ICC 22

Abstract Book

Wind Creek
Bethlehem

Bethlehem,
Pennsylvania

June 27-30, 2022

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WELCOME

On behalf of the ICC22 Organizing and Program Committees, we welcome you to the 22nd International Cryocooler Conference (ICC22) being held June 27-30, 2022, in Bethlehem, Pennsylvania, USA, and virtually. The ICC is held every other year and is the preeminent international conference on the development and usage of cryocoolers. It attracts international participants from all continents representing academia, government laboratories and industry.

At this meeting, you will have the opportunity to learn about the latest developments in cryocooler technology and to discuss these developments with authors from around the world. We will have three full days of oral presentations, including plenary sessions on Tuesday and Wednesday. To ensure that you will not miss any of the presentations, the program has been arranged so that there are no parallel sessions. As a participant, you will receive a copy of the proceedings, ***Cryocoolers 22***, approximately six months after the conference, which includes copies of the papers presented at ICC22. These papers are peer reviewed by the session chairs to assure the quality of the proceedings.

We are delighted to host ICC22 in the city of Bethlehem, located in the heart of Eastern Pennsylvania's Lehigh Valley, which has a long history of industrial and cryogenic innovation. The conference venue, Wind Creek Bethlehem, offers several dining options, in addition to a casino, spa and outlet shopping. The nearby SouthSide Arts and Historic Moravian Districts provide opportunities for further exploration.

Please join us for our Welcome Reception on Monday, June 27, from 6:00 PM to 9:00 PM in the Vision Bar at the Wind Creek Bethlehem.

Additionally, the ICC22 Conference Dinner will be held on Wednesday evening, June 29, from 6:00 PM to 9:00 PM at the ArtsQuest Center on the nearby SteelStacks campus.

We hope you will find the conference interesting, the venue enjoyable and your time well spent. Welcome to Bethlehem and ICC22!

Sarah J. Mitchell
Conference Chair

Donniel Hartzell
Conference Co-Chair

Peter E. Bradley
Program Co-Chair

Tamirisa R. Apparao
Program Co-Chair

CONFERENCE OVERVIEW

The biennial International Cryocooler Conference is the premier international forum for the presentation, discussion, and dissemination of the latest research and development activities related to all aspects of cryogenic cooling. Program topics include developments in commercial, military and space cryocoolers of all types, sizes and temperature ranges, as well as recent technological advances in the coolers and the instruments and devices they cool.

The 22nd International Cryocooler Conference (ICC22) will take place from June 27-30, 2022, at the Wind Creek Bethlehem in Bethlehem, Pennsylvania, USA, with virtual elements.

The Conference begins with a Welcome Reception on Monday evening, June 27, at 6:00 PM in the Vision Bar at the Wind Creek Bethlehem. The Technical Program commences at 8:00 AM on Tuesday, June 28, in the Event Center. Two plenary sessions, along with over 70 papers, will be presented during the ensuing three days, concluding on Thursday afternoon, June 30 at 4:45 PM. The papers are being presented in consecutive Oral Sessions. For your convenience, a complete overview of the Conference Schedule is provided both at the back of this book and on the website.

REGISTRATION

Both in-person and virtual attendees are encouraged to register online in advance of the conference. Onsite registration will be open throughout the event, and all attendees must be registered.

Onsite registration will take place in the **Vision Bar**, near the entrance to the Event Center. Hours are as follows:

Date	**Time**
Monday, June 27	1:00 PM – 6:00 PM
Tuesday, June 28	7:00 AM – 5:00 PM
Wednesday, June 29	7:00 AM – 2:00 PM
Thursday, June 30	7:00 AM – 11:00 AM

The onsite registration fee of $850 includes the Technical Program, all of the Social Program events and provided meals, conference materials, and the Conference Proceedings, which will be mailed to each participant approximately six months after the event.

Companion guest tickets to evening social events and breakfasts are available for an additional fee of $100. Guest tickets can be purchased prior to the conference when registering online or at the onsite registration desk.

The virtual registration fee includes access to the Technical Session presentation slides and pre-recorded videos, live stream access to the plenary sessions and the Conference Proceedings, which will be mailed to each participant approximately six months after the event.

Payments to ICC22 must be in U.S. currency by credit card. Purchase orders and checks will not be accepted. Registration is available online at www.cryocooler.org and onsite at the conference at the Registration Desk.

NATIONAL MUSEUM OF INDUSTRIAL HISTORY TOUR

In addition to the technical program, ICC will offer an optional private tour of the nearby National Museum of Industrial History (https://www.nmih.org/) on Monday, June 27, at 3:00 PM. The Museum is about a 15-minute walk from the Wind Creek. Tour attendees will meet in the Vision Bar prior to 3:00 PM and depart as a group.

Housed in the former Electric Repair Shop of the Bethlehem Steel plant site on the vibrant SteelStacks arts & culture campus, this Smithsonian-affiliated museum interprets industry past, present and future through dynamic exhibits, hands-on interactives and engaging programs.

The cost of the tour is $10 per person. Advanced registration is available as part of the conference registration process. On-site registration for the tour may be open the day of, based on availability.

WELCOME RECEPTION and CONFERENCE DINNER

The Welcome Reception will be held in the Vision Bar at the Wind Creek Bethlehem on Monday evening, June 27, from 6:00 PM to 9:00 PM. A variety of appetizers, finger foods, desserts and beverages will be served. This will give us time to unwind after travel, make new friends, catch up with old friends and get settled.

On Wednesday evening, June 29, from 6:00 PM to 9:00 PM, a custom, catered dinner awaits you at the ArtsQuest Center at the SteelStacks. The buffet dinner, featuring local and regional specialties, will be served in the Musikfest Café on the third floor. Weather permitting, the Wind Creek Deck will be open, also. Both areas feature full views of the old Bethlehem Steel blast furnaces. The ArtsQuest Center is located within walking distance of the Wind Creek Bethlehem (about a 10-minute walk).

At each event, you will be supplied with two drink tickets that can be used for alcoholic beverages. Additional alcoholic beverages will be available at the cash bar.

Additional guest tickets for the evening social events and breakfasts are available for $100 each. Guest tickets can be purchased prior to the event when registering online or at the onsite registration desk.

CONFERENCE MEALS

In addition to the Welcome Reception and Conference Dinner, your registration includes a light breakfast each morning (Tuesday through Thursday) between 7:00–8:00 AM in the Event Center prior to the day’s start of the Technical Program. Mid-morning and mid-afternoon refreshments will be provided in the Event Center during break times.

All Session Chairs are invited to the **Session Chair Breakfast Meeting** at 7:00 AM on Tuesday, June 28 in the Berks Meeting Room. This will be the only Session Chair Breakfast Meeting for the conference so please try to attend. The Program Chairs will address several topics, including how the sessions will run, the collection of papers, the paper review process and other pertinent information.

You will be on your own for lunch. There are restaurants within the Wind Creek complex. Additionally, the South Side of Bethlehem provides further dining options and is a 10-15 minute walk away.

BETHLEHEM, PENNSYLVANIA

The city of Bethlehem lies in the heart of the Lehigh Valley, blending the historic with the contemporary for a truly unique experience. Founded by the Moravian community on Christmas Eve 1741, the "Christmas City" has two distinct downtown areas:

The **SouthSide Arts District** houses the Wind Creek Bethlehem conference venue, as well as the ArtsQuest Center banquet site. The area is home to the former Bethlehem Steel mill, and today is anchored by the SteelStacks, a ten-acre community campus devoted to arts, culture and history.

The **Historic Moravian District (North Side)** is home to the city founders' original settlement. With more original structures than Colonial Williamsburg, it is a National Historic Landmark District and a UNESCO World Heritage candidate.

Both downtown areas are walkable, offering a variety of restaurants, shops and historic sites. Visitors can travel between the two by car, rideshare (Uber and Lyft) or walking (about 20-30 minutes).

Bethlehem is within easy driving distance of Philadelphia, New York City, Baltimore and Washington, DC. The Lehigh Valley International Airport Is less than 10 miles from the conference venue. It connects to several hubs in the Eastern United States, including Newark, Washington Dulles, Charlotte, Atlanta, Detroit and Chicago O'Hare.

Lehigh Valley: https://www.discoverlehighvalley.com/

City of Bethlehem: https://getdowntownbethlehem.com/

BETHLEHEM WEATHER

During the month of June, the average high temperature is 80° F (27°C) and the average low temperature is 59° F (15°C). The month averages nine days of rain.

WIND CREEK BETHLEHEM

The Wind Creek Bethlehem is the largest full-service hotel in the Lehigh Valley. In addition to the conference and welcome reception space, it offers a number of on-site amenities including:

- Five dining options
- Outlet shopping & Casino
- Salon & Spa, Indoor Pool and Fitness Room
- Complimentary Wi-Fi and Complimentary Parking

LOBBY RELOCATION

Due to the expansion of the Wind Creek Bethlehem in 2022, the Hotel Lobby has temporarily moved into The Outlets at Wind Creek Bethlehem.

Guests are welcome to utilize the new Hotel Check-In & Drop-Off entrance, located in the former retail parking lot. For those Guests who prefer to self-park in the surface lots or in the garage, the new Hotel Lobby can be found immediately inside the entrance to The Outlets (across from Carlo's Bakery). Signage will be posted upon arrival to the property to help you find the new location.

Wind Creek Bethlehem: https://windcreek.com/bethlehem

TRANSPORTATION

FROM LEHIGH VALLEY INTERNATIONAL AIRPORT (LVIA)

(www.flyabe.com) (~8 miles or 13 km)

Upon exiting the airport, make a right onto Airport Road/987 South. Take 22 East to 378 South. Turn left onto West 3rd Street and continue 1.5 miles to Wind Creek Blvd.

FROM NEW YORK CITY

Take I-78 West to Exit 67 in PA. Follow 412 North for 1.5 miles.

FROM NORTH/CENTRAL NEW JERSEY

Take I-78 West to Exit 67 in PA. Follow 412 North for 1.5 miles.

FROM PHILADELPHIA

Follow Northeast Extension / I-476 to Exit 56 for the Lehigh Valley.

Follow signs for I-78 East, and take I-78 East to Exit 67. Follow 412 North for 1.5 miles.

FROM HARRISBURG

Take I-81 North to I-78 East to Exit 67. Follow 412 North for 1.5 miles.

CAR RENTALS, TAXIS AND RIDESHARES

The Wind Creek Bethlehem does not offer shuttle service.

Multiple car rental companies service Lehigh Valley International Airport. If you choose not to rent a car, taxicabs are typically available, particularly during peak hours, and rideshare services like Uber and Lyft service the airport, also.

AUTHOR / PRESENTER INFORMATION

Complete Slide and Video Preparation Instructions:
https://cryocooler.org/Slide&Video-Instructions

INSTRUCTIONS FOR ORAL PRESENTERS (ONSITE)

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

All oral presenters are required to submit an electronic version of their presentations in advance of the Conference. Additionally, they are strongly encouraged to submit a video of their slides with verbal narration up to 15 minutes in length. Slides and videos will be available on the ICC website to both onsite and virtual attendees. Electronic submission via the ICC website will be open June 6-20, 2022.

Presentations must be submitted in Microsoft Power Point format (but may be saved as a PDF). It is strongly recommended that presenters save their Power Point presentations with True Type fonts attached.

All presentations will be scanned for viruses and subsequently loaded on an appropriate computer for presentation. All sessions will be equipped with a projector, a computer, and a screen. Presenters are not allowed to use their own personal laptops.

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

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

If a presenter has failed to submit his/her presentation by June 20, 2022, they may be required to present their paper without the accompanying presentation.

Papers not presented as an oral presentation will not be published in *Cryocoolers 22*.

INSTRUCTIONS FOR ORAL PRESENTERS (VIRTUAL)

Authors making Virtual Oral Presentations MUST submit (1) an electronic version of their presentations and (2) a video of their slides with verbal narration up to 15 minutes in length. Slides and videos will be available on the ICC website to both onsite and virtual attendees. Electronic submission via the ICC website will be open June 6-20, 2022.

During the live oral sessions, videos from virtual authors will be projected to the onsite audience during their scheduled presentation time slot.

Presentations must be submitted in Microsoft Power Point format (but may be saved as a PDF). It is strongly recommended that presenters save their Power Point presentations with True Type fonts attached.

All videos will be scanned for viruses and subsequently loaded on an appropriate computer for presentation.

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

If an author has failed to submit his/her presentation package by June 20, 2022, late submissions may or may not be presented at the onsite conference, at the discretion of the Program Chairs. Papers not presented as an oral presentation will not be published in *Cryocoolers 22*.

INSTRUCTIONS for PAPER SUBMISSION

Draft Manuscript Preparation Instructions:
https://cryocooler.org/Manuscript-Prep

Authors must submit their manuscripts and signed copyright contract forms electronically via the Conference website. The Author Upload Site will be activated on or around June 15, 2022. Manuscripts are due by July 1, 2022.

Technical papers for each session will be distributed to the respective session chairs by the conference staff for peer review prior to publication in the conference proceedings, *Cryocoolers 22*. A timely review and return of the marked up papers and the paper review form will help shorten the publication time of the proceedings.

TECHNICAL PROGRAM

The Technical Program for ICC22 is organized into 14 oral sessions containing over 70 papers. The conference will begin in the Wind Creek Event Center at 8:00 AM each morning.

Tuesday, June 28 will open with introductory remarks and instructions from the ICC22 Conference Chair. The first Plenary Session will begin immediately after.

Wednesday, June 29 will begin similarly with announcements, followed by the second Plenary Session.

Thursday, June 30 will start with any late-breaking announcements, before moving on to the remaining Oral Session. The conference ends at 4:45 PM.

There will be morning breaks each day of the conference, with afternoon breaks on Tuesday and Wednesday.

INTERNET ACCESS

Complimentary Wi-Fi is available in Guest Rooms, and throughout the hotel and conference center.

ABOUT THIS ABSTRACT BOOK

This Abstract Book is arranged in order of paper presentations. This is illustrated on the following page with the Days, Times, Session Numbers, Session Names and Session Chairs. The Table of Contents and the Abstracts that follow are arranged in the same chronological order.

This Abstract Book is also posted online at www.cryocooler.org

TECHNICAL PROGRAM AND SESSION CHAIRS

Tuesday, June 28, 2022

Start	End	Session	Category	Chair 1	Chair 2	Chair 3
8:15 AM	9:00 AM	Plenary I	JWST: Conceptual Design and Development History of the MIRI Cryocooler System on JWST	Ted Conrad	Tamirisa Apparao	Michael DiPirro
9:00 AM	10:45 AM	1	Aerospace Cryocoolers - Mature	Benjamin Nugent	Melora Larson	Michael DiPirro
10:45 AM	11:00 AM		**Break**			
11:00 AM	12:00 PM	2	Stirling & Pulse Tube Cryocoolers - Analytical	Srinivas Vanapalli	Ali Kashani	Ray Radebaugh
12:00 PM	1:45 PM		**Lunch**			
1:45 PM	3:00 PM	3	Brayton, J-T and Sorption Cryocoolers	Steffen Grohmann	Timothy Hanrahan	Franklin Miller
3:00 PM	4:00 PM	4	Sub Kelvin and Novel Cryocoolers	Lionel Duband	Jean-Marc Duval	Michael DiPirro
4:00 PM	4:15 PM		**Break**			
4:15 PM	5:30 PM	5	Other Cryocooler Technologies	Mark Zagarola	John Pfotenhauer	Xihuan Hao

Wednesday, June 29, 2022

Start	End	Session	Category	Chair 1	Chair 2	Chair 3
8:15 AM	9:00 AM	Plenary II	SHI's Two-Stage 4 K GM Cryocoolers: Enriching Emerging Technologies through Leading-Edge Advancements	Richard Dausman	Mark Zagarola	Peter Bradley
9:00 AM	10:30 AM	6	GM & GM-Type Pulse Tube Cryocoolers	Santhosh Kumar Gandla	Harrison Hones	Ravi Bains
10:30 AM	10:45 AM		**Break**			
10:45 AM	11:45 AM	7	Space Integration & Applications	Melora Larson	Srinivas Vanapalli	Peter Kittel
11:45 AM	1:45 PM		**Lunch**			
1:45 PM	3:15 PM	8	Aerospace Cryocoolers - Development	Ted Conrad	Melora Larson	
3:15 PM	3:30 PM		**Break**			
3:30 PM	4:30 PM	9	Cryocooler Drive & Control Electronics	Carl Kirkconnell	Ryan Taylor	Ray Radebaugh

Thursday, June 30, 2022

Start	End	Session	Category	Chair 1	Chair 2	Chair 3
8:15 AM	9:30 AM	10	Stirling & Pulse Tube Cryocoolers - Experimental	Ryan Taylor	Ingo Rühlich	Srinivas Vanapalli
9:30 AM	10:30 AM	11	Regenerator/Recuperator Investigations	Tian Lei	Mostafa Ghiaasiaan	Xihuan Hao
10:30 AM	10:45 AM		**Break**			
10:45 AM	11:45 AM	12	Superconductor Applications	Sastry Pamidi	Harrison Hones	Santhosh Kumar Gandla
11:45 AM	1:45 PM		**Lunch**			
1:45 PM	3:15 PM	13	Cryocooler Analysis & Modeling Techniques	Tian Lei	Mostafa Ghiaasiaan	Ali Kashani
3:15 PM	4:45 PM	14	Cryocooler Integration	Sastry Pamidi	Santhosh Kumar Gandla	Timothy Hanrahan

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1-6 HiPTC a Dual Stage Cryocooler for 10K-40K Cooling of Science Payloads [10:15 AM]
T. Wiertz, S. Quémerais, J.-M. Niot, S. Carpentier, P. Barbier, D. Lopes, G. Darque, and P.O. Mine, Air Liquide Aadvanced Technologies, Sassenage, France

1-7 Technology Demonstration of a Neon JT Cooler System for Ariel [10:30 AM]
M. Crook, M. Hills, G. Gilley, C. Padley, S. Brown, A. Eagles, B. Green, and E. Corlett, STFC Rutherford Appleton Laboratory, Harwell, Oxford, UK

2 SESSION 2: Stirling & Pulse Tube Cryocoolers – Analytical [Tuesday Morning 11:00 AM - 12:00 PM]

2-1 Impact on the Performance and Heat Flows of a PT Cooler Miniaturization [11:00 AM]
D. Dherbecourt, T. Romand, and J.M. Duval, University Grenoble Alpes, CEA, IRIG-DSBT, France; and L. Marelli, CNES, Toulouse, France

2-2 Low Cost Cryogenic Technology for Commercial IR Imaging [11:15 AM]
A. Veprik, R. Refaeli, and A. Wise, Cryotech Ltd, Ein Harod Meuhad, Israel

2-3 Development of Miniature Stirling Cryocooler for HOT Applications [11:30 AM]
A. Osterman and F. Megusar, Le-Tehnika, Slovenia

2-4 Development of 5W Class Pulse Tube Cooler for Space Use [11:45 AM]
Y. Hiratsuka, Technology Research Center, Sumitomo Heavy Industries, Yokosuka, Japan; and K. Otsuka, K. Kanao, and K. Narasaki, Industrial Equipment Division, Sumitomo Heavy Industries, Niihama, Japan

3 SESSION 3: Brayton, J-T and Sorption Cryocoolers [Tuesday Afternoon 1:45 - 3:00 PM]

3-1 Development of Sorption Compressor with Miniaturized Check Valves [1:45 PM]
J. Bae, D. Kwon, and S. Jeong, Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), South Korea

3-2 Progress in Sorption Compressor Research at Ariel University [2:00 PM]
N. Tzabar and S. Iraqi, Ariel University, Ariel, Israel

3-3 Progress Towards a High-Capacity 90 K Turbo-Brayton Cryocooler [2:15 PM]
A.L. Niblick, K.J. Cragin, and M.V. Zagarola, Creare LLC, Hanover, NH

3-4 Progress on the Development of 4 K Turbo-Brayton Cryocoolers [2:30 PM]
R.W. Hill, K.J. Cragin, G.W. Daines, and M.D. Jaeger, Creare LLC, Hanover, NH

3-5 JT Cooler Compressor Tailoring to Suit a Wide Variety of Applications [2:45 PM]
M. Crook, M. Hills, G. Gilley, and C. Padley, STFC Rutherford Appleton Laboratory, Oxford, UK

4 SESSION 4: Sub-Kelvin and Novel Cryocoolers [Tuesday Afternoon 3:00 - 4:00 PM]

Co-Chairs: *L. Duband, J.M. Duval and M. DiPirro*……………………………… **44**

4-1 Performance of a Miniature, Closed-Cycle Dilution Refrigerator at Tilt Angles between 0 and 30 Degrees [3:00 PM]
R. Snodgrass, J. Ullom, and S. Backhaus, NIST, Boulder, CO and University of Colorado, Boulder, CO

4-2 Continuous 350 mK Stage ADR Cooling for Space and Ground Application [3:15 PM]
J.M. Duval, J.L. Durand, and T. Prouvé, University Grenoble Alpes, CEA, IRIG-DSBT; C. Marin, University Grenoble Alpes, CEA, IRIG-PHELIQS; and J. André and L. Marelli, CNES, Toulouse, France

4-3 Heat Transfer Analysis of the Tube-in-Tube Heat Exchanger in Dilution Refrigerators [3:30 PM]
H. Zu, W. Dai, J. Shen, K. Li, and Y. Wang, Technical Institute of Physics and Chemistry, CAS, Beijing, China and University of CAS, Beijing, China

4-4 Lunar Night Survivability of Cryocooled Instruments Using PALETTE Thermally-Switched Enclosures [3:45 PM]
D. Bugby and J. Rivera, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; and S. Britton, NASA Langley Research Center, Langley, VA

5 SESSION 5: Other Cryocooler Technologies [Tuesday Afternoon 4:15 – 5:30 PM]

5-1 Increasing the Efficiency of He and H2 Liquefaction Using Small Coolers [4:15 PM]
M.A. Green, Lawrence Berkeley Laboratory, Berkeley, CA

5-2 Heat Transfer in an Eccentric Gas Gap Annulus [4:30 PM]
T.M. Kalter, M.A.J. van Limbeek, and S. Vanapalli, University of Twente, Enschede, The Netherlands

5-3 Prospects for High Temperature Cryocooling with Increased SWaP-C Enabled by Advanced DTP Solid-State Thermoelectrics [4:45 PM]
D. Crane, L. Bell, and R. Madigan, DTP Thermoelectrics, LLC, Altadena, CA

5-4 Laser Cryocooler Development for Space Applications [5:00 PM]
R. Vicente and G. Nogues, Néel Institute, CNRS, Grenoble, France; and Y. Juanico, A. Gardelein and P.O. Mine, Air Liquide Advanced Technology, Sassenage, France

5-5 Looped Thermoacoustic Cryocooler with Self-circulating Distributed Cooling [5:15 PM]
T. Steiner, Etalim, Canada

PLENARY II: SHI's Two-Stage 4 K GM Cryocoolers: Enriching Emerging Technologies through Leading-Edge Advancements [Wednesday Morning 8:15 - 9:00 AM]

T. Lei, S. Dunn, and B. Gronemeyer, Sumitomo (SHI) Cryogenics of America, Inc., Allentown, PA; and M. Xu, T. Morie, and Y. Hiratsuka, Sumitomo Heavy Industries, Ltd., Tokyo, Japan

6 SESSION 6: GM & GM-Type PT Cryocoolers [Wednesday Morning 9:00 – 10:30 AM]

6-1 Development of a High Capacity Single Stage GM Cryocooler [9:00 AM]
S.K Gandla, Q. Bao, J. Koch, M. Xu, S. Dunn, and R.C. Longsworth, Sumitomo (SHI) Cryogenics of America, Inc., Allentown, PA

6-2 Development of a 2W 4K Pulse Tube Refrigerator with Remote Valve [9:15 AM]
T. Lei and M. Xu, Sumitomo (SHI) Cryogenics of America, Inc., Allentown, PA

6-3 Contributions of Numerical Simulation in Development of Pulse Tube Cryocoolers [9:30 AM]
C. Wang, Consultant, Manlius, NY

6-4 Development of High Cooling Capacity 3 K Two-Stage Pulse Tube Cryocooler [9:45 AM]
X. Hao, J. Cosco, and R. Dausman, Cryomech, Inc., Syracuse, NY

6-5 Development of High Cooling Capacity and High Efficiency 4.2 K Pulse Tube Cryocoolers [10:00 AM]
X. Hao, J. Cosco, B. Zerkle, and R. Dausman, Cryomech, Inc., Syracuse, NY

6-6 Low Frequency Stirling Operation of a Two-Stage 4K Cryocooler without Rotary Valve Using a Metal Bellows Compressor [10:15 AM]
J. Hoehne, Pressure Wave Systems GmbH, Taufkirchen, Germany

7 SESSION 7: Space Integration & Applications [Wednesday Morning 10:45 AM – 11:45 AM]

7-1 Cryocooler Exported Vibration Reduction System (CEVRS) [10:45 AM]
R.C. Hon, C.S. Kirkconnell, and T.B. Smith, West Coast Solutions, Huntington Beach, CA

7-2 FPFD Radio Isotope Heat Sourced Stirling Engine for Powering Stirling Cryocooler and Other Devices in Space [11:00 AM]
M.A. Krishnan and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

7-3 Design of Zero Boil-off Cryogenic Storage Vessel Using Stirling Cryocooler for Cryogenic Rocket Engine Tanks [11:15 AM]
M.M. Shyam and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

7-4 Design of Thermal Systems for Cryocooled Sensors in Space Rovers with Feedback Loop [11:30 AM]
A.S. Vaisakh and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

8 SESSION 8: Aerospace Cryocoolers - Development [Wednesday Afternoon 1:45 - 3:15 PM]

Co-Chairs: *T. Conrad and M. Larson*……..…………………………………….**70**

8-1 Ball Klondike Cryocooler System Design, Development, Qualification and Performance [1:45 PM]
R. Taylor, B. Buchholtz, A. Brown, D. Glaister, Y. Kim, A. Contreras, and D. Oenes, Ball Aerospace, Boulder, CO; C. Fralick and D. Mansfield, Sunpower, Athens, OH; and K. Frohling, Iris Technology, Irvine, CA

8-2 Ball Verne Cryocooler System Design, Development, and Initial Qualification [2:00 PM]
R. Taylor, B. Buchholtz, D. Glaister, and Y. Kim, Ball Aerospace, Boulder, CO; C. Fralick and D. Mansfield, Sunpower, Athens, OH; and K. Frohling, Iris Technology, Irvine, CA

8-3 20 Watt 20 Kelvin Reverse Turbo-Brayton Cycle Cryocooler Testing and Applications [2:15 PM]
B.T. Nugent, R.J. Grotenrath, and W.L. Johnson, NASA Glenn Research Center, Cleveland, OH

8-4 Development and Testing of a High-Capacity 20 K Cryocooler [2:30 PM]
K.J. Cragin and M.V. Zagarola, Creare LLC, Hanover, NH

8-5 Development of a Space Closed Loop Hybrid J-T Cooler below 2K [2:45 PM]
Y. Ma, J. Quan, Y. Liu, J. Wang, J. Li, G. Wang, Z. Liu, and J. Liang, Key Laboratory of Technology on Space Energy Conversion, Technical Institute of Physics and Chemistry, CAS, Beijing, China

8-6 A Hundred-watts Cooling Power Coaxial Pulse Tube Cryocooler for Space Application [3:00 PM]
Y. Zhang, N. Wang, M. Zhao, and J. Liang, Key Laboratory of Technology on Space Energy Conversion, Technical Institute of Physics and Chemistry, CAS, Beijing, China

9 SESSION 9: Cryocooler Drive & Control Electronics [Wednesday Afternoon 3:30 – 4:30 PM]

Co-Chairs: *C. Kirkconnell, R. Taylor and R. Radebaugh*…………………………..**77**

9-1 Development and Qualification Testing of Cryocooler Systems for Affordable Space Missions [3:30 PM]
D.W. Fogg, R.W. Kaszeta, and M.V. Zagarola, Creare LLC, Hanover, NH; and C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

9-2 Deep Space Cryocooler Control Electronics for the Ricor K508 [3:45 PM]
K.D. Frohling, J.S. Fechter, and J.M. Moritz, Iris Technology, Irvine, CA; R.C. Blase, Southwest Research Institute, San Antonio, TX; and V. Segal, Ricor, En Harod Ihud, Israel

9-3 Testing of a High-Capacity Pulse-Tube Cryocooler System for Space Applications [4:00 PM]
R.W. Kaszeta, C.B. Cameron, D.W. Fogg, B.R. Pilvelait and M.V. Zagarola, Creare LLC, Hanover, NH

9-4 Compressor Stroke and Frequency Response Measurements Using Strain Gauges [4:15 PM]
H. Rana, M. Dadd, P. Bailey, and R. Stone, Department of Engineering Science, University of Oxford, Oxford, UK

10 SESSION 10: Stirling & Pulse Tube Cryocoolers - Experimental [Thursday Morning 8:15 – 9:30 AM]

Co-Chairs: *R. Taylor, I. Rühlich and S. Vanapalli*……………………………….**82**

10-1 Experimental Study on a Two-Stage Pulse Tube Cooler with an Active Phase Shifter for Liquid Hydrogen Temperature [8:15 AM]
X.P. Ding, Z.W. Li, W. Dai, and E.C. Luo, Technical Institute of Physics and Chemistry and University of CAS, Beijing, China; and X.T. Wang. Li, and Y.N. Wang, Technical Institute of Physics and Chemistry, CAS, Beijing, China

10-2 Experimental Performance of a Passively Driven Displacer [8:30 AM]
H. Rana, M. Dadd, M.A. Abolghasemi, P. Bailey, and R. Stone, Department of Engineering Science, University of Oxford, Oxford, UK

10-3 High-Availability Cooler Developments at Thales Cryogenics [8:45 AM]
D. Willems, R. Arts, G. De Jonge, P. Bollens, B. de Veer, and J. Mullié, Thales Cryogenics, The Netherlands

10-4 Overdriving a Pulse-Tube Coldhead with Twin Pressure-Wave Generators to Approximately Double Its Cooling Capacity [9:00 AM]
D. A. Wilcox and B. Jayasena, MVE Biological Solutions, Ball Ground, GA; P.S. Spoor and D.J. Carlo, Northside Research & Technology, Waterford, NY

10-5 Current Rotary Coolers Improvements Usable for Next Generation of Rotary Coolers [9:15 AM]
C. Vasse and V. Abousleiman, Thales LAS France, France; and T. Benschop, Thales Cryogenics BV, The Netherlands

11 SESSION 11: Regenerator & Recuperator Investigations [Thursday Morning 9:30 - 10:30 AM]

11-1 Role of Non-Temperature-Gradient Power Flow Terms in Low-Temperature Regenerators [9:30 AM]
R. Snodgrass, J. Ullom, and S. Backhaus, NIST, Boulder, CO, and University of Colorado, Boulder, CO

11-2 Influence of Regenerator Current Plate Layout and Inlet and Outlet Port Configuration on GM Refrigerator Performance: a CFD Study [9:45 AM]
Q. Qian, O. Zhengrong, and L. Junjie, High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei, China, and University of Science and Technology of China, Hefei, China

11-3 Research on the Thermal-Hydraulic Performance of Twisted Helical Bundle Heat Exchangers [10:00 AM]
Y.N. Wang, J.M. Pfotenhauer, and F.K. Miller, University of Wisconsin, Madison, WI

11-4 Compact Mesh-based Recuperator for 40 K Space Reverse Turbo-Brayton Cooler and Remote Cooling Applications [10:15 AM]
A. Onufrena and T. Koettig, CERN, Switzerland; T. Tirolien, ESA/ESTEC, The Netherlands; H.J.M. ter Brake, University of Twente, The Netherlands

12 SESSION 12: Superconductor Applications [Thursday Morning 10:45 AM – 11:45 AM]

12-1 Fabrication of 4 T HTS Magnet for Adiabatic Demagnetization Refrigerator (ADR) [10:45 AM]
D. Kwon, B. Kim, and S. Jeong, Korea Advanced Institute of Science and Technology (KAIST), South Korea

12-2 Modeling of Integrated Cryocooling Systems to Improve Resiliency of Superconducting Power Grids on Electric Transport Systems [11:00 AM]
R.D. Machorro Swain, C.H Kim, P. Cheetham, and S. Pamidi, Florida State University Center for Advanced Power Systems, Tallahassee, FL

12-3 Enabling High-Temperature Superconducting Magnets on Small Satellites Using a Miniaturized Cryocooler [11:15 AM]
J.R. Olatunji, N.M. Strickland, T. Berry, E.V.W. Chambers, and S.C. Wimbush, Robinson Research Institute, Victoria University of Wellington, Wellington, New Zealand

12-4 Solvay Cryocooler Cryostat for Quantum Material Characterization [11:30 PM]
R. Bains and M. Sedaille, Advanced Research Systems, Macungie, PA

13 SESSION 13: Cryocooler Analysis & Modeling Techniques [Thursday Afternoon 1:45 - 3:15 PM]

13-1 Improvement of a Two-Stage 4-K Pulse Tube Cryocooler with Low Input Power and Comparison to Numerical Simulation [1:45 PM]
J.-A. Schmidt, B. Schmidt, D. Dietzel, J. Falter, G. Thummes, and A. Schirmeisen, Justus-Liebig-Universität Giessen, Giessen, Germany, and TransMIT GmbH, Giessen, Germany

13-2 Modelling the Thermodynamic Response of a Cryocooler after Switching It Off [2:00 PM]
K.W. Lotze, H.J. Holland, and H.J.M. Ter Brake, University of Twente, The Netherlands

13-3 Optimizing Flow Uniformity through Regenerators of Large Cryocoolers Using CFD [2:15 PM]
A. Ghavami and S.M. Ghiaasiaan, Georgia Tech, Atlanta, GA; and C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

13-4 Square Wave Test for Characterization of Compressor Piston Blowby [2:30 PM]
R.G. Ross, Jr. and K. Penanen, Jet Propulsion Laboratory, Pasadena, CA; and J. Olson and E. Roth, Lockheed Martin Space-ATC, Palo Alto, CA

13-5 Numerical Investigations on Flow Resistance Values for Pulse Tube Cryocoolers [2:45 PM]
S.C. Chaudhari, A.A. Ketkar, A.A. Ketkar, P. Hemanth, O.P. Joshi, and M.V. Tendolkar, Veermata Jijabai Technological Institute, Mumbai, India

13-6 Design, Optimization and CFD Analysis of a Split Type Free Piston Stirling Cooler for Onboard Applications [3:00 PM]
A.B. Suresh and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

14 SESSION 14: Cryocooler Integration [Thursday Afternoon 3:15 – 4:45 PM]

Co-Chairs: *S. Pamidi, S.K. Gandla and T. Hanrahan*................................**105**

14-1 Rigid ADR Suspension [3:15 PM]
P. Owen, M. Snow, and J. West, FormFactor, Inc., Boulder, CO

14-2 Cryocoolers as Enabling Technology for Higher Brightness Photoguns [3:30 PM]
G.E. Lawler, J. Parsons, A. Fukasawa, N. Majernik, Y. Sakai, and J.B. Rosenzweig, UCLA, Los Angeles, CA

14-3 Preliminary Experimental Investigations of Large-Scale Helium Pulsating Heat Pipes [3:45 PM]
L.M. Kossel, J.M. Pfotenhauer, and F.K. Miller, University of Wisconsin - Madison, Madison, WI

14-4 Cryocooler Integration, Modeling, and Testing for the Ultra Compact Imaging Spectrometer Airborne (UCIS-A) Instrument [4:00 PM]
C.S. Kirkconnell, C.G. McNeal, T.B. Smith, A. Ghavami, and L.A. Bellis, West Coast Solutions, Huntington Beach, CA

14-5 Design and Development of Integral Cold Transportation System [4:15 PM]
S. Addala, Narasimham GSVL, Karunanithi R, and H.K. Hassan, Indian Institute of Science, Bengaluru, India

14-6 Development of 1.5W Cryostat for a Cold Trap Application [4:30 PM]
A. Osterman and F. Megusar, Le-Tehnika, Slovenia

PLENARY I: Conceptual Design and Development History of the 6K MIRI Cryocooler on JWST

Tuesday Morning
8:15 - 9:00 AM

Co-Chairs

Ted Conrad
Tamirisa Apparao
Michael DiPirro

Conceptual Design and Development History of the 6K MIRI Cryocooler on JWST

R.G. Ross, Jr., Jet Propulsion Laboratory, Pasadena, CA

The Mid Infrared Instrument (MIRI) of the James Webb Space Telescope (JWST) is a demanding application for the use of space cryocoolers. Used to cool JWST's 90 kg MIRI instrument down to 6 K, it is critical to enabling the mission's long-wave infrared science associated with studying the post-Big Bang early formation of the Universe.

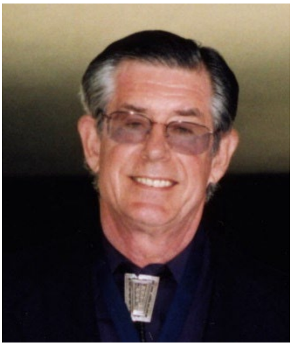
The selection and design of MIRI and its cryocooler started with the successes and limitations of JWST's precursor, the Hubble Space telescope. Planned as the follow-on to Hubble, JWST abandoned Hubble's astronaut-accessible low-Earth orbit for a colder and better-science environment a million miles from Earth. Targeted for its L2 location meant no servicing missions would be possible, and reliability and life would be critically important. JWST's increased size, with a 7-meter diameter mirror, meant significant deployments would be required post launch to allow the observatory to unfurl from its launch-vehicle shroud and separate the cold telescope from its hot and noisy spacecraft bus.

The design of the MIRI cryocooler had to accommodate these mission constraints by positioning its hot and vibration-generating compressor inside the spacecraft bus, while the MIRI instrument and the cryocooler's cold-end was positioned 10 meters away in the Science Instrument Module on the back of the telescope mirror. Accommodating the 2-meter deployment of the telescope away from the spacecraft and minimizing any vibration transmitted up the connecting refrigerant lines was a driving requirement on the cryocooler. Providing MIRI's large refrigeration load at 6 K, while simultaneously cooling MIRI 18K radiation shield required an all-new hybrid Pulse Tube/Joule Thomson cryocooler design implemented by

Northrop Grumman Space Systems and a whole team of folks from NASA/GSFC and the Jet Propulsion Laboratory.

This paper provides an overview of the MIRI cooler concept and development history as it evolved to meet these demanding JWST requirements over its nearly 20 year development. During this period it drew heavily on ongoing Pulse Tube cooler development at NGSS as well as a history of earlier hybrid J–T coolers addressed to the European First and Planck missions. With the successful launch and deployment of JWST this spring, we look forward to the successful operation and long life of this unique MIRI 6K cryocooler.

The Speaker



Dr. Ron Ross has over 50 years' experience researching and developing flight spacecraft hardware with an emphasis over the past 30 years on developing and integrating cryocoolers into space-science instruments. From 1988 until 2007 he managed JPL's cryocooler development group, including being the AIRS instrument cryocooler manager from 1990 to 2002 and NASA's 6K ACTDP cooler development manager from 2001 to 2005. When an ACTDP cryocooler was selected for MIRI on JWST, Ron became JPL's Subject Matter Expert (SME) for the MIRI 6 K cryocooler during its flight development phase. He has authored over 200 technical publications covering cryocooler design and performance, cryogenic instrument design, electronic packaging and solder fatigue, reliability physics, structural dynamics, and photovoltaics.

SESSION 1: Aerospace Cryocoolers - Mature

Tuesday Morning 9:00 - 10:45 AM

Co-Chairs

Benjamin Nugent
Melora Larson
Michael DiPirro

Mid-Infrared Instrument Cryocooler on James Webb Space Telescope: Cooldown, Commissioning and Initial Performance.

K. Penanen, D. Breda, B. Moore, B. Naylor, K. Sukhatme, A. Schneider, and M. Weilert, Jet Propulsion Laboratory, Pasadena, CA; K. Banks, NASA/GSFC, Greenbelt, MD

The focal plane modules and the optical bench of the Mid-Infrared Instrument (MIRI) on James Webb Space Telescope (JWST) require temperatures below 7K to operate. While other, near-IR instruments in the Observatory are cooled passively, MIRI cryogenic components are cooled by a dedicated distributed 4-stage hybrid Pulse Tube/Joule Thomson mechanical cryocooler, spanning all of the Observatory regions. MIRI cryocooler is designed to meet stringent heat lift, thermal stability, power draw, exported vibration, and reliability requirements. Cryocooler components stowed for launch are designed to be released as part of the JWST deployment sequence. Cryocooler pneumatic and thermal control configurations are progressed through a coordinated sequence as the Observatory is cooled. Here, we describe the initial stages of MIRI cryocooler commissioning and present functional performance results after the first three months on orbit.

Transient Thermal Model of the JWST MIRI Cryocooler

M.B. Petach, Northrop Grumman, Redondo Beach, CA; and B. Moore, Jet Propulsion Laboratory, Pasadena, CA

This paper describes the transient thermal model of the JWST MIRI cooler, including the active control loops in the cooler and lumped approximations of the MIRI instrument and JWST observatory. The model predictions are compared with data from ground testing and initial flight operation.

AIRS Pulse Tube Coolers Performance Update – Twenty Years in Space

R.G. Ross, Jr., D.L. Johnson, S. Broberg, and W. Mathews, Jet Propulsion Laboratory, Pasadena, CA

The Atmospheric Infrared Sounder (AIRS) instrument began operation 39 days after its May 4, 2002 launch into Earth orbit. It has now completed over twenty years of successful operation using a pair of Northrop Grumman pulse tube cryocoolers to cool its IR detectors. Designed with redundant cryocoolers (a primary and a backup), the instrument began operation using a single cooler to bear the load of both the detector and the nonoperating, backup cooler. However, 6 months after launch, a change in operating strategy was made to run both coolers simultaneously. This change led to the successful continuous 24/7 operation of both coolers over the past 19½ years. After a brief review of the AIRS instrument cryogenic design, detailed data are presented on the highly successful continuous operation of the AIRS pulse tube cryocoolers and instrument thermal design. A valuable feature has been the extremely stable temperatures provided to the instrument over its lifetime. This high level of operational stability not only indicates that the cryocoolers and thermal design have maintained near-constant efficiency, but the stability has also provided enormous benefits to the science data in terms of tracking long-term global changes.During its 20-year lifetime, the instrument itself has evolved in its mission scope and expanded its data gathering well beyond its original role as just a temperature sounder measuring global daily air temperature. It now generates a wealth of data not only on global air temperatures, but also on global and local greenhouse gas distributions. For example, AIRS can detect carbon monoxide emissions from large forest fires and can follow their giant plumes as the gas moves across the planet. At this time the cryocoolers continue in 24/7 operation and the AIRS instrument continues to generate daily scientific data on Earth's atmospheric parameters.

TIRS II Cryocooler System Performance and Initial On-Orbit Data

R. Boyle and T. Muench, Goddard Space Flight Center, Greenbelt, MD; and R. Taylor, B. Buchholtz, D. Glaister, D. Back, and J. Masciarelli, Ball Aerospace, Boulder, CO

The Thermal Infrared Sensor II (TIRS II) is the next generation of the original TIRS instrument on Landsat 8, launched in February 2013. TIRS and the Ball TIRS two-stage Stirling cryocooler for has been successfully operating on orbit for over nine years. Recently the TIRS II instrument and TIRS II cryocooler successfully completed all ground testing and was launched in December 2021. The TIRS II infrared focal plane is cooled by the second stage of a two-stage Ball Aerospace Stirling cycle cryocooler, operating at 40K. The first stage of this cryocooler provides shield cooling at 85K. This paper describes the TIRS II Cryocooler System, performance test results of two flight cryocoolers, and initial on-orbit performance.

SESSION 1: Aerospace Cryocoolers - Mature

Paper No. 1-5 Tuesday Morning 10:00 AM

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

L. Amouzegar, M. Petach, M. Norris, D. Durand, and O. Cupp, Northrop Grumman Space Systems, Redondo Beach, CA

Northrop Grumman Space Systems (NGSS) introduced their new class of pulse tube cryocooler, the Mini Cooler Plus (MCP) in 2019 [Ref]. This thermal mechanical unit (TMU) is an extension of our space qualified pulse tube coolers and is designed to provide a long-life (over ten years), low-mass, high cooling capacity for hyperspectral and infrared imaging payloads in tactical airborne and space applications. The cooler is of modular split configuration allowing flexibility in the compressor (wave generator) and cold head placements to meet the available envelope. The cold head assembly can be oriented at any position relative to the compressor assembly and the transfer line (length and shape) can be customized to individual applications. The TMU weighs less than 3kg and can lift 1.5 W at 45 K or 11 W at 110K with 150 W electrical input at 300 K reject.This paper reports on qualification testing of a MCP unit to a technology readiness level (TRL) of 6 for a planned upcoming spaceflight mission and presents the test data obtained in its flight configuration over a range of input powers and reject temperatures. The cooler was subjected to launch vibration and thermal cycling conditions for the range of operating and standby conditions appropriate to its space application. The measured load lines and unchanged refrigeration performance of the cooler throughout the qualification program demonstrated the readiness of the design for flight. A functional testing of the unit was also performed with Northrop Grumman`s TRL9 CCE (Control Electronics) and the exported vibration signature of the TMU without active vibration control were also characterized in all axes.

HiPTC a Dual Stage Cryocooler for 10K-40K Cooling of Science Payloads

T. Wiertz, S. Quémerais, J.-M. Niot, S. Carpentier, P. Barbier, D. Lopes, G. Darque, P.O. Mine, Air Liquide Advanced Technologies, Sassenage, France

Air Liquide Advanced Technologies, in cooperation with CEA and with the support of ESA, has developed a dual-stage pulse tube cooler for space science missions. It is named HiPTC, standing for Heat intercepted Pulse Tube Cooler. It is built with compressors by hales Cryogenics and a cold finger developed with CEA. A first Bread Board model was tested to validate the achievement of the 15K targeted cryogenic performance and securing TRL4. This model showed that temperatures below 9K were achievable. An engineering model was built to check consistency of performances, further explore the operating domain and raise the TRL.An extensive test campaign was performed on this model, with coupling of the mechanical cooler with a development electronics and validation of the operational scheme, including: (1) Cryogenic characterization over a wide temperature range of 10K – 40K, (2) Characterization of exported vibrations and validation of vibration reduction loop, and (3) Operational schemes for a science payload. Design maturity and test results confirm the suitability of this cryocooler for science payloads, either for directly cooling the instrument or the optics, or as part of a cryogenic chain. One single cooler can provide cooling power at two staged temperatures, between 70K and 100K on the middle stage, and between 10K and 40K on the cold stage. This versatility facilitates the thermal optimization of cryogenic chains.HiPTC is part of the baseline cryogenic cooling chain of ATHENA X-IFU payload. This cooler is also considered for the first levels of cooling in the LITEBIRD and MILLIMETRON missions. For MILLIMETRON, Air Liquide has performed a preliminary study in cooperation with Lebedev Institute of Physics, demonstrating the adequacy of this cooler with the needs of this ambitious mission. The presentation will display cooler characteristics, integration studies on several payloads, as well as recent test results and will discuss potential applications.

Technology Demonstration of a Neon JT Cooler System for Ariel

M. Crook, M. Hills, G. Gilley, C. Padley, S. Brown, A. Eagles, B. Green, and E. Corlett, STFC Rutherford Appleton Laboratory, Harwell, Oxford, UK

Ariel is the fourth medium (M4) mission in the ESA Cosmic Vision 2015-2025 programme. The mission was adopted in November 2020 and the payload development is ongoing towards the payload Preliminary Design Review in 2022, with a launch planned in 2029. The spacecraft will carry two instruments: a Fine Guidance System (FGS) and the Ariel InfraRed Spectrometer (AIRS). AIRS requires active cooling of both its channels to below 42 K and this will be provided by a neon Joule-Thomson (JT) cooler developed by the Rutherford Appleton Laboratory.Here we describe the Technology Demonstration Activities for achievement of Technology Readiness Level (TRL) 6 for the Ariel Active Cooler System (ACS). This paper follows on from the one presented at ICC 21 [Hills, M. et al, “A Neon JT Cooler for Ariel” Cryocoolers 21, pp 423–431] by describing the assembly of the ACS and the subsequent test campaign: we detail compressor assembly, acceptance testing and performance, demonstrating pressure and mass flow requirements; we then describe results from mechanical and thermal environment tests and also cryogenic performance tests of the complete cooler. The ACS has achieved cooling powers that exceed the Ariel requirements, at input powers that are within budget. We summarize the correlation of these test results with the cooler performance modelling. We conclude by reporting on progress towards the achievement of TRL 6 for the cooler and outline the next steps in the development of a qualification model cooler.

SESSION 2:
Stirling & Pulse Tube Cryocoolers - Analytical

Tuesday Morning
11:00 AM – 12:00 PM

Co-Chairs

Srinivas Vanapalli
Ali Kashani
Ray Radebaugh

Impact on the Performance and Heat Flows of a PT Cooler Miniaturization

D. Dherbecourt, T. Romand, and J.M. Duval, University Grenoble Alpes, CEA, IRIG-DSBT, France; and L. Marelli, CNES, Toulouse, France

A pulse tube cooler cooling below 10 K would allow the use of sensitive Terahertz detectors for astrophysics or earth observation. It could also simplify the cryogenic subkelvin chains if a 4 K cooling is performed. Such coolers have been previously prototyped and tested, but needed too much pre-cooling power to be compatible with spatial requirements.In order to achieve low temperatures when decreasing the heat flow, two PT prototypes have been designed and tested at CEA-DSBT, in collaboration with the French Spatial Agency (CNES). Both are coaxial, twice intercepted at two pre-cooling temperatures, and have the same length. The impact of a miniaturization of the PT sections are measured and analyzed. Interesting results have been observed, showing a decrease of both the lower temperature and the heat flow at intercepts when reducing the PT sections. An analysis of such behavior is proposed.Considering typical values of pre-cooling of 1 W @ 35 K and 3 W @ 100 K from a two-stage pulse tube, these coolers could be combined to achieve 9 K. Now this first proof of concept is validated, next steps are planned to optimize the whole geometry -and not only the sections- and study the regenerator composition in order to gain performance when keeping reasonable heat flow at intercepts.

SESSION 2: Stirling & Pulse Tube Cryocoolers - Analytical

Paper No. 2-2 Tuesday Morning 11:15 AM

Low Cost Cryogenic Technology for Commercial IR Imaging

A. Veprik, R. Refaeli, and A. Wise, Cryotech Ltd, Ein Harod Meuhad, Israel

The recent advancement of cooled infrared vision technology has resulted in a drastic increase of operational temperatures and subsequent reduction of parasitic (conductive and radiative) heat inflows. Eventual lessening of required heat lifts initiated development of a new generation of long-life and low SWaP+C mechanical cryocoolers. In response to this challenge, the industry adopted a risk-free way of sustaining innovation, primarily focusing on gradually downscaling/improving existing technologies, aiming primarily to develop/maintain a low-volume segment military market. Because of the inherent limitations—though significantly improved—the attended reliability and cost figures still prevent the broad use of cryogenically cooled infrared imagers in the price-sensitive and highly competitive commercial market. Uncooled infrared technology, albeit inferior in performance, is more affordable and reliable and, therefore, more ubiquitous. From the very moment of its inception in 2018, CryoTech adopted an approach of disruptive innovation, not only aiming to further improve SWaP indices but first and foremost to enable essential cost reduction and higher reliability while developing new (commercial) markets and business models. In doing so, the CryoTech team revisited almost all the major technological cornerstones, including working agents, the concepts of regenerative heat exchange, electromagnetic and pneumatic actuation, magnet springs, vibration control, and more.

The authors present the outcomes of a full-scale feasibility study, prototype life testing, and performance mapping.

Paper No. 2-3 Tuesday Morning 11:30 AM

Development of Miniature Stirling Cryocooler for HOT Applications

A. Osterman and F. Megusar, Le-Tehnika, Slovenia

To support needs of high-operating-temperature (HOT) applications, LE-TEHNIKA started development of suitable cryocoolers. This led to further miniaturization of its SRI (Stirling Rotary Integral) coolers. 2 new coolers were added to its lineup and are being tested at the moment – SRI483 and a bit bigger SRI483GP. Their mass is around 100g and 150g respectively (without a cold finger and electronics). They have both 12V internal motors and separate electronics and have an interface suitable for SWAP cold finger (6mm diameter). Their cooling powers are ranging from 0.5W to 1W (110K-150K, room temperature), GP version being more powerful. Together with development of these new coolers, development of suitable dewar vessels for measurements of their performance took place. As a result, several dewar vessels with thermal losses of around 150mW at 77K were manufactured in-house.

Development of 5W Class Pulse Tube Cooler for Space Use

Y. Hiratsuka, Technology Research Center, Sumitomo Heavy Industries, Yokosuka, Japan; and K. Otsuka, K. Kanao, and K. Narasaki, Industrial Equipment Division, Sumitomo Heavy Industries, Niihama, Japan

Sumitomo Heavy Industries, Ltd. (SHI) has been used a single-stage Stirling cooler as a cooler for infrared sensors and radiation shield for the Earth observation satellite Shikisai and the scientific satellites Suzaku, Kaguya and Akatsuki. In addition, the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) and the Hitomi X-ray science satellites are equipped with 4K cooler consisted of two-stage Stirling cooler and JT cooler to realize a liquid helium-free cooling system. Cooler for space use is required high reliability, small size, light weight, high efficiency and low vibration. SHI's Stirling coolers have an active balancer for the expander to decrease the induced vibration from displacer movement, and the driver for driving this balancer is a disadvantage compared with pulse tube cooler. The performance of a single-stage Stirling cooler made by SHI has a cooling capacity of 2.2 W at 77 K with electric input of 50 W. However, users plan to increase the number of sensors to improve observation accuracy in the near future. There is a possibility that the cooling capacity needs to be increased, and there is a similar demand for a 4K cooler. Since the pulse tube expander has no moving parts, it is advantageous for the reliability of cooler and no necessary of a driver for the active balancer of expander. We started to develop single-stage pulse tube with cooling capacity of 5 W at 77 K since 2017, and we tested three types of expander (In-line type, U-shape type and co-axial type). This paper describes the design of the cooler and the results from the cooler performance test, the induced vibration measurement of new compressor, the performance calculation results by numerical simulation.

SESSION 3: Brayton, J-T and Sorption Cryocoolers

Tuesday Afternoon
1:45 - 3:00 PM

Co-Chairs

Steffen Grohmann
Timothy Hanrahan
Franklin Miller

Development of Sorption Compressor with Miniaturized Check Valves

J. Bae, D. Kwon, and S. Jeong, Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), South Korea

A sorption J-T cooler can be utilized to cool sensitive sensors of space observatory missions since it is operated with "vibration-free" sorption compressor, which utilizes adsorption characteristic of adsorbent such as activated charcoal. The activated charcoal which fills the compressor cell can adsorb and desorb the helium according to its temperature. The pressure swings in the cell are thermally generated without any mechanical vibration. The compressor cell developed in this paper has a thin-plate shape to reduce the heating and cooling time so that the pressure swing can be accelerated. Its width, height and the thickness are 100 mm, 100 mm and 4.6 mm, respectively. In the cell, the cubic pillars with one side length of 1 mm, are arranged to reinforce the structural rigidity and thermal diffusion into the activated charcoal. For heating the cell, a polyimide film heater is attached to the top surface of the cell. For cooling the cell, the cold head of commercial G-M(Gifford-McMahon) cryocooler is thermally connected to the cell via copper thermal link. Two identical cells are operated alternately to build a continuous pressure gradient for the J-T cooler. In addition, the passive check valve is developed to continuously provide sufficient pressure from the compressor to the J-T expansion part, rectifying the mass flow from the cells. When the flow direction is reversed in the valve, the leakage is passively prevented by contacting two metal surfaces at low temperature (20 K). The essential parts of the valve are critically miniaturized and welded to minimize the overall thermal inertia of the system. The mass flow rate from the compressor and its efficiency are measured for performance comparison with other thermal compressors. Consequently, the strategy to increase the mass flow rate and the efficiency of the compressor are discussed.

Progress in Sorption Compressor Research at Ariel University

N. Tzabar and S. Iraqi, Ariel University, Ariel, Israel

An ongoing research on sorption compressors is executed in the TEST laboratory at Ariel University. Recently, the construction of a three stage compressor, aiming for compressing nitrogen for driving Joule-Thomson cryocooler in space applications, is completed. In addition, a one-dimensional numerical model is developed and successfully validated against various experimental results. The model is fully parametric and suitable for describing the performances of any adsorbent-adsorbate pair, any number of compressing stages, with any number of sorption cells at each compressing stage, and with any cylindrical cell design (dimensions and materials). Currently, both the numerical model and the physical compressor are used to research the option of compressing different fluids for various applications. In the current paper we present our first steps in investigating sorption compression of carbon-dioxide and R404A

Progress Towards a High-Capacity 90 K Turbo-Brayton Cryocooler

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

Creare is developing for NASA a high-capacity turbo-Brayton cryocooler to support their initiatives for space-borne zero-boil-off storage and liquefaction of oxygen and methane. The cooler is optimized to provide more than 150 W of refrigeration at temperatures from 90 K to 120 K for compatibility with a broad range of storage pressures for both cryogens. The cryocooler is a scaled-up version of the 20 W at 90 K cryocooler that Creare delivered to NASA in 2012 and was used in NASA's seminal demonstrations of reduced boil-off hydrogen storage and zero-boil-off oxygen storage. The cryocooler includes 1) a new 2 kW-class permanent magnet compressor that incorporates efficiency improvements demonstrated in other Creare turbomachines over the last 10 years, 2) a micro-tube recuperator that is a larger version of the unit developed for our high-capacity 20 K cryocooler, and 3) a high-capacity turboalternator that was based on our prior 500 W-class compressor with materials updated for operation at cryogenic temperatures and optimized aerodynamics. The cryocooler will utilize these components in two development and test cycles. In the first cycle, we will integrate the components in a brassboard configuration to obtain initial performance data before committing to a flight-like configuration. In the second cycle, we will integrate the cryocooler in a flight-like configuration and perform qualification tests including thermodynamic performance and launch vibration testing. This paper reviews the component testing and initial testing of the brassboard cryocooler.

Progress on the Development of 4 K Turbo-Brayton Cryocoolers

R.W. Hill, K.J. Cragin, G.W. Daines, and M.D. Jaeger, Creare LLC, Hanover, NH

Creare is developing low temperature, turbo-Brayton cryocoolers for space and terrestrial applications. The terrestrial version is being developed for cooling superconducting electronics for digital communications. This cooler provides refrigeration at 4.2 K and rejects heat at 77 K to an upper-stage cryocooler or through boil-off of liquid nitrogen. The space-borne version also provides refrigeration at 4.2 K and rejects heat at nominally 300 K through radiation to space. Cooling loads at 4.2 K are in the range of 100 to 400 mW. The key developments for both cryocoolers are the low-temperature recuperators and the 4 K expansion turbine. The low temperature recuperators are based on Creare's silicon slotted plate recuperator technology with further miniaturization and optimization to address low flow rates while preserving its inherent size, weight and performance benefits. The 4 K turboalternator is based on our isothermal turboalternator with further miniaturization for high efficiency at low flow rates and cooling capacity. An additional challenge for the 4 K turboalternator is the operation of gas bearings at extremely low temperatures and viscosities. This paper reviews the development and testing of these key cryocooler components.

JT Cooler Compressor Tailoring to Suit a Wide Variety of Applications

M. Crook, M. Hills, G. Gilley, and C. Padley, STFC Rutherford Appleton Laboratory, Oxford, UK

Joule-Thomson (JT) coolers are a becoming increasingly prominent in science missions that require very low temperatures. By extending the range of temperatures achievable by mechanical cryocoolers down to less than 2 K, JT coolers are a key enabling technology for such missions, either as the final cryogenic stage, or as a pre-cooler in a cryogenic chain extending to sub-Kelvin temperatures. Such missions are usually highly bespoke, leading to very significant differences in requirements and the JT cooler must be adapted to suit the operating conditions of a particular application. Cryocooler compressor development can be a lengthy and costly process and it is advantageous to be able to use a single compressor design to cover as many applications as possible. In this paper we describe a modular JT compressor developed at the Rutherford Appleton Laboratory to address this need. Through three case studies, a 2K JT cooler, a 4K JT cooler and a 30K JT cooler, we show how the compressor can be tailored to these three very different applications by adjustment of the modular piston only; the compressor being identical in all other aspects for the three cases.

SESSION 4:
Sub-Kelvin and Novel Cryocoolers

Tuesday Afternoon
3:00 - 4:00 PM

Co-Chairs

Lionel Duband
Jean-Marc Duval
Michael DiPirro

Performance of a Miniature, Closed-Cycle Dilution Refrigerator at Tilt Angles between 0 and 30 Degrees

R. Snodgrass, J. Ullom, and S. Backhaus, NIST, Boulder, CO and University of Colorado, Boulder, CO

Miniature, closed-cycle dilution refrigerators (DRs) are being explored as an alternative to adiabatic demagnetization refrigerators for suborbital balloon missions that require cooling of sensors to mK temperatures. These DRs do not use large, room-temperature gas handling systems; instead, the recirculating 3He is pumped by a split condenser that is cooled by two 4He-3He evaporator pairs and is returned to the mixing chamber by gravity. The two adsorption-pumped evaporator pairs run in antiphase to achieve continuous cooling of the condenser. The balloon mission requires that the DR and evaporator pairs be tipped at 20 degrees relative to gravity, which may degrade their performance. To validate performance and explore possible design improvements, we are testing a miniature DR (manufactured by Chase Cryogenics) at tilt angles from 0 to 30 degrees from vertical and at azimuthal rotations of up to 360 degrees around the tilted axis. A goal of this study is to determine the orientation of the cryostat that yields maximum performance and the performance reductions for other orientations. In addition to testing the integrated system, we plan to isolate and test each subsystem (4He evaporator, 3He evaporator, and split condenser) to determine their individual performance and contribution to the integrated system performance.

Continuous 350 mK Stage ADR Cooling for Space and Ground Application

J.M. Duval, J.L. Durand, and T. Prouvé, University Grenoble Alpes, CEA, IRIG-DSBT; C. Marin, University Grenoble Alpes, CEA, IRIG-PHELIQS; and J. André and L. Marelli, CNES, Toulouse, France

LiteBIRD is a planned JAXA-led mission aimed at the measurements of the polarization of cosmic microwave background. To reach the desired sensitivity, its detectors must be cooled to 100 mK. The proposed cooler, based on a succession of Adiabatic Demagnetization Refrigerator (ADR) stages, includes a 350 mK continuous stage driving the overall mass. Experimental demonstration of 350 mK cooling have been achieved based on a 2.7 K interface from a laboratory pulse tube. Optimization using the 1.7 K available interface is on-going including a reduced size stage. In addition to experimental results, numerical modelling helps emphasize some main driving design parameters. This type of cooler operation is also well suited for ground applications and benefit from space optimization: the mass and size reduction necessary for space design can translate to cost reduction for a dedicated ground design.

Heat Transfer Analysis of the Tube-in-Tube Heat Exchanger in Dilution Refrigerators

H. Zu, W. Dai, J. Shen, K. Li, and Y. Wang, Technical Institute of Physics and Chemistry, CAS, Beijing, China and University of CAS, Beijing, China

Dilution refrigeration is widely used in the frontier research fields of condensed-matter physics, astronomical observation, and quantum computing, and heat exchangers are the critical components affecting its performance. The heat exchanger is significant to the normal operation and efficiency evaluation of the whole system, especially in the cold-cycle dilution refrigerators with small driving force. At present, there are few reports on the comprehensive analysis and quantitative calculation of heat exchanger at home and abroad, especially under low flowrate conditions. This paper focuses on the continuous tube-in-tube heat exchanger in dilution refrigerators, establishes the theoretical and numerical models, and uses MATLAB to calculate the optimum size and heat transfer performance under low flowrate conditions. It is found that the Kapitza thermal resistance between the dilute liquid and the tube wall is the most critical factor. In the design and optimization of the heat exchanger, to improve the performance and reduce entropy production, the heat transfer area of the dilute fluid should be increased as much as possible while restraining the axial liquid thermal conduction and viscous heating. This paper lays a foundation for the further design and research of dilution refrigerators.

SESSION 4: Sub-Kelvin and Novel Cryocoolers

Paper No. 4-4 Tuesday Afternoon 3:45 PM

Lunar Night Survivability of Cryocooled Instruments Using PALETTE Thermally-Switched Enclosures

D. Bugby and J. Rivera, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; and S. Britton, NASA Langley Research Center, Langley, VA

The Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project is developing four new thermal management techniques that will allow cryocooled and/or ambient temperature science payloads to survive multiple lunar day/night cycles. The targeted science payloads are those slated to fly on upcoming commercial lunar payload services (CLPS) landers, none of which will likely be able to survive the first lunar night. This paper will provide a status update on those four techniques, which include: (1) thermally-switched enclosures, featuring a nested pair of Vectran tension cable supported cube-shaped enclosures, which are thermally-switched using a reverse-operation DTE thermal switch (ROD-TSW) in series with a propylene miniature loop heat pipe (mini-LHP); (2) 3D-printable parabolic reflector radiators (PRRs), which can be very affordably produced and enable side-facing, low sink temperature radiators at low-latitude lunar sites; (3) spacerless MLI, which is a new concept with a tested e* value < 0.002 that hangs 8-10 layers of double aluminized Mylar from the Vectran tension cables between the enclosures; and (4) advanced thermal isolators using optimized Ti64 and polymeric designs. These techniques are already being used in the upcoming JPL Farside Seismic Suite (FSS), which will put two seismometers on the lunar farside in 2025. FSS, which has its own C&DH, batteries, radio, and solar panel, is expected to operate for at least four months on the lunar surface with communications provided by a relay satellite. One application for PALETTE technology described in the paper is a concept for using lunar night cryogenic temperatures and a thermal storage unit (TSU) to augment the cooling capacity of cryocooled science payloads. The paper will include the latest test data from the PALETTE project, which is a 3-year effort initiated in April 2020 and is funded by the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program.

SESSION 5:
Other Cryocooler Technologies

Tuesday Afternoon
4:15 – 5:30 PM

Co-Chairs

Mark Zagarola
John Pfotenhauer
Xihuan Hao

Increasing the Efficiency of He and H2 Liquefaction Using Small Coolers

M.A. Green, Lawrence Berkeley Laboratory, Berkeley, CA

People have been re-condensing helium and hydrogen with coolers for many years. There are a number of companies that sell systems that liquefy helium gas at room temperatures. These same coolers can be used to re-liquefy hydrogen at room temperature as well. This author has used coolers to cool-down a superconducting magnet and and liquefy helium in its cryogenic vessel. The rate of liquefaction was affected by several factors. This paper will talk about ways of making the liquefaction of helium and hydrogen more efficient. Both helium and hydrogen require much more cooling to cool down the gas from room temperature to the liquefaction temperature at the 0.1013 MPa boiling point temperature than it does to change the gas to a liquid. This means that the precooling of theses gases is very important.

Heat Transfer in an Eccentric Gas Gap Annulus

T.M. Kalter, M.A.J. van Limbeek, and S. Vanapalli, University of Twente, Enschede, The Netherlands

Heat transfer in the annular region between two cylindrical surfaces is widely studied in the context of gas-gap heat switches operating at cryogenic temperatures. At University of Twente, using a similar working principle, a tissue snap freezer is developed where a vial is cooled by a cold reservoir through a gas gap. In this presentation, the question that will be addressed is how the eccentricity of the gas gap annulus influence the overall heat transfer. For small Biot numbers, temperature gradients in the vial may be neglected and a lumped capacitance assumption is valid. The cooling rate increases as the eccentricity between the two cylindrical surfaces increase. However, when the local Biot number of the vial is large this assumption does not hold. An angular dependence heat transfer model is developed to account for the eccentricity. The model predicted temperature gradients in the vial when the eccentricity is large. Experiments were performed to verify this model. The main conclusion from this study is that eccentricity in the gas gap annulus has a significant effect on the overall heat transfer.

Prospects for High Temperature Cryocooling with Increased SWaP-C Enabled by Advanced DTP Solid-State Thermoelectrics

D. Crane, L. Bell, and R. Madigan, DTP Thermoelectrics, LLC, Altadena, CA

Conventional thermoelectric (CTE) systems can provide temperature differences up to 140K, which is not sufficient for most cryocooling applications. Distributed Transport Property (DTP) Thermoelectrics, thermoelectric material systems with properties that vary optimally throughout the material, exhibit significant gains in cooling capacity, efficiency, and maximum temperature difference. Initial empirical test results and numerical modeling indicate that temperature differences greater than 220K are possible with DTP, opening up a broad range of new opportunities for cryocooling applications.
DTP solid state devices present a new and attractive SWaP-C benefit package not attainable with other cryocooling options. In this paper, we show where temperature control systems based on DTP materials can meaningfully impact cryocooling applications such as cryosurgery and cooling of electronic devices. We compare performance and other critical characteristics of CTE, DTP and traditional cryocooler technologies and identify applications where DTP systems create the option of compact solid state temperature control in the higher operating temperature range of cryocoolers.

Laser Cryocooler Development for Space Applications

R. Vicente and G. Nogues, Néel Institute, CNRS, Grenoble, France; and Y. Juanico, A. Gardelein, and P.O. Mine, Air Liquide Advanced Technology, Sassenage, France

Laser coolers are an innovative class of coolers capable of reaching cryogenics temperatures in a miniaturized, contact-less and entirely vibration free technology. They are based on optical refrigeration in solids: upon illumination at the appropriate wavelength, rare-earth doped cooling crystals possess the property to extract heat out of their crystalline lattice, re-emitting more light than they have absorbed. This promising effect, known as anti-Stokes cooling, has seen major improvements over the last decade.

We report on our progress with the development and demonstration of the first fiber-coupled Laser Cryocooler prototype aimed at space applications, in a partnership led by Air Liquide Advanced Technologies. On top of a design suitable for easy integration onboard a satellite, our results show that our prototype reaches cryogenics temperatures with reduced parasitic thermal loads, thanks to the small dimensions of cooling crystals and the optical, contact-less power supply method.

This newcoming technology among existing cryocoolers solutions opens the door to active, entry-level cryogenic cooling in a number of applications where size, weight and vibrations are critical, such as in small Earth observation satellites but also in ground applications.

Looped Thermoacoustic Cryocooler with Self-circulating Distributed Cooling

T. Steiner, Etalim, Canada

A self-circulating loop replaces the expansion heat exchanger as an extension to a previously discussed 450 Hz thermoacoustic cryocooler. A self-circulating loop allows for a distributed cooling load without requiring long-distance thermal conduction of heat. Instead, heat is transported by a steady flow of the working gas around a loop. Acoustic power directly provides the driving pressure for the circulation without requiring any moving parts and can work at low temperatures. A Venturi mechanism previously proven in a thermoacoustic waste heat recovery engine provides the driving pressure. Modelling a proposed system using thermoacoustic theory shows that the acoustic power dissipated driving the loop can be less than what would otherwise be dissipated in an expansion heat exchanger. Thus distributed cooling is possible with no loss of cooling capacity. The high frequency of operation enables a compact machine that is furthermore very low cost and ultra-reliable.

PLENARY II: SHI's Two-Stage 4 K GM Cryocoolers: Enriching Emerging Technologies through Leading-Edge Advancements

Wednesday Morning
8:15 - 9:00 AM

Co-Chairs

Richard Dausman
Mark Zagarola
Peter Bradley

PLENARY II

Wednesday Morning 8:15 AM

SHI's Two-Stage 4 K GM Cryocoolers: Enriching Emerging Technologies through Leading-Edge Advancements

T. Lei, S. Dunn, and B. Gronemeyer, Sumitomo (SHI) Cryogenics of America, Inc., Allentown, PA; and M. Xu, T. Morie, and Y. Hiratsuka, Sumitomo Heavy Industries, Ltd., Tokyo, Japan

The SHI Cryogenics Group, along with its parent company Sumitomo Heavy Industries, Ltd., is a global leader in cryogenic technology. During its 60-year history it has grown to design and manufacture the broadest array of cryocoolers and related cryogenic systems worldwide, serving magnetic resonance imaging (MRI), semiconductor, laboratories, aerospace and other research applications. Aligning with our goal to create a better tomorrow through innovative solutions, we particularly support emerging technologies through advancements in cryocooler development, and provide exceptional performance and service through our global network.

With our customers facing helium supply shortages and higher costs, we developed the leading-edge RDE Two-Stage 4 K Gifford-McMahon (G-M) Cryocooler Series, enabling the move from a full helium bath design to the low cryogen design used by the latest MRIs. Specifically, we will present the RDE-418D4 Cryocooler, which increases cooling performance by 20% over our previous model and provides 2.0 W at 4.2 K and 50 W at 50 K, with a power consumption as low as 7.5 kW at 60 Hz.

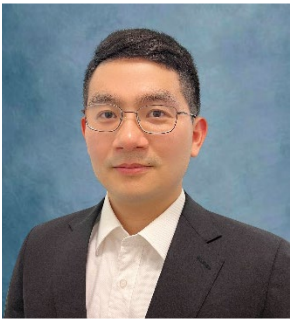
For the fast growth of quantum technologies, our RDK-101D(L) cryocooler, which is the world's smallest two-stage 4 K Cryocooler, continues to evolve and enables supporting applications like desktop quantum systems, single photon detectors and optical quantum systems. This innovative, low-vibration cryocooler features a guaranteed minimum temperature of <2.3 K and provides 0.16/0.2 W at 4.2 K (50/60 Hz) with about 1 kW input power. Our pulse tube refrigerator product line also has expanded rapidly, with the newest model, RP-

222B3S, providing 2.0 W at 4.2 K and more for scaling-up dilution refrigerators and quantum computing systems.

These cryocooler innovations, as well as their performance characteristics and applications, are presented and discussed.

Speakers

Dr. Mark Derakhshan was named President and Chief Executive Officer of Sumitomo (SHI) Cryogenics of America, Inc. (SCAI) in April 2021, overseeing operations in five facilities across the United States. He joined SCAI in March 2019 as Director, SCAI Engineering, leading and supporting new product development and other related initiatives.
Prior to his time with SHI, Dr. Derakhshan gained over 20 years of progressive engineering and managerial experience in the healthcare diagnostic imaging industry, including 14 years in MRI magnet design and development. He holds a Ph.D. in Mechanical Engineering from Tennessee Technological University and has authored over a dozen patents within the healthcare industry.



Dr. Tian Lei is currently a Principal R&D Engineer with Sumitomo (SHI) Cryogenics of America, Inc. (SCAI). He received his B.S. degree in 2009 and M.S. degree in 2012 from the Zhejiang University, China, and his Ph.D. degree in 2016 from the Technical University of Denmark, all in Mechanical Engineering. His research explores the development and application of regenerative cooling systems, including thermoacoustic engines, magnetocaloric refrigerators and regenerative cryocoolers. He has authored or coauthored over 40 journal and conference articles and over 10 patents. His current research interests include efficient Gifford-McMahon and pulse tube cryocoolers, and their applications.

SESSION 6: GM & GM-Type Pulse Tube Cryocoolers

Wednesday Morning
9:00 - 10:30 PM

Co-Chairs

Santhosh Kumar Gandla
Harrison Hones
Ravi Bains

SESSION 6: GM & GM-Type Pulse Tube Cryocoolers

Paper No. 6-1 Wednesday Morning 9:00 AM

Development of a High Capacity Single Stage GM Cryocooler

S.K Gandla, Q. Bao, J. Koch, M. Xu, S. Dunn and R.C. Longsworth, Sumitomo (SHI) Cryogenics of America, Inc., Allentown, PA

Markets for single-stage GM cryocoolers are pushing towards higher-capacity systems with higher efficiencies. Sumitomo (SHI) Cryogenics of America, Inc. has developed a high-performance, low-noise single-stage cryocooler for LN2 generators, HTS applications and circulating cooling system applications, leading to higher liquefaction rates, faster cool down and better efficiencies. The development of this high-capacity single-stage GM cryocooler, which has a capacity of more than 600 W at 77K at 60 Hz is described in this paper. The presented research includes trade-off studies during development, such as the cryocooler performance at different speeds, heat exchanger efficiencies and regenerator designs.

Development of a 2W 4K Pulse Tube Refrigerator with Remote Valve

T. Lei and M. Xu, Sumitomo (SHI) Cryogenics of America, Inc., Allentown, PA

A two-stage pulse tube refrigerator, having a capacity of 2 W at 4.2 K and simultaneously 60 W at 50 K, has been developed by Sumitomo (SHI) Cryogenics of America, Inc. for applications such as large cryogen-free dilution refrigerators and superconducting magnets. This pulse tube refrigerator has a low-vibration design using a remote valve. The development of this pulse tube refrigerator and its performance characterization, including improvements in system efficiency, are described in this paper. Characteristics of the new pulse tube refrigerator in potential applications are also discussed.

Contributions of Numerical Simulation in Development of Pulse Tube Cryocoolers

C. Wang, Consultant, Manlius, NY

Numerical simulations of pulse tube cryocoolers revealed the internal operating processes and led to the innovation and improvement of the pulse tube cryocooler. This paper reviews some major contributions of numerical simulation in the development of pulse tube cryocoolers: (1) revealed and confirmed the concept of "gas piston" in the pulse tube; (2) revealed a phase shifting mechanism of an orifice pulse tube cryocooler; (3) revealed the double-inlet functions and helped invent a double-inlet pulse tube cryocooler; (4) discovered and revealed "DC flow" effects in pulse tube cryocoolers; (5) helped understand unique features of 4 K regenerators; (6) helped understand the enthalpy losses in 4 K regenerators and utilize the enthalpy losses for precooling; (7) helped invent and understand new phase shifters for pulse tube cryocoolers.

Development of High Cooling Capacity 3 K Two-Stage Pulse Tube Cryocooler

X. Hao, J. Cosco, and R. Dausman, Cryomech, Inc., Syracuse NY

The quantum computing and dilution refrigerator (DR) market is growing very rapidly, and development of high cooling capacity, ultra-low vibration, fast cool-down, high energy efficiency and reliable cryocoolers for this market is of great importance. This application has the potential to become another major industrial market for cryocoolers in the near future. Higher cooling capacities are normally required at 3 K or below, rather than 4.2 K, for most dilution refrigerators. Commercial 4 K cryocoolers (either Pulse Tube or G-M) are normally designed for optimum performance at 4.2 K. In addition to higher cooling capacities at 3 K, lower no-load temperatures are also required for this application. A high cooling capacity 3 K two-stage pulse tube cryocooler has been developed at Cryomech, which can provide more than 1.0 W at 3.0 K on the 2nd stage with 33 W at 35 K on the 1st stage simultaneously operating on either 60 or 50 Hz power. The no-load base temperature is lower than 2.30 K. The input powers are 13.0 kW (60 Hz) and 12.0 kW (50 Hz) at steady state. The cooling performance and experimental results will be presented in this paper.

SESSION 6: GM & GM-Type Pulse Tube Cryocoolers

Paper No. 6-5 Wednesday Morning 10:00 AM

Development of High Cooling Capacity and High Efficiency 4.2 K Pulse Tube Cryocoolers

X. Hao, J. Cosco, B. Zerkle, and R. Dausman, Cryomech, Inc., Syracuse, NY

Cryomech has been continuously improving both cooling capacity and energy efficiency of its 4.2 K two-stage pulse tube cryocoolers. The model PT425 was launched in March 2021, which can provide more than 2.7 W at 4.2 K on the 2nd stage with 55 W at 45 K on the 1st stage simultaneously operating on either 60 or 50 Hz power. The input powers are 13.0 kW (60 Hz) and 12.0 kW (50 Hz) at steady state. Its optimized design is based on the existing model PT420 (2.0 W at 4.2 K), without increasing the cryocooler's physical size and compressor model. It allows for swap-and-switch implementation on existing customer designs.

Meanwhile, a high efficiency 1.5 W/4.2 K two-stage pulse tube cryocooler has also been developed. The power consumption of our conventional 1.5 W/4.2 K pulse tube cryocooler (Cryomech model PT415) is 10.7 kW (60 Hz) and 9.2 kW (50 Hz) at steady state. The recently developed 1.5W/4.2 K cryocooler can provide more than 1.5 W at 4.2 K on the 2nd stage with 45 W at 45 K on the 1st stage simultaneously operating on either 60 or 50 Hz power. The power consumption is only 8.5 kW (60 Hz) and 7.3 kW (50 Hz) at steady state, which is very close to the energy efficiency of commercial 1.5 W/4.2 K G-M cryocoolers in the market.

The cooling performance and experimental results will be presented in this paper.

Paper No. 6-6 Wednesday Morning 10:15 AM

Low Frequency Stirling Operation of a Two-Stage 4K Cryocooler without Rotary Valve Using a Metal Bellows Compressor

J. Hoehne, Pressure Wave Systems GmbH, Taufkirchen, Germany

The energy efficiency of low frequency GM and pulse tube cryocoolers is partially limited by the rotary valve. Moreover, there is a desire to build cryocooler systems with less mechanical parts that might fail or show wear. Pressure Wave Systems started the development of a metal bellows compressor for low frequency Stirling operation of 4K GM and pulse tube cryocoolers without the rotary valve. In this paper we report first results of successfully using a modified version of our commercially available 1kW bellows compressor to directly drive the TransMIT SUSY two-stage pulse tube cryocooler in low frequency Stirling mode at around 2Hz operating frequency. Future work on using this technique with 4K GM cryocoolers will be discussed.

SESSION 7:
Space Integration & Applications

Wednesday Morning
10:45 AM - 11:45 AM

Co-Chairs

Melora Larson
Srinivas Vanapalli
Peter Kittel

Cryocooler Exported Vibration Reduction System (CEVRS)

R.C. Hon, C.S. Kirkconnell, and T.B. Smith, West Coast Solutions, Huntington Beach, CA

High power 4 K cryocoolers are required for several proposed NASA space missions, including the Lynx X-ray telescope and the Origins Space Telescope (OST). High power linear cryocoolers, such as the Lockheed Martin 4-stage pulse tube cryocooler, are contemplated for these missions. Exported vibration from these large cryocoolers poses a jitter concern for these optically-sensitive deep space astronomy missions. West Coast Solutions is developing a standalone active vibration reduction system, called Cryocooler Exported Vibration Reduction System (CEVRS), that will reduce the vibrations exported from the cryocooler subsystem at the source. Recent progress and future plans for two approaches are described. The first, dubbed Electromechanical Vibration Cancellation (EVC), creates forces and moments that are equal and opposed to the forces and moments generated by the cryocooler mechanisms such that from the view of the attached structure, little or no net force exists. The second approach is Piezoelectric Vibration Decoupling (PVD), wherein the strategy is to dynamically decouple the cryocooler from the attached structure, allowing the cryocooler to move under its own generated vibration forces and moments without transmitting those forces and moments to the larger system.

FPFD Radio Isotope Heat Sourced Stirling Engine for Powering Stirling Cryocooler and Other Devices in Space

M.A. Krishnan and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

Cryocoolers are used in space applications to cool the sensors and other electronic equipment. In satellites, Image capturing sensors are used for enhancing the spectral coverage range of these devices from visible to far-infrared, which requires low temperature cooling. An onboard power system is used to drive the cryocooler. This poses significant challenges if traditional solar arrays are used to power the rover. Dynamic Radioisotope Power systems, which are far more efficient compared to solar arrays and the currently used Radioisotope Thermoelectric Generator (RTG), are still under development and their capability to power the cryocooler along with the subsystems in the rover have not been studied extensively. In this study, a Free Piston Stirling Engine, in the medium power range, is designed to work with Radioisotope Power Source to power the rover. Part of the generated power is used to run a Stirling Cryocooler, which is designed to work with minimum power. Both the engine and the Cryocooler are designed using SAGE software and the engine results are verified using an Axisymmetric 2D CFD analysis in ANSYS Fluent. The developed CFD model is further validated using the available results from GMRL GPU-3 engine, The designed engine is found to have a maximum efficiency of 40% at a power output of 250 W and is found to be sufficient to power the Cryocooler as well as other subsystems in the rover.

Design of Zero Boil-off Cryogenic Storage Vessel Using Stirling Cryocooler for Cryogenic Rocket Engine Tanks

M.M. Shyam and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

Heat inleak into the cryogenic vessel is a major problem that occurred during the cryogenic storage. With the help of cryogenic insulation, the heat inleak can be reduced to a considerable amount. Among different cryogenic insulation, the Multilayer Insulation (MLI) ensures minimum heat inleak. The optimum layer density of MLI depends upon the parameters such as emissivity of shield, number of layers, the pressure of entrapped gas between the layers, etc. Even so, using MLI still there will be some boil-off of cryogen takes place inside the storage vessel. This boil-off creates a huge volume of vapour resulting in thermal stratification and self-pressurization which may lead to pump cavitation. This can be avoided by designing a zero-boil-off system with the help of a cryocooler. The cooling effect produced by the cryocooler is made to circulate around the insulations of the cryogenic storage vessel continuously to maintain a lower temperature and thereby ensure zero boil-off. The heat inleak to the MLI can be obtained by knowing the outer temperature with the help of a computer program. A Stirling-type cryocooler is used here for producing the zero boil-off condition. With the help of SAGE11 software, the Stirling cryocooler is designed and optimized for the above application. The feasibility study of the proposed system is checked in SIMSCAPE.

Design of Thermal Systems for Cryocooled Sensors in Space Rovers with Feedback Loop

A.S. Vaisakh and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

The lifespan, performance and efficiency of planetary rovers mainly depends on how efficiently the thermal management system works. In order to maintain the desired temperature level of the sensors, a cooling system preferably cryocooler is required. This paper deals with incorporating a cryocooler with a feedback control system for ensuring an effective cooling. Of all the different types of cryocoolers, Stirling cryocooler is used in this study. The feasibility of the proposed control system is checked in SIMSCAPE(MATLAB) software package and the complete model of the Stirling cryocooler is designed and optimised using SAGE v.11 software. In SIMSCAPE, a sine wave generator is used to imitate the variation in the temperature of the sensors during its operation. The heat loss from the sensor by conduction and convection is also considered in the study. Cryocooler generally have a large starting time, which makes the feedback system less responsive to sudden variations. The whole system is controlled using a feedback loop and a relay which takes the corresponding planetary reference temperature of sensor as the control parameter.

SESSION 8: Aerospace Cryocoolers - Development

Wednesday Afternoon
1:45 - 3:15 PM

Co-Chairs

Ted Conrad
Melora Larson

Ball Klondike Cryocooler System Design, Development, Qualification and Performance

R. Taylor, B. Buchholtz, A. Brown, D. Glaister, Y. Kim, A. Contreras, and D. Oenes, Ball Aerospace, Boulder, CO; C. Fralick and D. Mansfield, Sunpower, Athens, OH; and K. Frohling, Iris Technology, Irvine, CA

Current and future cryogenic space payloads are pushing the limits of current space rated cryocooler systems. Industry expectations for future cryocooler systems include shorter lead time, >5x cost reduction, and higher efficiency/capacity. Ball has developed a productized, turn-key cryogenic cooling system called Klondike that meets and exceeds these expectations. The Ball Klondike Cryocooler System includes a TRL9 Low Exported Vibration Cryocooler Assembly (CCA) mated to a TRL8 Sunpower DS-30 cryocooler, TRL8 Iris Technology HP-LCCE2 Cryocooler Control Electronics (CCE), flight harnesses, cold-tip thermal strap, and standard heat rejection interface. The Klondike system successfully passed qualification and has been delivered to a government customer for a flight program of record. This paper discusses the design, development, qualification and Thermodynamic and EFT (Exported Force and Torque) performance of the Klondike Cryocooler System.

Ball Verne Cryocooler System Design, Development, and Initial Qualification

R. Taylor, B. Buchholtz, D. Glaister, and Y. Kim, Ball Aerospace, Boulder, CO; C. Fralick and D. Mansfield, Sunpower, Athens, OH; and K. Frohling, Iris Technology, Irvine, CA

Low-cost proliferated cryogenic space payloads are driving use of tactical cryocoolers to meet SWAP-C requirements. Historically tactical cryocoolers have not been considered for space flight due to short MTTF (0.5-1yr) against typical mission lifetimes on the order of 3-5 years. To mitigate reliability concerns, Ball has worked closely with our partners at Sunpower Inc. to develop a very low-cost, turn-key cryogenic cooling system called Verne that is designed for a 3-year mission life. The Ball Verne Cryocooler System includes a TRL6 Low Exported Vibration Cryocooler Assembly (no launch-locks) mated to a TRL8 Sunpower DS-MINI cryocooler, TRL8 Iris Technology ICE-G2 Cryocooler Control Electronics (CCE) and includes a low-cost thermal strap heat rejection system. The Verne system has successfully passed vibration and Exported Force and Torque qualification and has been baselined for a future spaceflight mission. This paper discusses the design, development, and initial qualification of the Verne Cryocooler System.

20 Watt 20 Kelvin Reverse Turbo-Brayton Cycle Cryocooler Testing and Applications

B.T. Nugent, R.J. Grotenrath, and W.L. Johnson, NASA Glenn Research Center, Cleveland, OH

Long-term storage of cryogens is an essential capability required to enable NASA's anticipated missions to both the Lunar and Martian surfaces. A key component to furthering these capabilities is the development of a high capacity, low temperature cryocooler to allow for zero-boil-off storage of liquid hydrogen propellant. The technology being developed by NASA to meet this objective is a reverse turbo-Brayton cycle cryocooler capable of removing 20 Watts (W) of heat at 20 Kelvin (K). This hardware was recently tested at Creare LLC in a vacuum chamber to simulate a relevant mission environment. This testing demonstrated the hardware's functionality and established a baseline for the cryocooler's capabilities. Additional NASA led characterization testing is underway and will provide a broader picture of the operational capability of the cryocooler. This paper will discuss the results of this recent testing, along with highlighting the applications for high capacity cryocoolers on future NASA missions, such as Nuclear Thermal Propulsion (NTP) and a sustainable lunar architecture.

Development and Testing of a High-Capacity 20 K Cryocooler

K.J. Cragin and M.V. Zagarola, Creare LLC, Hanover, NH

Creare is developing a high-capacity 20 K cryocooler to support NASA's initiatives for zero-boil-off storage and liquefaction of hydrogen in space. The cryocooler is a single-stage turbo-Brayton cryocooler that is designed to produce 20 W of refrigeration at 20 K and reject heat at 300 K. The turbomachines are derived from prior designs and have been optimized for operation in helium and at high volumetric flow rates. The recuperator is new technology developed through a collaboration with Mezzo Technologies and Edare LCC, Creare's sister company, and optimized for high mass flow rates, low pressure loss and high thermal effectiveness. The high effectiveness recuperator enables the cryocooler to operate between 300 K and 20 K in a single stage. Three centrifugal compressors in series provides the pressure ratio which is expanded through a single turbo-alternator at the cold end. The cryocooler components are packaged and integrated in a flight-like configuration suitable for launch vibration testing. This paper reviews the component testing, integration and initial testing of the cryocooler.

Development of a Space Closed Loop Hybrid J-T Cooler below 2K

Y. Ma, J. Quan, Y. Liu, J. Wang, J. Li, G. Wang, Z. Liu, and J. Liang, Key Laboratory of Technology on Space Energy Conversion, Technical Institute of Physics and Chemistry, CAS, Beijing, China

The hybrid J-T cooler is taking the place of super-flow helium cryostat due to its advantages of small size and weight and long life. A hybrid J-T cooler below 2K, composed of a 3He JT cooler precooled by a two-stage thermally coupled pulse tube cooler, is developed by our laboratory. The influence of charge pressure on the performance of the hybrid J-T cooler is experimentally tested. And the comparison of the heat transfer characteristics of 3He and 4He in counter-flow heat exchangers is presented. Besides, discussion of the difference between 3He J-T process and the 4He J-T process is demonstrated. Finally, temperature of below 1.8K is achieved when the total power consumption is lower than 280W.

A Hundred-watts Cooling Power Coaxial Pulse Tube Cryocooler for Space Application

Y. Zhang, N. Wang, M. Zhao, and J. Liang, Key Laboratory of Technology on Space Energy Conversion, Technical Institute of Physics and Chemistry, CAS, Beijing, China

In recent years, the cooling capacity of space pulse tube cryocoolers (PTCs) used in cooling space infrared detectors is in tens of watts mostly. For reserving cryogenic liquids and cooling complete optical systems in space, the demand of high cooling power to PTCs has been proposed. However, there are few studies on high cooling power space PTCs. In order to meet the future demand for space cooling capacity, this paper reports a hundred-watts cooling power PTC used in space. The PTC has a cooling power of 100W at 80K,with the Relative Carnot Efficiency relate to the PV power is 19.3%. The entire cold finger measures 140*140*210 mm and weighs 8.8kg. With the design of split-type structure, the vibration and noise of the PTC is slighter to adapt to the demand of micro disturbance.

SESSION 9:
Cryocooler Drive & Control Electronics

Wednesday Afternoon
3:30 – 4:30 PM

Co-Chairs

Carl Kirkconnell
Ryan Taylor
Ray Radebaugh

Development and Qualification Testing of Cryocooler Systems for Affordable Space Missions

D.W. Fogg, R.W. Kaszeta, and M.V. Zagarola, Creare LLC, Hanover, NH; and C. Kirkconnell, West Coast Solutions, Huntington Beach, CA

An increased number of space missions are utilizing constellations of small satellites to replace larger and more costly strategic satellites. These constellations offer enhanced coverage and resilience in comparison to one or several exquisite satellites. To address this growing market, Creare and our collaborators at West Coast Solutions developed low-cost space cryocooler systems based on our micro-sized cryocooler control electronics (MCCE). These electronics were qualified in 2020 and soon baselined for several space missions. This paper describes the qualification of these systems for space missions utilizing the MCCE with two tactical cryocoolers, the AIM SF070 and Thales LPT9510.

Deep Space Cryocooler Control Electronics for the Ricor K508

K.D. Frohling, J.S. Fechter, and J.M. Moritz, Iris Technology, Irvine, CA; R.C. Blase, Southwest Research Institute, San Antonio, TX; and V. Segal, Ricor, En Harod Ihud, Israel

In this topic Iris Technology in cooperation with Southwest Research Institute (SwRI) will present the design and test of the MASPEX Cryocooler Electronics Board (MCEB) for SwRI's MAss Spectrometer for Planetary EXploration (MASPEX) instrument for NASA's Europa Clipper mission to Jupiter's moon Europa. The challenges of developing deep space electronics will be discussed along with the challenges of driving rotary cryocoolers. An overview of the MCEB development process from conceptual design to deep-space electronics implementation will be given. The MCEB performance data will be presented along with lesson learned along the way. In addition the testing and qualification of Ricor K508 cryocooler performed by SwRI will be discussed.

Testing of a High-Capacity Pulse-Tube Cryocooler System for Space Applications

R.W. Kaszeta, C.B. Cameron, D.W. Fogg, B.R. Pilvelait, and M.V. Zagarola, Creare LLC, Hanover, NH

Creare is developing high-reliability, long-life cryocooler control electronics for Stirling and pulse-tube cryocoolers. These electronics are derived from our low-cost cryocooler control electronics that were developed and qualified for tactical space missions. The new electronics offer increased reliability and enhanced features that are tailored for the strategic space marketplace. Air Liquide's LPTC pulse-tube cryocooler is an ideal cryocooler for mating with our new electronics. The LPTC has been developed for high-reliability space missions and provides up to 7 W of refrigeration at 80 K with 160 W of AC power. Air Liquide Advanced Technologies and Creare have collaborated on an initial demonstration of the LPTC cryocooler couple with prototype electronics. This paper reviews the initial test results.

SESSION 9: Cryocooler Drive & Control Electronics

Paper No. 9-4 Wednesday Afternoon 4:15 PM

Compressor Stroke and Frequency Response Measurements Using Strain Gauges

H. Rana, M. Dadd, P. Bailey, and R. Stone, Department of Engineering Science, University of Oxford, Oxford, UK

LVDTs are commonly used displacement transducer devices integrated into cryocooler compressors in order to measure displacement stroke. They present the particular drawback of phase lag in the measurement signal. When flexure springs in an Oxford-style cryocooler fail, the off-axis forces on the moving motor shaft will increase and lead to a compressor failure that will halt the operation of the cryocooler. It is therefore important that a suitable method for detecting cryocooler stroke is in place during operation in order to detect early signs of off-axis movement and potential failure. The suitability of a novel method using strain gauges in a full Wheatstone bridge configuration, integrated onto a spring-moving magnet motor setup, is investigated in this study. Finite Element Analysis was conducted to explore regions of highest strain in the spring for a given displacement, which permitted appropriate strain gauge installation. The strain gauge bridge configuration was calibrated with an Omron laser displacement transducer and validated with the FEA model. A variety of tests were then conducted on the system to understand its harmonic characteristics. Finally, a series of dynamic and impact tests were conducted, where measurement during continuous operation and during impact collisions of increasing force were investigated. An analysis of the strain gauge bridge signal output and phasor characteristics of the integrated setup was completed. This measurement technique was successful in measuring in-situ compressor stroke as well as demonstrating a strong frequency response with the ability to detect small impacts on the compressor amid operation.

SESSION 10:
Stirling & Pulse Tube Cryocoolers - Experimental

Thursday Morning
8:15 – 9:30 AM

Co-Chairs

Ryan Taylor
Ingo Rühlich
Srinivas Vanapalli

SESSION 10: Stirling & Pulse Tube Cryocoolers - Experimental

Paper No. 10-1 Thursday Morning 8:15 AM

Experimental Study on a Two-Stage Pulse Tube Cooler with an Active Phase Shifter for Liquid Hydrogen Temperature

X.P. Ding, Z.W. Li, W. Dai, and E.C. Luo, Technical Institute of Physics and Chemistry and University of CAS, Beijing, China; and X.T. Wang. Li and Y.N. Wang, Technical Institute of Physics and Chemistry, CAS, Beijing, China

Pulse tube cooler (PTC) has the advantages of high compactness, reliability, and long MTTF due to the elimination of moving components at the cold end. It already becomes a strong candidate in the fields of infrared detection, high-temperature superconductivity, and space science. However, the current efficiency of PTC at liquid hydrogen temperature is low. It is a hot topic of current research to improve the efficiency of PTC at this low temperature. In this paper, based on the Sage simulation, a two-stage gas-coupled Stirling-type PTC with pre-cooling working in the liquid hydrogen temperature region is built. The first stage uses inertance tube and reservoir, and the second stage uses active motors as phase shifters. The middle of the second stage pulse tube will be pre-cooled by consuming part of the cooling capacity of the first stage through the intermediate heat exchanger. The simulation result demonstrates that the application of active motors can significantly improve the phase distribution of the whole PTC so as to obtain a higher relative Carnot efficiency. This paper will verify from the experimental point of view, how the active motors will improve the phase distribution of the whole system. Meanwhile, the influence of factors such as charge pressure and frequency on the performance will also be discussed.

Experimental Performance of a Passively Driven Displacer

H. Rana, M. Dadd, M.A. Abolghasemi, P. Bailey, and R. Stone, Department of Engineering Science, University of Oxford, Oxford, UK

Stirling pulse tube cryocoolers (SPTCs) incorporate a warm end displacer into a pulse tube cryocooler, where previous studies have demonstrated that an active displacer integrated into an SPTC yields good performance and better efficiencies than pulse tube cryocoolers with inertance tubes. Using an active displacer that is driven by a motor requires a second phase from the power electronics. This results in an increased complexity of the design due to the extra motor and electrical feedthrough; hence it is preferable to have a passively driven displacer. This study presents the experimental testing and validation of a passively driven displacer integrated within a coaxial Stirling pulse tube cryocooler cooling to 80K. The pressure and harmonic driving forces of the displacer are analysed and validated with the theoretically modelled operation of the passive displacer. An insight into the mass flow, pressure pulse and phase angles is presented, providing an understanding into the passive displacer activity for work recovery in a coaxial Stirling pulse tube cryocooler.

High-Availability Cooler Developments at Thales Cryogenics

D. Willems, R. Arts, G. De Jonge, P. Bollens, B. de Veer, and J. Mullié, Thales Cryogenics, The Netherlands

Thales Cryogenics has previously presented its developments in the field of High-Availability (HA) coolers. In this paper, we will present the recent advances in this development program. The initial development was aimed at a HA Stirling cooler for HTS filter applications. An update of lifetime numbers of those Stirling coolers, now running continuously for nearly 5 years without degradation, will be given, indicating the current and expected availability of the technology.

Recent advances include the development of two new Stirling coolers. We will present development status and performance measurements of these coolers which are developed to be integrated with industry-standard ¼” and ½”(SADA2) dewars. This allows the use of HA Stirling coolers in a wide variety of Infrared applications. In addition, the use of pulse-tube coolers for infrared sensing applications will be discussed, as the pulse-tube cooler remains the technology of choice for applications requiring a vanishingly small failure probability.

Overdriving a Pulse-Tube Coldhead with Twin Pressure-Wave Generators to Approximately Double Its Cooling Capacity

D.A. Wilcox and B. Jayasena, MVE Biological Solutions, Ball Ground, GA; P.S. Spoor and D.J. Carlo, Northside Research & Technology, Waterford, NY

MVE Biological Solutions, makers of the Fusion self-sustaining 1500-liter biological freezer, have recently demonstrated the feasibility of a larger, 1800-liter model. The larger freezer is enabled by a cryocooler with approximately double the cooling capacity of that used in the original Fusion. To leverage existing components and reduce the development cycle, the cryocooler configuration consists of the same coldhead used in the existing Fusion cryocooler, driven by two Fusion pressure-wave generators (PWG's) in tandem. This concept carries at least two technical risks: first, that the twin PWG's might not operate in perfect synchronization if they are at all mismatched, and second, that higher amplitude in the coldhead might degrade performance due to nonlinear effects. Though such amplitude effects have been observed in larger-scale coldheads (with capacity of ~200W at 80K) prior experience suggests these smaller coldheads, with nominal capacity of ~30W at 80K, might be relatively immune. The data suggest that little or no degradation results from "overdriving" the Fusion coldhead, with double the cooling capacity obtained from double the acoustic power input. Data from these tests will be presented, along with a discussion of possible limitations of using this approach.

Current Rotary Coolers Improvements Usable for Next Generation of Rotary Coolers

C. Vasse and V. Abousleiman, Thales LAS France, France; and T. Benschop, Thales Cryogenics BV, The Netherlands

Today, many new systems using cryocoolers have a prime requirement to be compact, low weight, and have a low power consumption. These system requirements have a direct impact on the cryocooler technology to be used within these applications. Furthermore, the cooling technology and product definition should be compliant with the required product reliability and the system operational requirements (Robustness, Induced Vibrations, EMI-levels, ROHS, etc.). Improvements and technology developments of cooled IR sensors have had significant impact on the required cryogenic cooling power and temperature to be produced by the cryocooler. Originally, the detectors used to be cooled to a cryogenic temperature of 77K. More recently, depending on detector technology, bandwidth and required performance, the detector operating temperature may vary in a broader range, between 60K to 170K. Furthermore, greater cooler efficiency and power density are required to ease the definition of compact and flexible IR-cores.This paper focuses on next generation cooler characteristics linked to the mentioned system requirements. The latest cooler developed by Thales, the RMs1 is used as case study to illustrate these characteristics leading to a compact and efficient cooler, low induced vibration and noise combined with a high reliability.In the first part of the paper, the definition and the basic cryogenic performance of the RMs1 cooler is presented. In the second part of the paper, the latest improvement is presented such as the impact on overall performance of the newly developed and qualified electronic driver. Based on the results achieved with the RMs1, an approach for future generation compact cryocoolers is presented. The RMs1 cooler and its future spin-offs may be used in different market segments and is surely not restricted to the cooling of IR sensors.

SESSION 11: Regenerator & Recuperator Investigations

Thursday Morning
9:30 - 10:30 AM

Co-Chairs

Tian Lei
Mostafa Ghiaasiaan
Xihuan Hao

Role of Non-Temperature-Gradient Power Flow Terms in Low-Temperature Regenerators

R. Snodgrass, J. Ullom, and S. Backhaus, NIST, Boulder, CO and University of Colorado, Boulder, CO

The total power flow in regenerators of pulse tube refrigerators is key to their performance because it reduces the gross cooling power available at the cold heat exchanger. At low temperatures (below approximately 10 K), the real-fluid properties of helium and the finite heat capacity of regenerator matrix solids create physical mechanisms for total power flow that depend only on the fluid's mean temperature, i.e., "non-gradient" mechanisms; these mechanisms add to those that depend on the gradient of mean temperature. The conservation of total power flow and the sensitivity of real-fluid properties to mean temperature leads to rapid variation of mean temperature along the regenerator axis. Using analytical calculations and experiments where we vary the regenerator warm-end and cold-end temperatures, we show that the relative magnitude of non-gradient power flow terms at the warm and cold ends of the regenerator determine the general shape of the mean temperature profile—whether a large temperature gradient appears at the warm or cold end of the regenerator while the opposite end shows nearly zero temperature gradient. We use the relatively abrupt boundary between these two types of profiles as a probe to better understand the non-gradient power flow mechanisms in regenerators and show its utility in determining where and how to improve materials and design in low-temperature regenerators.

Influence of Regenerator Current Plate Layout and Inlet and Outlet Port Configuration on GM Refrigerator Performance: a CFD Study

Q. Qian, O. Zhengrong, and L. Junjie, High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei, China, and University of Science and Technology of China, Hefei, China

In this paper, the first stage regenerator of a two-stage GM refrigerator whose performance is mainly dependent on the regenerator is numerically studied. Regenerator is an important part of refrigerator, which has important influence on the cooling effect of refrigerator. In this current work, CFD solutions have been selected for numerical purposes. The cooling behavior, heat transfer at the cold and internal pressure change of regenerator are analyzed in detail by using FLUENT. To change regenerator current plate layout position, other parameters remain the same. The cylinder regenerator with a length of 106mm and an internal diameter of 72.5mm with a working frequency of 1Hz for all cases did not change all cases. The results show that there is an optimal position of current plate for wire mesh regenerator. The change of internal pressure is also analyzed. The structure of inlet and outlet ports was changed to obtain the relevant temperature distribution and pressure drop curve under the condition of 1Hz, pressure 2MPa and flow 4g/s. To get an optimum parameter experimentally is a very tedious for GM refrigerator job so the CFD approach gives a better solution which is the main purpose of the present work.

Research on the Thermal-Hydraulic Performance of Twisted Helical Bundle Heat Exchangers

Y.N. Wang, J.M. Pfotenhauer, and F.K. Miller, University of Wisconsin, Madison, WI

A recuperative heat exchanger is an important component in a recuperative cryocooler system, which is commonly applied for the cooling of superconducting electronics, infrared sensors, power systems, etc. Since the flow in this kind of heat exchanger goes through a large temperature span, a twisted helical bundle heat exchanger is being designed and optimized to achieve miniaturization and high effectiveness. The thermo-hydraulic characteristics of flow in the shell side is being explored using CFD simulation. In this geometry, the curve of each inner tube is generated by 3D sinusoidal equations, and the configuration can be specified by the number of bundles, number of tubes per bundle, twist pitch of the bundle and tube diameter. The influence of these parameters on the thermal-hydraulic performance has been investigated. Nusselt number and friction factor correlations have been developed based on Reynolds number and dimensionless geometrical parameters including the conduction shape factor. Compared with spiral wound heat exchangers and staggered stacked slotted plate heat exchangers, the increase of both Nusselt number and friction factor is obvious. The tortuous flow path is assumed to be the reason for the thermal enhancement, due to its promotion of bulk flow mixing and redistribution of energy. The design of the overall heat exchanger includes manufacturability considerations, and a model of the complete heat exchanger will be built to obtain its overall effectiveness.

Compact Mesh-based Recuperator for 40 K Space Reverse Turbo-Brayton Cooler and Remote Cooling Applications

A. Onufrena and T. Koettig, CERN, Switzerland; T. Tirolien, ESA/ESTEC, The Netherlands; H.J.M. ter Brake, University of Twente, The Netherlands

The high-effectiveness compact recuperator (or counter-flow heat exchanger) is a critical component of the 40 K Reverse Turbo-Brayton Cryocooler, which is currently developed for space applications. Also, in remote systems that aim to distribute the cooling power of a cryocooler by means of an active fluid circulation, high-effectiveness recuperators are of paramount importance. A series of novel mesh-based recuperators has been designed, constructed and tested in a collaboration between ESA, CERN and University of Twente. The designs were accomplished using a numerical model based on experimental and theoretical data. Their performance in the 10-290 K temperature and 1-5 bar pressure operation ranges was experimentally tested and analyzed. The test stand was constructed to measure the effectiveness and the pressure drop of both fluid streams at variable system pressure, mass flow rate and temperature conditions. A tremendous increase in effectiveness from 94.9 % (NTU = 18.8) to 98.0 % (NTU = 49) was achieved between the first and second design iterations in the tests with helium. The numerical model was correlated with the test results, and two designs of a 40 K neon recuperator with 98.6 % predicted effectiveness are proposed.

SESSION 12: Superconductor Applications

Thursday Morning
10:45 AM – 11:45 AM

Co-Chairs

Sastry Pamidi
Harrison Hones
Santhosh Kumar Gandla

Fabrication of 4 T HTS Magnet for Adiabatic Demagnetization Refrigerator (ADR)

D. Kwon, B. Kim, and S. Jeong, Korea Advanced Institute of Science and Technology (KAIST), South Korea

A high temperature superconducting (HTS) solenoid is fabricated to provide time-varying magnetic field for adiabatic demagnetization refrigerator (ADR). The fabricated magnet has the outer diameter of 88 mm, the inner diameter of 24 mm, and the height of 54 mm. The magnet is designed to operate in a ramping mode with the maximum field of 4 T, and to be conductively cooled by a 4 K Gifford-McMahon cryocooler. Since the changing current operation of the superconducting magnet involves inevitable energy dissipation and the temperature increase of HTS the tape, the copper thermal drains are inserted into every layers of the magnet winding. A thermal analysis is conducted to confirm the effectiveness of the thermal drain and to predict the transient temperature variation of the conductor inside the winding pack. The time-varying AC loss of the HTS magnet is calculated by using T-A formulation which is based on the calculation of the current vector potential T and the magnetic vector potential A. According to the results of thermal analysis, the operation scenario of the magnet is appropriately proposed. The detailed design and the fabrication process are presented in this paper.

Modeling of Integrated Cryocooling Systems to Improve Resiliency of Superconducting Power Grids on Electric Transport Systems

R.D Machorro Swain, C.H Kim, P. Cheetham, and S. Pamidi, Florida State University Center for Advanced Power Systems, Tallahassee, FL

With the increasing demand for large all-electric transportation systems, resiliency and sustainability of cryogenic circulation systems is needed to facilitate high temperature superconducting (HTS) power devices such as generators, motors, and power distribution cables. For such large and critical power systems, it is advantageous to design the cryogenic circulation system based on the platform level design constraints to ensure greater resiliency. Utilizing multiple integrated cryocoolers within the cryogenic cooling system increases overall efficiency, resiliency, reconfigurability, simplified designs, and allows maintenance to be performed without shutting off the devices. A novel scheme to integrate multiple cryocoolers in one large heat exchanger is introduced to design efficient, expandable, and resilient integrated cryocooler units. The temperature of the gaseous helium cryogen at the outlet of the cryocooling unit and detailed temperature distribution in the unit are simulated by the finite element method (FEM) using COMSOL. The results provide useful insights in determining the internal structure which can be optimized for the sustainability of the cryocooling system at the required cooling power. The key design factors of an integrated cryocooling system are discussed along with the detailed models and feasibilities of building a high power-dense and resilient HTS power system cooled with an integrated cryocooler system.

Enabling High-Temperature Superconducting Magnets on Small Satellites Using a Miniaturized Cryocooler

J.R. Olatunji, N.M. Strickland, T. Berry, E.V.W. Chambers, and S.C. Wimbush, Robinson Research Institute, Victoria University of Wellington, Wellington, New Zealand

High-temperature superconducting (HTS) tapes can carry very large electrical currents through very thin wires with no electrical resistance. This means HTS tape can be wound into lightweight, high field electromagnets that do not generate heat. HTS electromagnets therefore have the potential to be very useful in the space domain, which has extreme size and weight restrictions, and where it can be difficult to radiatively dissipate the amount of heat generated by conventional copper electromagnets. HTS is therefore posited as a miniaturisation technology, capable of generating high magnetic fields onboard small satellites for applications such as electric propulsion, radiation shielding, attitude control and inductive energy storage.

HTS devices require to be operated below some critical temperature, typically ~75 K. Maintaining these cryogenic temperatures in space can be achieved using an electrical cryocooler. The nature of the cryocooler and how it is integrated with the HTS electromagnet has a significant impact on the SWaP (size, weight and power) requirements.

This paper presents modelling and preliminary physical testing of an HTS electromagnet design, to be integrated into a 12U CubeSat. With satellite dimensions of 200 × 200 × 300 mm, this work investigated whether a single miniaturised cryocooler can cool an HTS electromagnet to below its critical temperature, using both a numerical modelling and experimental approach. Using a Sunpower CryoTel MT cryocooler, weighing only 2.1 kg and with a length and diameter of just 243 mm and 73 mm, respectively, a magnet temperature of less than 75 K was obtained, using only 40 W of input power and a 40°C hot end temperature. This demonstrates that HTS electromagnets can be operated on board small satellites using miniaturised, single stage cryocoolers.

Solvay Cryocooler Cryostat for Quantum Material Characterization

R. Bains and M. Sedaille, Advanced Research Systems, Macungie, PA

ARS has developed a novel cryostat specifically for Quantum Material Property Testing. With the promise of Quantum Computing there is a great interest in testing; optical, electrical and magnetic properties of materials. The regions of interest such as quantum dots are in the atomic scale, therefore vibrations, drift and temperature stability become critical performance specifications of this cryostat. The ARS-SOLVAY cryocooler the engine to power the cryogenics of this system, has a unique drive mechanism which has very low vibrations in the temperature range of 2.8K to 4.2K. this feature coupled with additional proprietary vibration isolation techniques allows sub-picometer vibrations at the sample for near field microscopy such as AFM and STM. This paper describes the experimentation and results of the AFM test performed at JILA, Research Institute at Boulder, CO.

SESSION 13: Cryocooler Analysis & Modeling Techniques

Thursday Afternoon

1:45 - 3:15 PM

Co-Chairs

Tian Lei
Mostafa Ghiaasiaan
Ali Kashani

SESSION 13: Cryocooler Analysis & Modeling Techniques

Paper No. 13-1 Thursday Afternoon 1:45 PM

Improvement of a Two-Stage 4-K Pulse Tube Cryocooler with Low Input Power and Comparison to Numerical Simulation

J.-A. Schmidt, B. Schmidt, D. Dietzel, J. Falter, G. Thummes, and A. Schirmeisen, Justus-Liebig-Universität Giessen and TransMIT GmbH, Giessen, Germany

The development and optimization of a new cryocooler working at liquid helium temperature is a long and time-consuming process that can be supported and improved by using suitable numerical software. The numerical simulation software Sage is appropriate for the representation of such cryogenic systems, but difficulties in converging in the range of liquid helium temperatures are well known. Nonetheless, this work proves it to be a powerful tool for analyzing complete low temperature systems in the 4K range.

More specifically, a numerical model in Sage has been constructed, which displays a two-stage 4 K GM-type pulse tube cryocooler with a low input power of about 1 kW, where the coefficient of performance has been doubled. The cryocooler was initially designed for use with single photon detectors at 6 K and has recently been improved for the usage at 4 K. The geometry and regenerator matrix is optimized in two steps to increase the cryocooler's cooling performance. For each step a prototype was manufactured and the corresponding numerical model was calculated. The calculated cooling power is in good agreement to the experimental findings. The numerical models now give insight on the changing thermodynamic parameters due to improved geometry and regenerator matrix. The expected influences of the described optimizations are well represented by the numerical calculations and will be displayed in the presentation. Thereby, it is demonstrated, how Sage simulations allow to draw conclusions on the design and improvement of new pulse tube prototypes beforehand.

Modelling the Thermodynamic Response of a Cryocooler after Switching It Off

K.W. Lotze, H.J. Holland, H.J.M. Ter Brake, University of Twente, The Netherlands

In order to reduce thermal noise, devices may be cooled down to cryogenic temperatures. In many such cases, interference caused by the cooler (such as vibrations or electromagnetic noise) is not acceptable. Therefore, standard off-the-shelf coolers need to be operated remotely with some kind of thermal link, or need to be switched off during the sensitive operation of the device. In the latter case, the noise-free operating time is an important parameter. In order to estimate this operating time in the design phase of the total system, the thermodynamic response of the cooler to its interrupted operation needs to be known. For that purpose, a thermodynamic model of a warming-up cooler is developed. Basically, each stage of the cooler is modelled as a lumped heat capacity linked to the warmer stage by a thermal conductor (or as the reciprocal analogue, by a thermal resistor). Heat capacity and thermal conductance are considered temperature dependant, but the exact materials are unknown. We present a method for determining these model parameters based on a set of experiments. The method is illustrated with experiments performed on a two-stage pulse tube cooler (Cryomech PT405). Heat capacity and conductance results of these experiments are discussed and the warm-up behaviour predicted by the resulting model is compared to experimental data and discussed.

Optimizing Flow Uniformity through Regenerators of Large Cryocoolers Using CFD

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

Regenerators are a key component of any cryocooler from small to large scale. A desirable regenerator should have low friction factor in the flow direction, high thermal capacity and low conduction from hot to cold end. To achieve these conditions, an advanced regenerator is under development by West Coast Solutions (WCS) and Georgia Tech for a co-axial single stage pulse tube cryocooler with 150W @ 90K cooling power. High flow uniformity through the regenerator at both cold and warm ends is critical for high efficiency performance of the regenerator and reduced flow losses. Any flow non-uniformity deteriorates the regenerator performance in comparison with an ideal one-dimensional operation. This study focuses on optimizing the flow through a large regenerator by designing specific flow distribution components composed of perforated blocks with open and screen mesh-filled plena. All analyses and optimizations are performed using Computational Fluid Dynamics (CFD). The depth of open plenum, mesh screen type, and the number of mesh screens in the mesh screen-filled plenum are among the parameters in the sensitivity and optimization study.

SESSION 13: Cryocooler Analysis & Modeling Techniques

Paper No. 13-4 Thursday Afternoon 2:30 PM

Square Wave Test for Characterization of Compressor Piston Blowby

R.G. Ross, Jr. and K. Penanen, Jet Propulsion Laboratory, Pasadena, CA; and J. Olson and E. Roth, Lockheed Martin Space-ATC, Palo Alto, CA

Modern cryocooler linear compressors commonly use clearance seals as the primary sealing mechanism between the piston and cylinder. Such clearance seals are just very narrow non-contacting radial gaps on the order of 5 to 10 microns (0.0002"-0.0004") that limit the gas flow past the piston to a tolerable level. Such clearances are quite demanding to produce and are extremely difficult to measure accurately, even when the piece parts are available before final assembly. One means of testing the gaps is via a blowby test – conducted prior to compressor completion–where the flowrate of gas through the assembled clearance seal is measured as a function of differential pressure applied across the piston. For narrow clearance-seal type gaps, the gas flowrate is proportional to the cube of the gap radial distance, so the blowby test can be a sensitive measure of the initial clearance seal dimensions in a compressor.Because piston blowby is often an important factor in cryocooler efficiency, and increased blowby can be an important indicator of possible life limiting piston/cylinder wear, having an independent means of assessing blowby in an operational cooler is very desirable. Unfortunately, once a compressor is assembled and sealed into a working cooler, the direct measurement of piston blowby is no longer possible. However, indirect means of qualitatively assessing blowby are possible. One means is the square wave test described in this paper. This test involves driving the compressor pistons with a low-frequency square-wave voltage while simultaneously measuring the piston stroke response over time.

Numerical Investigations on Flow Resistance Values for Pulse Tube Cryocoolers

S.C Chaudhari, A.A Ketkar, A.A Ketkar, P. Hemanth, O.P Joshi, and M.V Tendolkar, Veermata Jijabai Technological Institute, Mumbai, India

Pulse tube cryocoolers are usually modelled as one-dimensional flow fields. It has been proven that this assumption holds only for components having large L/D ratios [1]. However, during these CFD analyses of cryocoolers, there has always been some discrepancy between the modelled and the actual operating conditions. Commonly, a pulse tube cryocooler model consists of a compressor, an aftercooler, a regenerator, a pulse tube, hot and cold end heat exchangers, a phase shift device along with a reservoir. Modelling of the regenerator, hot and cold heat exchangers using realistic input values of viscous and inertial resistances prove to be crucial towards the assumption of one-dimensional flow fields.The present work deals with the numerical investigations on the effect of these viscous and inertial resistance values for all porous media. Analyses of individual porous components, viz. regenerator along with cold end heat exchanger and aftercooler along with hot end heat exchanger are executed. The base case taken under investigation is by Cha et al. [1]. The results of resistance values for unidirectional flow and at room temperature by using Ergun's equation are validated. The case is further modified for the operating pressure suitable to employ the resistance values for oscillating flow and at cryogenic temperatures. It is concluded that there is a substantial difference in the predictions of the cryocooler performance, mainly in terms of the no load temperature. This makes the model much more realistic.[1]. Cha, J. S., Ghiaasiaan S. M., Desai, P. V., Harvey, J. P. and Kirkconnell C. S., "Multi-Dimensional Flow Effects in Pulse Tube Refrigerators," Cryogenics 46, (2006), pp. 658–665.

Design, Optimization and CFD Analysis of a Split Type Free Piston Stirling Cooler for Onboard Applications

A.B. Suresh and B.T. Kuzhiveli, Centre for Advanced Studies in Cryogenics, Department of Mechanical Engineering, National Institute of Technology, Calicut, India

A Stirling cryocooler is a device that is working on a closed thermodynamic cycle, which is used for producing the cooling effect. These Stirling coolers are capable of producing a cooling effect that ranges from milliwatts to watts according to the need. The main applications of these Stirling cryocoolers are for cooling the Infrared sensors in Satellites. A free-piston Stirling cooler is a type of Stirling cooler in which the power piston is operated with the help of a linear motor. In the initial part of this study, a novel moving magnet type split free-piston Stirling cryocooler of 0.5 W cooling capacity is designed and optimized with the help of SAGE 11 software. It produces a Carnot efficiency of 0.14303 %.Then the effect of various input and geometric parameters were analysed with the help of SAGE 11 software. In the second part of the study, a 2-D model of the split type free-piston Stirling cryocooler has been done. Then the CFD analysis of the split type free-piston Stirling cooler has been done. The dynamic mesh approach is used for incorporating the back-and-forth linear motion of the piston and the displacer. The main results obtained after the simulations are presented in tabular and graphical forms in this paper.

SESSION 14: Cryocooler Integration

Thursday Afternoon 3:15 – 4:45 PM

Co-Chairs

Sastry Pamidi
Santhosh Kumar Gandla
Timothy Hanrahan

Rigid ADR Suspension

P. Owen, M. Snow, and J. West, FormFactor, Inc., Boulder, CO

Insulating fiber suspensions are commonly used in adiabatic demagnetization refrigerators to position paramagnetic salt pills into the bore of a superconducting high field magnet. Minimizing conducted heat flow from higher temperature levels to the coldest stages of the ADR is key to achieving useful hold times for target regulation temperatures below 100 mK. However, conducted heat flow is only one component of the total heat energy input to the adiabatic cooling system. For systems which are installed in high vibration environments, the heat generation which occurs from physical oscillations of the paramagnetic salt pill through the magnetic field results in major contributions to the total heat dissipation. The design and construction of a rigid suspension spider system which provides a first harmonic response above 400 Hz while insulating a 70 mK salt pill with a characterized parasitic heat leak of 1.2 µW is described in this paper.

Cryocoolers as Enabling Technology for Higher Brightness Photoguns

G.E. Lawler, J. Parsons, A. Fukasawa, N. Majernik, Y. Sakai, and J.B. Rosenzweig, UCLA, Los Angeles, CA

The next generation of electron particle accelerators will likely focus on increasing a figure of merit known as beam brightness. Several important concepts propose to increase brightness by cryogenic operation of the photogun used to produce electron beams. The most relevant concepts are the Ultra-compact xray free electron laser (UC-XFEL) and Cool Copper Collider (C3), an electron-positron collider. Large cooling infrastructure is not conducive to the university-scale research and development of proofs of principles for these concepts. Cryocoolers have made the design of a small-scale cryogenic test accelerator possible. We present the continuing development of a beamline to demonstrate the feasibility of a cryogenic radiofrequency (RF) photogun with photoemission-based cathode. The main issues considered for our targeted 45K operation are RF pulse heating in the cavity, temperature stability across necessary structures, and minimizing cool down time. Considerations will further be given towards schemes for manipulation of the cathode at low temperatures. Results from the first cryocooler commissioning tests and low temperature measurements will also be presented.

Preliminary Experimental Investigations of Large-Scale Helium Pulsating Heat Pipes

L.M. Kossel, J.M. Pfotenhauer, and F.K. Miller, University of Wisconsin - Madison, Madison, WI

Helium pulsating heat pipes (PHPs) are an emergent heat transfer technology with the potential to provide efficient, long-distance cooling power for numerous low-temperature technologies, such as superconducting magnets and space telescopes. In addition, helium PHPs are especially valuable as an enabling component for cryocooler utilization in that they can readily transfer the localized cooling power from the tip of a regenerative cooler over long distances to a variety of heat loads. In this study, an experimental facility is developed to test the performance of vertically oriented, large-scale helium pulsating heat pipes with adiabatic lengths up to 1.75 m. The PHPs consist of 14 parallel stainless-steel tubes with an inner diameter of 0.5 mm, approximately the diameter required to maintain a plug-slug flow regime via capillary forces. Each end of the pulsating heat pipe is fixed to a thin copper plate where the condenser end is cooled by a 4 K cryocooler with a 1.5 W cooling capacity, while a resistive heater provides a prescribed heat load to the evaporator end. Motivated by previous experimental results where helium PHPs displayed a constant conductance despite an increasing adiabatic length, these experiments aim to characterize the length-independence of helium PHPs by evaluating the performance of PHPs with adiabatic lengths longer than 1 m. Preliminary results show that a helium pulsating heat pipe with an adiabatic length of 1.25 m can operate steadily with effective conductivities over 100 kW/m-K.

Cryocooler Integration, Modeling, and Testing for the Ultra Compact Imaging Spectrometer Airborne (UCIS-A) Instrument

C.S. Kirkconnell, C.G. McNeal, T.B. Smith, A. Ghavami, and L.A. Bellis, West Coast Solutions, Huntington Beach, CA

Objects of interest to the DoD community require higher resolution and broader spectral range compared to typical commercial cameras. While commercially available Hyper-Spectral-Imagers (HSI) have typical spectral ranges of 500 to <1,100 nm or 1,300 to 2,000 nm, a wider spectrum of 400 to 2,500 nm is optimum for the broad range of objects of interest to the DoD community. Additionally, high Signal-to-Noise-Ratio (SNR), low scatter, and low Ground Sample Distance (GSD) are needed for desired detection properties. The Ultra Compact Imaging Spectrometer Airborne (UCIS-A), being developed by Jet Propulsion Laboratory with support from West Coast Solutions and others, embodies all of these characteristics at state-of the-art levels. The cryogenic cooling requirement on UCIS-A is met with an AIM SF070 flexure-type linear Stirling cryocooler for the lower stage (focal plane assembly) and a similar but larger SF100 cooler for the upper stage (optics). An aggressive < 2-hour cool-down time from takeoff drove the need for two cryocoolers. This paper describes how this and other unique mission requirements drove the cryocooler selection and integration, the detailed and system level thermal-cryocooler modeling approach and results, and experimental data (benchtop and in situ).

Design and Development of Integral Cold Transportation System

S. Addala, Narasimham GSVL, Karunanithi R, and H.K. Hassan, Indian Institute of Science, Bengaluru, India

A new cold transportation system for a pulse tube refrigerator (PTR) that allows remote placement of the DTC (Device To be Cooled) with respect to the PTR is investigated. Such a system has practical applications in onboard space vehicles for cooling of sensors. The system works on the principle of a DC flow circuit and consists of a pressure wave generator, precooler, check valves and heat exchangers at the cold head of the PTR and the load (DTC). The precooler is a regenerator while the other heat exchangers are recuperators. All the heat exchangers are analyzed and designed to match the heat transfer requirement. In the experimental test rig, the cold head is simulated with a liquid nitrogen bath and the load, with a resistance heater. The entire test rig is placed in a cryostat which is maintained at high vacuum condition. Different experiments are performed at both room and cryogenic temperatures. The experiments include pressure testing to observe the AC-DC conversion of flow across the check valves. The temperature variation at different points of the flow circuit is monitored in time to ensure steady state. The load on the cryocooler is estimated by measuring the boil-off rate of LN2 which plays the role of cryocooler in this experimental setup. The boil off is measured by using a series of PT-100 type temperature sensors placed on a Teflon rod. The sensors are wound with nichrome wire to give a small heat input. The time taken for the rise in temperature of two consecutive sensors is used to calculate the boil-off rate. Results for the quantities of interest such as DTC load and cold head load are presented.

Development of 1.5W Cryostat for a Cold Trap Application

A. Osterman and F. Megusar, Le-Tehnika, Slovenia

A laboratory cryostat for analysis of gas isotopes was developed based on industrialized version of SRI475 cryocooler. At room temperature and 77K, SRI475 cryocooler has cooling power of about 1.5W. This cryocooler was selected as a compact solution with a lot of cooling power was needed. A need for cooling power was significant because there was a substantial thermal mass to be cooled during a cool-down as the cryostat has a removable cold trap mounted on a cold tip. The cryostat uses active vacuum to reduce convective losses. Interface between the cold tip and the cold trap was made of nickel-plated OFHC copper. Because it is a very soft material, additional threaded parts were brazed on it for mounting of the cold trap. To compensate for possible displacement of the cold tip because of mounting forces and moments, internal clearance of a displacer piston towards a cold finger wall had to be increased. Nevertheless, after integration of the cryocooler with the cold trap measurements showed very good results with performance of the cryostat within expected range.

ICC22 DAILY SCHEDULE

Local Time	Monday, June 27	Tuesday, June 28	Wednesday, June 29	Thursday, June 30	Local Time
7:00 AM		Session Chair Breakfast Meeting; Continental Breakfast	Continental Breakfast	Continental Breakfast	**7:00**
7:15 AM					7:15
7:30 AM					7:30
7:45 AM					7:45
8:00 AM	Foundations of Cryocoolers Short Course	Welcome Announcements	Announcements	Late Breaking Announcements	**8:00**
8:15 AM		Plenary I - JWST	Plenary II - SHI's Two-Stage GM Cryocoolers in Emerging Technologies	Session 10: Stirling & Pulse Tube Cryocoolers - Experimental	8:15
8:30 AM					8:30
8:45 AM					8:45
9:00 AM		Session 1: Aerospace Cryocoolers - Mature	Session 6: GM & GM-Type Pulse Tube Cryocoolers		**9:00**
9:15 AM					9:15
9:30 AM				Session 11: Regenerator & Recuperator Investigations	9:30
9:45 AM					9:45
10:00 AM					**10:00**
10:15 AM					10:15
10:30 AM			Break	Break	10:30
10:45 AM		Break	Session 7: Space Integration & Applications	Session 12: Superconductor Applications	10:45
11:00 AM		Session 2: Stirling & Pulse Tube Cryocoolers - Analytical			**11:00**
11:15 AM					11:15
11:30 AM					11:30
11:45 AM			Lunch (On Your Own)	Lunch (On Your Own)	11:45
12:00 PM		Lunch (On Your Own)			**12:00**
12:15 PM					12:15
12:30 PM					12:30
12:45 PM					12:45
1:00 PM	Registration				**13:00**
1:15 PM					13:15
1:30 PM					13:30
1:45 PM		Session 3: Brayton, J-T & Sorption Cryooolers	Session 8: Aerospace Cryocoolers - Development	Session 13: Cryocooler Analysis & Modeling Techniques	13:45
2:00 PM					**14:00**
2:15 PM					14:15
2:30 PM					14:30
2:45 PM					14:45
3:00 PM	NMIH Tour	Session 4: Sub-Kelvin & Novel Cryocoolers			**15:00**
3:15 PM			Break	Session 14: Cryocooler Integration	15:15
3:30 PM			Session 9: Cryocooler Drive & Control Electronics		15:30
3:45 PM					15:45
4:00 PM		Break			**16:00**
4:15 PM		Session 5: Other Cryocooler Technologies			16:15
4:30 PM					16:30
4:45 PM					16:45
5:00 PM					**17:00**
5:15 PM					17:15
5:30 PM					17:30
5:45 PM					17:45
6:00 PM	Welcome Reception		Conference Banquet		**18:00**
6:15 PM					18:15
6:30 PM					18:30
6:45 PM					18:45
7:00 PM					**19:00**
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8:00 PM					**20:00**
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8:45 PM					20:45
9:00 PM					**21:00**

- Event Center (Rear)
- Event Center (Front)
- Bucks Meeting Room
- Berks Meeting Room
- Vision Bar
- National Museum of Industrial History (Offsite)
- ArtsQuest Center (Offsite)

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