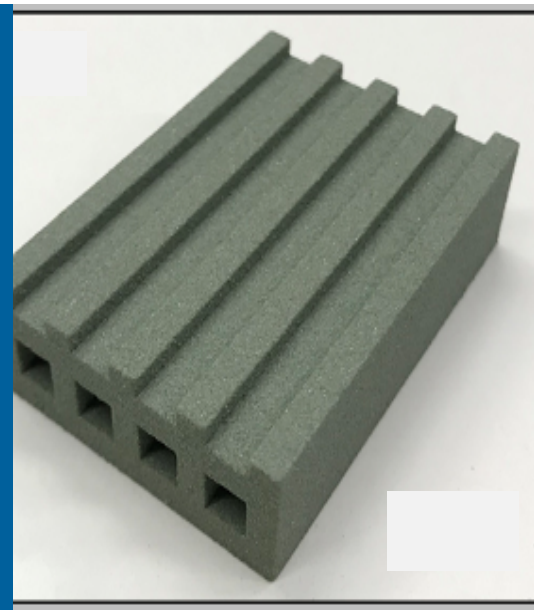
DEVELOPMENT OF LOW-COST CERAMIC HEAT EXCHANGER FOR THE GEN 3 CSP



D. Singh, W. Yu, D. France, M. Du, B. Barua, M. Messner, and M. Banda

Argonne National Laboratory

Gen 3 CSP Summit 2021
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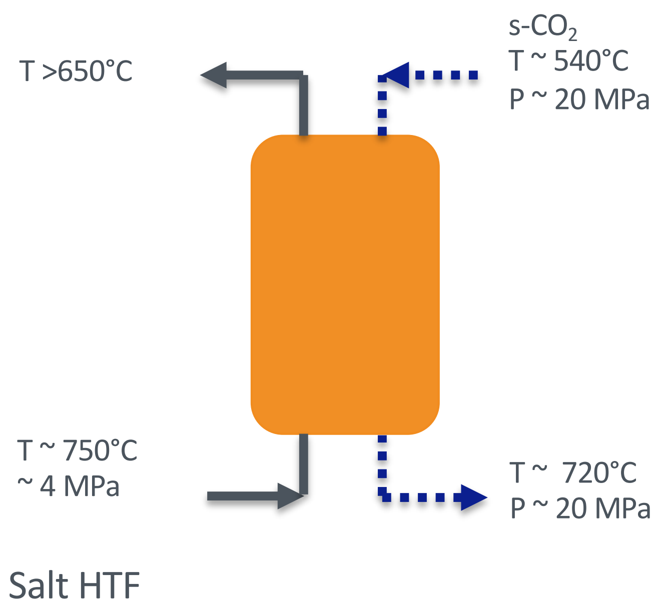
BACKGROUND

- 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

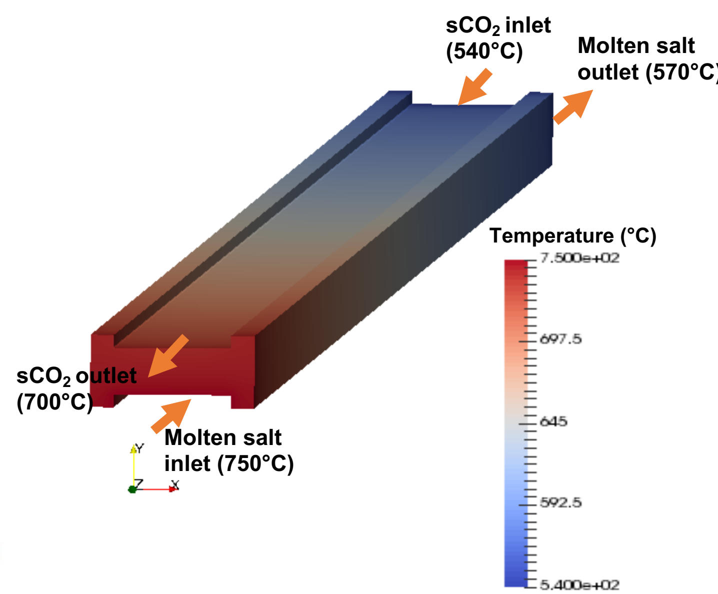
- Development of ceramic HXs for CSP applications
  - Corrosion and oxidation resistance of ceramics
- Optimization of HX design
  - Maximum heat transfer performance
  - Stress requirements
- Development of additive manufacturing (AM) approaches
  - Fabrication of HX parts
- Physical and thermo-mechanical property characterizations
  - Measure properties of AM fabricated material and compare with desired properties
- Demonstrate ceramic HX performance

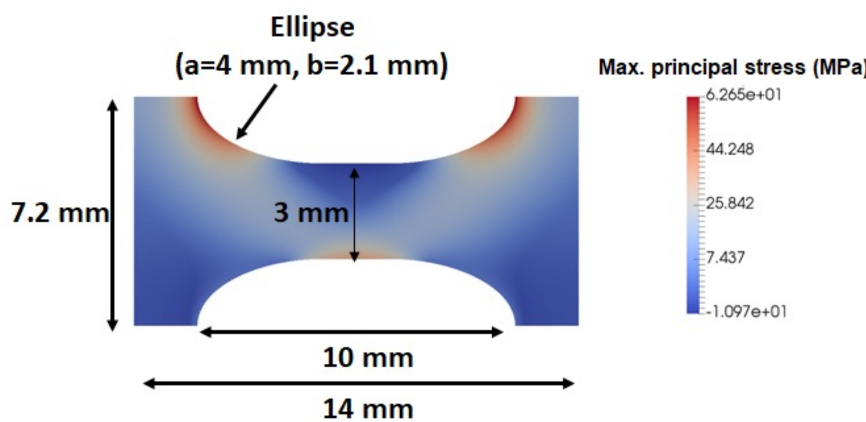
TECHNICAL APPROACH

- 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



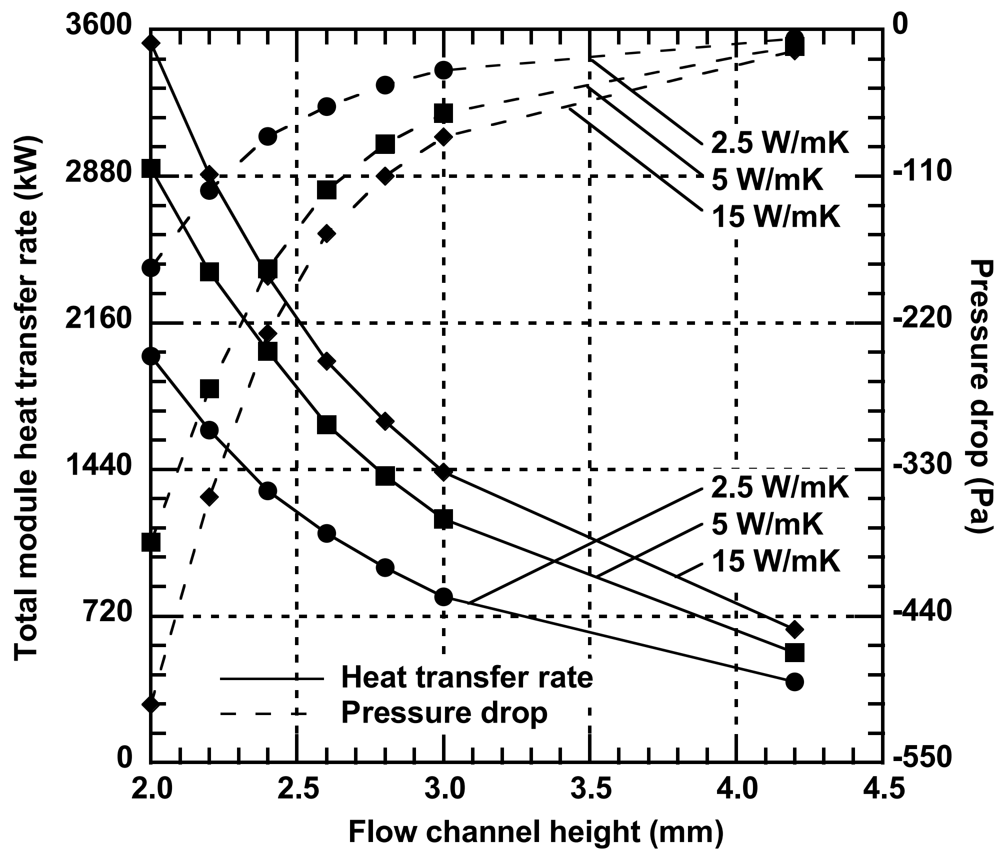


65-MPa maximum principal stress

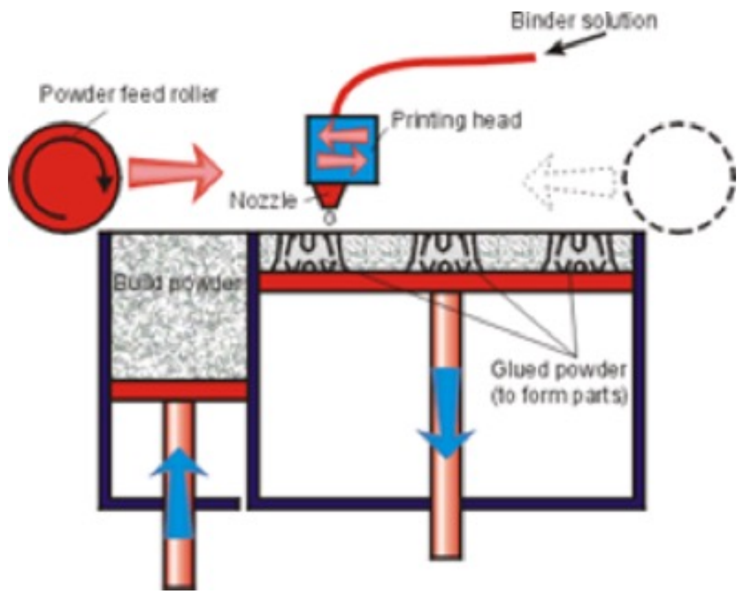
PARAMETERIC STUDIES

- Key parameters
  - Flow channel height (*h*)
  - SiC thermal conductivity (*k*)

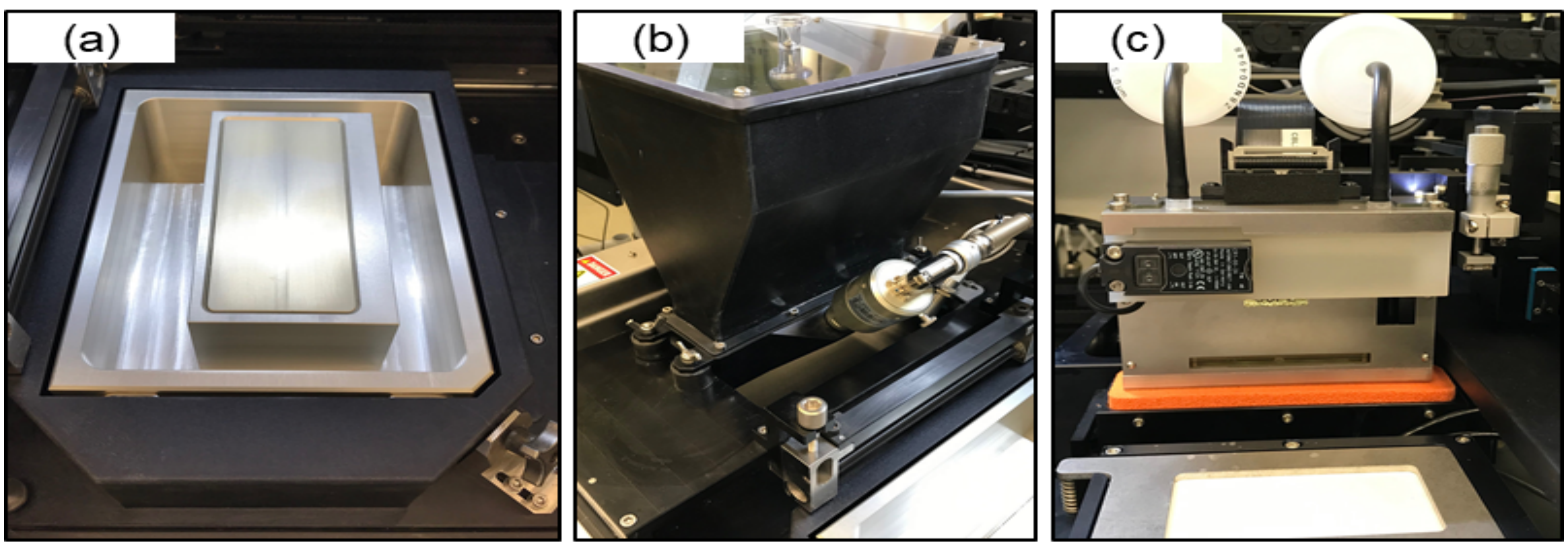
- Module heat transfer rate
  - Module size of 1 m × 1 m × 1m
  - Heat transfer rate of 0.7 MW



BINDER JETTING PRINTING



Binder jetting printing process



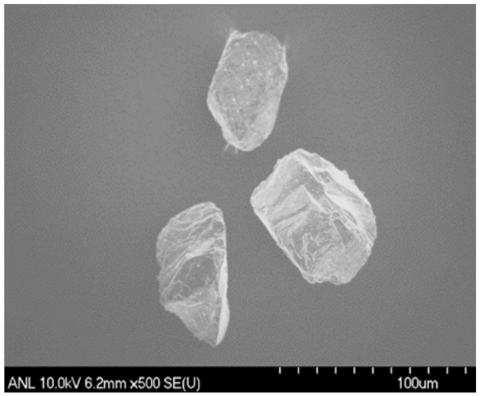
Build box

Powder dispenser

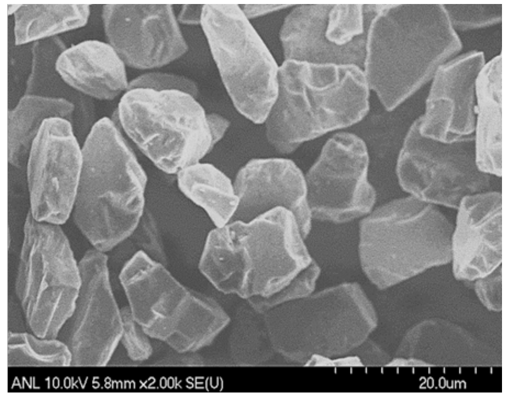
Binder jet head

POWDER OPTIMIZATION

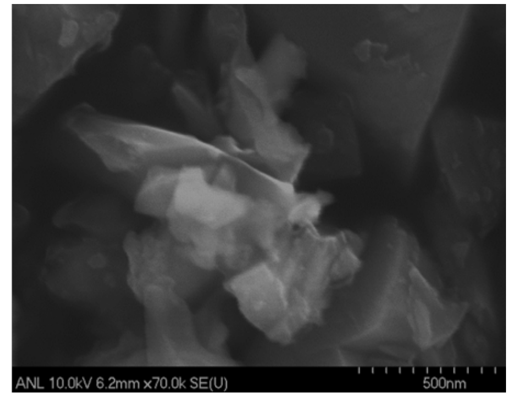
Commercial α-SiC powders



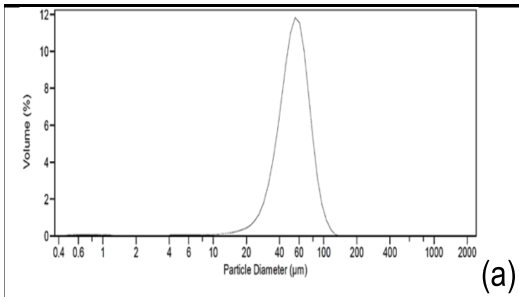
50 μm

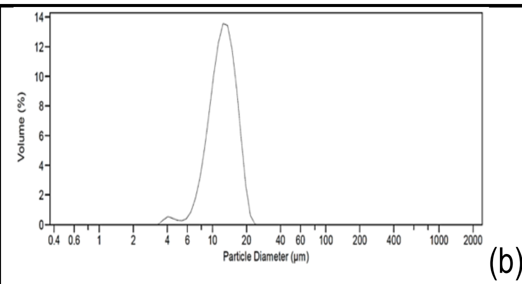


10 μm



1 μm





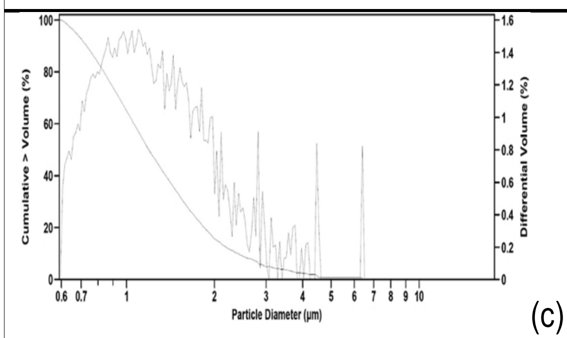
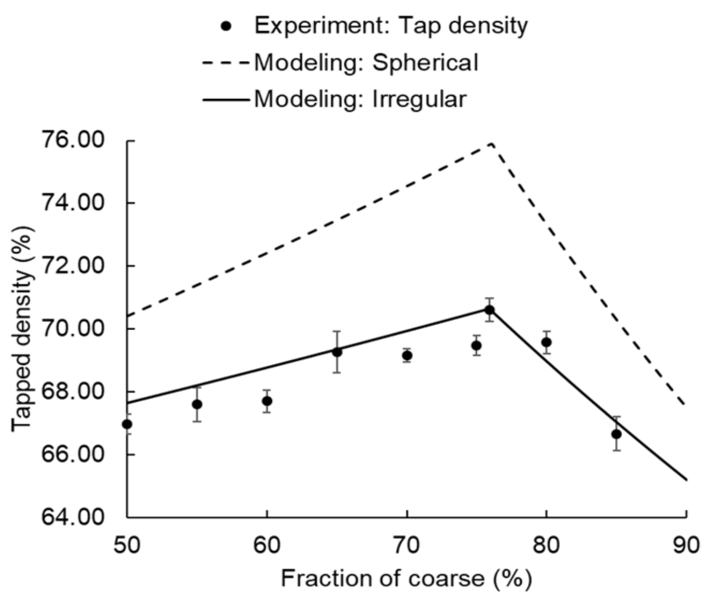


Figure 3.4. Particle size distribution of the (a) 50 μm powder, (b) 10 μm powder, and (c) 1 μm powder.

Particle size distributions measured using Dynamic Laser Scattering

POWDER OPTIMIZATIONS

Commercial SiC powders



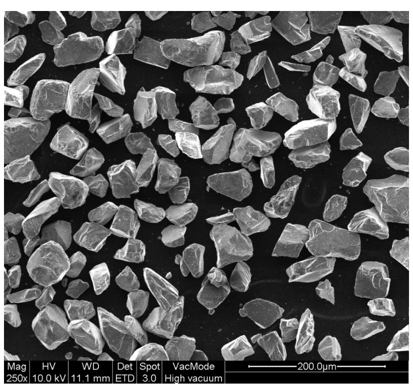
Linear Powder Packing Model for Multi Component System

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

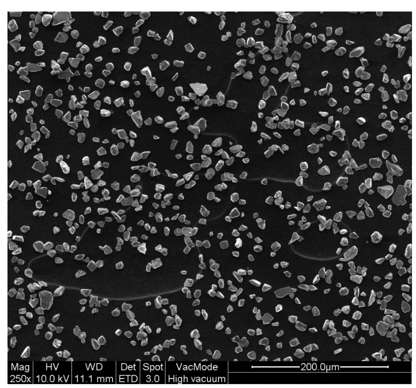
Powder packing model developed to include angular particles

(*Ceramics International., doi.org/10.1016/j.ceramint.2020.04.098, (2020)*)

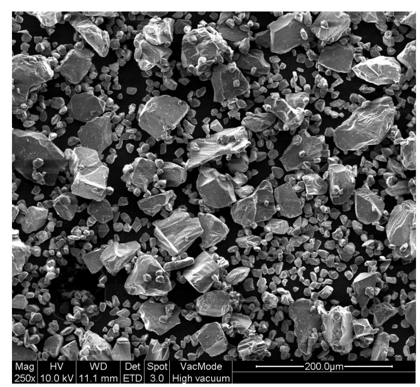
50 µm and 10 µm SiC powders



50 µm unimodal



10 µm unimodal



50 and10 µm bimodal

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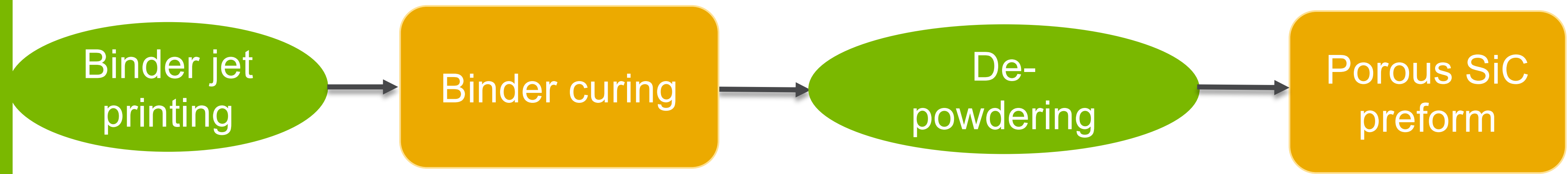
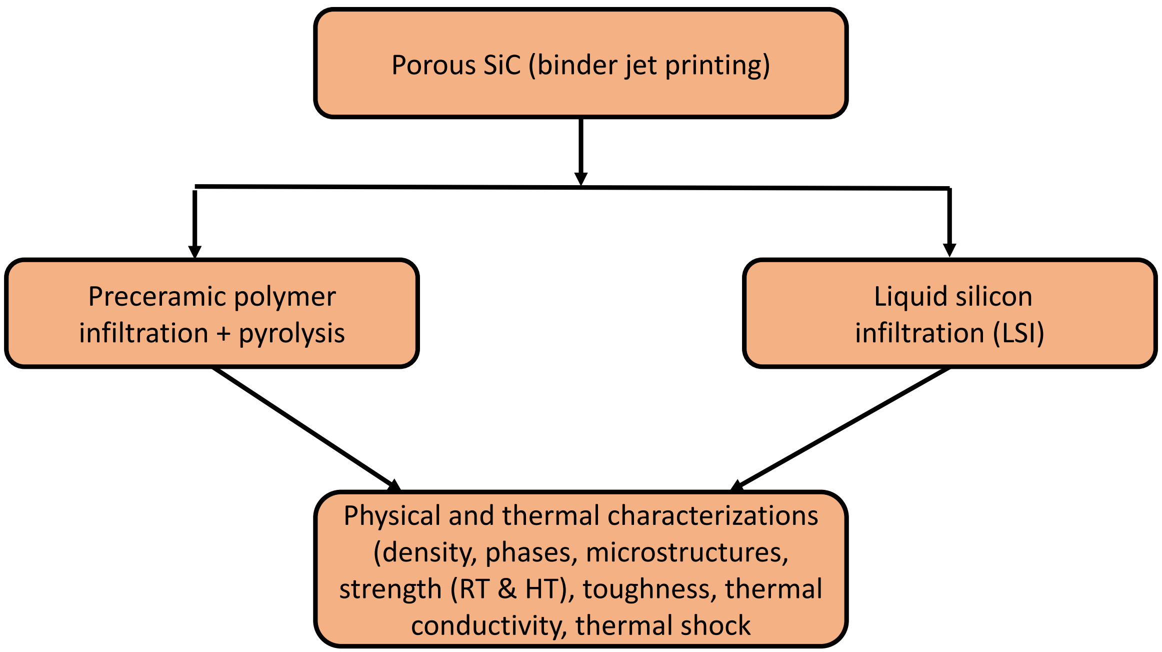
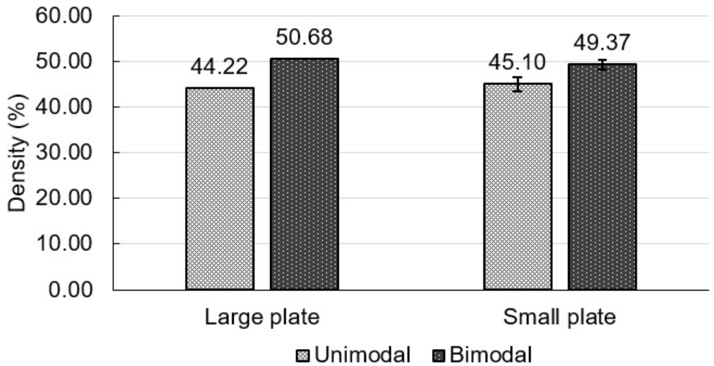
PROCESSING AND CHARACTERIZATIONS



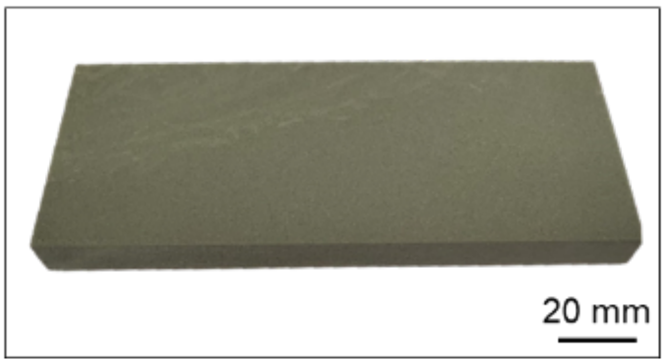


Melt Infiltration System

PRINTING AND DENSIFICATION OF SiC PLATES & HX CHANNELS

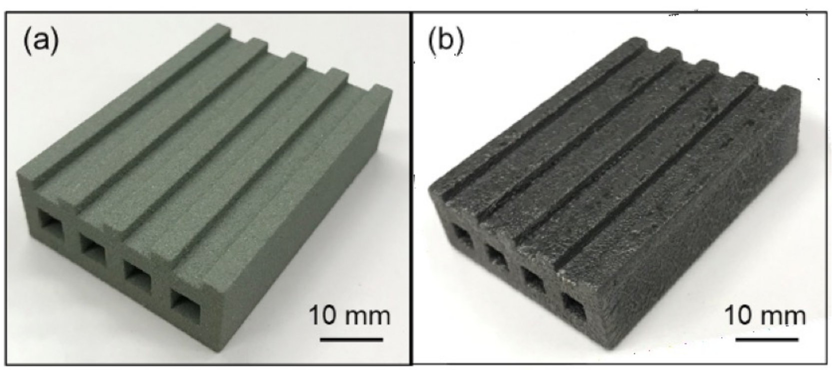


Bi-modal powders result in higher green part density



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

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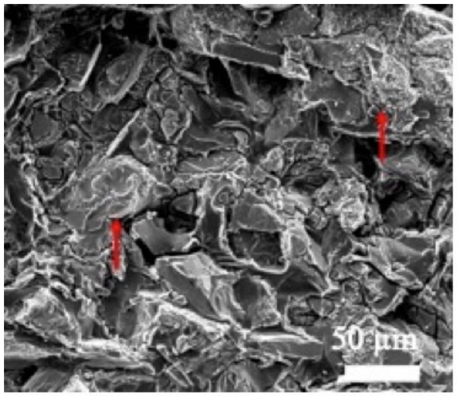
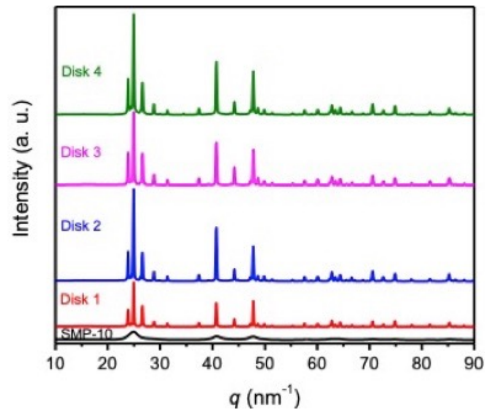
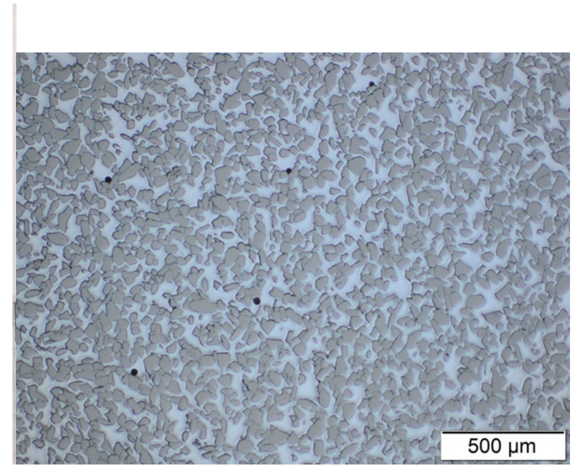
MICROSTRUCTURE, PHASE STRCUTURE, THERMAL CONDUCTIVITY

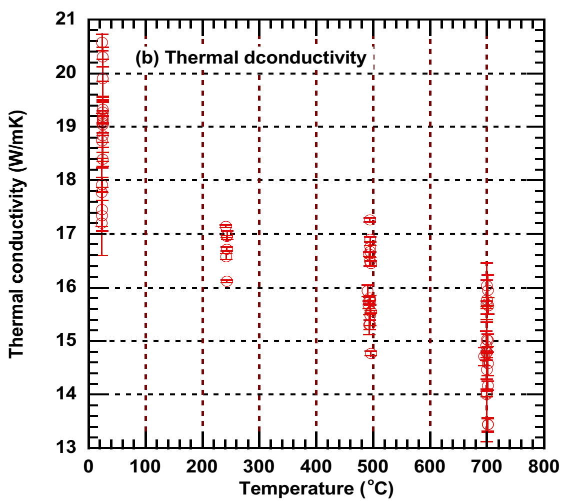


SiC post densification

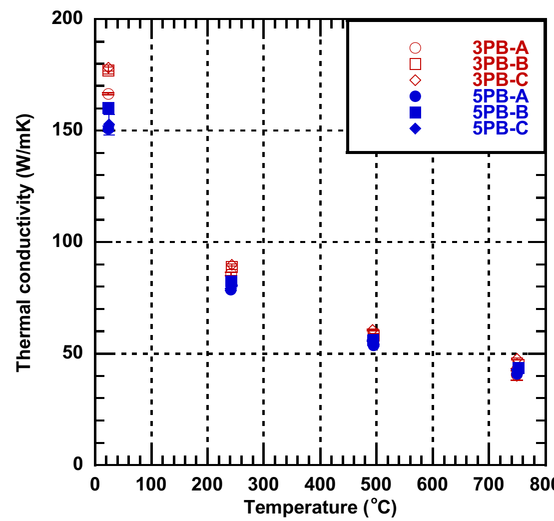


crystalline SiC formed





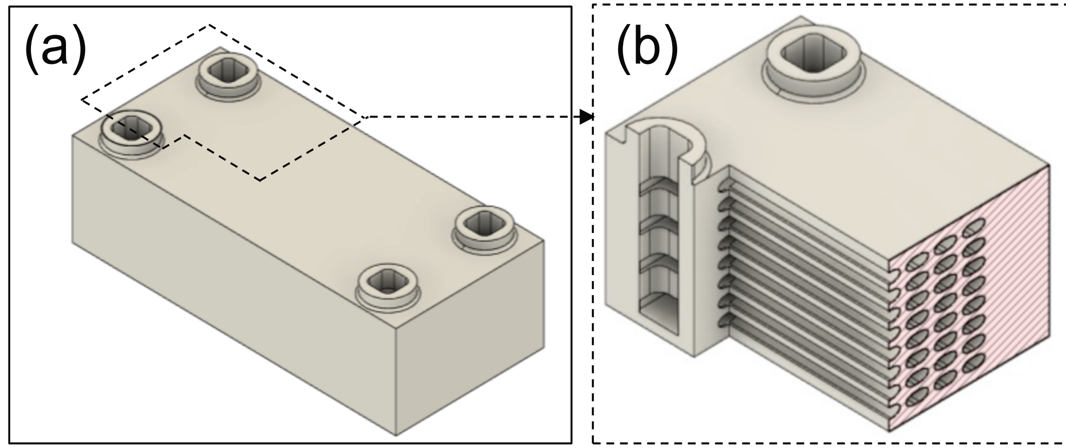
preceramic polymer infiltration/pyrolysis



SiC/Si

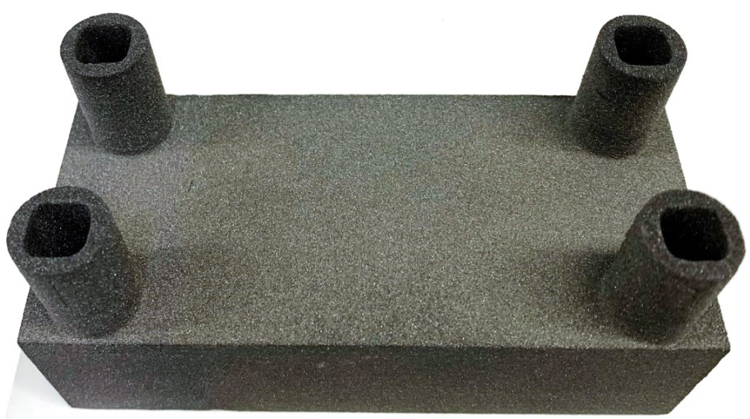
Mechanical properties meet the target strength requirements

FABRICATION OF PROTOTYPES

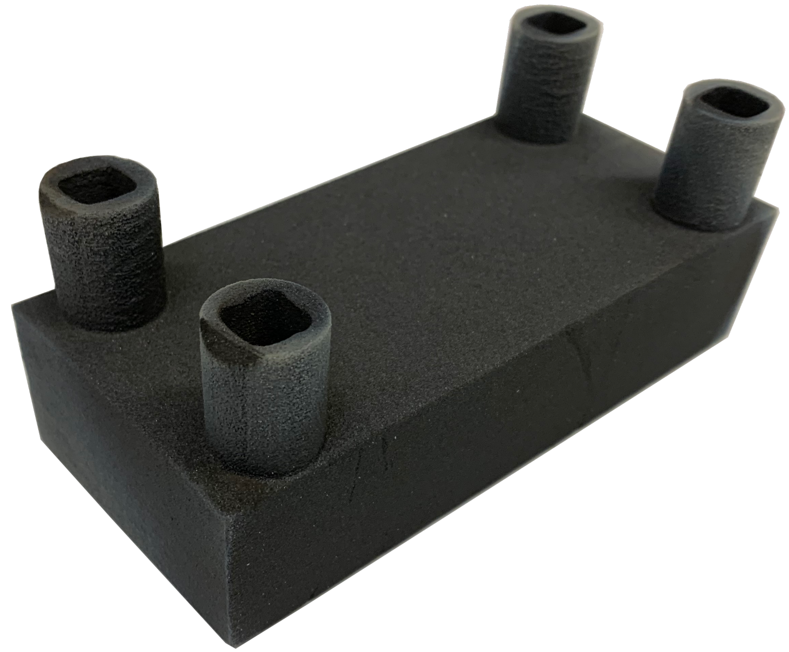


Green part

After debinding



Dimensional variations being monitored at each step



Post densification

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

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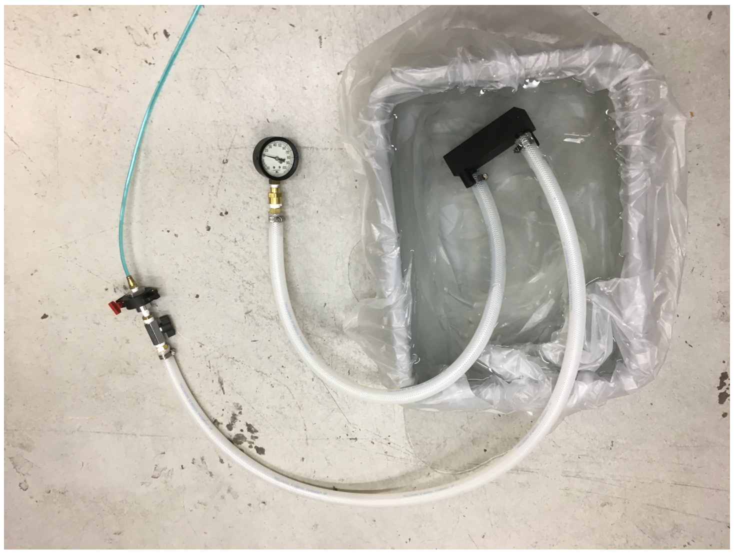
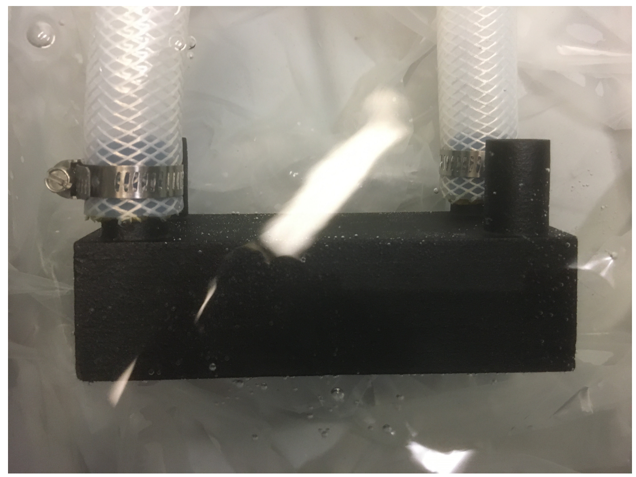
PROTOTYPE TESTING

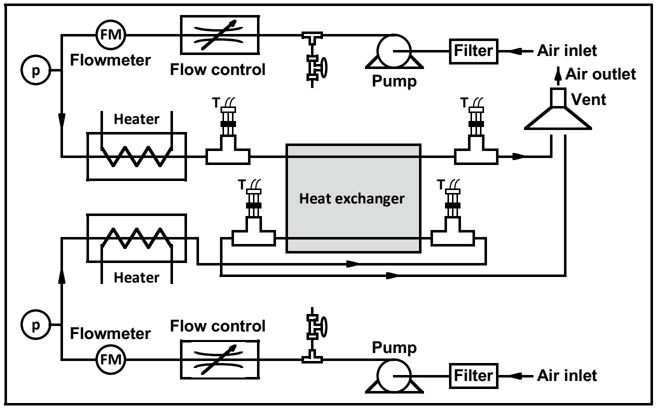
Water-pressure leak testing



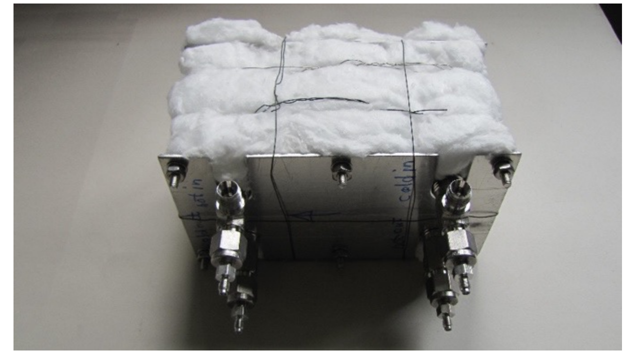


No leaks detected over several hours of testing

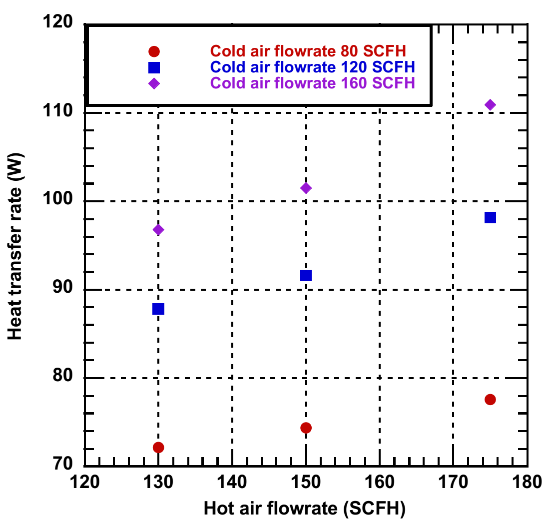
PROTOTYPE TESTING

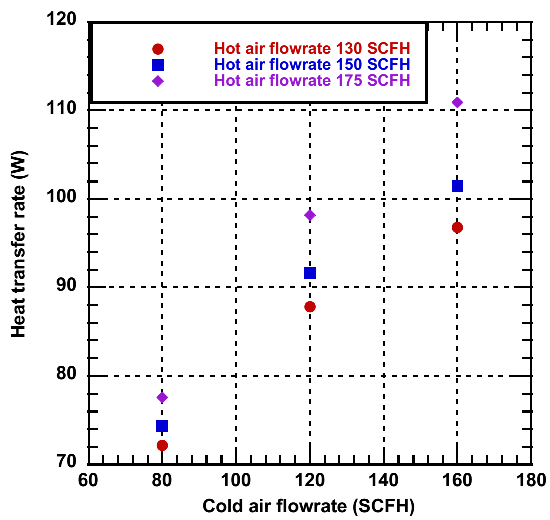


Test Loop for Ceramic HX testing

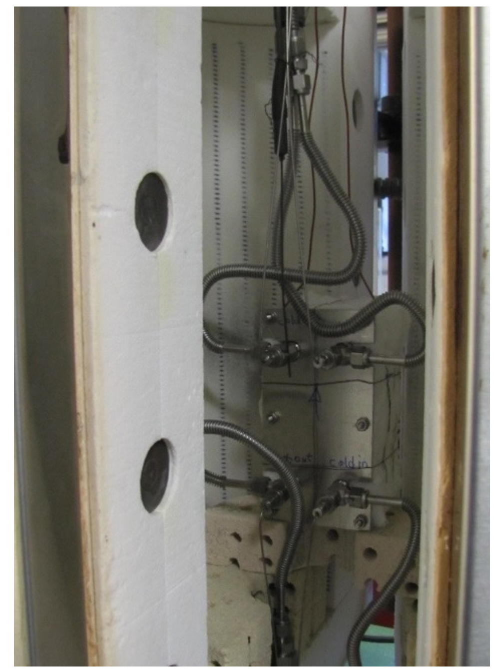


Insulated test prototype





- 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



Integration of prototype to test loop

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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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- DOE-EERE Technical Program Managers: Drs. Kamala Raghavan, Vijay Rajagopal and Levi Irwin