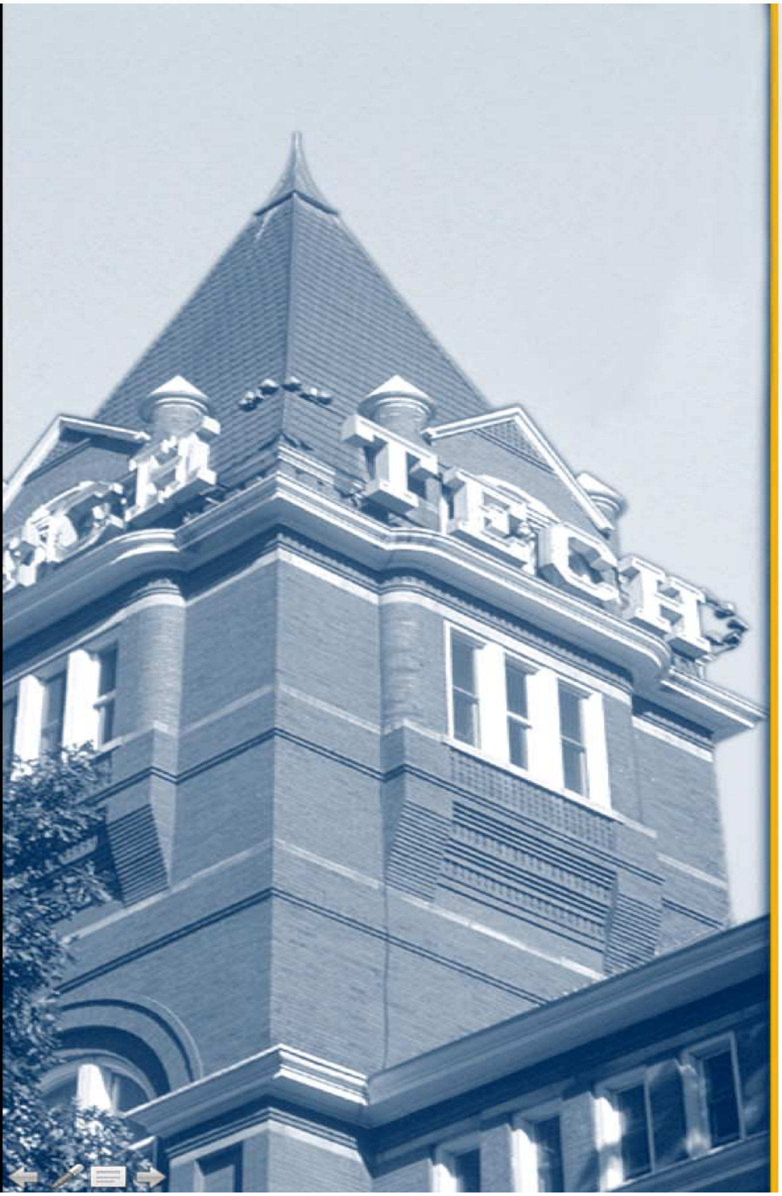

Computational Analysis of Ceramic Heat Exchangers for Supercritical CO_2 Brayton Cycle in CSP Applications at High-Temperatures

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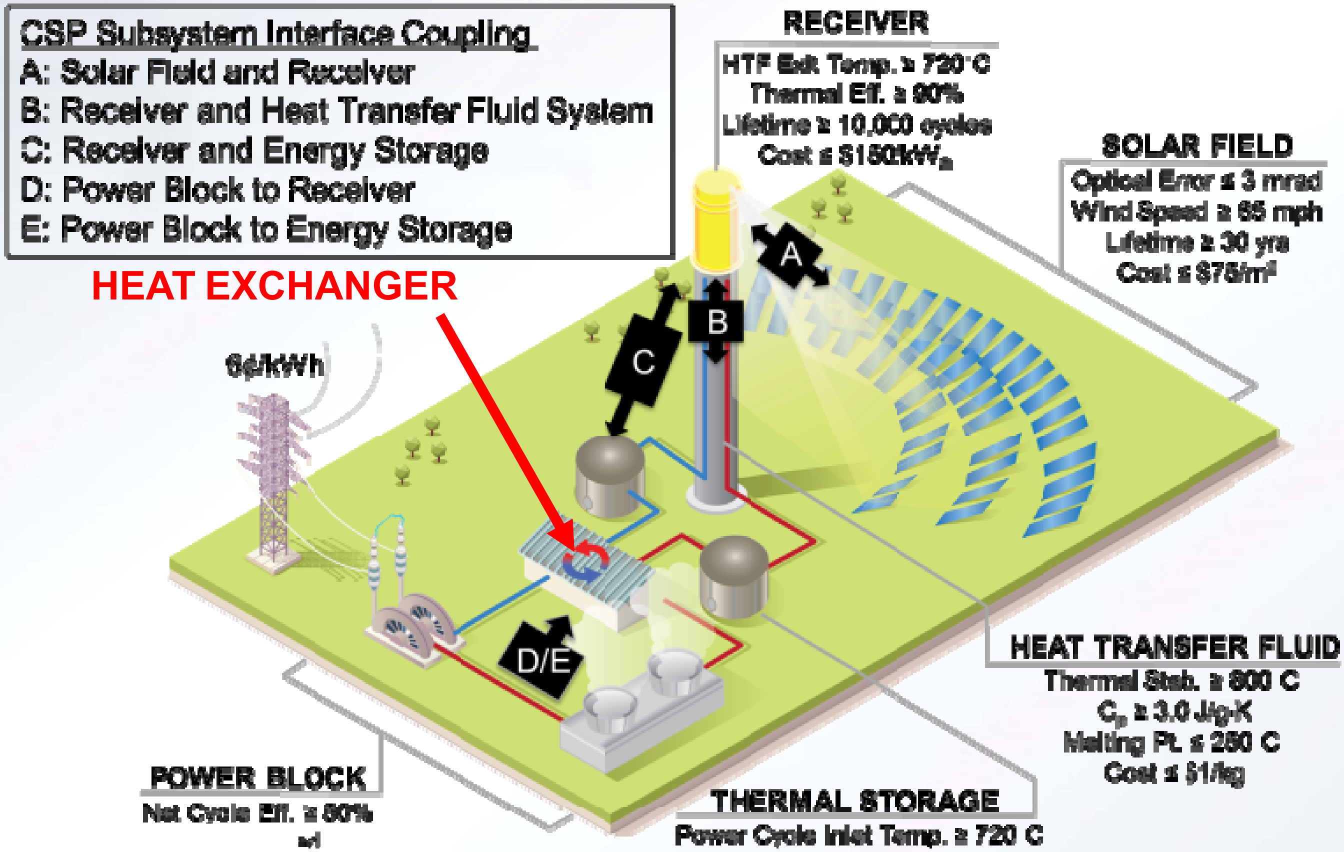
STAM Lab
Shock Tube and Advanced Mixing Laboratory

Overview



CSP Subsystem Interface Coupling
A: Solar Field and Receiver
B: Receiver and Heat Transfer Fluid System
C: Receiver and Energy Storage
D: Power Block to Receiver
E: Power Block to Energy Storage

HEAT EXCHANGER

RECEIVER
HTF Exit Temp. ≥ 720°C
Thermal Eff. ≥ 90%
Lifetime ≥ 10,000 cycles
Cost ≤ $150/kW$_{th}$

SOLAR FIELD
Optical Error ≤ 3 mrad
Wind Speed ≥ 85 mph
Lifetime ≥ 30 yrs
Cost ≤ $75/m^2

6¢/kWh

HEAT TRANSFER FLUID
Thermal Stab. ≥ 800 C
C_p ≥ 3.0 J/g-K
Melting Pt. ≤ 250 C
Cost ≤ $1/kg

POWER BLOCK
Net Cycle Eff. ≥ 50%
el

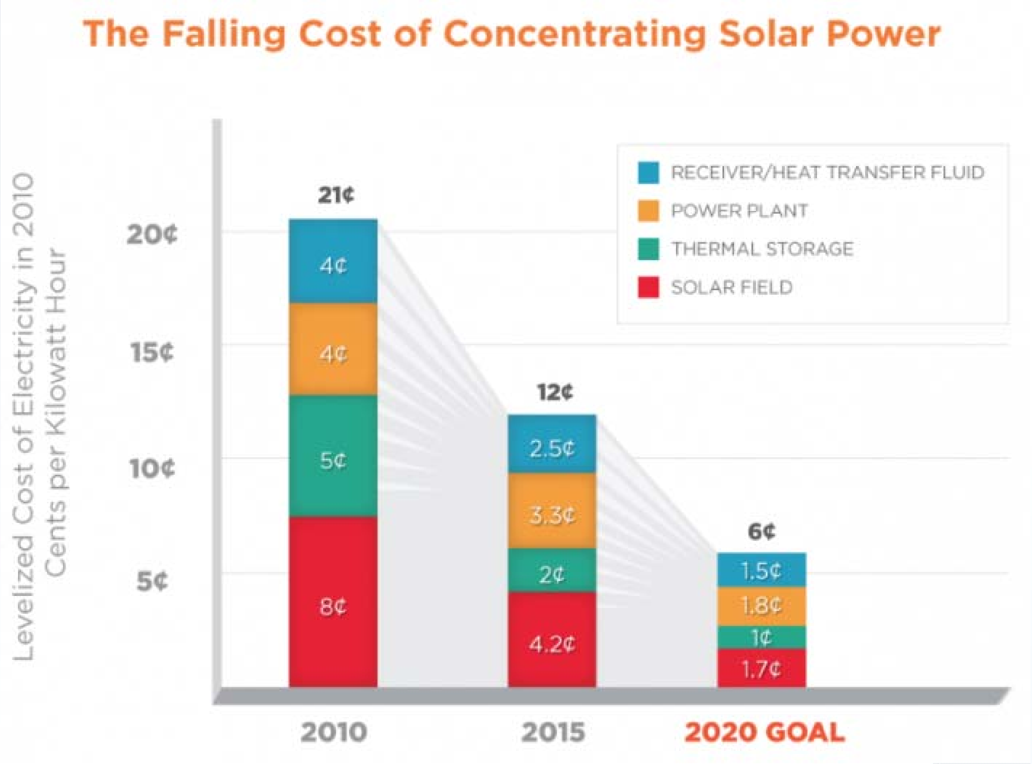
THERMAL STORAGE
Power Cycle Inlet Temp. ≥ 720 C

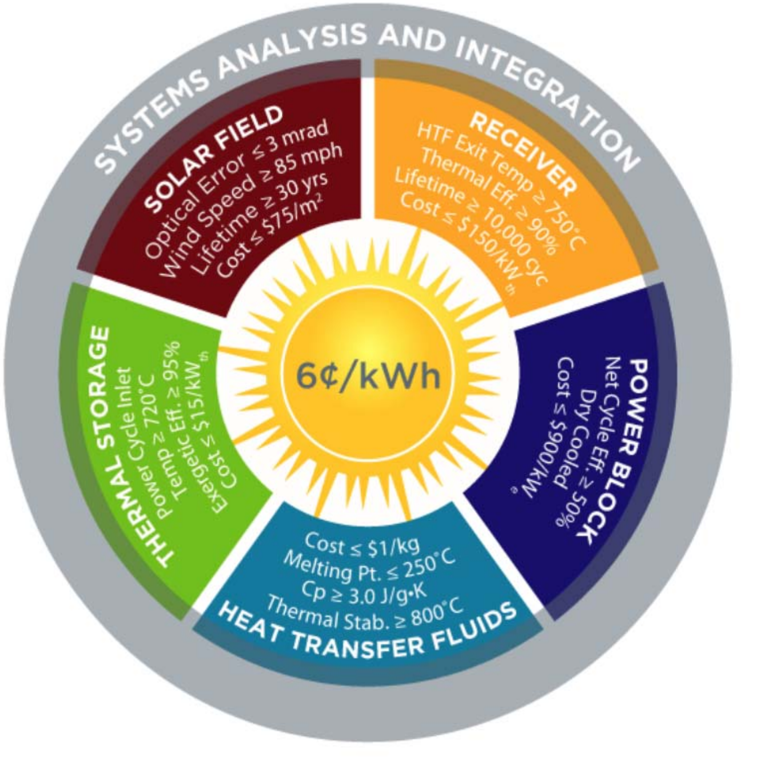
https://www.energy.gov/eere/solar/csp-component-research-and-development

DOE-SunShot Goals

SunShot
U.S. Department of Energy

Levelized cost of electricity for CSP has decreased about 36 percent, already over half of the way toward achieving the SunShot goal of $0.06 KW/h.

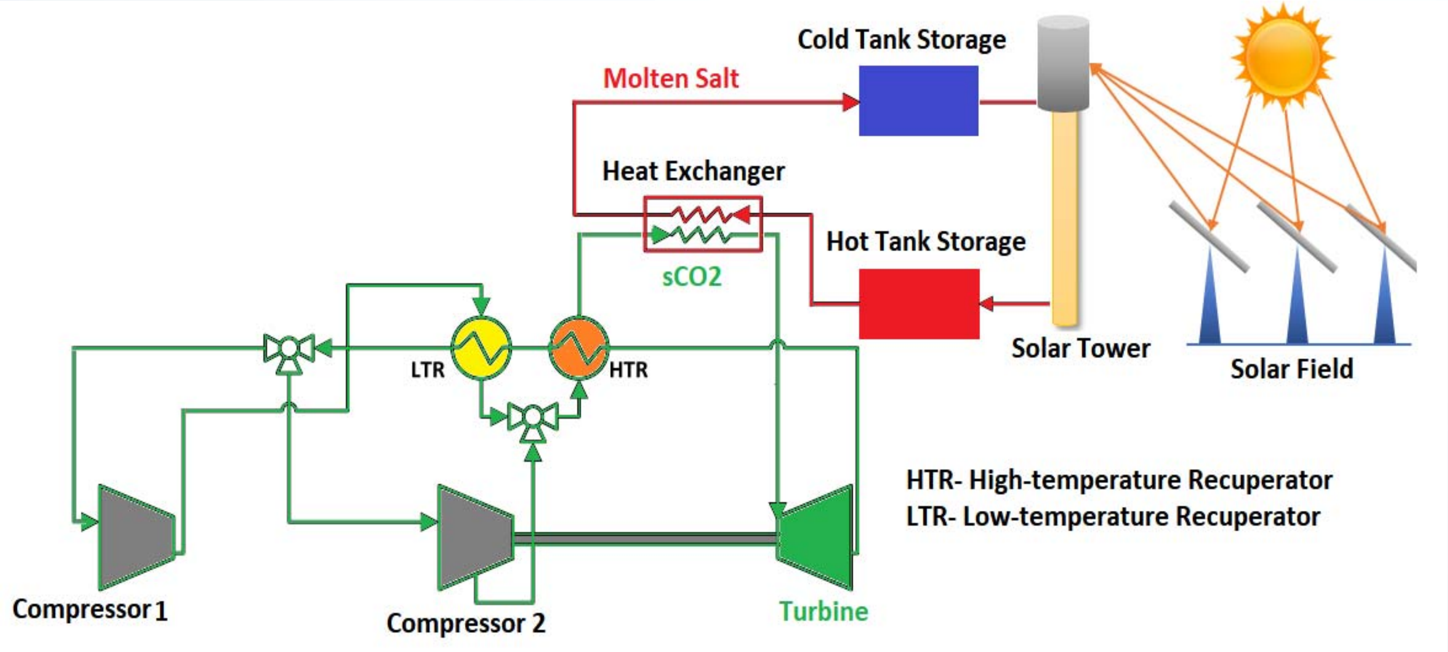




https://www.energy.gov/eere/solar/concentrating-solar-power

Motivation

Heat-to-electricity conversion efficiency of closed-cycle Supercritical CO2 (SCO_2) turbine systems may be significantly increased (>20%) with an increase in turbine inlet temperatures from <823K to >1023K



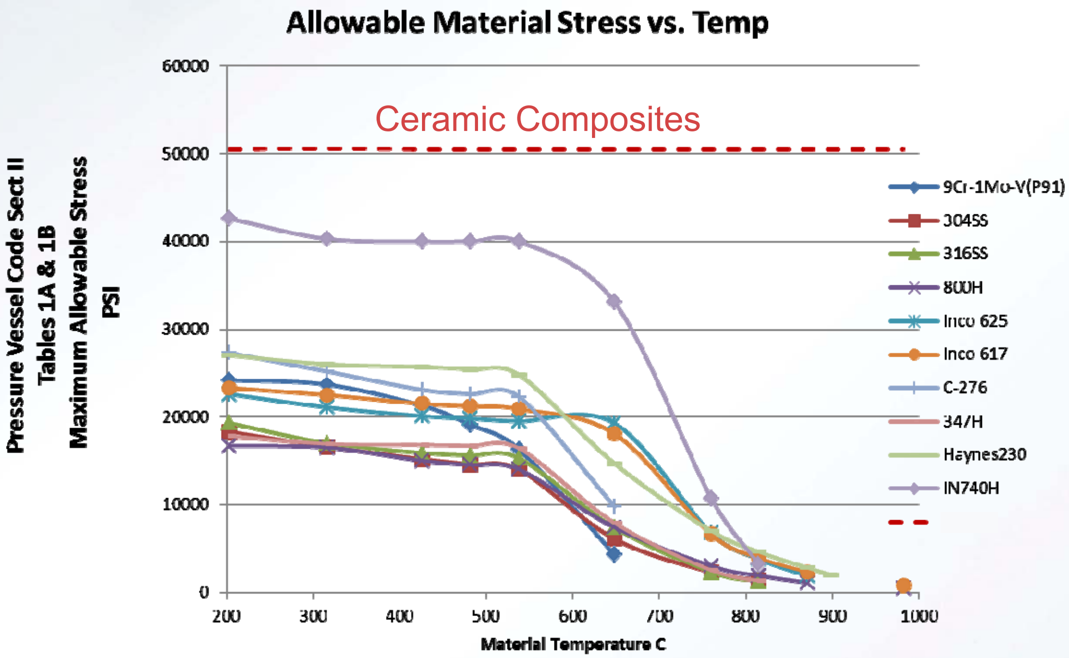
HTR- High-temperature Recuperator
LTR- Low-temperature Recuperator

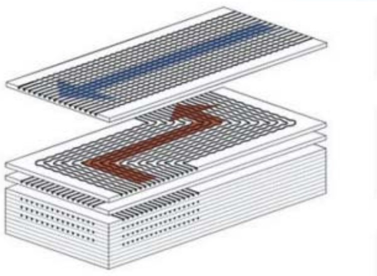
Recompression SCO_2 power cycle integrated with the concentrated solar power plant

Material Limitation

Current HEX Technology:

- Printed Circuit HEXs:
- Patterned etching of metallic alloy plates, then diffusion bonding.
- Upper use temperature of conventional alloys < $600^{o}C$

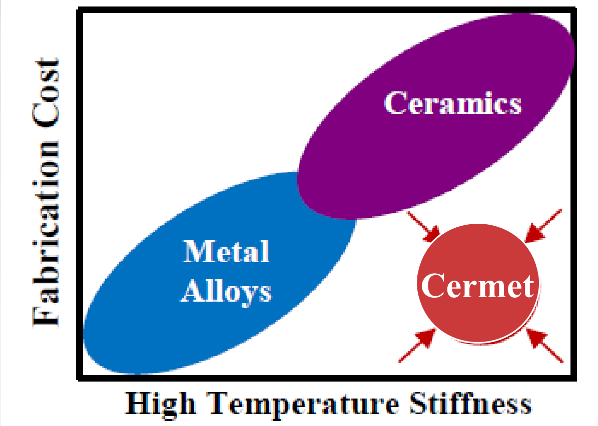




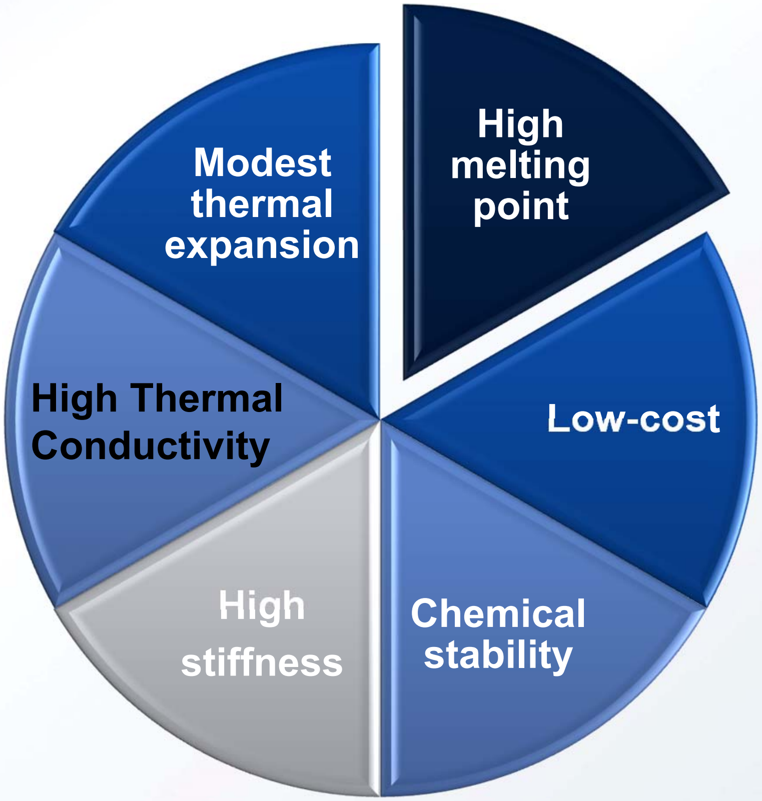
Need material with strength above $750^{o}C$

2010 ASME Boiler Pressure Vessel Code, Sec. II, from Tables 1A and 1B, July 1, 2010, New York, NY (compiled by Dr. M. Anderson)

New Ceramic Material



Thermophysical and mechanical properties of cermet at 800°C.	
Density (kg/m^3)	**11400**
Conductivity (W/m.K)	**65.8**
Specific Heat (J/kg.K)	**285**
Thermal Diffusivity (m^2/s)	**0.2×10^{-4}**
Thermal Expansion Coefficient (1/K)	**6.39×10^{-6}**
Young Modulus (GPa)	**407**


High melting point

Low-cost

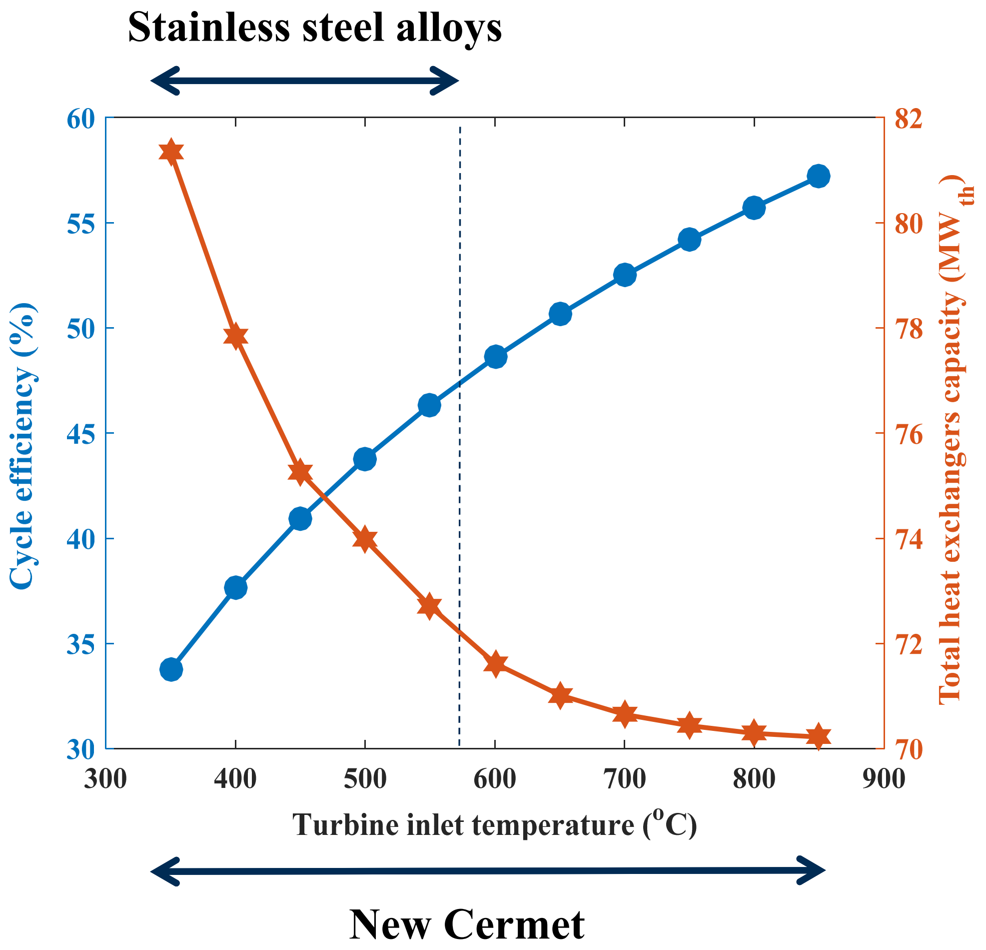
Chemical stability

High stiffness

High Thermal Conductivity

Modest thermal expansion

Expected Outcomes



Low-cost manufacturing

Gain in power efficiency

zero Carbon emission

reductions in LCOE

Work in Progress

◆ **Processing Thrust:**
- Manufacturing of Ceramic Composite HEXs

◆ **Properties Thrust:**
- Chemical Stability in Molten Salts, SCO_2
- Thermal and Mechanical Properties

◆ **Performance Thrust:**
- HEX Modeling and Testing
- Techno-Economic Analyses

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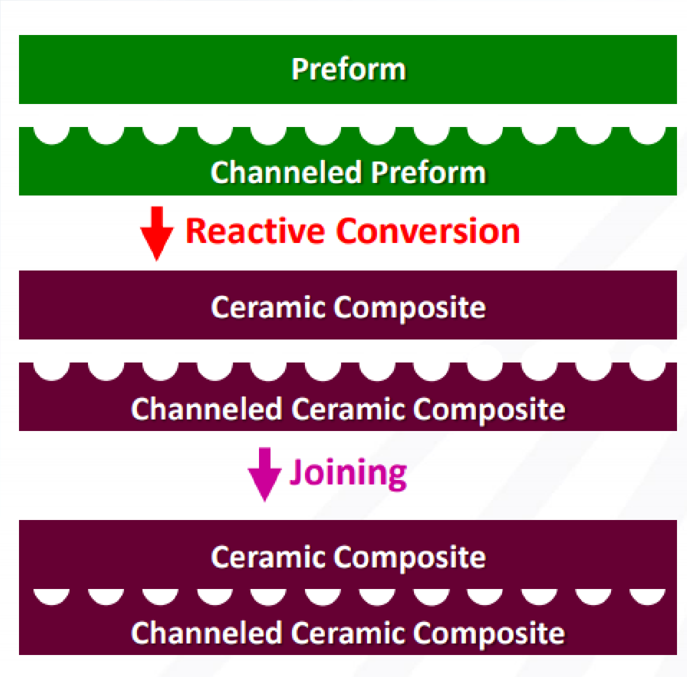
Ceramic Heat Exchanger

- Toughened ceramic-based HEXs: preform pressed into HEX shape, then converted into toughened composite
- Green body (“preform”) plates with desired channel



Preform

Channeled Preform

Reactive Conversion

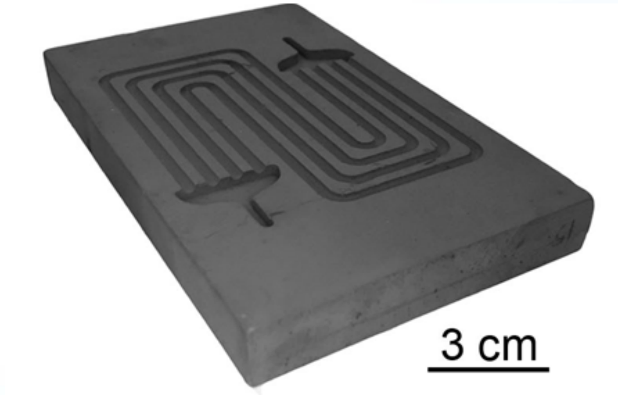
Ceramic Composite

Channeled Ceramic Composite

Joining

Ceramic Composite

Channeled Ceramic Composite



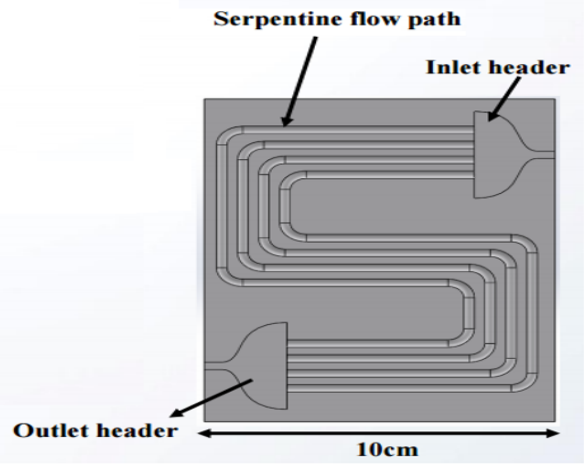
9 cm x 15 cm x 1 cm porous, preform plate:
4 parallel millichannels (3 mm wide) in a
serpentine pattern with 2 flat-bottom headers.

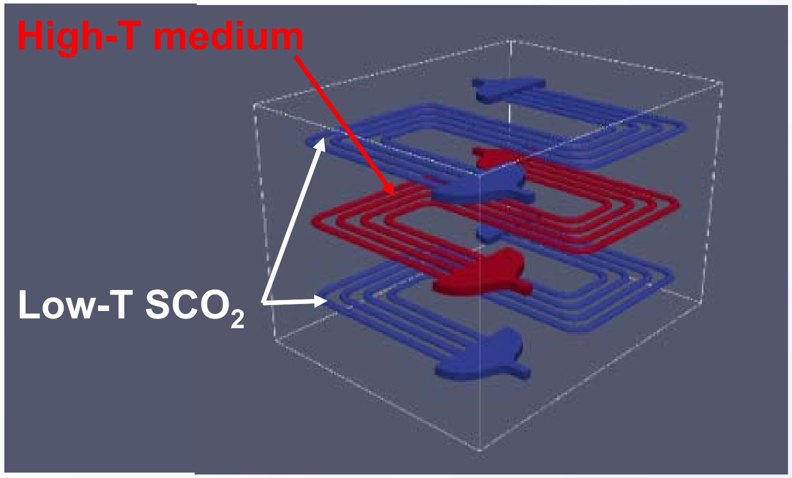
Ken H. Sandhage, CSP Program Summit 2016

Modeling Goals

- To develop a simulation framework to guide the design of ceramic composite-based HEXs with optimal geometries.
- The proposed ceramic HEX model is 10 cm wide, 15 cm long and 10 cm thick.
- Not a full-scale HEX at this stage.

Design Target → **Power density >1 MW/m^3** → **Pressure drop <100 kPa**





Modeling Details

- A coupled solver for fluids and solids of the OpenFOAM modified to work with molten salt and SCO_2.
- Standard *k-ϵ* integrating and FIT (Fluid Property Interpolation Tables) program into the CFD solver to implement SCO_2 thermophysical properties.
- Simulate the transient fluid flow and heat transfer between the fluid and solid regions in the heat exchanger.

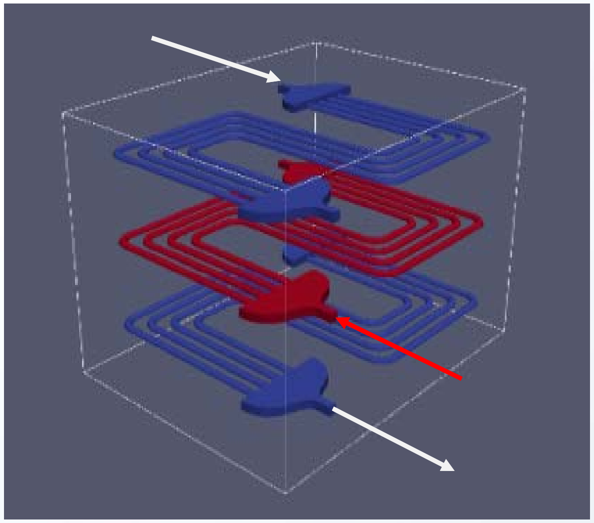
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_i u_j + p\delta_{ij} - \tau_{ij}\right] = 0$$

$$\frac{\partial \rho e_0}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho e_0 u_j + u_j p + q_j - u_j \tau_{ij}\right] = 0$$

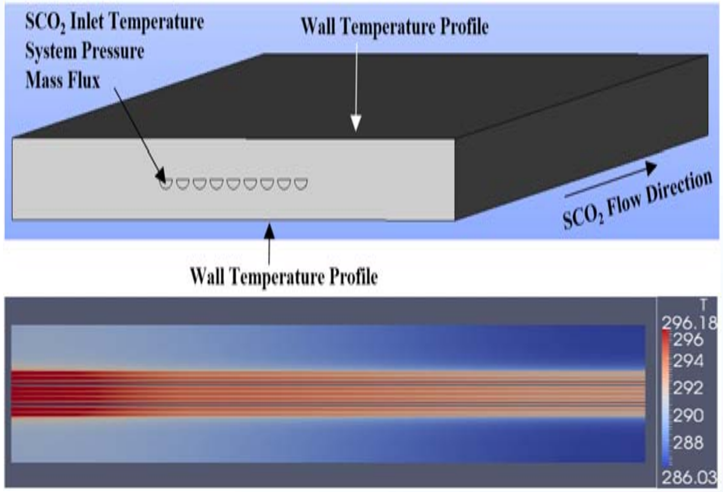
$$e_0 = e + \frac{u_i u_i}{2}$$

$$\frac{\partial}{\partial x_j}\left(\kappa \frac{\partial T}{\partial x_j}\right) = 0$$



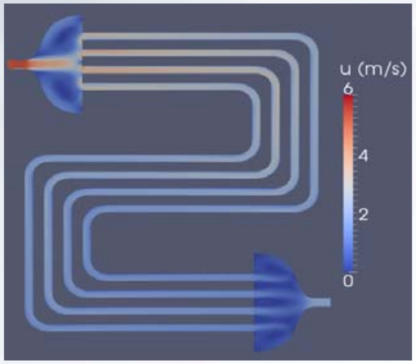
Comparison with Experiment

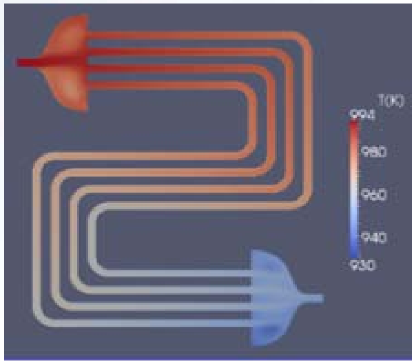
- A fourth order polynomial curve fitted to the experimental wall temperature has been imposed as the boundary conditions on the top and bottom walls.
- Comparing the experimentally measured power removal for 7.5 MPa, 25C, and 762 kg/m^{2}s demonstrated a 10% error.
- Power removal $\dot{Q}_{CO2} = GA(h_{in} - h_{out})$



Kruizenga, A., et al. JTSEA, 2011.

Initial Conditions





Inlet conditions for SCO$_2$ flow for different computational cases.

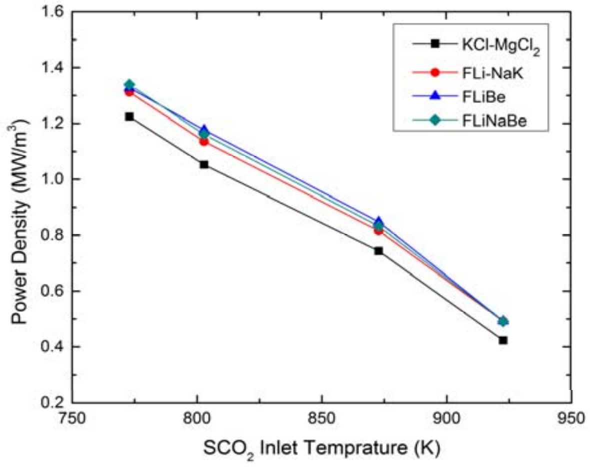
Case	T_{in} (K)	p_{in} (MPa)	$\dot{m}$ (kg/s)
1	803	20	0.01
2	873	20	0.012
3	923	20	0.012
4	773	20	0.012
5	773	20	0.008
6	773	20	0.006
7	773	20	0.01

- The inlet temperature of the molten salt for all computational cases is 993K based on DOE requirement.
- The mass flow rate and velocity of the molten salt are 0.029 kg/s and 2 m/s, respectively.

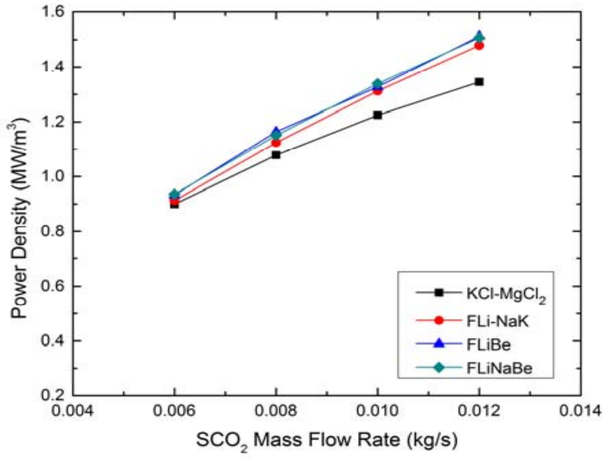
Molten Salt Properties

	Salt Mixture					
	FLiBe	**FLiNaK**	**FLiNaBe**	**KCl-MgCl$_2$**	**Solar Salt**	**Hitec**
Melting Point (K)	730	727	569	705	495	415
Maximum Temperature (K)	**1073**	**1050**	**1025**	**1030**	873	808
Density (kg/m^3)	2413	2579.3-0.624T	2435.8-0.45T	2007-0.4571T	2263.6-0.636T	2279.8-0.7324T
Temperature range for density correlation (K)	788-1094	933-1170	800-1025	1017-1174	573-873	448-773
Heat Capacity (J/kg.K)	**2385**	**1880**	**2200**	**1155**	1396.1+0.17T	1560
Thermal Conductivity (W/m.K)	**1.10**	0.85	0.70	**0.55**	0.45	0.48

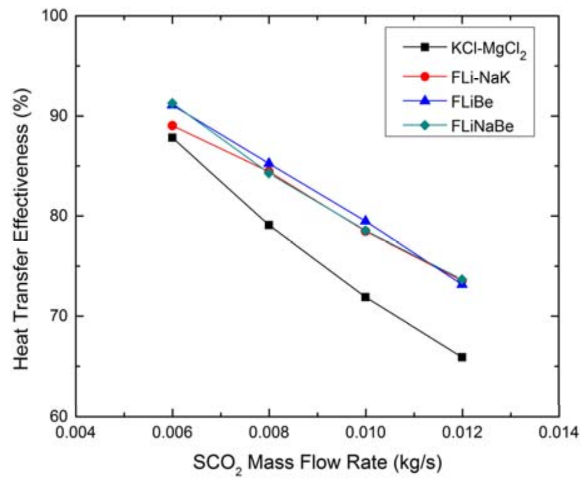
Fluoride salts offer higher power density and effectiveness.



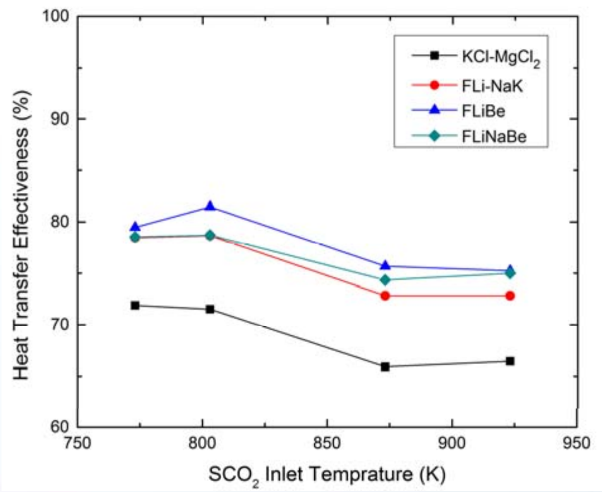
SCO_2 mass flow rate = 0.001 kg/s



SCO_2 inlet temperature= 773K



SCO_2 inlet temperature= 773K



SCO_2 mass flow rate = 0.001 kg/s

Optimum Design Conditions

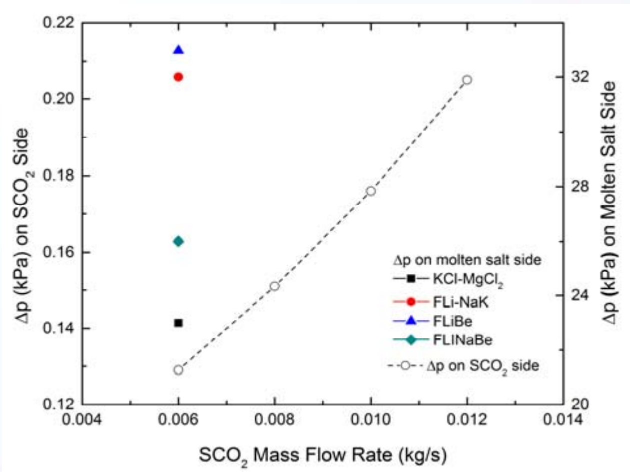
Molten Salt (T_{in}= 993 K)	SCO_2 Inlet Temp. (K)	SCO_2 Mass Flow Rate (kg/s)	Effectiveness (%)	Power Density (MW/m^3)
$KCl-MgCl_2$	773	0.008	79.9	1.107
FLi-NaK	773	0.007	86.7	1.106
FLiBe	773	0.007	88.1	1.048
FLiNaBe	773	0.007	87.9	1.043

Target met

Power density >1 MW/m^3

Pressure drop <100 kPa

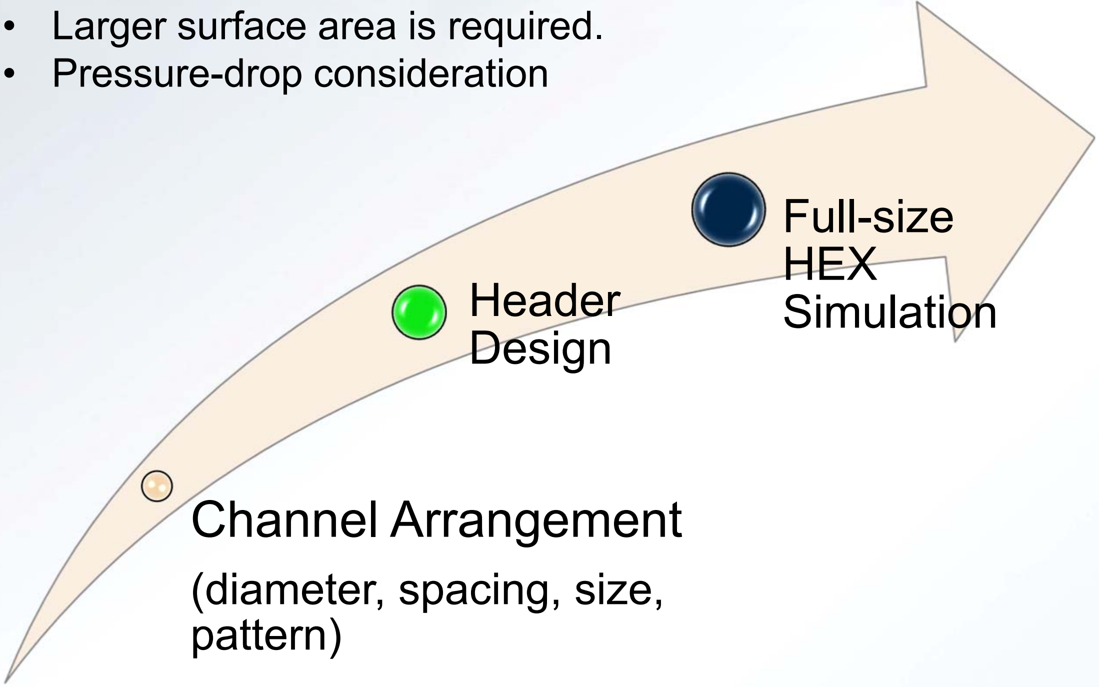
SCO_2 inlet temperature= 773K



Overall Heat Transfer

On-going Work

- Heat transfer coefficient is below the commercially available metal alloy PCHE.
- Larger surface area is required.
- Pressure-drop consideration

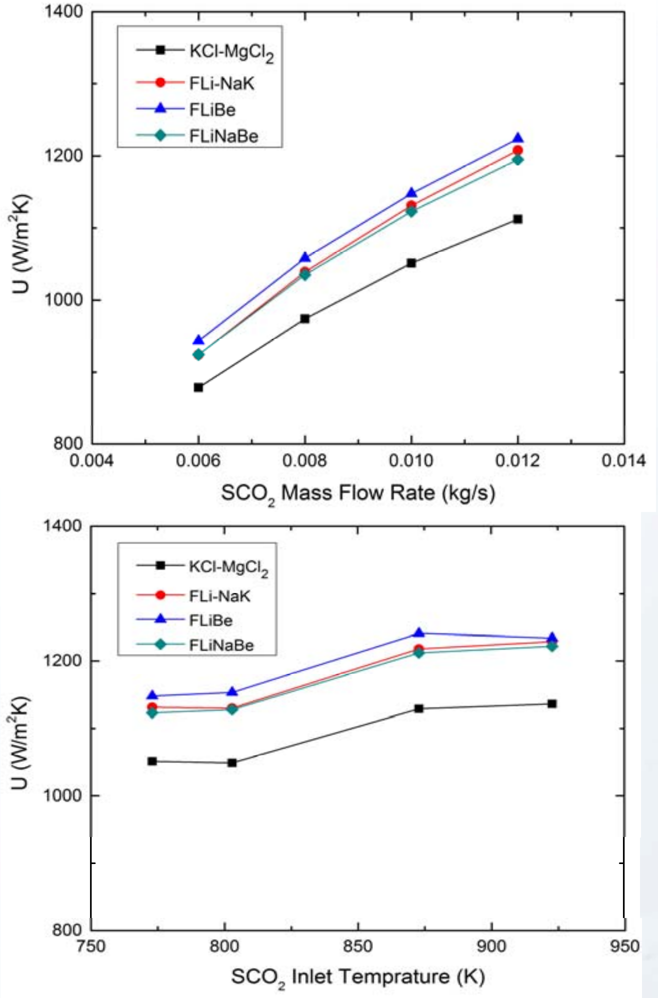


Channel Arrangement

(diameter, spacing, size, pattern)

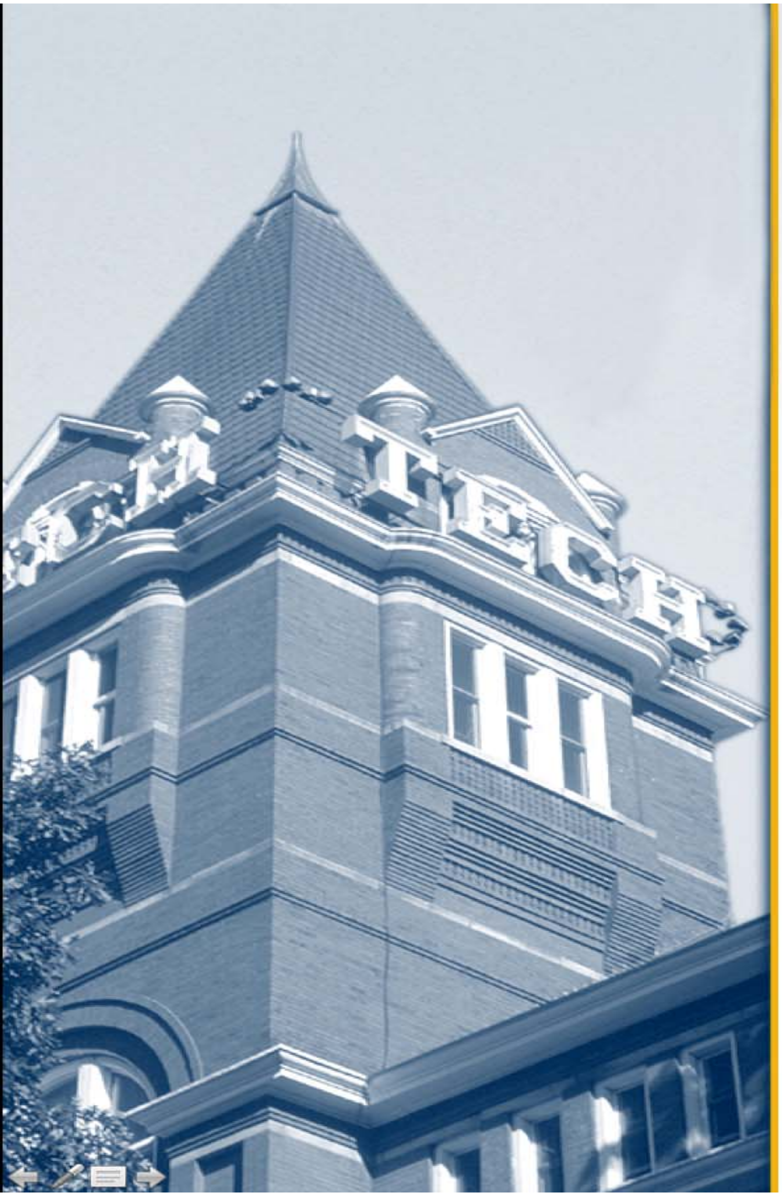
Header Design

Full-size HEX Simulation



Conclusions

- The heat-to-electricity conversion efficiency of closed-cycle SCO_2 significantly increased (>20%) with an increase in turbine inlet temperatures from <823K to >1023K.
- Ceramic HEXs will exhibit better performance than state-of-the-art metal-based PCHEs at a lower cost, and also enable operation at higher temperatures > 1023K.
- Such cost-effective, robust, high-temperature composite PCHEs can enable significant enhancements in SCO2 power conversion efficiencies,
- Leading to a lower levelized cost of electricity (LCOE) in power production processes that utilize SCO2 as the working fluid.
- Power density > 1 MW/m3 and pressure drop<< 100 kPa is achieved with SCO_2 inlet temperature of 773K.
- $KCl\text{-}MgCl_2$ provides acceptable power density > 1 MW/m^3.



Thank you!

Questions?

Principal Investigators

Ken H. Sandhage
Devesh Ranjan,
Asegun Henry
Mark H. Anderson

SunShot U.S. Department of Energy

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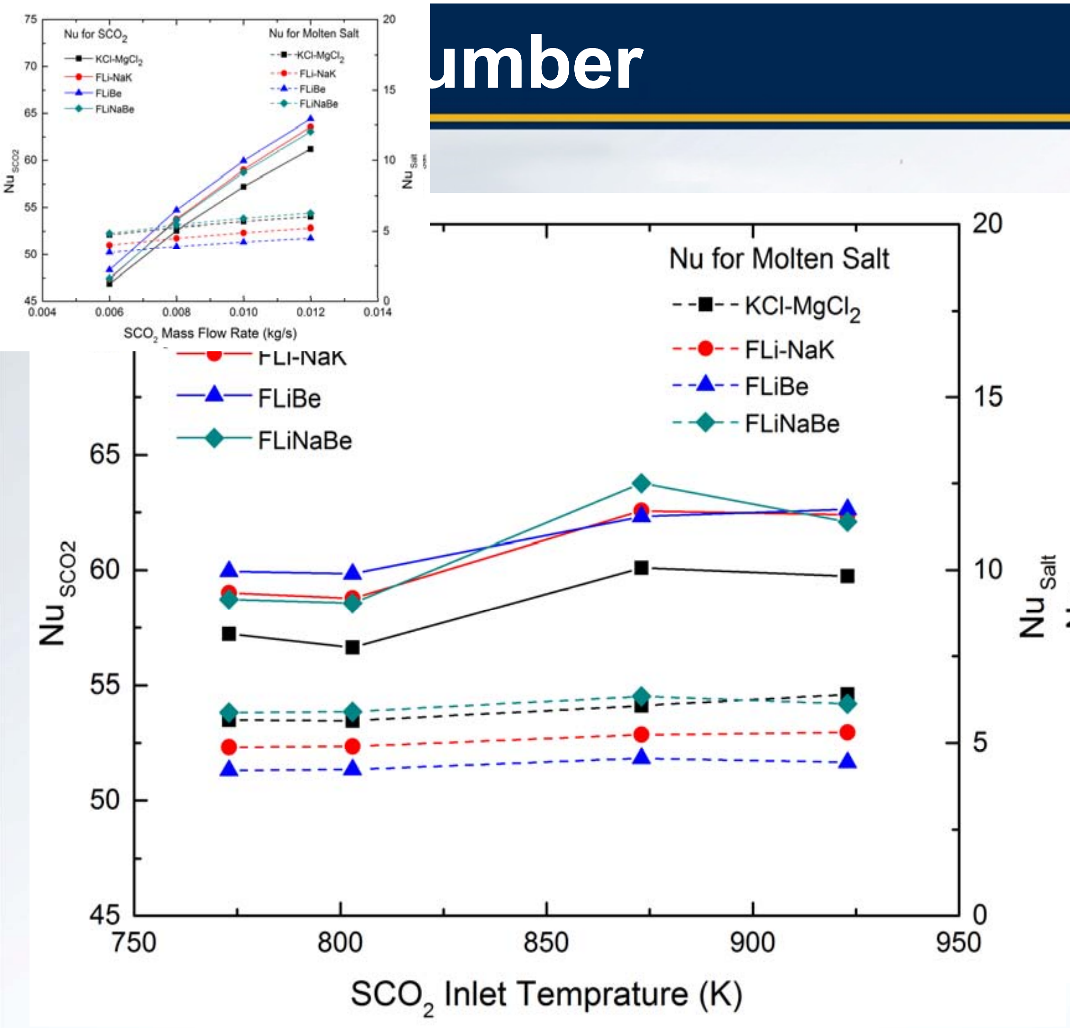
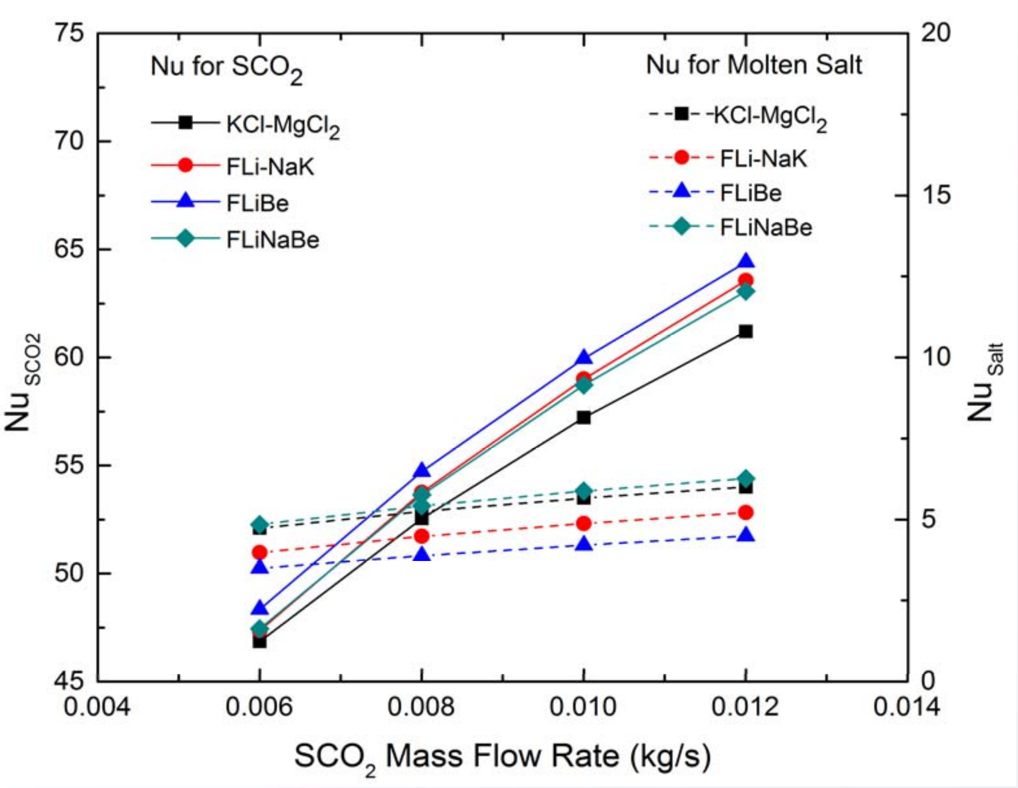
BACK UP SLIDES

umber



Nu for SCO$_2$
Nu for Molten Salt
KCl-MgCl$_2$
FLi-NaK
FLiBe
FLiNaBe
Nu$_{SCO2}$
Nu$_{Salt}$
SCO$_2$ Mass Flow Rate (kg/s)
0.004
0.006
0.008
0.010
0.012
0.014
45
50
55
60
65
70
75
0
5
10
15
20
Nu for Molten Salt
KCl-MgCl$_2$
FLi-NaK
FLiBe
FLiNaBe
FLi-NaK
FLiBe
FLiNaBe
Nu$_{SCO2}$
Nu$_{Salt}$
45
50
55
60
65
0
5
10
15
20
750
800
850
900
950
SCO$_2$ Inlet Temprature (K)



Nu for SCO$_2$
KCl-MgCl$_2$
FLi-NaK
FLiBe
FLiNaBe
Nu for Molten Salt
KCl-MgCl$_2$
FLi-NaK
FLiBe
FLiNaBe
Nu$_{SCO2}$
Nu$_{Salt}$
45
50
55
60
65
70
75
0
5
10
15
20
0.004
0.006
0.008
0.010
0.012
0.014
SCO$_2$ Mass Flow Rate (kg/s)

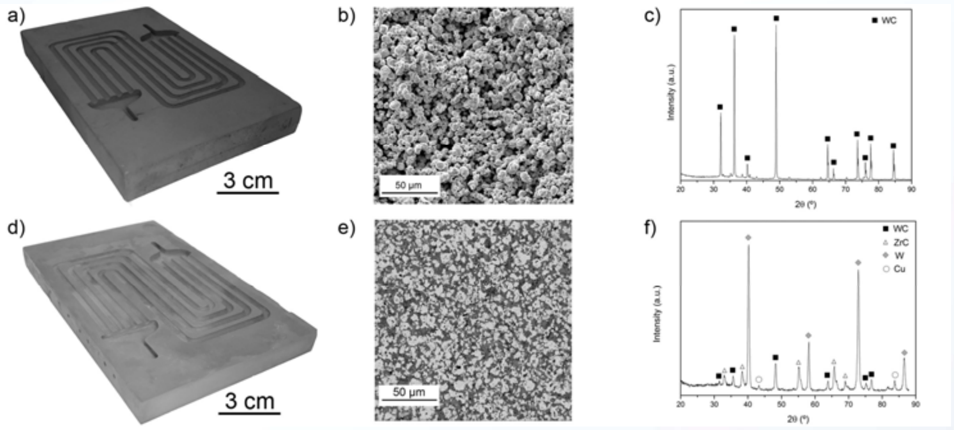
Future Paths

- The heat-to-electricity conversion efficiency of closed-cycle Supercritical CO2 (SCO2) turbine systems may be significantly increased (>20%) with an increase in turbine inlet temperatures from <823K to >1023K
- However, closed-cycle SCO_2 turbine systems are currently limited to inlet temperatures <823K, due to the rapid decline at higher temperatures in the thermomechanical properties of metal-based heat exchangers (HEXs) used to transfer heat to the SCO_2
- we demonstrate for the first time, the cost-effective processing of tailorable ceramic/metal composite heat exchanger (HEX) plates, with attractive thermal, mechanical, and chemical properties at $\geq$1023K

- The ZrC/W composites exhibit thermal conductivity values 2-3 times greater than Fe- or Ni-based alloys, and exhibit temperature-independent failure strengths up to 1073K (unlike Fe- or Ni- based alloys).
- With proper tailoring of composite surfaces and/or the fluid, the ZrC/W composites were resistant to corrosion in SCO_2-based fluids at 1023K
- Simulations and cost modeling show that industrial-scale versions of these ZrC/W-based HEXs will exhibit better performance than state-of-the-art metal-based PCHEs at a lower cost, and also enable operation at higher temperatures $\geq$ 1023K.
- Such cost-effective, robust, high-temperature composite PCHEs can enable significant enhancements in SCO2 power conversion efficiencies, leading to a lower levelized cost of electricity (LCOE) in power production processes that utilize SCO2 as the working fluid.

- high-melting
- thermally conductive
- enhanced resistance to fracture
- modest thermal expansion
- and dense (hot pressed) ZrC/W composites are resistant to thermal shock at high heating rates (>1000K/sec).REFs
- considered as thermal shock/erosion-resistant materials for solid-fuel rocket components
- tailoring of such composites for high-temperature HEXs have not been reported.

- Dense ZrC/W-based plates containing channels with tailorable patterns have been fabricated here via the shape-preserving reactive infiltration of green-machined porous WC preforms
- such a rigid, porous WC plate possessing four parallel channels arranged in a serpentine pattern with flat-bottomed headers



- machinable porous WC preform plates can be prepared with tailorable channel patterns and then converted via pressureless reactive liquid infiltration into dense ZrC/W-based composite plates with high-fidelity retention of the shapes and sizes of the overall preform and of the channels.
- Photograph of a 9 cm x 15 cm x 1 cm porous, rigid WC porous preform plate after green surface machining of 4 parallel millichannels (3 mm wide) in a serpentine pattern with 2 flat-bottom headers.