DEVELOPMENT OF LOW-COST CERAMIC HEAT EXCHANGER FOR THE GEN 3 CSP

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BACKGROUND

- Supercritical CO\(_2\) power cycle operating >700°C can improve the overall CSP plant efficiency and help meet the SETO LCOE target of $0.05/kWh\(_e\) with 12-h storage for Gen 3

- Higher power cycle temperatures (>700°C) requires system components (e.g., primary HXs for transferring heat from receivers to power block) that can perform reliably

- Ceramics can operate at those conditions without creep (at high temperatures) and corrosion/oxidation challenges

- Low-cost manufacturing approaches are needed for ceramics
OBJECTIVES

• Development of ceramic HXs for CSP applications
  • Corrosion and oxidation resistance of ceramics

• Optimization of HX design
  • Maximum heat transfer performance
  • Stress requirements

• Development of additive manufacturing (AM) approaches
  • Fabrication of HX parts

• Physical and thermo-mechanical property characterizations
  • Measure properties of AM fabricated material and compare with desired properties

• Demonstrate ceramic HX performance
TECHNICAL APPROACH

• Silicon carbide (SiC) as the material for HXs
  ▪ excellent corrosion and oxidation resistance
  ▪ amenability to AM processes such as binder jetting

• Design optimization
  ▪ heat transfer by using COMSOL Multiphysics
  ▪ stress analysis by using Multiphysics Object Oriented Simulation Environment (MOOSE)

• Material development and AM
  ▪ powder optimization
  ▪ binder jetting printing
  ▪ densification
  ▪ characterizations

• Joining and integration approaches

• Fabrication and testing of lab-scale prototypes
COUNTER FLOW HX DESIGN

• Coupled heat transfer and stress analysis
  - Iterations of heat transfer performance and stress requirements

• Flow channel shape
  - Semi-elliptical flow channel cross section
  - Minimum stress concentration

• Flow channel dimensions
  - Maximum heat transfer
  - Manufacturability

65-MPa maximum principal stress
PARAMETERIC STUDIES

• Key parameters
  ▪ Flow channel height ($h$)
  ▪ SiC thermal conductivity ($k$)

• Module heat transfer rate
  ▪ Module size of 1 m × 1 m × 1m
  ▪ Heat transfer rate of 0.7 MW
BINDER JETTING PRINTING

Binder jetting printing process

(a) Build box
(b) Powder dispenser
(c) Binder jet head
POWDER OPTIMIZATION

Commercial $\alpha$-SiC powders

Figure 3.4. Particle size distribution of the (a) 50 µm powder, (b) 10 µm powder, and (c) 1 µm powder.

Particle size distributions measured using Dynamic Laser Scattering
POWDER OPTIMIZATIONS

Commercial SiC powders

Linear Powder Packing Model for Multi Component System

- packing density of each particle size
- volumetric fractions
- particle interaction functions

50 µm and 10 µm SiC powders

Powder packing model developed to include angular particles
PROCESSING AND CHARACTERIZATIONS

Binder jet printing → Binder curing → De-powdering → Porous SiC preform

Porous SiC (binder jet printing)

Preceramic polymer infiltration + pyrolysis

Liquid silicon infiltration (LSI)

Physical and thermal characterizations (density, phases, microstructures, strength (RT & HT), toughness, thermal conductivity, thermal shock)

Melt Infiltration System
PRINTING AND DENSIFICATION OF SiC PLATES & HX CHANNELS

Bi-modal powders result in higher green part density

Printed green plate
120 mm × 50 mm × 10 mm

Polymer derived ceramic densified plate

Printed green part with channels and post densification

Excellent dimensional control and repeatability
SiC post densification

crystalline SiC formed

precursor polymer infiltration/pyrolysis

SiC/Si

Mechanical properties meet the target strength requirements
FABRICATION OF PROTOTYPES

Green part

Dimensional variations being monitored at each step

W110 x L55.5 x H38.5 mm$^3$

Post densification

(a) (b)
PROTOTYPE TESTING

Water-pressure leak testing

No leaks detected over several hours of testing
• Heat transfer rate as a function of flow rates
• The volumetric heat transfer rates of the lab-scale tests are in the similar range of the full-scale ceramic HX

Insulated test prototype

Integration of prototype to test loop
SUMMARY AND FUTURE PLANS

Summary
- A modular SiC based primary HX for CSP plant for application at >700°C has been designed
- AM technique has been used to fabricate simple shapes and parts with HX channels
- Material densification and characterization have been conducted
  - Thermo-mechanical property characterizations meet the target properties
- Lab-scale HX prototypes have been fabricated and tested

Future Plans
- Design optimization for a particle/s-CO2 system
- Process scale-up for the ceramic HX
- Develop integration approaches for the HX
- Demonstrate performance at temperatures in the range of 500°C-700°C; long-term reliability
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