Use of 1-D Finite Enthalpy Method for a High-Temperature Recuperator Made of Polymer Derived Ceramic Composite for a Supercritical Carbon Dioxide Power System

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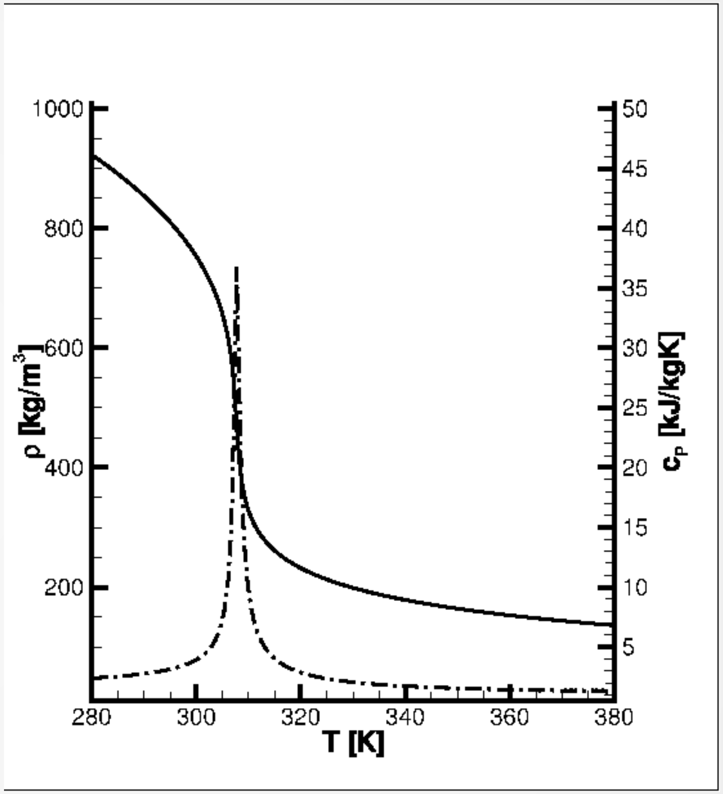
Outline

- Introduction
- Finite Enthalpy Method (FHM)
- Optimization Process
- Polymer Derived Ceramic Composites
- Concept of Heat Exchanger
- Stress Analysis

Introduction

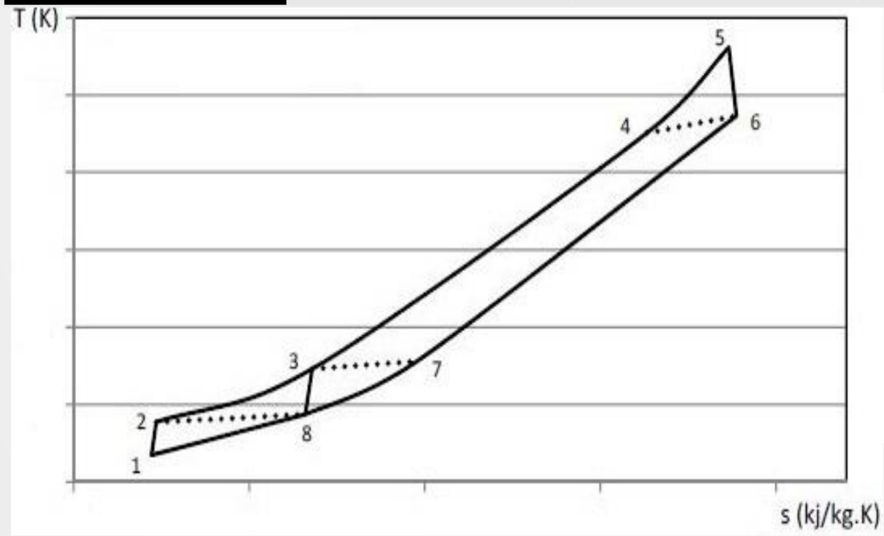
- Low temperature to reach supercritical state
- Higher density than air
- Low cost operation (compared to Helium)
- High variation in thermodynamic properties in the supercritical region

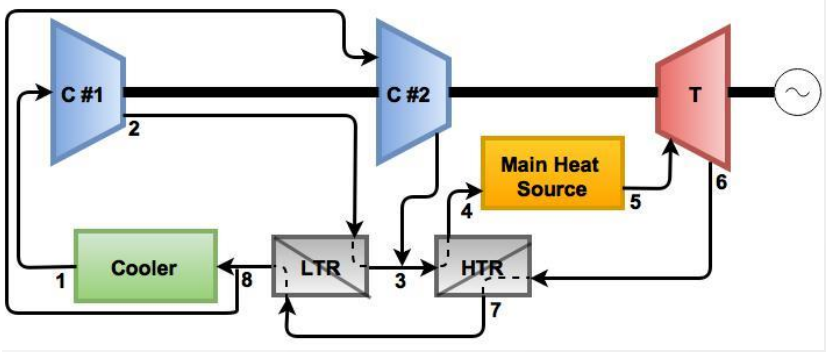


Thermodynamics properties of CO_2 at P=8MPa

Recompression Recuperated Cycle

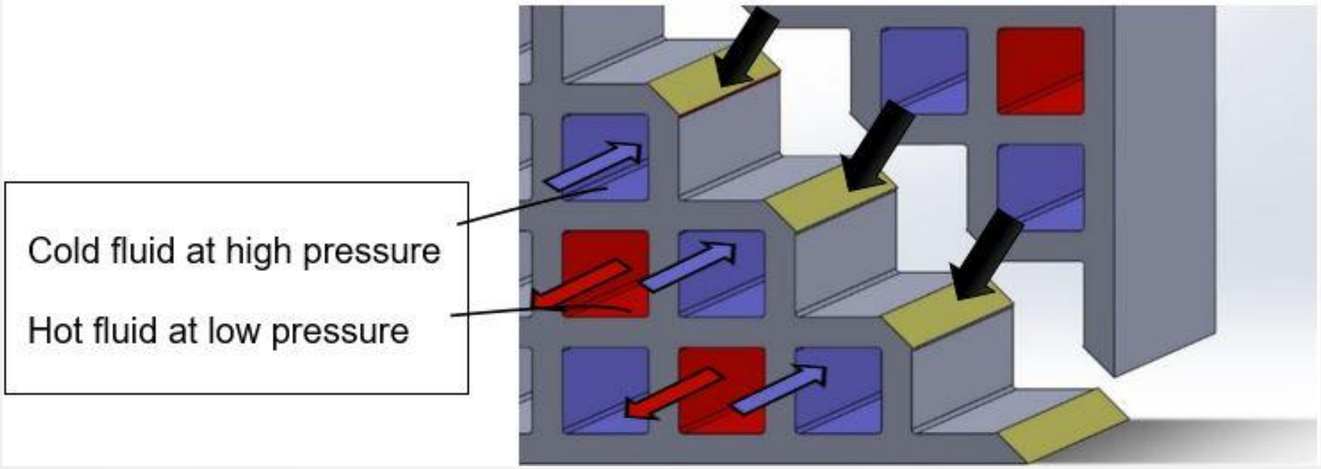
Point	T (K)	P (kPa)	h(kJ/kg)	ρ (kg/m^3)	s $(kJ/kg.K)$
1	320.0	9500	382.5	374.3	1.579
2	378.9	24000	420.5	544.2	1.599
3	487.9	23976	606.8	295.8	2.035
4	1154.4	23952	1455.6	103.8	3.134
5	1350.0	23904	1713.0	88.6	3.34
6	1196.6	9691	1511.8	41.9	3.359
7	498.2	9643	662.9	109.3	2.305
8	388.9	9595	529.7	162.7	2.003





Concept of Heat Exchanger

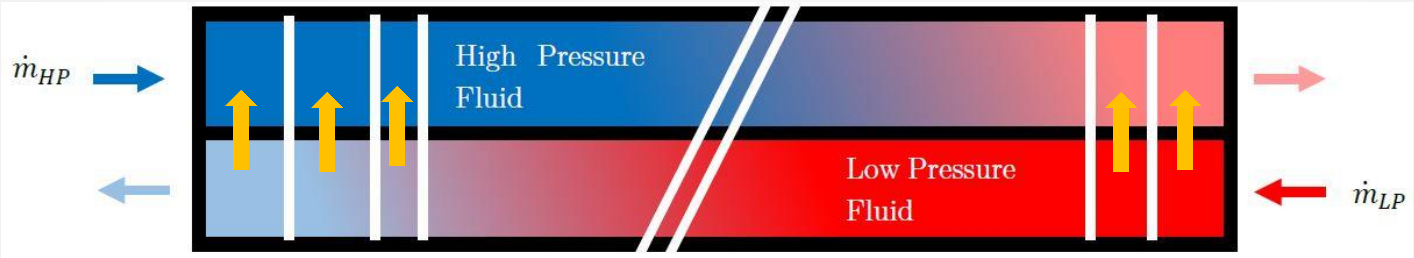
Counter flow heat exchanger, made of square channels.



Finite Enthalpy Method

- Purpose:
    - ***To accurately identify any internal pinch-point***
    - To obtain faster convergence even with high variations in thermodynamic properties

- Process:
    - To apply equal and finite heat transfer per element ($\Delta \boldsymbol{Q} = \boldsymbol{Q}/n$)



Note: Each "orange" arrow represents equal amount of heat transfer. However, the physical length of each element may not be same, and is computed from the heat exchange calculation.

- Computation Parameters to Iterate:
    - Hydraulic diameter or channel side
    - Number of channels for hot or cold side
    - Number of discretized elements

Finite Enthalpy Method

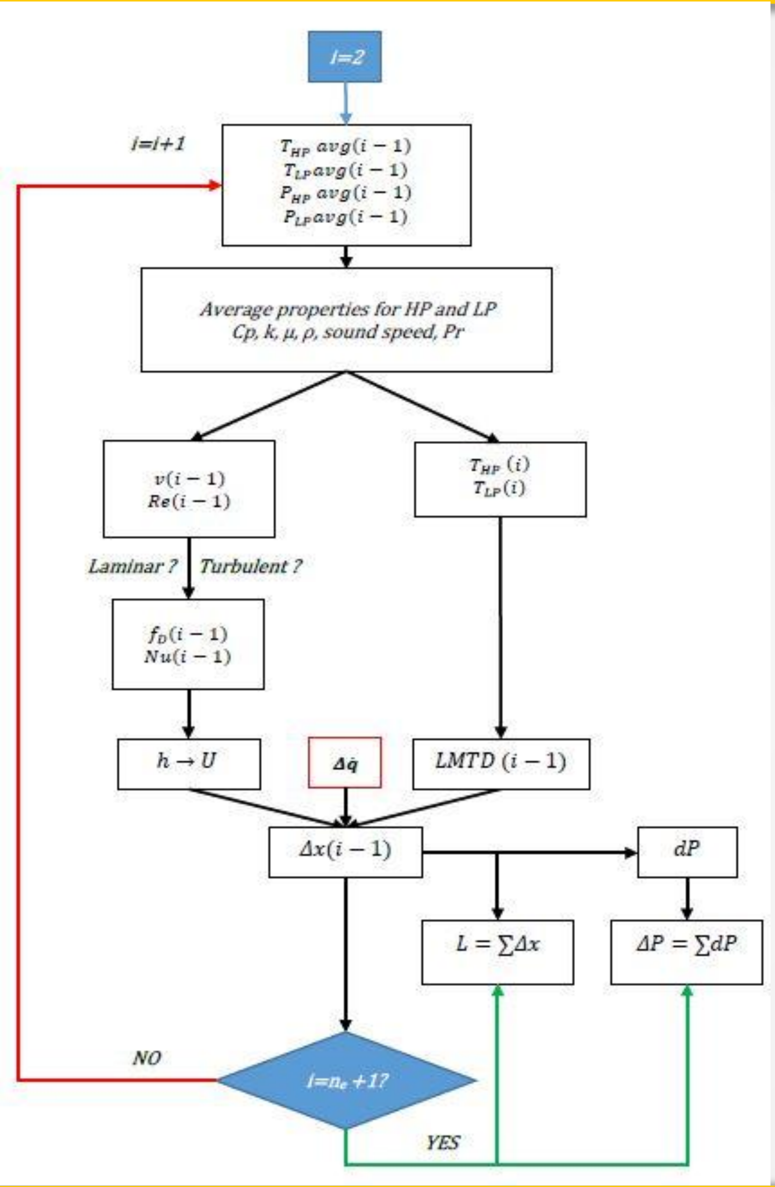
- Properties are called from REFPROP

- Input parameters and decision variables

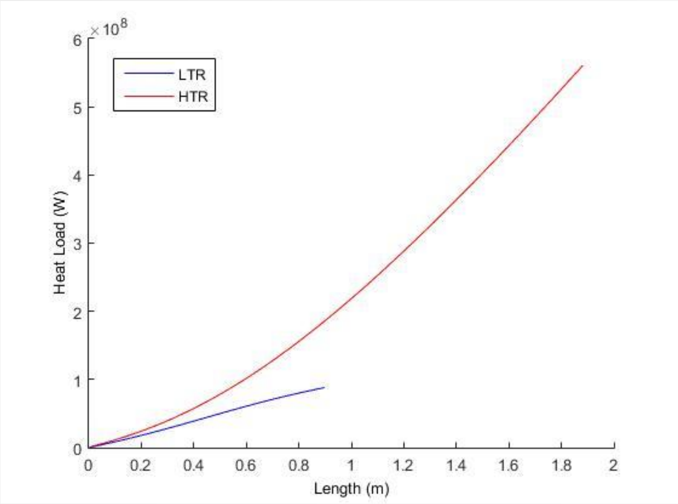
Input Parameters		
Geometry	Channel thickness	t
LP and HP fluids	Inlet and outlet temperature (K)	$T_{L/HP_{in}}, T_{L/HP_{out}}$
Inlet and outlet pressure (kPa)	$P_{L/HP_{in}}, P_{L/HP_{out}}$	
Mass flow rate (kg/s)	$\dot{m}_{L/HP}$	
Computation Parameters		
Geometry	Hydraulic Diameter	D_h
	# of channels	$n_{channels}$
	# of elements	n_e

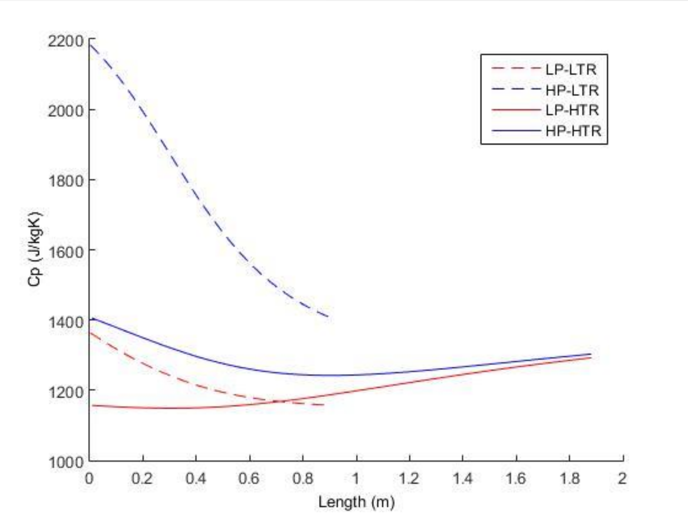
Property	Equations & Correlation
Heat per element (W)	$\Delta\dot{Q} = \dot{Q}/n$
Average temperature for j[th] iteration	$T_{H\backslash LP\,avg}(i-1) = \frac{1}{2}T_{H\backslash LP_j}(i-1) + \frac{1}{2}T_{H\backslash LP_{j-1}}(i)$
Temperature (K)	$T_{H\backslash LP}(i) = T_{H\backslash LP}(i-1) + \frac{\Delta\dot{Q}}{\dot{m}_{H\backslash LP} C_{p\,H\backslash LP}(i-1)}$
LMTD (K)	$LMTD(i) = \frac{\left((T_{LP}(i) - T_{HP}(i)) - (T_{LP}(i+1) - T_{HP}(i+1)\right)}{\ln(\frac{T_{LP}(i) - T_{HP}(i)}{T_{LP}(i+1) - T_{HP}(i+1)})}$
Velocity (m/s)	$V = \frac{\dot{m}}{\rho . s}$
Reynolds number	$Re = \frac{\rho V D_H}{\mu} = \frac{\dot{m} D_H}{\mu . s}$
Darcy friction factor	$f_D = \frac{64}{Re}$
	$\frac{1}{\sqrt{f_D}} = -2\log(\frac{\varepsilon}{3.7D_H} + \frac{2.51}{Re\sqrt{f_D}})$
Nusselt number	$Nu = 3.61$
	$Nu_D = \frac{\left(\frac{f_D}{8}\right)(Re_D - 1000)Pr}{1 + 12.7\sqrt{\frac{f_D}{8}}(Pr^{2/3})}$
Heat transfer coefficient ($W/_{m^2.K}$)	$h = Nu\frac{k_{fluid}}{D_H}$
Overall heat transfer coefficient	$U = \frac{1}{\frac{1}{h_{LP}} + \frac{1}{h_{HP}} + \frac{t}{k}}$
Δx (m)	$\Delta x(i) = \frac{\Delta\dot{Q}}{4D_H\, LMTD(i) U(i)}$
Pressure loss	$dP(i) = 0.5\rho f_D \Delta x(i)\frac{V^2}{D_H}$

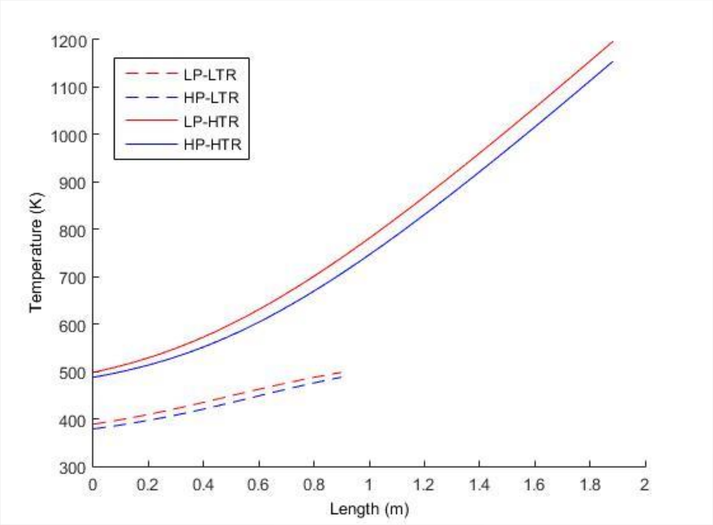
Developing-region correlations can be used as necessary


i=2
i=i+1
$T_{HP}\ avg(i-1)$
$T_{LP} avg(i-1)$
$P_{HP}\ avg(i-1)$
$P_{LP} avg(i-1)$
Average properties for HP and LP
Cp, k, μ, ρ, sound speed, Pr
$v(i-1)$
$Re(i-1)$
$T_{HP}\ (i)$
$T_{LP}(i)$
Laminar ?
Turbulent ?
$f_D(i-1)$
$Nu(i-1)$
$h \rightarrow U$
$\Delta\dot{q}$
$LMTD\ (i-1)$
$\Delta x(i-1)$
dP
$L = \sum \Delta x$
$\Delta P = \sum dP$
NO
$i = n_e + 1?$
YES

$k_{cross}\ (W/m.K)$		
$10^{-11}T^4 - 2*10^{-8}T^3 + 2*10^{-5}\,T^2 + 0.0104T + 5.7944$		
$k_{long}\ (W/m.K)$	ε (m)	
5	$15\text{x}10^{-6}$	
MCHE dimensions		
	LTR	**HTR**
Hydraulic Diameter	1.003 mm	1.014 mm
t	0.35 mm	0.35 mm
$n_{channels}$	770	1107
Heat load	87.96 MW	560.59 MW
Mass flow rate	$\dot{M}_{LTR_{LP}} = 510.21\ kg/s$ $\dot{M}_{LTR_{HP}} = 364.8\ kg/s$	$\dot{M}_{HTR} = 510.21\ kg/s$
n_e	580	700
Iterations	7	7
Length	0.89927 m	1.88 m
Width	2.08 m	3.02 m
Total mass	1757 kg	7676 kg

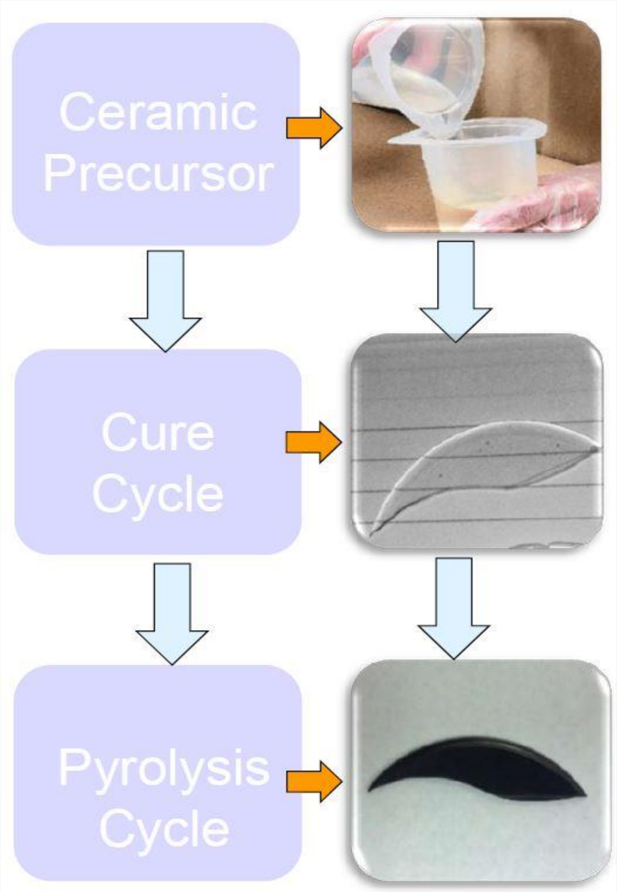

× 10^8
Heat Load (W)
LTR
HTR
Length (m)


Cp (J/kgK)
LP-LTR
HP-LTR
LP-HTR
HP-HTR
Length (m)


Temperature (K)
LP-LTR
HP-LTR
LP-HTR
HP-HTR
Length (m)

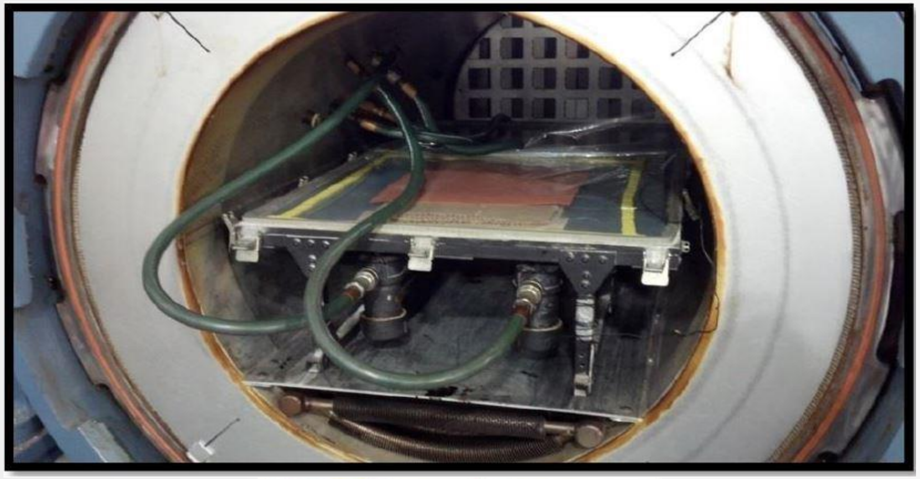
Polymer Derived Ceramic Composites

- Composite materials that can be converted to ceramic composites
- Pros:
  - Exhibition of creep resistance for up to 1450 C
  - Relatively low fabrication cost that depends on cost of fiber
  - Can be used as a coating
  - Can form complex shapes
- Cons:
  - Brittleness of ceramics



Cox, S. B. (2004)

Manufacturing of PDCC

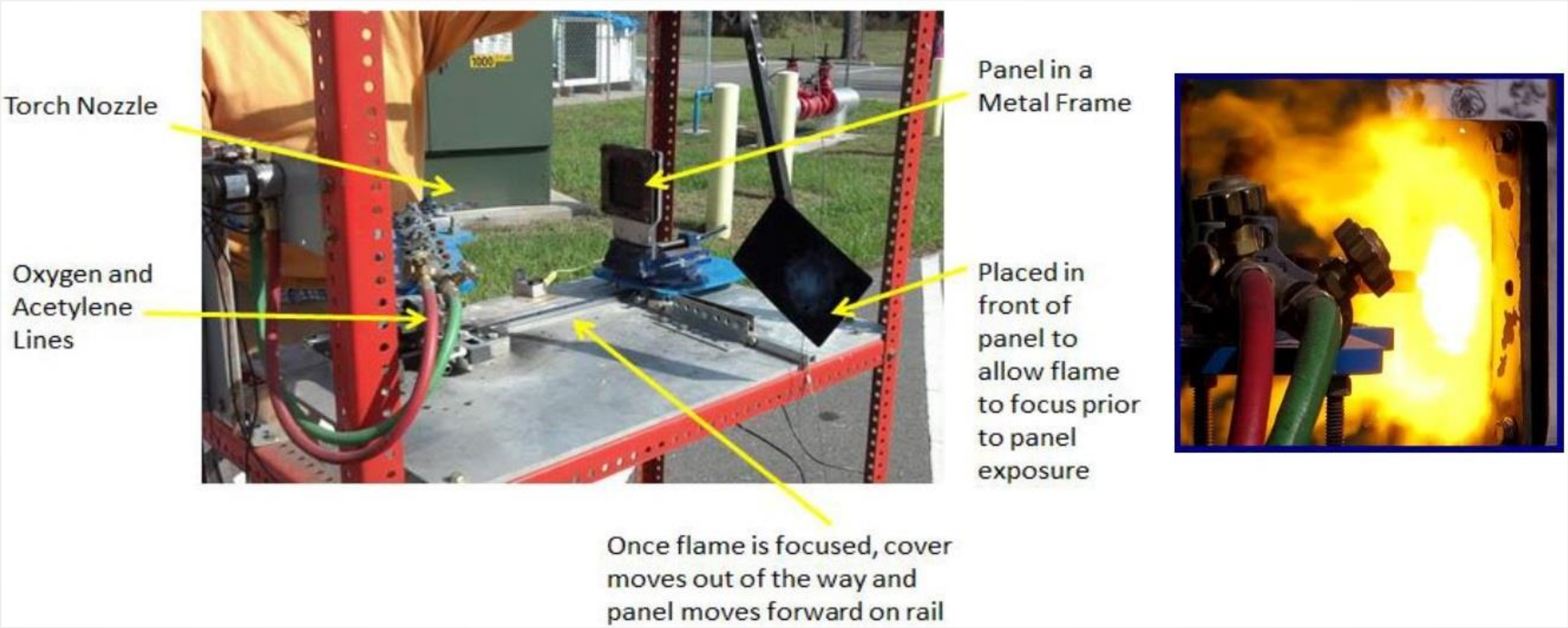


Polymer Infiltration and Pyrolysis (PIP)

- Infiltration of polymer resin precursor into ceramic fabric
- Wet lay-up
- Cure cycle inside an autoclave
- Pyrolysis inside a kiln to produce ceramic backbone

PDCC Testing

- Oxyacetyline torch testing (ASTM E285)
- 3-point bend testing (ASTM C1341)



PDCC: Fiber Options

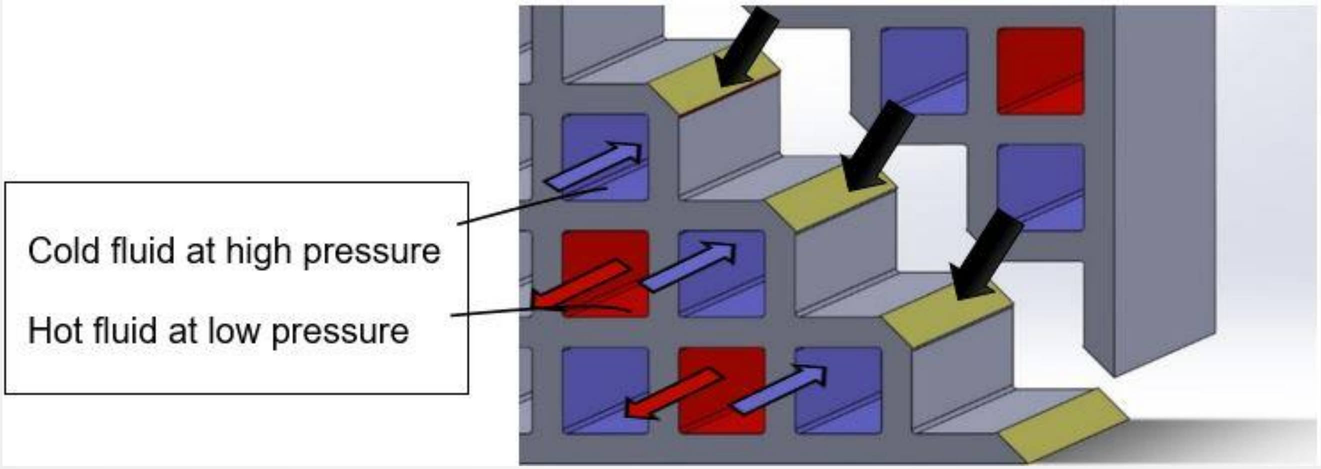
Trade-Name	Manufacturer	Use temperature	Cost ($/kg)	Filament diameter (μm)	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Composition	Thermal expansion (Ppm/℃)
T300	Toray	300~350 ℃	68	7	1.74	3100	230	C	-0.7
Nextel 720	***3M***	***1204*** ℃	***660***	***10~12***	***3.4***	***2930***	***260***	***Al_2O_3/SiO_2***	***6***
SCS-Utra	Specialty Material	1371 ℃	~9000	142	3.08	3900	380	SiC	4.1
SiC-1900X	MATECH	~1482 ℃	-	10~12	3.14	2500	367	β-SiC	-
Nicalon NL-200	Nippon Carbon	1100 ℃	~2000	14	2.55	3000	220	SiC	3.1-3.2
Hi-Nicalon	Nippon Carbon	1230 ℃	8000	14	2.74	2800	270	SiC	3.3-3.5
Hi-Nicalon (Type S)	***Nippon Carbon***	***1450*** ℃	***13000***	***12***	***3.1***	***2600***	***420***	***SiC***	***3.5***
Sylramic	COI Ceramics	1420 ℃	10000	10	3.55	3200	380	SiC	5.4
Tyranno SA 1-3	***Ube Industries***	***1700*** ℃	***5000***	***10***	***3.02***	***2800***	***375***	***SiC***	***-***

PDCC: Resin Options

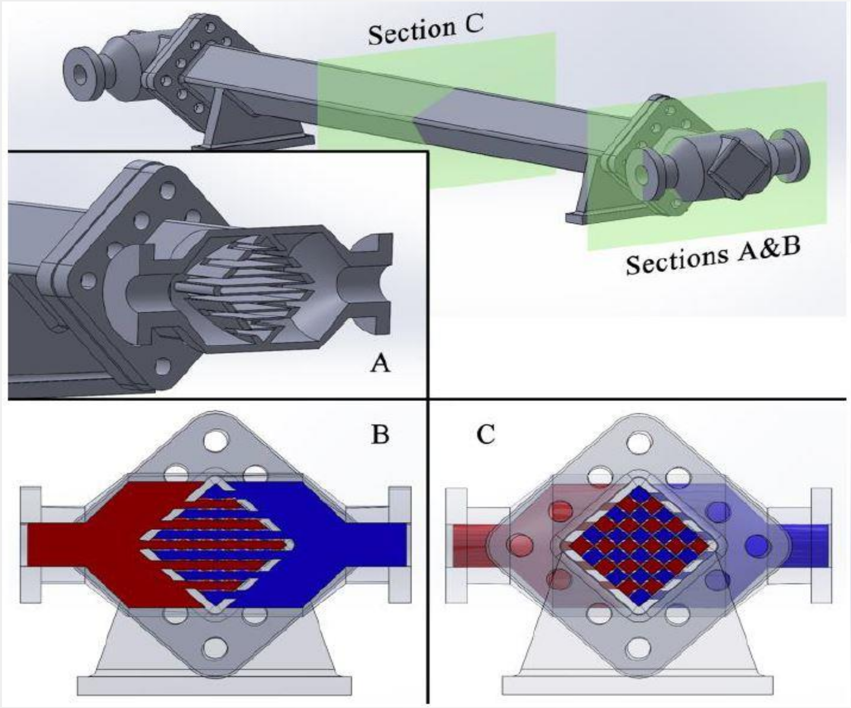
	SPR-688	SMP-10
Density (g/cm^3)	1.11	0.998
Viscosity ($mPa.s$ at 25$°C$)	300-2000	40-100
Flash point ($°C$)	93	89
Operating temperature (as ceramic) ($°C$)	1100	1800

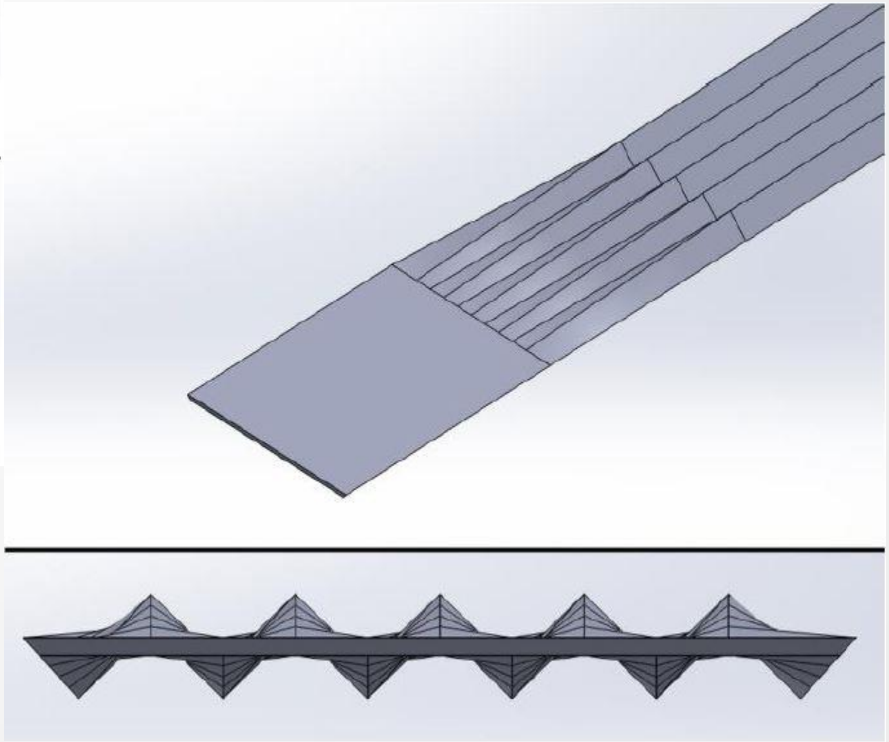
Concept of Heat Exchanger

- Counter flow heat exchanger
- Formed of PDCC
- Plates bonded at 45°
- Bonded using PDCC resin



Previous Work on MCHE (Stair-Step) (Schmitt, 2015)

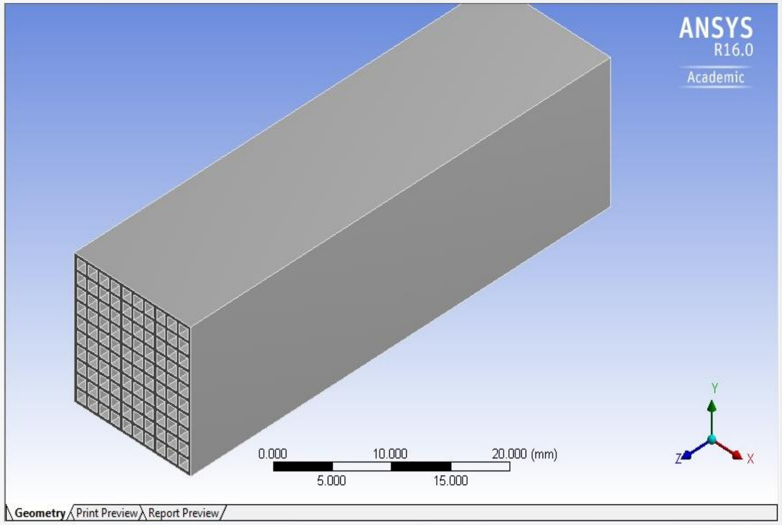




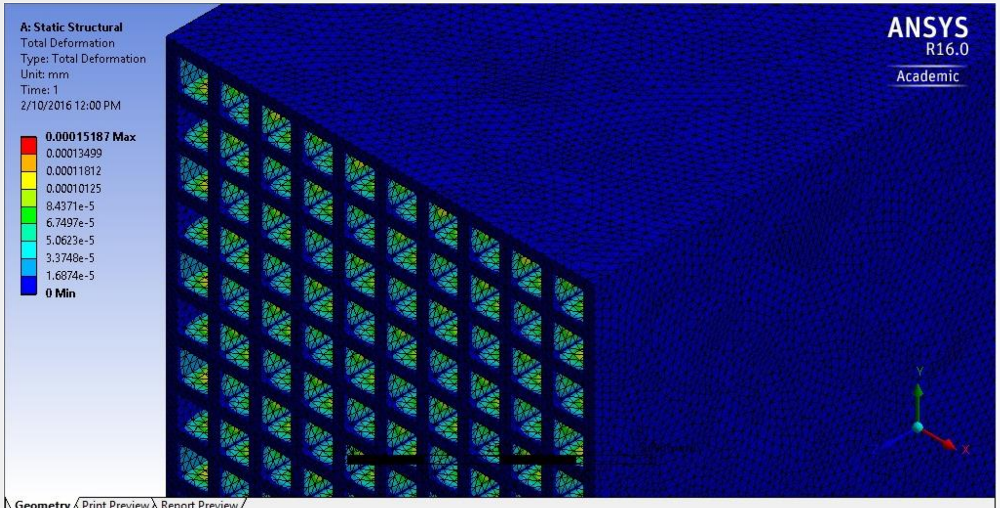
Stress Analysis

Structural calculations – Work in progress; composite delamination yet to be looked at.

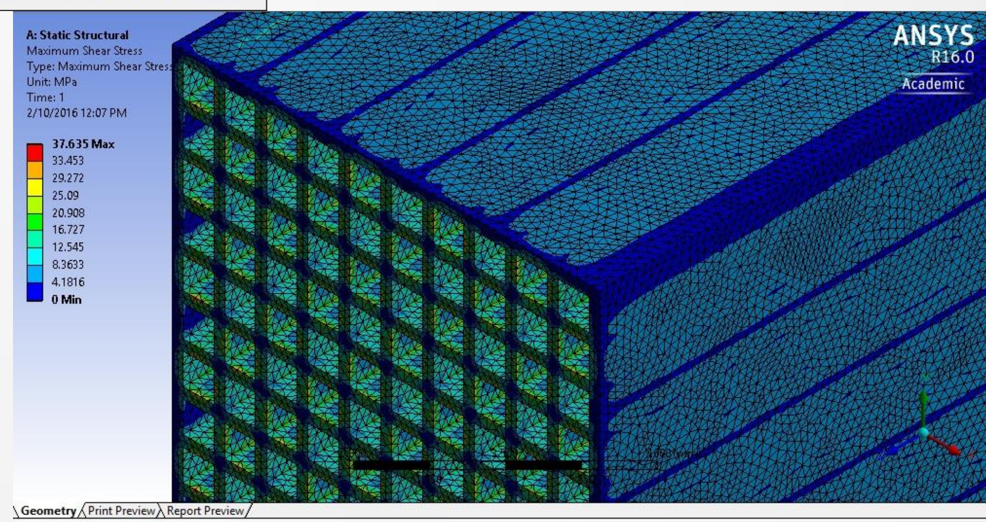
- Constraints and assumptions:
  - Reduced number of channels for computational purposes
  - Length is maintained at 50xHydraulic diameter
  - 6 faces constrained on 6-DOF



Poisson's ratio	0.225
Tensile Strength	$1.7\ GPa$
Young's Modulus (E)	$2\ GPa$
Density (ρ)	$2000\ (^{kg}/_{m^3})$



Total deformation: in the magnitude of micrometer
Max = 0.135 microns



Max shear stress:
37.64 MPa

Background – Our Past Papers

Joshua Schmitt, David Amos, Jayanta Kapat. "Design and Real Fluid Modelling of Micro-channel Recuperators for a Nominal 100MW Class Recuperated Recompression Brayton Cycle Using Supercritical Carbon Dioxide," Proceedings of the ASME Turbo Expo 2015, Paper No. GT2015-43761 June 15-19, 2015, Montreal, Quebec, Canada.

Joshua Schmitt, Rachel Willis, David Amos, Jayanta Kapat, and Chad Custer, "Study of a Supercritical CO2 Turbine With TIT of 1350 K for Brayton Cycle With 100 MW Output: Aerodynamic Analysis of Stage 1 Vane," Proceedings of the ASME Turbo Expo 2014, Paper No. GT2014-27214, June 16-20, Dusseldorf, Germany.

Mahmood Mohagheghi, Jayanta Kapat, and Narashimha Nagaiah, "Pareto-Based Multi-Objective Optimization of Recuperated S-CO2 Brayton Cycles," Proceedings of the ASME Turbo Expo 2014, Paper No. GT2014-27152, June 16-20, Dusseldorf, Germany.

Mahmood Mohagheghi, and Jayanta Kapat, "Thermodynamic Optimization of Recuperated S-CO2 Brayton Cycles for Waste Heat Recovery Applications," Proceedings of the 4th International Symposium on Supercritical CO2 Power Cycles, Paper No. 43, September 9 – 10, 2014, Pittsburgh, Pennsylvania.

Mahmood Mohagheghi, Jayanta Kapat, "Thermodynamic Optimization of Recuperated S-CO2 Brayton Cycles for Solar Tower Applications," Proceedings of the ASME Turbo Expo 2013, Paper No. GT2013-94799, June 3-7, San Antonio, Texas, USA.

QUESTIONS?

Backup slide-Compressor data

	Main Compressor (C #1)	Recompression (C #2)
Total mass flow rate (kg/s)	660.405	
Mass flow fraction ($frac$)	0.715	0.285
Mass flow (kg/s)	472.19	188.215
Intake power (kW)	179389	14504.6

Genetic Algorithm

- Purpose:
  - To optimize the cycle

- Objective:
  - Minimize overall mass
  - Keep relative pressure drop ≤ assumption in cycle calculation

- Algorithm steps:
  1. Assume a value for hydraulic diameter, number of elements and total number of channels
  2. Do calculations
  3. Validate objective criteria
  4. Iterate (if needed)