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Challenges for High-Temperature, High-Pressure Heat Exchangers

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HITEMMP Heat Exchanger Goals

- The HITEMMP Program Has the Goal of Extending the Operating Range of Heat Exchangers to >800 deg C and 250 bar
- While Fielded Heat Exchangers Operate at these Conditions Independently, Operation at the Combined Conditions Is Unusual
- At these Conditions Heat Exchanger Design, Configuration, and Material Selection Will Vary with Application and Specific Requirements
- As such, Different Potential Applications for the Developed Technology May Result in Different Heat Exchanger Concepts

Relevant Heat Exchangers

- Terrestrial Distributed Power Systems
  - Recuperators
  - Heat Source Heat Exchangers
  - Primary Heat Exchangers
- Aircraft Systems
  - Recuperators
  - Cooled-Cooling Air Heat Exchangers
  - Precoolers

Heat Exchanger Optimization

- To Efficiently Develop and Optimize Advanced High-Temperature, High Pressure Heat Exchangers it Is Necessary to Define the Optimization Goals
- Optimization Goals Are Critical
  - Typical Heat Exchanger Key Parameters Include Weight, Size and Shape, Production Cost, Thermal Performance, Pressure Drop, Life, and Reliability
  - Optimization Goals Would Likely Vary for Different Platforms
    - Optimization for Terrestrial Distributed Power Applications Will Be Different than for Aerospace Applications

Key Development Risk Areas

- Thermal Performance and Pressure Drop
  - Generally Drives Heat Exchanger Size
- Structural Capability
- Manufacturability
- Fluid Compatibility

Thermal Performance

- In General, Thermal Performance Is Not a Strong Function of Temperature and Pressure
- Supercritical CO2 Is One of the Targeted Heat Exchanger Fluids
  - Fluid Thermophysical Properties Are Anomalous in the Critical Region
  - However, the ARPA-E Specified Conditions for the Terrestrial Distributed Power Recuperator Are Far Away from the Critical Region
  - NIST REFPROP CO2 Thermophysical Properties for the Recuperator Conditions Indicate a Well-Behaved Dense Gas
  - There Is Nothing “Special” Concerning Heat Transfer at the Specified Conditions
- Some Potential High-Temperature Materials Exhibit Low Thermal Conductivity (e.g., Ceramic Oxides) that Could Result in Decreased Performance Due to Increased Thermal Resistance and/or Decreased Fin Efficiency

Thermal Performance—Heat Exchanger Size

- The Size of a Heat Exchanger Is Related to the Overall Thermal Conductance (UA) Required
  - The UA Is a Function of Flow Configuration (Counterflow, Crossflow, etc.), Heat Exchanger Effectiveness, Capacity Rate Ratio, and Heat Transfer Rate
  - In General, Recuperators Want to Operate at High Effectiveness and Capacity Rate Ratios Close to Unity
    - These Attributes Result in Much Larger Required UA Compared to Other Types of Heat Exchangers for the Same Heat Transfer Rate
    - For Example, A Recuperator for an Aircraft Gas Turbine Engine May Require Three Times the UA of a Precooler or Cooled-Cooling Air Heat Exchanger for the Same Heat Transfer Rate
- The Unfortunate Physics Dictate that Increasing Recuperator Effectiveness Requires Significant Increases in Heat Exchanger UA and Resulting Size

Pressure Drop

- The Pressure Level and Pressure Drop Do Not Directly Have a Significant Effect on Heat Transfer Performance Since the Required UA Is Essentially Unchanged
- However Meeting the Pressure Drop Requirements for Heat Exchangers with Gas-like Fluids Almost Always Results in a Larger Heat Exchanger
  - The Heat Transfer Coefficient Cannot Be Maximized Due to the Accompanying Increase in Frictional Pressure Losses
  - This Effect Is Mitigated and Reduced By the High Operating Pressure of the ARPA-E Recuperator—High Density Gases Are Beneficial for Pressure Drop
  - This Benefit Can Be Used to Reduce Heat Exchanger Size (while Meeting Pressure Drop Requirements) or Allowing Size to Increase While Providing Lower Pressure Losses to the System
  - Lower Pressure Drop Can Be Extremely Beneficial for Both Distributed Terrestrial Power and Aerospace Applications

Structural Capability

- High-Temperature Heat Exchanger Structural Design Generally Includes the Following Critical Aspects
  - Pressure Containment (A)
  - Pressure Cycling (A)
  - Thermal Mismatch (A)
  - Flow-Induced Vibration (A)
  - Thermal Fatigue (B)
  - Creep (B)
  - External Vibration (A)
- Stress Calculations for the (A) Items Should Be Relatively Straightforward
  - Relevant Structural Properties May Not Be Completely Available for the Selected Material at All Temperatures of Interest
- The (B) Items Will Likely Require Significant Effort Possibly Including New Structural Analysis Techniques

Thermal Fatigue and Creep

- Thermal Fatigue and Creep Are Likely to Be the Key Drivers for Structural Design
- State-of-the-Art Aerospace Heat Exchangers Are Usually Life-Limited by Thermal Fatigue—Caused by Continual Rapid Temperature Transients Due to Aircraft Takeoff, Landing, and Other Operations
  - Creep Can Usually Be Controlled By Material Selection and Wall Thickness
  - Creep and Maximum Pressure Stresses Usually Occur at Different Locations than Thermal Fatigue—Little Stress Interaction
  - Designs Typically Undergo Analysis and Testing to Full Cyclic Life
- For Terrestrial Applications Thermal Fatigue Damage Can Potentially Be Controlled By Reducing Startup and Shutdown Flow and Temperature Transients

ARPA-E Conditions

- The ARPA-E Temperature and Pressure Conditions Can Potentially Result in Significant Creep Damage
- For the Required New Aerospace Heat Exchanger Designs There May Be Creep and Thermal Fatigue Interaction
  - Advanced Analysis Approaches May Need to Be Developed
  - Test Validation Techniques May Need to Be Developed as Full-Life Testing Would Not Be Practical
- For Both Aerospace and Terrestrial Applications, New Creep and Thermal Fatigue Structural Material Properties May Need to Be Generated

Manufacturability

- To Meet the ARPA-E Requirements New Heat Exchanger Designs Will Be Necessary
- It Is Critical that the Concept of “Design for Manufacturability” Be Considered for Any New Design Approach
  - Experience Has Shown that Often Heat Exchanger Designs that Look Good on Paper Cannot be Manufactured in an Efficient Manner and Are Unlikely to Be Fielded
- Scale-up
  - The ARPA-E Heat Exchanger Heat Transfer Requirement Is 50 kW(t)
  - For the Intended Platforms of Terrestrial Distributed Power and Aerospace Heat Exchangers the Fielded Heat Exchanger Capacity Will Likely be an Order of Magnitude Larger
  - This Ultimate Scale-up Must Be Considered for the 50 kW(t) Design

Fluid Compatibilty

- The Required High-Temperature Conditions May Result in Fluid Compatibility Issues that Must Be Addressed
  - Oxidation or Corrosion of Hot Exposed Surfaces in Ambient Air
  - Internal Oxidation if Air Is the Working Fluid in the Heat Exchanger
  - Potential Reaction with CO2
    - Carbon-carbon Is Known to React with CO2 Forming CO
    - Other Materials with Substantial Free Carbon May Have Similar Issues