscillatory flow field. Dynamic pressure transducers recorded waveforms upstream and downstream of the porous section at charge pressures of 2.86 and 3.55 MPa. Tests were performed in the axial direction at frequencies ranging from 50 to 200 Hz. Hydrodynamic parameters were determined using a CFD-assisted methodology. The experimental test section and its vicinity were simulated using Fluent code and mesh fillers were modeled as a porous structure. Model porous media hydrodynamic parameters were iteratively adjusted to match the model predictions to the experimental results. Sample directional resistances related to the Darcy permeability and Forchheimer's inertial coefficient, were obtained at discrete frequencies.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P140]

## Oscillating Flow and Heat Transfer in Porous Structure Regenerator in Pulse Tube Cryocooler

X. Chang
Technical Institute of Physics and Chemistry, CAS, China

A numerical study is performed for the oscillating flow and heat transfer in regenerator of pulse tube refrigerator. The main configuration of regenerator is similar to porous media. In order to depict the porous configuration of regenerator, the quartet structure generation set (QSGS) is proposed based on the stochastic cluster growth theory for generating realistic microstructures of porous media. A coupled double-distribution-function lattice Boltzmann method which is developed for the compressible Navier-Stokes equation is used to calculate the friction coefficient of oscillating flow and the heat transfer characteristics in porous media. The oscillatory flow is driven by a periodic pressure wave or velocity wave, and isothermal and adiabatic boundary conditions are considered. The bounce-back boundary condition is used to tackle the interface between solid and fluid of porous media. The flow characteristics at a pore scale, and the influences of Reynolds number on friction coefficient and some parameters on the mean heat flux are studied. The simulation results prove coupled double-distribution-function lattice Boltzmann method for the compressible Navier-Stokes equations can simulate the oscillating flow and heat transfer in regenerator.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P072]

## Comparison of Thermoelectric and Stirling Type Cryocoolers Using Control Thermodynamic Model

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*Air Force Research Laboratory AFRL/RVSS, Kirtland NM, USA

New efforts are underway to develop thermoelectric materials for cooling of infrared detectors at cryogenic temperatures. Stirling Type cryocoolers routinely produce cooling at cryogenic temperatures with good efficiency but challenges remain in their miniaturization, reliability, and vibration reduction for space applications. In this study, a thermodynamic comparison of Stirling Type and Thermoelectric (TE) cryocoolers is made for a typical second stage cryogenic refrigerator (30 K to 80K). It is assumed that a reservoir at 80 K is available and a cooling load at 40 K is desired. It is shown that under the assumption of availability of TE materials with a reasonably high figure of merit a multistage TE cryocooler is required. For comparison of the performance of the cryocoolers, thermodynamic models of the Stirling Type and the multistage TE cryocoolers are developed. The effect of important system parameters on the performance of the cryocoolers is presented. The thermal design challenges of miniaturization of Stirling Type cryocoolers and the development of multistage TE cryocoolers with high efficiency are discussed.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P156]

## A study of temperature gradient inside the AMR bed at room temperature

H. SAKAMOTO, S. UCHIMOTO, H. NAKAGOME, T. KOBAYASHI*, S. KAJI*, A. SAITO*

Chiba University, Japan
*Toshiba Corporation, Japan

Magnetic refrigeration is based on magnetocaloric effect (MCE) in magnetic materials. At room temperature, Gd or Gd-R is widely used as the magnetic refrigerant and the active magnetic regeneration (AMR) cycle is suitable for refrigeration. AMR refrigerator makes temperature gradient inside the AMR bed by using the heat transfer fluid, so, temperature of the magnetic material in the bed is different by position. Generally, the working temperature region of magnet refrigerant is restricted by the magnetic entropy change which depends on temperature. The case of Gd and Gd-R, the entropy change shows sharp peak. Therefore, characteristic peak points of work, which depend on physicality, initial temperature, and so on, exist inside the AMR bed. In addition, the peak point moves on while the AMR cycle operation, making the temperature gradient, AMR refrigeration has many unknown. This paper will show the temperature profiling and analysis on the process of the making temperature gradient.

# SESSION- WP5 [Poster]: Cryocooler Modeling Wednesday, May 19, 2010 – Poster Session: 3:00 PM – 4:00 PM

## [WP5-P087]

## Investigation on the Phase Characteristics of High Frequency Inertance Pulse Tube Cryocoolers above 50 K

S. Li, H. Dang, Y. Wu, L. Wang, K. Yang
Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

Phase characteristics of an inertance pulse tube cryocooler (IPTC) mainly include the mass flow, the pressure amplitude and the phase angle between them, which are decisive factors for the cooler performance, while often change evidently when inertance tubes vary. In this paper, theoretical analysis and experimental study were carried out on the phase characteristics of high frequency single-stage IPTCs developed in our laboratory operating between 50 K and 200K with a variety of inertance tube geometries. The theoretical analysis focused on investigating the amplitude and phase angle at various locations and setting up an optimum phasor relationship of the cooler by combining phasor analysis, REGEN 3.2 and turbulent-flow thermoacoustic model for the inertance tube. The COP was calculated, also the influence of compressor efficiency was analyzed. The experimental study stressed on evaluating the phase characteristics of the cooler by making measurements of the key parameters. The measurements included the compressor piston position using LVDT (linear variable differential transformer), the pressure amplitude in the reservoir, at outlet of compressor and the warm end of the pulse tube, and the phase angle among them. The measured results were compared with the theoretical model. Both theoretical and experimental investigations implied that the change of the inertance characteristics had a great influence on the pressure difference, cooling power, PV power and the compressor efficiency, and thus the optimization of the inertance tube should consider both the cold finger efficiency and the compressor resonance simultaneously to achieve an optimum efficiency of the IPTC.

# SESSION- WO6 [Oral]: Pulse Tube Cryocooler Analysis and Experiments Wednesday, May 19, 2010 – Oral Session: 4:00 PM – 5:30 PM

## [WO6-P174]

## Flow and Heat Transfer Processes in an Orifice type Pulse Tube Refrigerator

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Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia PA, USA

An experimental and numerical study is reported here to investigate the fundamental flow and heat transfer processes in an orifice type pulse tube refrigerator (OPTR). The general design of an OPTR incorporates a pressure wave generator, a transfer line, an after cooler, a regenerator, a pulse tube, a pair of heat exchangers for the cold and hot ends, an orifice valve and a reservoir. The pressure wave generator used has dual opposed piston arrangement. The experiments and simulations are done at different frequencies with helium as the working fluid. The experimental study includes pressure and temperature measurements at key locations along the system. The analysis of the OPTR system operating under a variety of thermal boundary conditions is carried out via computational fluid dynamics (CFD) at different frequencies. The simulation represents fully coupled systems operating in steady-periodic mode. The externally imposed boundary conditions are a cyclically moving piston wall at one end of the tube and constant temperature or heat flux boundaries at the external walls of the hot end and cold end heat exchangers. The combined experimental and computational studies attempt to carry out a performance analysis of the system. The existence of an optimum frequency corresponding to the minimum cold end temperature for given operating boundary conditions is investigated. The appearance of secondary-flow recirculation at the vicinity of component-to-component junctions is known to reduce the heat pumping effect from low temperature heat exchanger to high temperature heat exchangers. At low frequencies, the low pumping rate affects the minimum temperature attained. The frequency for optimum system performance is determined both experimentally and numerically.

# SESSION- WO6 [Oral]: Pulse Tube Cryocooler Analysis and Experiments Wednesday, May 19, 2010 – Oral Session: 4:00 PM – 5:30 PM

## [WO6-P175]

## Effect of Component Geometry on Flow Nonuniformities In A Large Pulse Cryocooler

M. Lewis, R. Taylor*, P. Bradley, R. Radebaugh

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A single-stage pulse tube cryocooler was designed to achieve 50 W of refrigeration power at 50 K when driver by a pressure oscillator that can produce up to 2.8 kW of acoustic power at 60 Hz. Initial experimental data produced no-load temperatures that were considerably higher than expected. Improvements were made with the warm end heat exchanger and aftercooler and diffusion bonding of the copper screen matrix materials which produces significant improvements to the low end temperatures. The primary diagnostic tools utilized were four equidistant azimuthally spaced thermocouples located at the aftercooler exit, center plane of the regenerator component, and center plane of the pulse tube component. These tools provided temperature distribution information throughout the system and how specific geometry changes throughout the pulse tube cryocooler would affect overall performance. This paper address specific geometry changes to several major components of the cryocooler and their effect on the cryocooler performance. These include the transition piece from the inertance tube where the helium gas is entering and exiting the warm end heat exchanger and pulse tube. Pulse tubes with various aspect ratios are tested to find the optimum aspect ratio. A major modification to the cold end heat exchanger matrix design will be implemented for more uniform gas flow through the diffusion bonded copper screen stacks. The effect of interspersing various amounts of copper screen along the stainless steel regenerator packing is also investigated.

# SESSION- WO6 [Oral]: Pulse Tube Cryocooler Analysis and Experiments Wednesday, May 19, 2010 – Oral Session: 4:00 PM – 5:30 PM

## [WO6-P095]

## Two-Dimensional Analysis and Optimization of an Inertance Tube Pulse Tube Refrigerator

R. Jahanbakhshi, M. Saidi, F. Roshanghalb

Sharif University of Technology, Tehran, Islamic Republic Of Iran

Pulse Tube Refrigerator (PTR) has an exceptional feature among all similar refrigerators, because of its unique characteristics such as long lifetime, compact size and no moving parts in low temperature. Despite of all these advantages because of its low efficiency, many researchers are trying to optimize performance of this refrigerator. Most of these efforts are based on one-dimensional simulation of the system. In this paper, a two-dimensional analysis is performed to study the nature of flow field in an Inertance Tube Pulse Tube Refrigerator (ITPTR). This analysis is based on a numerical modeling of an entire ITPTR. To reach this purpose the two-dimensional form of mass, momentum and energy equation with an axi-symmetric assumption solved by a commercial computational fluid dynamic (CFD) code. For verifying the simulation a pulse tube refrigerator prototype has been designed, fabricated and tested in our laboratory. In this simulation the modeled system is studied in different operational and geometrical conditions to achieve an optimum performance. In favor of this purpose the effect of some key parameters on the performance of ITPTR are studied. These parameters include variable mesh size in regenerator, pulse tube's aspect ratio, length of Inertance tube, operating pressure and pressure amplitude. Also to achieve a phenomenal understanding of oscillatory flow in PTR, the flow pattern in different local and temporal position is studied and its effect on efficiency of system is reported.

# SESSION- WO6 [Oral]: Pulse Tube Cryocooler Analysis and Experiments Wednesday, May 19, 2010 – Oral Session: 4:00 PM – 5:30 PM

## [WO6-P119]

## Second Law Based Analysis of High Frequency Two-Stage Pulse Tube Cryocoolers

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High frequency multi stage Pulse Tube Cryocoolers (PTCs) have been taken into consideration recently because of reliability, long life and absence of moving part at their cold head. This paper represents a comprehensive numerical simulation method to investigate a two-stage PTC with 30-50 Hz operating frequencies, which is intended to achieve 4 K at the second stage. Whole components of the two-stage PTC are modeled employing the nodal analysis technique to discretize the mass, momentum and energy conservation equations. SUTPTC code has been developed in cryocooler laboratory of Sharif University of Technology (SUT) to analyze and optimize the two-stage cryocooler performance. A quasi Newtonian method, namely the Broyden technique has been used to improve the convergence of the numerical code and running time without losing the accuracy. The SUTPTC code has been validated with the experimental data of the existing PTC at our laboratory and the literature as well. Employing the proposed code, the effect of first stage precooling, type of screen meshes in the regenerators, characteristics of tube sections and opening of the double inlet orifices on performance of the two-stage PTC have been investigated. In this respect, Second law of thermodynamics has been employed to analyze and optimize the performance of the cryocooler.

# SESSION- WO6 [Oral]: Pulse Tube Cryocooler Analysis and Experiments Wednesday, May 19, 2010 – Oral Session: 4:00 PM – 5:30 PM

## [WO6-P167]

## Performance analysis of a contoured pulse tube refrigerator

M. Gholamrezaei

Sharif University of Technology, Tehran, Islamic Republic of Iran

This paper presents the results of a proposed contoured inertance-type pulse tube refrigerator. While a tapered pulse tube introduces the variation of the cross section of the pulse tube with a constant cone angle, the present results indicate that the performance is further improved by local optimization of the cone angle along the pulse tube. A two dimensional model for the contoured pulse tube is developed. Linearized conservation equations of mass, momentum, and energy for the working gas in conjunction with the energy equation for the tube wall are applied to the pulse tube. The outer surface of the pulse tube wall is assumed adiabatic. The effects of contoured pulse tube on the axial velocity and mean temperature are obtained. A comparison is made between uniform cross-section pulse tube, tapered pulse tube, and contoured pulse tube. In addition, the results are discussed for small and large capacity cryocoolers.

# SESSION- WO6 [Oral]: Pulse Tube Cryocooler Analysis and Experiments Wednesday, May 19, 2010 – Oral Session: 4:00 PM – 5:30 PM

## [WO6-P168]

## Numerical simulation of heat and fluid interaction of a contoured pulse tube refrigerator

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Sharif University of Technology, Tehran, Islamic Republic Of Iran

This paper presents the results of a numerical simulation of heat and fluid interaction of a viscous compressible oscillating flow for a proposed contoured inertance-type pulse tube refrigerator. While a tapered pulse tube introduces the variation of the cross section of the pulse tube with a constant cone angle, the present results indicate that the performance is further improved by local optimization of the cone angle along the pulse tube. The continuity equation, the two-dimensional Navier–Stokes equation, and the conservation equation of energy for viscous compressible gas are numerically solved by employing the finite element method. The magnitude and the distribution of the secondary flow are examined. A comparison is made between uniform cross-section pulse tube, tapered pulse tube, and contoured pulse tube.

# SESSION- THO1 [Oral]: Single Stage Stirling/Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

## [THO1-A068]

## Performance Investigation on SITP's 60K High Frequency Single-stage Coaxial Pulse Tube Cryocoolers

H. Dang, L. Wang, Y. Wu, S. Li, K. Yang

Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SITP/CAS) has developed a series of high frequency single-stage coaxial pulse tube cryocoolers to provide reliable low-noise cooling at 60 K for the space-borne long wave infrared focal plane array. The design and optimization are based on a simplified and efficient numerical simulation method developed in the same group by analyzing the thermodynamic behavior of gas parcels in the oscillating flow. The cooler prototypes generally provide 2 W of cooling power at 60 K with around 100 W of electric input power and 293 K reject temperature. 2.5W@60K can be achieved when the input power increases to 127 W. For a typical cooler, the outer diameter of the cold finger is around 20 mm, and the overall weight including cooler control electronics is below 10 kg. The split arrangement is adopted and an Oxford-type linear compressor with dual-opposed piston is connected to the cold finger with a 20 cm flexible metallic tube. The inertance tubes together with a gas reservoir serve as the only phase-shifting mechanism. Both cold tip and warm heat exchange are all fine slit configuration fabricated with electro discharge machining technology to enhance heat exchange performance. This paper describes the application background and system design, and detailed performance characteristics of the coolers are investigated and evaluated.

# SESSION- THO1 [Oral]: Single Stage Stirling/Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

## [THO1-A114]

## HEC Pulse Tube Coaxial Cold Head Coolers

T. Nguyen, G. Toma, C. Jaco, M. Michaelian, J. Raab,

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A large number of NGAS high efficiency coolers (HEC) have been manufactured for 6 different space payload designs using a linear configuration cold head that is integrally mounted to the compressor. One of the payloads has been in orbital operation since 2005 and a second since 2009. For some applications it may be desirable to have a different cold head mechanical and thermal interface in order to ease integration into the system. For that purpose we have developed both one and two stage HEC coolers that incorporate coaxial cold heads that are integrally mounted to the compressor. The single thermal and mechanical mounting interface of this integral configuration eases integration with a payload and reduces its complexity compared to a split cold head version that requires two warm interfaces rather than one. In this paper we present the measured performance of the single stage HEC coaxial cold head cooler in its integral configuration and compare its performance with the linear cold head version. We also present the measured performance of the parallel cold head 2 stage version of the cooler designed for the simultaneous cooling of both focal planes at temperatures > 35K and optics and filters at temperatures > 75K.

# SESSION-THO1 [Oral]: Single Stage Stirling/Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

## [THO1-A170]

## Single-Stage Large Pulse-Tube Cooler for 50K, with Tapered Buffer Tube

P. Spoor

CFIC Inc., Troy NY, USA

The ability of large-capacity single-stage pulse tube coolers to reach low temperatures is often limited by Rayleigh streaming, or the natural boundary-layer convection that occurs in the buffer tube (pulse tube). In Olson and Swift's landmark 1997 paper, they explained how a tapered buffer tube could suppress this streaming. Subsequent work by Swift and others has shown that the streaming can also be suppressed by judicious choice of terminating impedance (inertance tube length, e.g.). This is the approach usually taken, for a straight buffer tube is simpler and the impedance that suppresses streaming is close to that which optimizes the Stirling cycle phasing in the regenerator. However, at temperatures below 70K, the ideal cycle phasing begins to diverge from the streaming-suppression phasing, and a theoretical benefit can be derived from using a tapered buffer tube to reach lower temperatures in a single stage. Measurements on a recently built large pulse tube cooler with a tapered buffer tube will be presented, and the effects of the taper angle will be discussed.

# SESSION- THO1 [Oral]: Single Stage Stirling/Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

## [THO1-A070]

## Development of SITP's Large Capacity High Frequency Coaxial Inertance Pulse Tube Cryocoolers

H. Dang, Y. Wu, L. Wang, S. Li, K. Yang

Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

Large capacity high frequency single-stage coaxial inertance pulse tube cryocoolers have been developed in Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SITP/CAS) in order to provide larger cooling powers in the range of 80-100 K for the space-borne infrared detector systems. The typical cooling performance of the cooler prototypes is to provide 5 W at 80 K or 8 W at 100 K with around 125 W of electric input power and 310 K reject temperature while the forced air cooling is employed at the warm end. A split dual opposed piston linear compressor with a maximum swept volume of 8.0 cc is connected to the cold finger by a 30 cm flexible tube. The design and performance optimization approaches for the system are discussed in detailed, and some key factors influencing the performance are indentified. This paper also describes the efforts to realize the engineering prototypes of the coolers.

## SESSION- THO1 [Oral]: Single Stage Stirling/Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

### [THO1-A078]

# A 100 Hz pulse tube cryocooler working at liquid nitrogen temperature

J. Hu, X. Wang, L. Zhang, W. Dai, E. Luo

Technical Institute of Physics and Chemistry, CAS, China

Higher operating frequency generally allows the size and mass of a linear compressor to be reduced for a given electric power input. Increasing the operating frequency is an effective way to produce a more compact pulse tube cryocooler driven by a linear compressor. However, simply increasing the frequency leads to large losses in the regenerator of the pulse tube cryocooler. So it is of great importance to design an efficiency pulse tube cryocooler with high frequency. This paper will introduce the performance of a small fast cool-down pulse tube cryocooler with high energy density. The diameter of the regenerator is 8 mm and the operating frequency is 100 Hz. At reject temperature of 293 K, the lowest cooling temperature of the pulse tube cryocooler is 73 K with 5 W acoustic power input. Increasing the acoustic power to 34.8 W, the lowest cooling temperature reaches 46 K. It only takes less than 3 minutes to reach 77 K and lift 2.36 W cooling power. If a linear compressor with efficiency of 70% is obtainable, the relative Carnot efficiency of the cryocooler is 14.2%.

# SESSION- THO1 [Oral]: Single Stage Stirling/Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

## [THO1-A138]

## Performance of a Stirling-type Pulse Tube Cooler for high efficiency operation at 100Hz

X. Wang, W. Dai, J. Hu, E. Luo, Y. Zhou

Technical Institute of Physics and Chemistry, CAS, China

High efficiency pulse tube cooler driven by linear compressor usually operates between 30 and 60 Hz. This article presents the performance of a high efficiency in-line PTC with an operating frequency of 100 Hz. To couple the PTC, the parameters of linear compressor are optimized using compressor governing equation. The theoretical model of PTC is described using thermoacoustic theory. The analytical results indicate that an appropriate phase at hot end of pulse tube can be easily obtained at such a high frequency with inertance tube plus the reservoir as the phase shifter. Different aspects of the PTC performance are investigated experimentally. A no load temperature of 43 K and a cooling power of 8.55 W at 77 K are obtained with 180 W input electric power.

# SESSION- THO1 [Oral]: Single Stage Stirling/Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 8:00 AM – 9:45 AM

## [THO1-A183]

## Experimental Investigation on a Single-stage Stirling-type Pulse Tube Cryocooler Working around 30 K

J. Ren, W. Dai, E. Luo, J. Hu, X. Wang

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

Stirling-type pulse tube cryocoolers are promising candidates for space application and cooling HTS devices. It is rather difficult for a Single-stage Stirling-type pulse tube cryocoolers (SSPTCs) to reach a cooling temperature below 30 K. In this article, a SSPTC driven by linear compressor was designed, fabricated and experimentally investigated. By optimizing operating conditions, without the double-inlet phase shifter, the cryocooler has reached a no-load cooling temperature around 30 K at 35 Hz. An impedance match between the cold head and the compressor are investigated. At this frequency, since the inertance tube alone cannot provide sufficient phase for the cooler, double-inlet is further used for a lower temperature.

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# SESSION- THO2 [Oral]: Commercial Industrial Cryocooler and Applications Thursday, May 20, 2010 – Oral Session: 10:15 AM – 11:30 AM

## [THO2-A030]

## Development of High Efficiency 4K Two-Stage Pulse Tube Cryocooler

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Sumitomo Heavy Industries Ltd., 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. SHI has been continuously improving the efficiency of 4K pulse tube cryocooler in order to be exchangeable with 4K GM cryocooler. Cooling capacity has been improved to be equivalent to 4K GM. And also, performance in helium atmosphere has been measured and improved. The performance in helium atmosphere has been improved significantly. Experimental results will be reported in this paper.

# SESSION- THO2 [Oral]: Commercial Industrial Cryocooler and Applications Thursday, May 20, 2010 – Oral Session: 10:15 AM – 11:30 AM

## [THO2-A043]

## An oil-free DC compressor for GM type cold heads.

A. Caughley
Industrial Research Ltd., New Zealand

Industrial Research Ltd (IRL) has developed a novel metallic-diaphragm pressure wave generator technology for large high frequency (30-60 Hz) pulse tube cryocoolers. A diaphragm pressure wave generator, using a conventionally lubricated motor-crank drive, provides a clean pressure wave for a cryocooler. High frequency pulse tubes are their most efficient when closely coupled to pressure wave generators. There are, however, many applications which require the physical separation of the compressor from the cold head such as a Gifford McMahon (GM) system. Furthermore, GM cryocoolers perform well at low temperatures due in part to their low frequency (~1Hz) operation. GM cryocoolers typically employ compressors related to air conditioning compressors which need filters to remove the compressor oil from the helium flow, thus increasing maintenance. This paper describes the development of an oil free DC compressor fabricated by fitting a reed valve assembly to the outlet of a 200ml swept-volume diaphragm pressure wave generator. The system was designed to charge a high pressure tank to 16 bar drawing gas from a low pressure tank held at 5 bar. Helium mass flow rate was predicted to be 3.2 g/s. Results of testing the compressor firstly with an orifice flow restriction, then secondly with a GM cold head will be presented.

# SESSION- THO2 [Oral]: Commercial Industrial Cryocooler and Applications Thursday, May 20, 2010 – Oral Session: 10:15 AM – 11:30 AM

## [THO2-A195]

## Experimental study of Active Magnetic Regenerator (AMR) composed of spherical GdN

Y. Hirayama, H. Okada, T. Nakagawa, T. Yamamoto, T. Kusunose, T. Numazawa*, M. Koichi**, T. Irie***, E. Nakamura***
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*National Institute for Materials Science, Japan
**Kanazawa University, Japan
*** SANTOKU Corporation, Japan

For the hydrogen society expected in the near-future, high efficiency transport and storage of hydrogen is one of the most important requirements. The magnetic cooling method may provide higher efficiency, even at low temperature. This technology relies on solid materials exhibiting large magnetocaloric effect, a nearly reversible temperature change induced by a magnetic field change. Though AMR refrigeration devices have the potential to be more efficient than those using conventional refrigeration techniques, to realize it, optimum materials, regenerator design, and cycle parameters must be determined. We have found that the mononitrides of rare earth (RE) elements, Gd, Tb, Dy, Ho, Er, and their binary nitrides are promising candidate materials for magnetic cooling to be cooled down to the temperature of liquid hydrogen (20K). To verify their effectiveness for a magnetic refrigerant, GdN sphere material without crack was synthesized by the Hot Isostatic Pressing. The magnetization and specific heat of the nitride material was measured, and its curie temperature was found about 65K. Magnetic entropy change DS and adiabatic temperature change DTad were evaluated from the entropy curves. DS and DTad are larger in the wide temperature range than those of intermetallic compounds so far reported. We observed that temperature swinging of 5 degrees are steadily induced by field changes of DH = 2.43T with the apparatus charged with the nitride spheres in the temperature range between 55 and 65K.

# SESSION- THO2 [Oral]: Commercial Industrial Cryocooler and Applications Thursday, May 20, 2010 – Oral Session: 10:15 AM – 11:30 AM

## [THO2-A133]

## Development of a High Frequency Pulse Tube for an HTS Magnet

N. Emery, A. Caughley, N. Glasson, A. Tucker*, M. Gschwendtner**
Industrial Research Ltd, New Zealand
*University of Canterbury, New Zealand
**TS-dot Engineering Ltd, New Zealand

A single-stage pulse tube cryocooler has been designed and fabricated to provide cooling at 50 K for a high temperature superconducting magnet. Sage software was used to design the pulse tube, with a predicted 25 W of cooling power at 50 K, and an indicated input power of 1.7 kW. The fabricated pulse tube is closely coupled to a metallic diaphragm compressor (pressure wave generator) with a 60 ml swept volume, operating at 50 Hz, and with a mean helium working gas pressure of 25 bar. Details of the development, experimental results and correlations to the Sage model are discussed.

# SESSION- THO2 [Oral]: Commercial Industrial Cryocooler and Applications Thursday, May 20, 2010 – Oral Session: 10:15 AM – 11:30 AM

## [THO2-A116]

## Dynamic operation of 4 K pulse tube cryocooler with an inverter driven compressor

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The 4 K pulse tube cryocoolers have been used for conductive cooling or recondensing helium in cryostats. The pulse tube cryocooler is usually selected to have more capacity than the cryostat needed. In order to maintain the cryostat temperature at 4 K, a heater is used to compensate for the excess cooling capacity from the pulse tube cryocooler. A few kilowatts of input power could be wasted during steady system operation. We introduce an inerter driven compressor for 4 K pulse tube cryocooler for maintaining a desired cryostat temperature by reducing cooling capacity at 4 K with less compressor input power. The system will operate more efficiently. The performances of the 4 K pulse tube cryocooler, model PT410 have been measured with input frequency of compressor from 46 to 70 Hz. The 4 K pulse tube cryocooler performs well with these input frequencies. The 2nd stage cooling capacity varies from 0.5 W to 1.1 W at 4.2 K and the 1st stage cooling capacity from 22 W to 42 W at 45K while the compressor input power changes from 5.0 kW to 8.6 kW. Dynamic operation of the 4 K pulse tube cryocooler has been successfully performed to maintain the desired cryostat temperature and vapor pressure in the liquid helium cryostat.

# SESSION- THO3 [Oral]: Multi-stage Stirling and Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 1:00 PM - 2:15 PM

## [THO3-P120]

## Application of New Figures Of Merit for Multi-Stage Cryocoolers

J. Delmas, A. Kadin, R. Webber, E. Track
Hypres Inc., USA

Evaluation of the overall performance of a multi-stage cryocooler, including the cooling power available on the intermediate stages, is not trivial but is necessary to choose or design efficiently a cooler for a defined application. We have recently proposed two simple definitions of electrical "figures of merit" (FoM) for multi-stage cryocoolers that represent the distributed refrigeration power for applications where heat-sinking of power and signal leads at intermediate stages is available. These FoMs are designed to have universal applicability and to convey the relative performance of such cryocoolers in a much more effective manner than simple weighted averages based on the coefficient of performance (CoP) of the various stages. We demonstrate the utility of these FoMs by applying them to a four-stage cryocooler over a broad range of temperatures, enabling us to determine the optimal operating temperature and heat lift of each stage of the cooler. We also show, using properties of a real superconducting electronic system operating at 4 K, how these FoMs can be used to help in the specification and design of an improved multi-stage cryocooler to fit efficiently the needs of such a system.

# SESSION- THO3 [Oral]: Multi-stage Stirling and Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 1:00 PM - 2:15 PM

## [THO3-P146]

## A Three-stage Stirling Pulse Tube Cryocooler Approaching 4 K

Q. Cao, L.M. Qiu, Z.H. Gan, Y.B. Yu
Zhejiang University, Hangzhou, China

It is a great challenge for a Stirling Pulse tube cryocooler (PTC) to reach liquid-helium temperature, which has promising applications in the field of Low-Tc superconducting digital electronics, Mid Infrared Instrument and so on and attracts a world-wide interest. LMATC first achieved a temperature below 4 K with a four-stage configuration and He-3 as working fluid. A single-stage Stirling PTC precooled by a self-made two-stage GM-type PTC has been constructed and tested to explore the loss mechanism of 4 K PTC working at high frequency at Zhejiang University. Temperature as low as 4.2 K has been successfully obtained with He-4 as working fluid by the end of 2008. In this paper, we report a newly-designed three-stage PTC, which aims to reach 4 K and to further simplify the configuration of multi-state pulse tube coolers. The 4 K cooler is of thermal-coupled type, which is easy to control the mass flow distribution between stages and to investigate the energy flows. It will be working with He-4 instead of the rare He-3. Up to now, the first stage has been finished. A bottom temperature of 35 K and 9 W@80 K with 300 We input has been achieved, which is in good agreement with the model. The second stage is designed to get down to 11 K and supplies precooling at 20 K. The third stage is expected to reach below 5.0 K at 30 Hz. The experiment apparatus will be ready for test soon.

# SESSION- THO3 [Oral]: Multi-stage Stirling and Pulse Tube Cryocoolers Thursday, May 20, 2010 – Oral Session: 1:00 PM - 2:15 PM

## [THO3-P171]

## Vibration-Free, Hybrid Cryocooler for 4 K Space Applications

M. Zagarola, W. Chen
Creare Inc., USA

Future astronomical observatories and surveillance satellites utilizing infrared, far infrared, and sub-millimeter detectors will require long-life, mechanical cryocoolers that provide cooling at temperatures down to 4 K. These missions share a set of core requirements. Current space cryocoolers for 4 K operation are inefficient, and laboratory cryocoolers that provide cooling at 4 K are inefficient and lack a clear development path towards flight. This paper describes a new type of cryocooler that is lightweight, compact, reliable, and efficient. The cryocooler uses a hybrid cycle, consisting of centrifugal compressors at the warm end that provide continuous flow to a reverse-Brayton upper temperature stage and a Joule-Thomson (JT) lower temperature stage. The Brayton stage is expected to operate at nominally 15 K, and the JT stage is expected to operate at 3-5 K. The Brayton and JT cycles are both continuous flow cycles, allowing significant separation distances between the warm and cold components. The cryocooler produces negligible vibration and can uniformly cool remote and distributed loads with extremely small temperature differences and performance penalties. In addition, the components utilized in the cryocooler are relatively mature with high Technology Readiness Level (TRL).

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## [THO3-P178]

## Performance of the 4 K Stage in a High Frequency, Pulse Tube Cryocooler Incorporating a Room Temperature Phase Shifter

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High frequency 4 K pulse tube cryoccolers prove challenging, due to losses from non-ideal gas properties and diminished regenerator heat capacity. Recent modeling with REGEN3.3 shows that the use of He-3 can lead to reduced losses below 10 K compared with those of He-4. The modeling also shows the importance of achieving significant phase shifts between the flow and pressure at the cold end in order to reduce the losses further. However, at 4 K acoustic power is sufficiently low that inertance tubes are not very effective as a phase shifter. In this paper we present measured and calculated performance of the 4 K stage in a multi-stage pulse tube cryocooler. A Gifford-McMahon cryocooler is used to precool this 4 K stage to about 30 K to 35 K. A small linear compressor operated as an expander at room temperature provides a wide range of phase shifts for these measurements. A novel coupling method is employed between the pulse tube warm end at 30 K and the warm expander. The test regenerator for the 4 K stage is layered with gadolinium oxysulphate (GOS) spheres at the cold end and erbium-praseodymium (ErPr) spheres at the warm end.

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## [THO3-P062]

## Experimental Investigations on 20 K Stirling-type Two-Stage Pulse Tube Cryocooler with Inline Configuration

M. Tendolkar, K. Narayankhedkar*, M. Atrey
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Multistaging in a Stirling-type Pulse Tube Refrigerator (PTR) is employed to reach down the temperature range of 20 K and below, where the former stage provides precooling for the next stage. Various configurations of the two-stage PTRs can be used to reach such lower temperature values; while every configuration has its own advantages and limitations. Inline, 'U' type, coaxial or combinations of these are the different configurations possible to design a two-stage PTR. In addition to the above, they can be of integral or split type also. The present work describes the experimental investigations carried out on the Stirling-type two-stage PTR with inline, integral configuration for both the stages. This configuration is thermodynamically advantageous as it involves the least dead space and minimum flow resistance. The phase shift mechanism used is inertance tubes for both the stages. The second-stage alone is added with a double-inlet valve along with the inertance tube. A linear compressor is used to provide the input power to the PTR and is maintained at 350 W. The investigations are carried out for different operating conditions.

**break**

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**break**

# SESSION- THO4 [Oral]: Space Cryocoolers Thursday, May 20, 2010 – Oral Session: 2:45 PM - 4:15 PM

## [THO4-P117]

## Pulse Tube Cryocoolers Development and Qualification for Space Applications

A. Ravex
Air Liquide, France

Under CNS and ESA support and in partnership with CEA/SBT and Thales Cryogenics Bv., Air Liquide Advanced Technology Division is developing Pulse Tube Cryocoolers for Space Applications. A MiniPulseTube, MPTC (1.5W at 80K / 35Welec) and a LargePulseTube, LPTC (2.3W at 50K / 160Welec) have already been developed and are undergoing thermal and mechanical qualification tests for integration in future european earth observation missions. A heat intercepted PulseTube has been developed (300mW at 20K) and an engineering model is under industrialisation. More recently a new development for a 300 mW at 15K has been initiated under ESA funding. Status of demonstrated performances and results of qualification tests for these different Pulse Tube coolers will be presented.

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## [THO4-P154]

## Experimental Results of 15 K Pulse Tube Cold Fingers for Space Applications

J. Duval, I. Charles, A. Coynel, A. Gauthier
CEA Grenoble, France

Pulse tube coolers for space applications have been developed for many years at CEA/SBT. After successful developments of products in the 50 – 80 K range, our focus includes now temperature below 20 K. Our work is based on compressor delivering about 100 W of mechanical input power to the cold fingers with a goal of several hundred milliwatts of cooling power. Most of the work performed to achieve such low temperature is based on an intercepted configuration, which permits to focus our research on the low temperature stage. A review of the different phase shifting method (including active phase shift, cold inertance) and the associated measured performances will be presented. In parallel, studies on regenerator performances have been undertaken. Experimental results are presented on pulse tube cooler with minimum temperature below 10 K.

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**2:45 PM - 4:15 PM**

## [THO4-P181]

# MIRI Cooler System Design Update

J. Lin, D. Durand, M. Petach, M. Michaelian
Northrop Grumman, USA

The Mid InfraRed Instrument (MIRI) for the James Webb Space Telescope (JWST) requires cooling at 6 Kelvin for the SiAs focal planes, provided by the active cooler. The four stage cooler consists of: a three stage pulse tube pre-cooler, Joule Thompson (JT) circulator and upper stage recuperators, located on the JWST spacecraft bus, and the final stage recuperator and 6K JT expander, located at the remote instrument module with a 12 meter round trip line at 18-22K between the spacecraft and instrument. Since our last report on the cooler design, the JWST program has made design changes to the overall thermal design, including the addition by Goddard Space Flight Center (GSFC) of an actively cooled thermal shield surrounding the MIRI Optical Module to increase the overall thermal efficiency and thereby increase the margin between the cooler lift capability and the expected heat loads. This change shifts a portion of the thermal load from the 6K cooler stage to the 18-22K stage. Meeting the increased thermal load at 18-22K and realizing the benefit from the decreased load at 6K requires operating the cooler at a considerably different set of operating points. In this paper we report on the required changes to the cooler's operation and design, and demonstration that the basic design has the capacity to meet the new requirements.

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## [THO4-P185]

## Raytheon Low-Temperature RSP2 Cryocooler Design, Fabrication and Test

R. Hon, J. Shrago, M. Ellis, B. Schaefer
Raytheon Space and Airborne Systems, USA

The Low-Temperature Raytheon Stirling / Pulse Tube 2-stage ("LT-RSP2") hybrid cryocooler is a long-life, robust machine designed to operate efficiently at second stage temperatures below 12 K with a nominal capacity of several hundred milliwatts. An oscillating or steady-flow third stage is not required with this cryocooler, and design features have been included to allow for fine active vibration control. While some aspects of the expander warm-end mechanical design are carryovers from the existing High Capacity RSP2, the compressor module and expander cold head have been substantially optimized for increased efficiency and capacity at low cryogenic temperatures. The LT-RSP2 design was finalized in mid-2009, with piece-part fabrication taking place in late 2009 and early 2010. Assembly and initial testing in an ambient benchtop configuration occurred in early 2010. Major aspects of the mechanical and thermodynamic design will be presented in this paper, including information regarding the final operating point, performance, and packaging details. Results from the fabrication, assembly, and testing will be discussed, as will observations regarding the achieved system performance. Future testing and design enhancement plans will be discussed as well.

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## [THO4-P190]

## Very High Capacity Aerospace Cryocooler

J. Olson, P. Champagne, E. Roth, J. Mix, T. Nast
Lockheed Martin Space Systems Company, USA

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

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## [THO4-P206]

## AIM Space Cryocooler Programs

M. Mai
AIM Space Cryocooler Programs, Germany

As experienced supplier of tactical IR-technology AIM is now involved in several IR space programs covering applications in different wavelength.To meet demands in compactness and weight AIM has focused on Integrated Detector Cooler Assemblies (IDCA). This approach allows the elimination of the detector - cooler interfaces on the customer side. Crycoolers used within the IDCA configuration are based on designs of the AIM Flexure Bearing Moving Magnet family. Due to volume production all relevant components and manufacturing processes have achieved a high level of maturity and thus enabling accurate reliability prediction. To apply standard processes for the fabrication of space IDCAs the coldfinger needs to fit into a standard dewar interface. Therefore the Pulse Tube coldfinger was developed in standard Stirling type dimensions. To retain maximum flexibility the coldfinger is designed for use with different sizes of Flexure Bearing compressors. Buffer volume and inertance tube are optimized for individual compressor type and performance requirement. The qualification activities of two different space programs are ongoing and respective results will be presented within this paper. Furthermore detailed performance characteristics at variable conditions will be discussed.

# The Georgia Tech Hotel and Conference Center

## Second Floor