Thar Energy
Manufacturer of Heat Exchangers for sCO$_2$ Power Cycles

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Outline

• Introduction
• Thar Energy Projects
• Modular Recuperator Project
Thar has a history of successfully designing & commercializing **Green Products using recycled Carbon Dioxide.**

- **1982**
  - Earn PhD
  - U.S. Patents 4,814,089 & 4,871,453

- **1985**
  - Launch Thar Brand

- **1990**
  - Launch Operating Div.
    - Thar Instruments
    - Thar Process
    - Thar Pharma

- **2007**
  - Acquired Berger from Metler Toledo

**Products and Processes Commercialized**

- Awards & Patents Received
  - U.S. Patents #5,336,869, #5,461,648, #5,694,973, #5,850,934, #5,879,081, #5,886,293, #6,908,557, #7,091,366, #6,698,214.

2001, 2002 Governor’s Export Excellence Award Finalist
2002 National Small Business Exporter of the Year
2002 NIST ATP Awardee (Microrefrigeration)
2002, 2003 Top 25 Biotech Companies
2002, 2003 Top 100 Fastest Growing Companies
2003 Fastest Growing Small Manufacturer Award
2004 Manufacturer of the Year
Over 5,000 green installations world wide

Over 20 Industrial green installations world wide
Thar Timeline (cont.)

- NIST funds micro-refrigeration project
- Thar Instruments, ~125 strong, Offices worldwide, Sold to Waters
- 1st R744 Geothermal Cooling Demonstration
- Validated potential for R744 DX heat pump cycle
- Air Side HX
- Laboratory testing and component development
- Demonstrations at commercial scale - geothermal heating & cooling system (15-20 ton)

2002
- Micro Refrigeration Patent US 7,140,197

2005
- Evaluation of Commercial Drill Technology

2009
- 1st R744 Geothermal Cooling Demonstration

2010
- Launch
- Geothermal Energy System Patent US 8,468,845

2012
- Radiant Floor
- Vertical and Horizontal well fields installed

2014
- High Pressure sCO₂ Pumps
- Advanced Heat Exchanger Technology Demonstration
### S-CO₂ Heat Exchanger and Power Cycle Projects

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<td>2nd Generation Recuperator - 100 kW</td>
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<td>Modular - 47 MW Recuperator</td>
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<td>Sunshot - 2.5 MW Heater</td>
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<td>Oxy Combustion sCO₂ Power Cycles</td>
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<td>Absorption/Desorption sCO₂ Power Cycles</td>
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Phase 2: Two years
Why sCO\textsubscript{2}? 

- sCO\textsubscript{2}, He, Supercritical Steam, and Superheated Steam are from Driscoll MIT-GFR-045, 2008
Typical sCO₂ Recuperated Recompression Brayton Cycle
Thar Energy sCO₂
Recuperators, Heater HXs & Precooler HXs

Counter-Current Micro-tube
sCO₂ - sCO₂
5.5 MW

Low Temp Recuperator
High Temp Recuperator

Compressor
Recompressing Compressor

Precooler
Cooling Air

Microchannel sCO₂ Gas Cooler

Primary Heater
Heat Input

2.5 MW Inconel 740H Hot Air–sCO₂ HX

Typical sCO₂ Recuperated Recompression Brayton Cycle
Sunshot Heater HX Design – 2.5 MW
Hot Gas to sCO\textsubscript{2} HX
Inconel 740H Construction

Design Conditions:
Gas Fired Burner/Blower Outlet Temperature: 870°C
sCO\textsubscript{2} Outlet Temperature: 715°C
sCO$_2$ Gas Cooler HXs
35-500 kW

CO$_2$-Air Approach
Temperature as Low as 2°C

Test Facility

Design

AHU_2_TE1
AHU_2_TE2

115 Tons

CO$_2$-Air
Approach
Temperature as Low as 2°C
1st Generation Recuperator Design

sCO₂ counter-current - microchannel heat exchanger

- Over 5 MW Capacity
- Operating Conditions: 567°C and 255 bar
- Design Conditions: 575°C @ 280 bar
- Floating Head Design
- Serviceability and Maintenance
- Replaceable Tube Bundle
- Easier to manufacture and assemble
- Small size of 9” Dia and 60” long

*Designed per ASME Sec VIII, Div 1*
Sunshot Recuperator Tube Bundle

- Micro-tubes
- High Pressure $\text{sCO}_2$
- Annular Space
- Low Pressure $\text{sCO}_2$

> 20,000 micro-tubes

Tube Bundle
4,500 m²/m³
Recuperator Tube Bundle Cross Section
9” diameter, 5’ long, over 20,000 micro-tubes

Microchannel Printed Circuit HX
Opacity: 38%

Opacity: 74%

Entropy 2015, 17, 3438-3457; doi:10.3390/e17053438
Perforated Separator Sheet Analysis
Improve the Pressure Drop to HTC ratio

~23% increase HTC &
~7% increase Pressure Drop
Modular, Low-Cost, High-Temperature Recuperators for sCO₂ Power Cycles

• **Performance**
  - Temperatures ≥ 700°C
  - Differential pressures ~200 bar
  - Lifetime (corrosion, creep, etc.)
  - Ease of maintenance

• **Scalability**
  - 10 - 1,000 MWe Facilities
  - Transport

• **Cost < $100/kWt**
  - Materials Selection
  - Manufacturability
Focus of New Recuperator Designs

- Improve Performance/Cost Ratio
- Optimized materials’ use for hot and cold sides
- Improved reliability
- Easier to assemble
Modular, Low-Cost, High-Temperature Recuperators for sCO₂ Power Cycles

- Engineering Assessment of Advanced Recuperator Concepts
  - Critical enabling technologies or components
  - Manufacturability of the proposed concepts
  - Potential n\textsuperscript{th} of a kind production cost
  - Anticipated recuperator performance with respect to current state of the art

- Prototype Fabrication, Testing and Evaluation

- Down Select and Fabrication of 47 MWt Recuperator
Modular, Low-Cost, High-Temperature Recuperators for \(sC0_2\) Power Cycles

**Timeline**

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
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<tr>
<td>10/1/15-3/31/17</td>
<td>10/1/15-3/31/17</td>
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<tr>
<td>Q1</td>
<td>Q2</td>
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<tr>
<td>1/1/17-3/31/17</td>
<td>10/1/17-3/31/19</td>
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Summary
Specializes in Low Cost Heat Exchangers Through Design and Manufacturability

• **Advanced Recuperators**
  • High Temperature Recuperators: up to 750°C
    • SS 316, Inconel 625, Inconel 740H
  • Low Temperature Recuperators
    • SS316, Aluminum

• **Advanced Heaters**
  • Up to 750°C
    • SS 316, Inconel 625, Inconel 740H

• **Coolers**
  • Aluminum microchannel heat exchangers
  • Approach temperatures of up to 2°C
Thank you for your kind attention!

Contact:

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ADDITIONAL BACKGROUND SLIDES
## “Typical” sCO₂ Cycle Conditions

<table>
<thead>
<tr>
<th>Application</th>
<th>Organization</th>
<th>Motivation</th>
<th>Size [MWe]</th>
<th>Temperature [deg C]</th>
<th>Pressure [bar]</th>
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<tbody>
<tr>
<td>Nuclear</td>
<td>DOE-NE</td>
<td>Efficiency, Size</td>
<td>300 - 1000</td>
<td>400 - 800</td>
<td>350</td>
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<tr>
<td>Fossil Fuel</td>
<td>DOE-FE</td>
<td>Efficiency, Water Reduction</td>
<td>500 - 1000</td>
<td>550 - 1200</td>
<td>150 - 350</td>
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<tr>
<td>Concentrated Solar Power</td>
<td>DOE-EE</td>
<td>Efficiency, Size, Water Reduction</td>
<td>10, 100</td>
<td>500 - 1000</td>
<td>350</td>
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<td>Shipboard Propulsion</td>
<td>DOE-NNSA</td>
<td>Size, Efficiency</td>
<td>10, 100</td>
<td>400 - 800</td>
<td>350</td>
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<td>Shipboard House Power</td>
<td>ONR</td>
<td>Size, Efficiency</td>
<td>&lt; 1, 1, 10</td>
<td>230 - 650</td>
<td>150 - 350</td>
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<td>Waste Heat Recovery</td>
<td>DOE-EE, ONR</td>
<td>Size, Efficiency, Simple Cycles</td>
<td>1, 10, 100</td>
<td>&lt; 230; 230-650</td>
<td>15 - 350</td>
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<tr>
<td>Geothermal</td>
<td>DOE-EERE</td>
<td>Efficiency, Working fluid</td>
<td>1, 10, 50</td>
<td>100 - 300</td>
<td>150</td>
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Fossil Based sCO₂ Power Cycles

• Competition
  – Indirect: Supercritical Steam with CCS
  – Direct: Natural Gas Combined Cycle

• Advantages
  – High power efficiencies at “Moderate” temperatures
  – Oxy-combustion facilitates integrated carbon capture
  – Compact turbomachinery lead to compact power blocks
  – Partially offset by recuperation to achieve high cycle efficiencies

• Challenges
  – 250 C thermal input temperature widow (recompression cycle) is not ideal for combustion based systems
    • 400 C Combustor inlet for 650 C Turbine Inlet
    • 950 C Combustor inlet for 1200 C Turbine inlet
  – Flue gas cleanup for direct fired systems
  – Non-trivial efficiency losses for indirect cycles
Nominal 10 MWe RCBC test facility