High Temperature Ceramic Heat Exchanger for Solid Oxide Fuel Cell

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DOE Award No.: DE-FE0024090
DOE Program Manager: Sydni Credle, Ph.D.
Crosscutting Research Division
National Energy Technology Laboratory (NETL)

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MiTi: What We Do

ORC Turbogenerator

65 kWe @ 30,000 rpm

Air Cycle Machine

120,000 rpm

Hydrogen Blower

360,000 rpm

Fuel Cell Compressor

120,000 rpm

Hydrogen Pipeline Compressor

60,000 rpm

Flywheel Electromechanical Battery

60 kWe @ 60,000 rpm

Micro Machining

500,000 rpm

By Use of Ultra High Speed, We Deliver Compact, Power-Dense Engines!

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At the Core: MiTi’s Advanced Foil Bearings

Fourth and Fifth Generation Foil Bearings

- Oil-Free ⇔ Maintenance/Contamination Free
- Ultra High Speed: Proven to 1,000,000 rpm
- With Korolon® 1350/2250 ⇔ High Temperature Operation ⇔ Turbine Exhaust Conditions, up to 810ºC (1500ºF)
- Negligible Friction Power Loss ⇔ High Mechanical Efficiency

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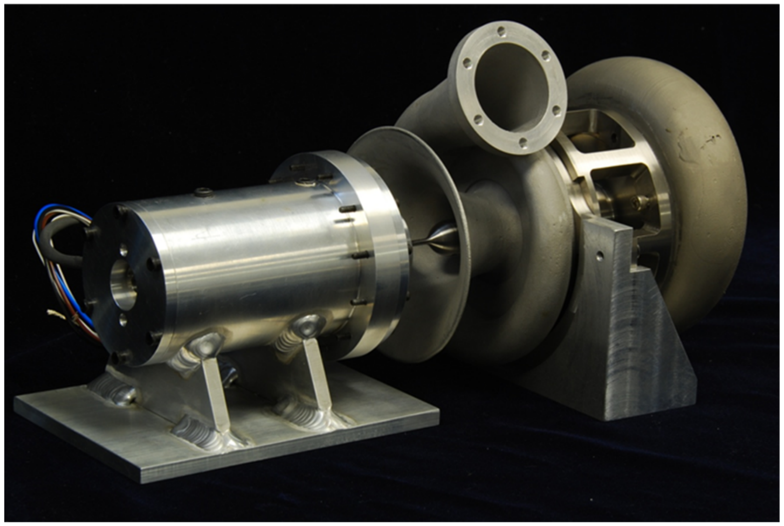
Background

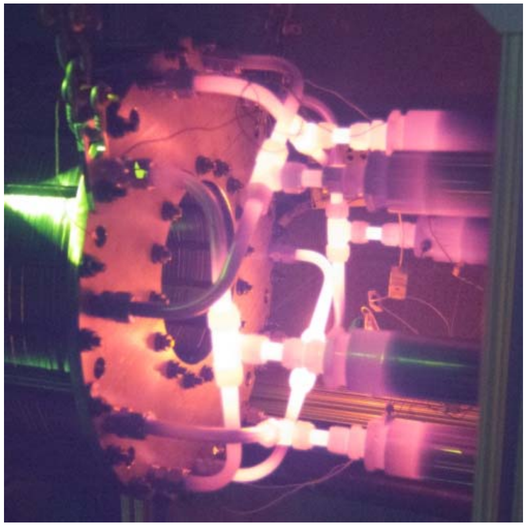
MiTi® 8 kW Turboalternator

- 1.6 kW/kg (1 hp/lbm)
- Oil-free foil bearings/Process-air lubricated
- Design speed: 184,000 rpm
- 12% Thermal Efficiency (Unrecuperated)



Recuperator

- Low pressure drop: < 3 psi
- High Effectiveness: ε □ 0.9
- Radial geometry fits around combustor
- Increase in Thermal Efficiency from 12 to 33%



References:

- Heshmat, H., Walton, J. F., and Hunsberger, A., "Oil-Free 8 kW High-Speed and High Specific Power Turbogenerator," Proceedings of ASME Turbo Expo 2014, GT2014-27306
- Córdova, J. L., Walton, J. F., and Heshmat, H., “High Effectiveness, Low Pressure Drop Recuperator for High Speed and Power Oil-Free Turbogenerator”, Proceedings of ASME Turbo Expo 2015, GT2015-43718

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Project Team

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- Hooshang Heshmat, Ph.D.
  - Technical Director
  - Principal Investigator
- James F. Walton II
  - Sr. Program Manager
- Jose L. Cordova, Ph.D.
  - Program Manager
  - Project Engineer

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

- Hossein Ghezel-Ayagh, Ph.D.
  - FCE Lead
- Micah Casteel, Ph.D.
  - Mechanical Engineer
- Stephen Jolly
  - Systems Design Engineer

Objective

- Develop a High Heat Transfer Effectiveness, Low Pressure Drop *Ceramic* Heat Exchanger for Application as Solid Oxide Fuel Cell Cathode (SOFC) Air Preheater.
  - Possible Materials: Ceramics, Cermet, Hybrid Ceramics, Elastic Ceramics

Purpose of Heat Exchanger

- SOFC cathode requires a fresh air supply at ~700^{o}C for operation.
- Anode exhaust contains CO and H_2.
  - These are post-combusted in a catalytic oxidizer, yielding high temperature heat.
  - Heat is recovered in *heat exchanger* and used to preheat supplied air.

(Continued)

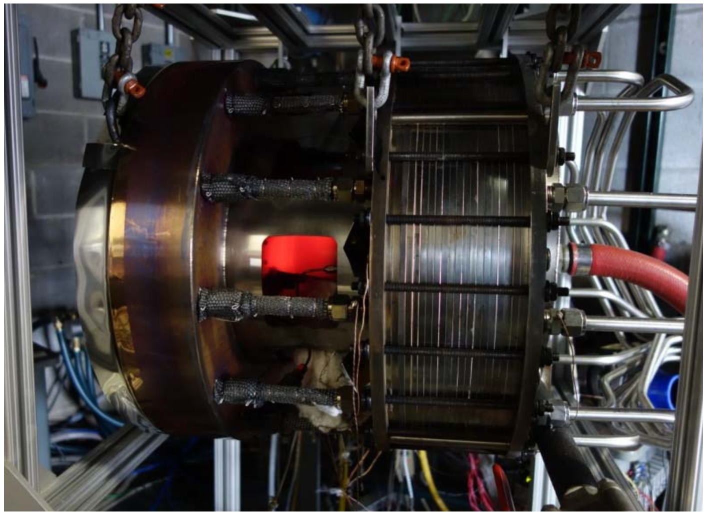
Motivation for Use of Ceramics

- Humidity in air supply causes metal alloys (e.g.: steels, nickel-based and other super-alloys) used in typical heat exchangers to release volatilized chromium.
  - Chromium reacts with cathode materials to degrade cell voltage and ultimately poison cathode elements.

- Alternate materials (i.e., ceramics, cermets, hybrid ceramics, elastic ceramics) may offer best choice for SOFCs.

Overview of Approach

- Leverage MiTi's Novel Gas Turbine Recuperator
  - Original application: 8 kW gas turbine-based turboalternator
    - Turbine engine specifications, operating at 42 psi, allowed pressure drop of 3 to 5 psi.



  - Attained 90% heat transfer effectiveness (measured) at engine operating conditions.
  - Greater than Two-Fold Increase of Cycle Thermal Efficiency
    - from 12% to 30% (measured)
- Extend Technology to SOFC
  - Ceramic Materials
  - Reduce pressure drop

Major Program Elements

1. Solid Oxide Fuel Cell Definition of Requirements
2. Heat Transfer Analysis and Heat Exchanger Sizing
3. Ceramic Materials Review and Selection
4. Fabrication of Heat Exchanger Prototype
5. Pressure drop and thermal performance testing

Target Application: Solid Oxide Fuel Cell Operating Conditions

IDENTIFICATION OF TARGET SOFC AND PROTOTYPE REQUIREMENTS

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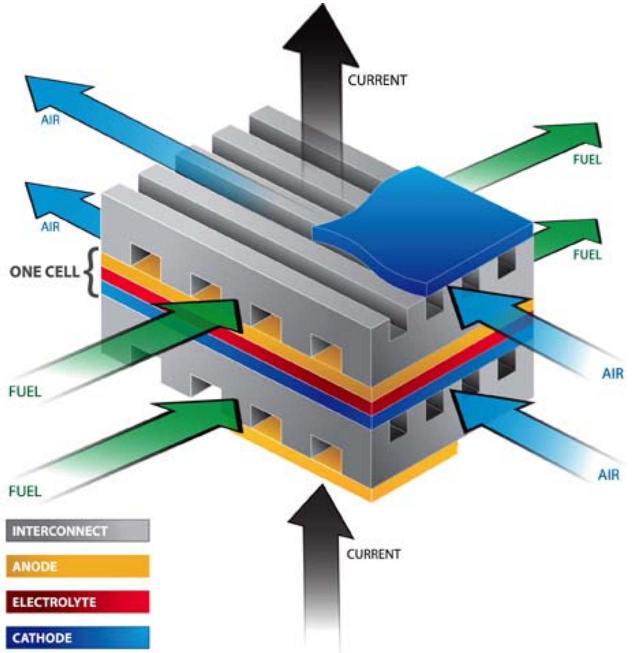
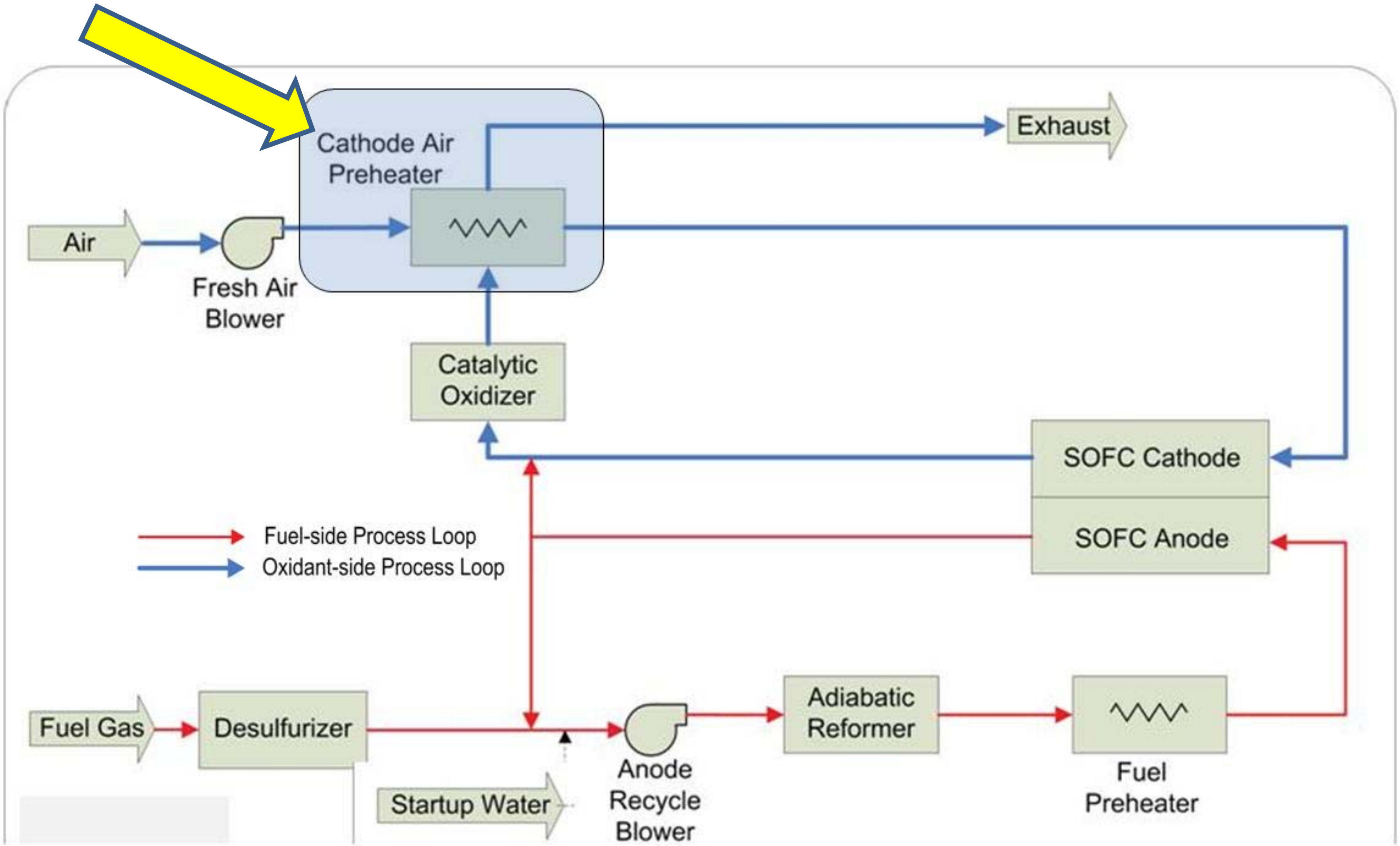
Target Application

- FuelCell Energy Inc.
  - Proof Of Concept (POC) 50 kW$_e$ SOFC



SOFC System Schematic



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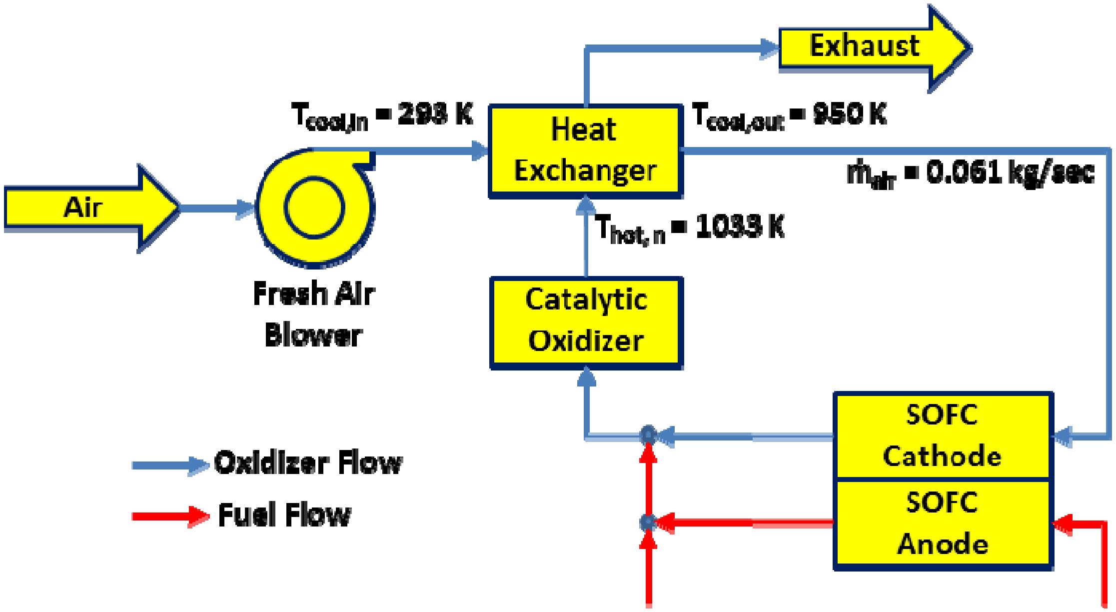
50 kWe POC Operating Conditions



- Required Preheater Heat Transfer:

$$Q = \dot{m}\, c_p\, (Tair_{out} - Tair_{in}) \approx 41 \text{ kW}$$

- Total Allowable Pressure Drop:

$$\Delta P_{tot} = 3447.4 \text{ Pa } (= 13.8 \text{ inH}_2\text{O} = 0.5 \text{ psi})$$

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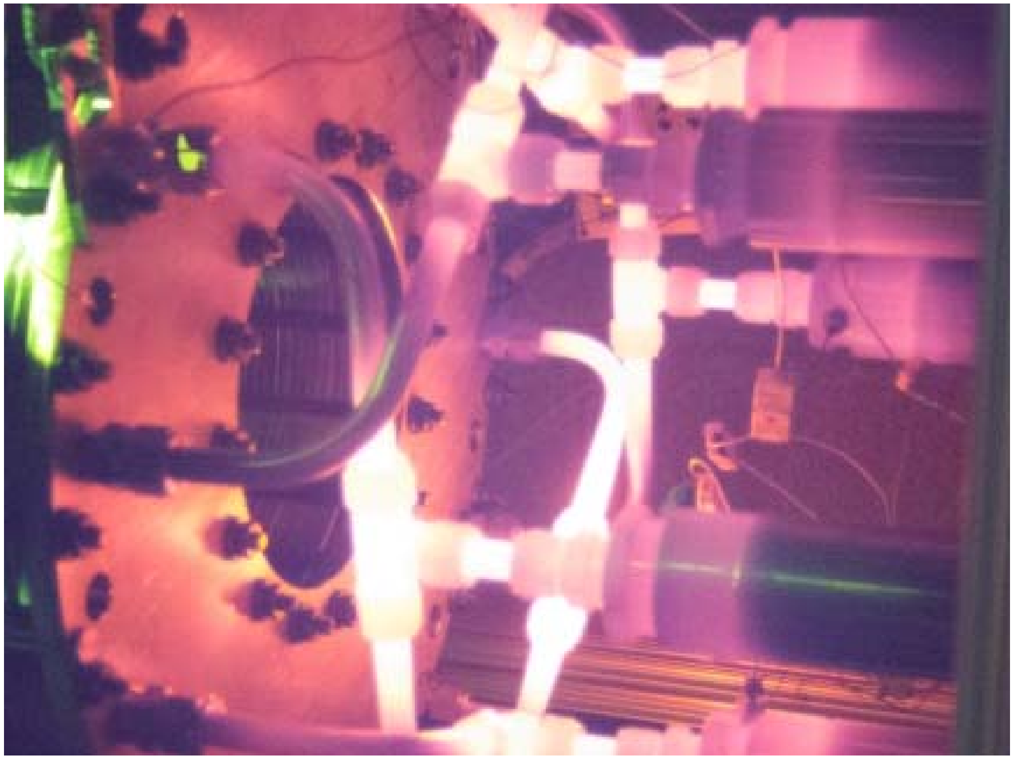

Background

MiTi'S RECUPERATOR EXPERIENCE

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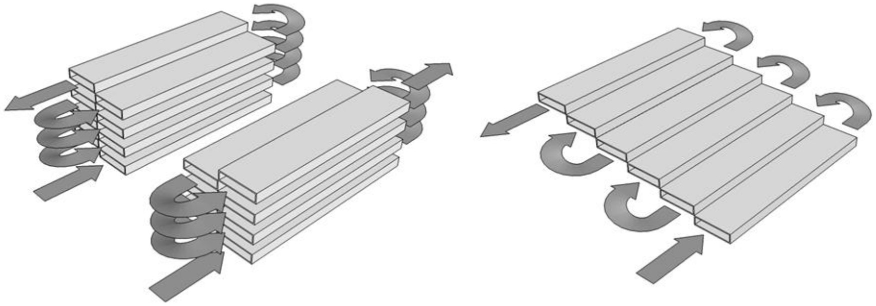
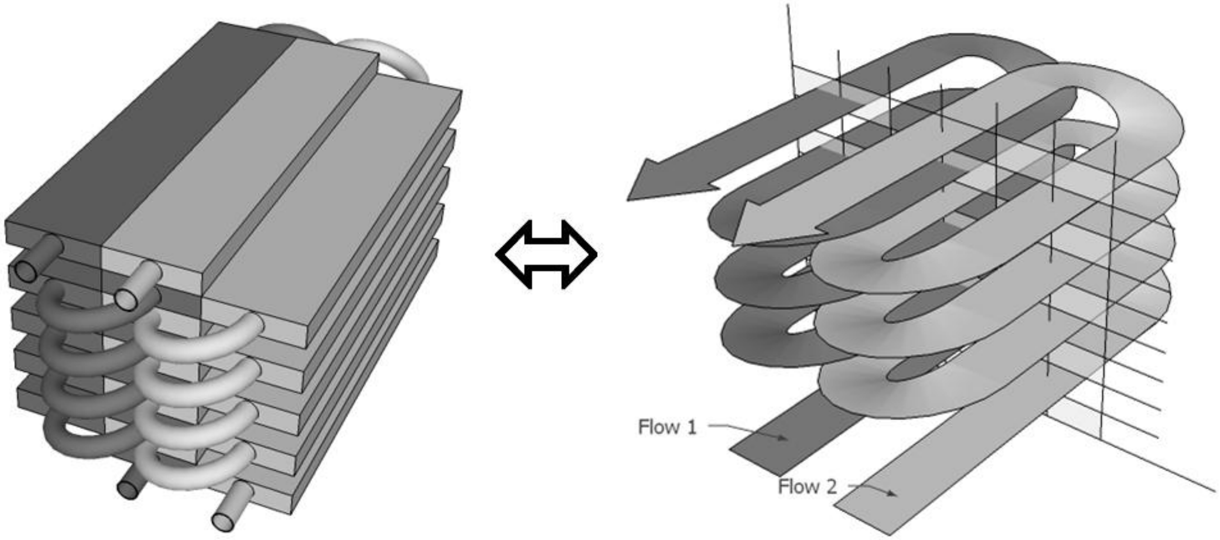
MiTi’s Recuperator Concept

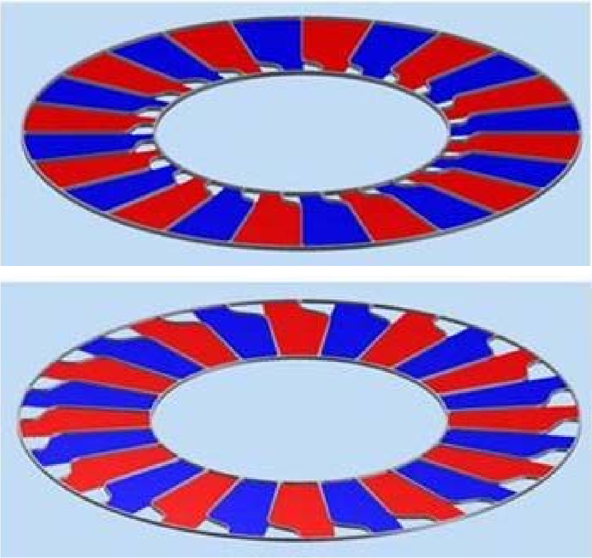
- Overlapping quasi-helical flow paths
  - *Patent Pending: U.S. Provisional Patent Application US62/040,559*

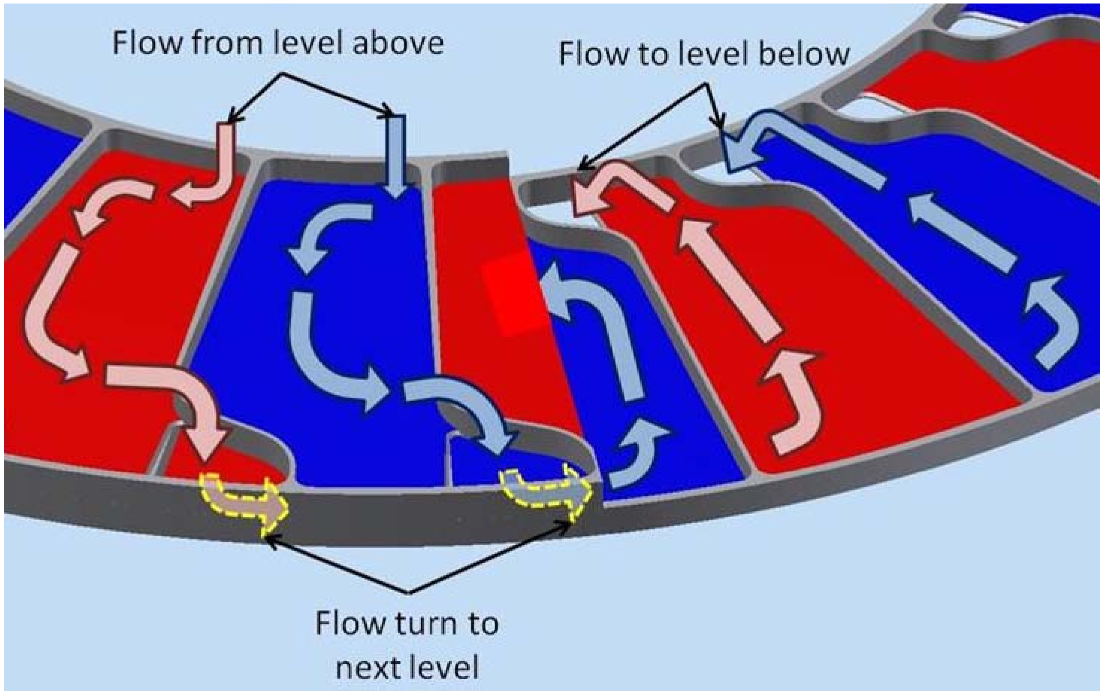




Patent Pending Design

- Passages formed by stack of trays with wedge-shaped passage segments
  - Two types of trays: alternating openings at inner/outer radius
  - Openings turn the flow to diagonally adjacent wedge ⇔ chessboard pattern





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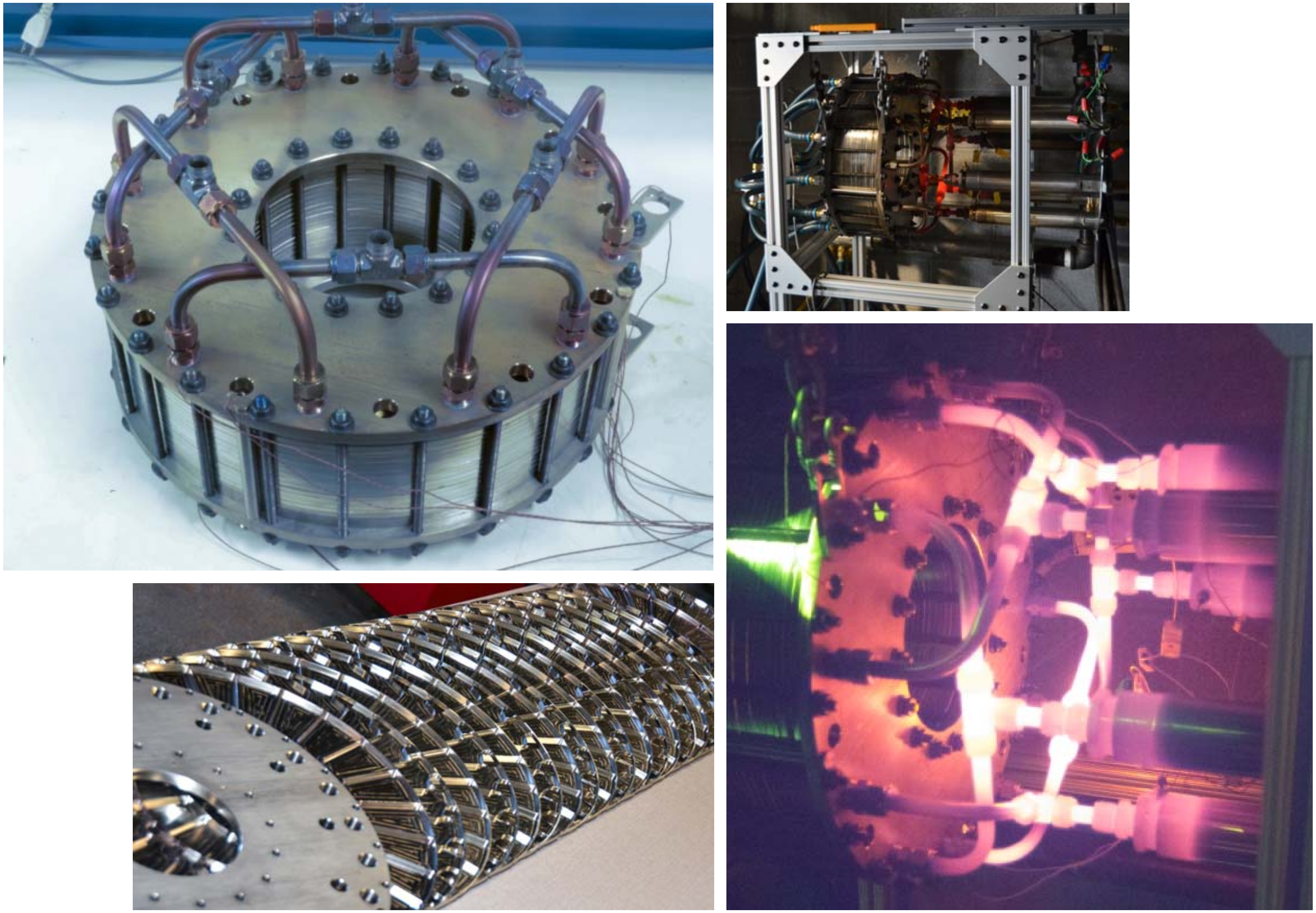
Recuperator Prototype



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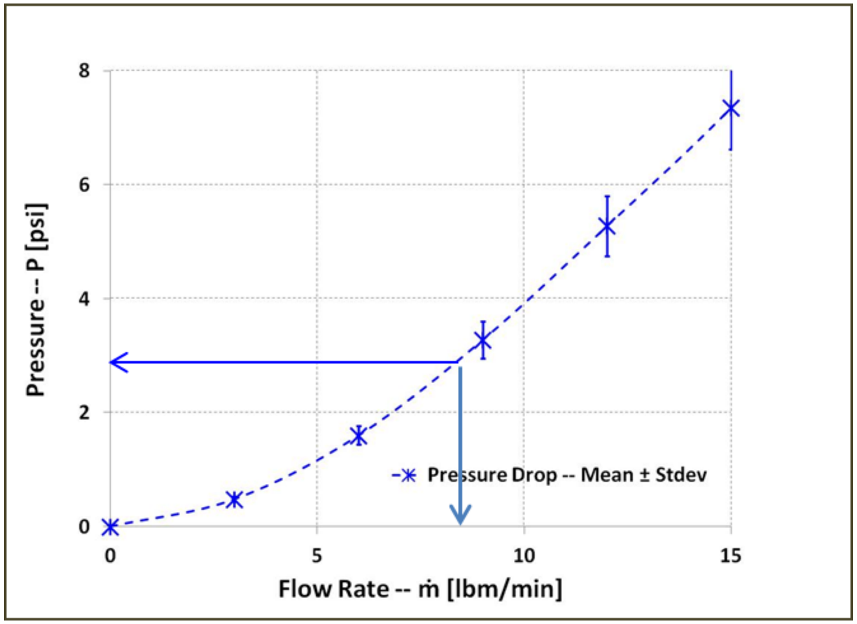
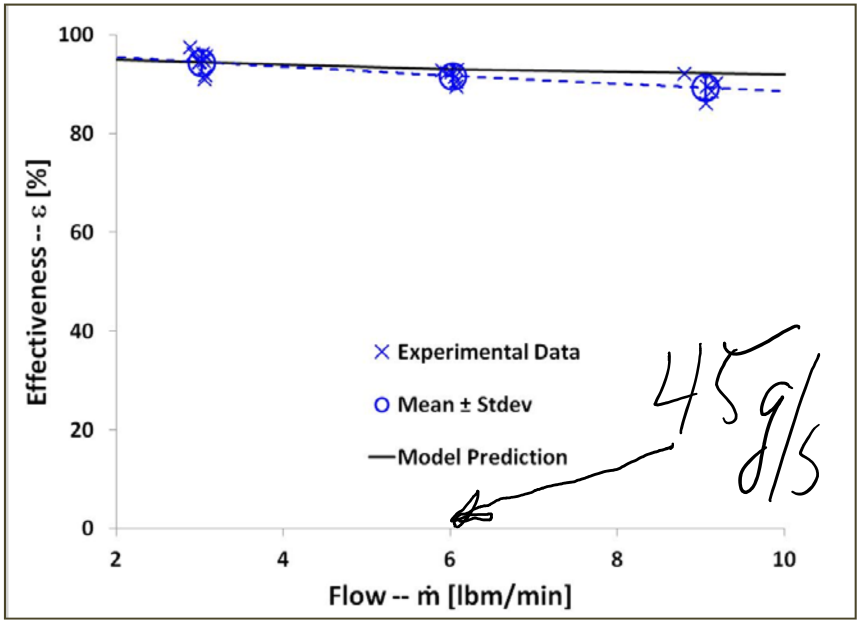
Experimental Performance

Pressure Drop (ΔP vs. ṁ)

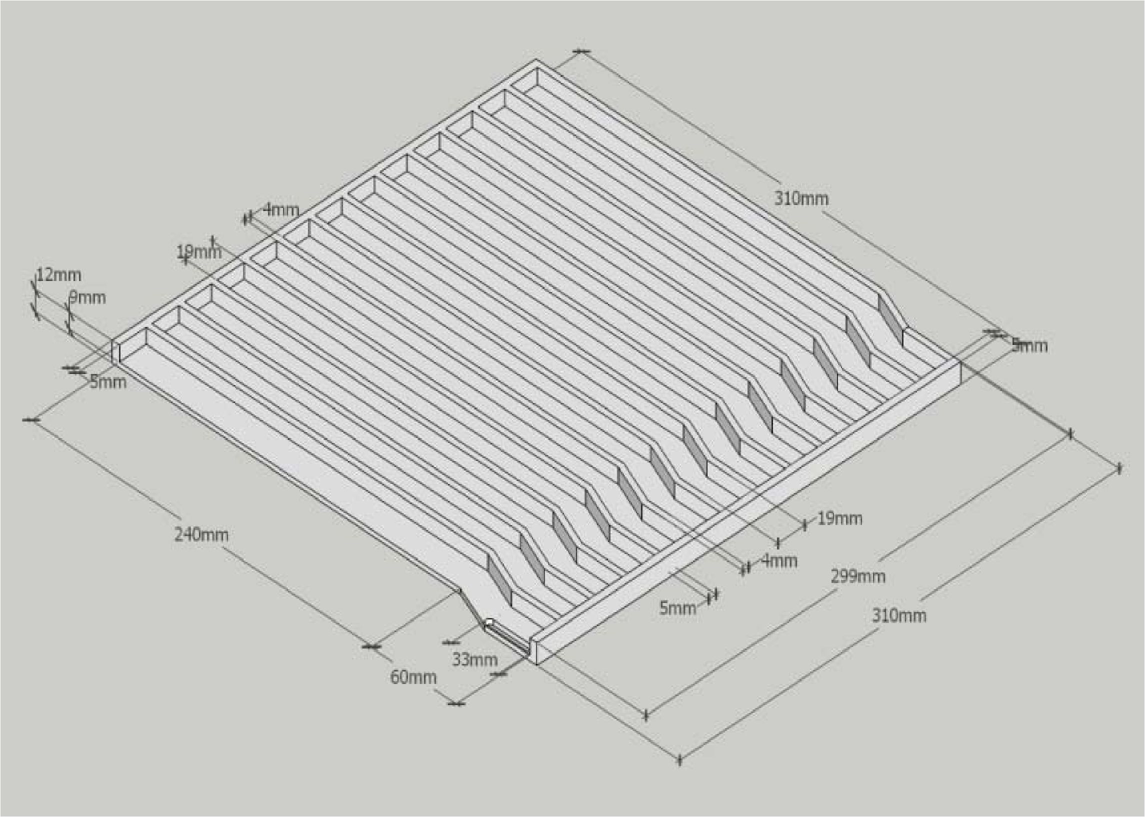


Effectiveness (ε vs. ṁ)



45 g/s

$$\varepsilon_R = \frac{(\dot{m}\,c_p)_{\mathrm{h}}(T_{\mathrm{h,in}} - T_{\mathrm{h,out}})}{(\dot{m}\,c_p)_{\mathrm{min}}(T_{\mathrm{h,in}} - T_{\mathrm{c,in}})} = \frac{(\dot{m}\,c_p)_{\mathrm{c}}(T_{\mathrm{c,out}} - T_{\mathrm{c,in}})}{(\dot{m}\,c_p)_{\mathrm{min}}(T_{\mathrm{h,in}} - T_{\mathrm{c,in}})}$$



Heat Transfer Analysis and Heat Exchanger Sizing

HEAT EXCHANGER DESIGN

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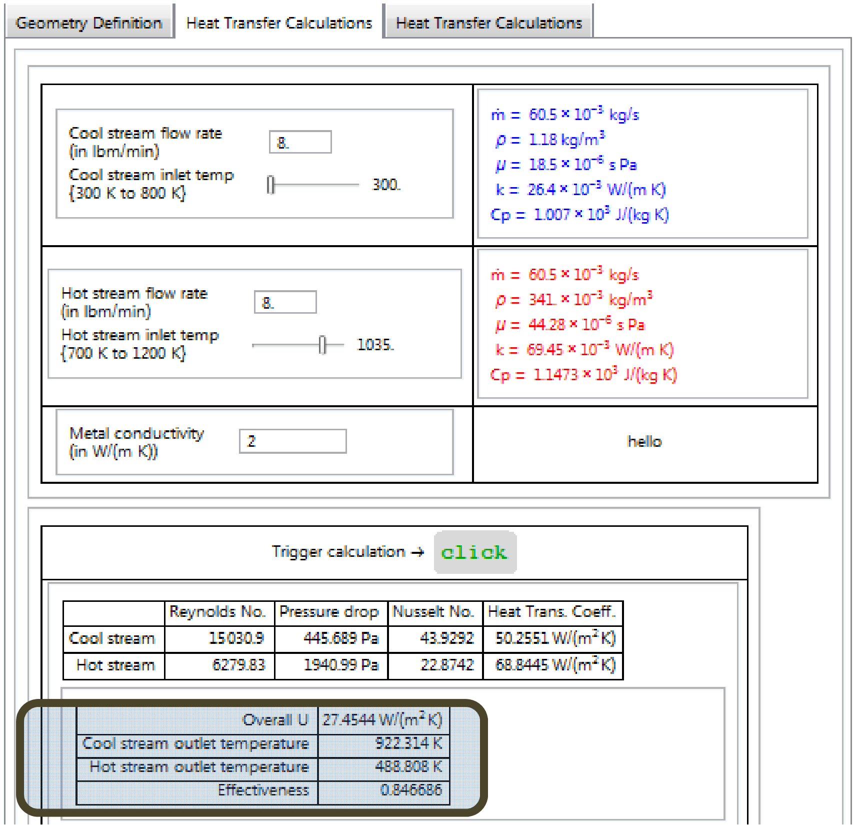
50 kWe POC Heat Exchanger Design

- MiTi’s Modeling/Design Tool
  - Written in *Mathematica*
  - Solves fundamental heat transfer governing equations
- First Iteration Sizing Results:
  - Preheated air temperature
    $Tair_{out}$ = 1200°F
  - Pressure drop ΔP = 0.33 psi
  - Effectiveness = 85%



Cool stream flow rate (in lbm/min) 8.

Cool stream inlet temp {300 K to 800 K} 300.

$\dot{m}$ = 60.5 × 10^{-3} kg/s
ρ = 1.18 kg/m^3
μ = 18.5 × 10^{-6} s Pa
k = 26.4 × 10^{-3} W/(m K)
Cp = 1.007 × 10^3 J/(kg K)

Hot stream flow rate (in lbm/min) 8.

Hot stream inlet temp {700 K to 1200 K} 1035.

$\dot{m}$ = 60.5 × 10^{-3} kg/s
ρ = 341. × 10^{-3} kg/m^3
μ = 44.28 × 10^{-6} s Pa
k = 69.45 × 10^{-3} W/(m K)
Cp = 1.1473 × 10^3 J/(kg K)

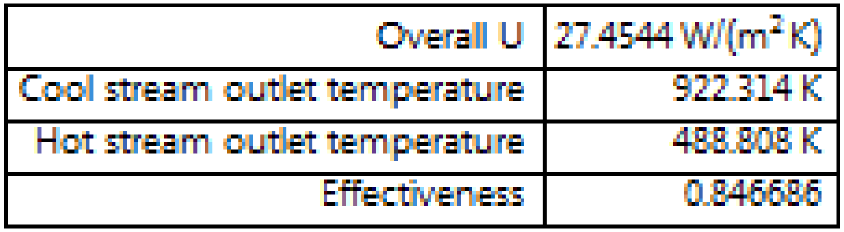
Metal conductivity (in W/(m K)) 2

hello

Trigger calculation →

	Reynolds No.	Pressure drop	Nusselt No.	Heat Trans. Coeff.
Cool stream	15030.9	445.689 Pa	43.9292	50.2551 W/(m^2 K)
Hot stream	6279.83	1940.99 Pa	22.8742	68.8445 W/(m^2 K)

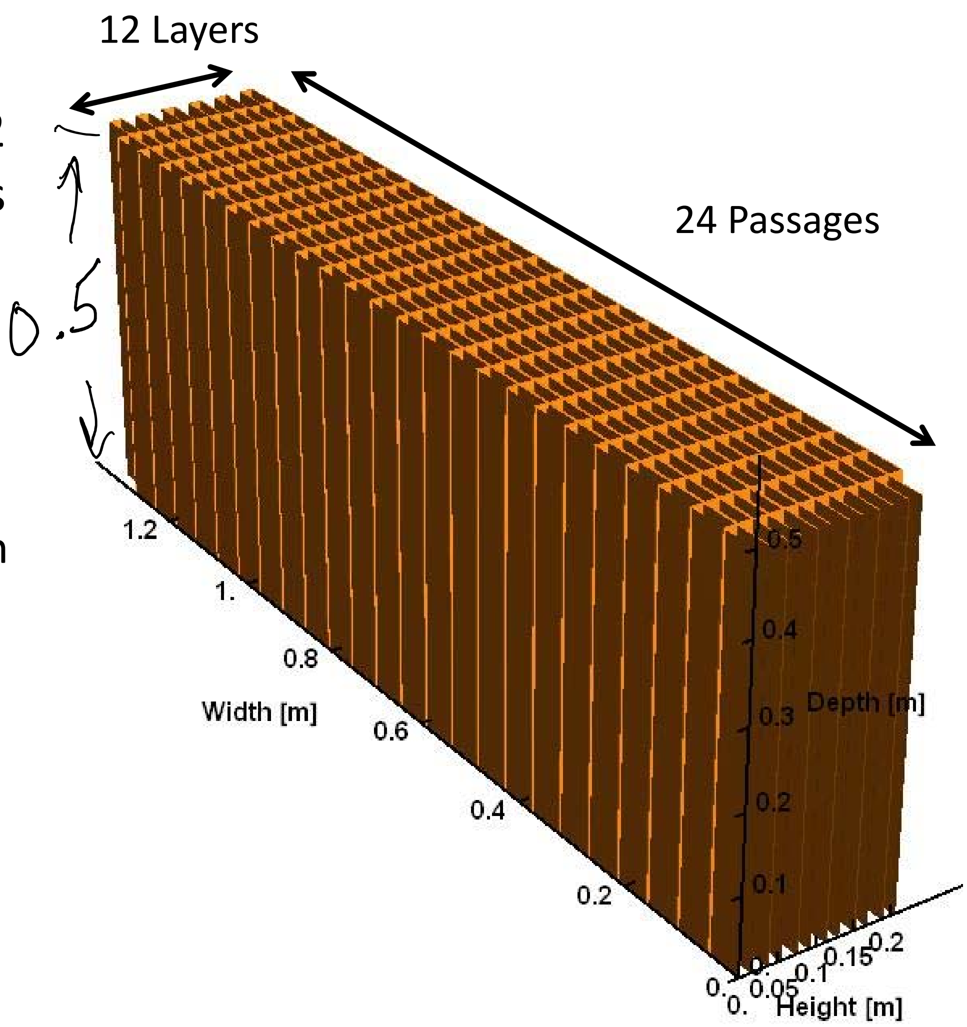
Overall U	27.4544 W/(m^2 K)
Cool stream outlet temperature	922.314 K
Hot stream outlet temperature	488.808 K
Effectiveness	0.846686



Overall U	27.4544 W/(m^2 K)
Cool stream outlet temperature	922.314 K
Hot stream outlet temperature	488.808 K
Effectiveness	0.846686

A Conceptual Heat Exchanger Layout

- Subdivide hot and cold flow into 12 Passages Each (Total of 24 Passages Wide),
- Make Stack of 12 Layers Deep
- Geometry of heat exchange elements:
  - Total length single flow path: 6.0 m
  - Wall thickness: 0.004 m
  - Passage width: 0.05 m
  - Passage height: 0.015 m


12 Layers

24 Passages

0.5

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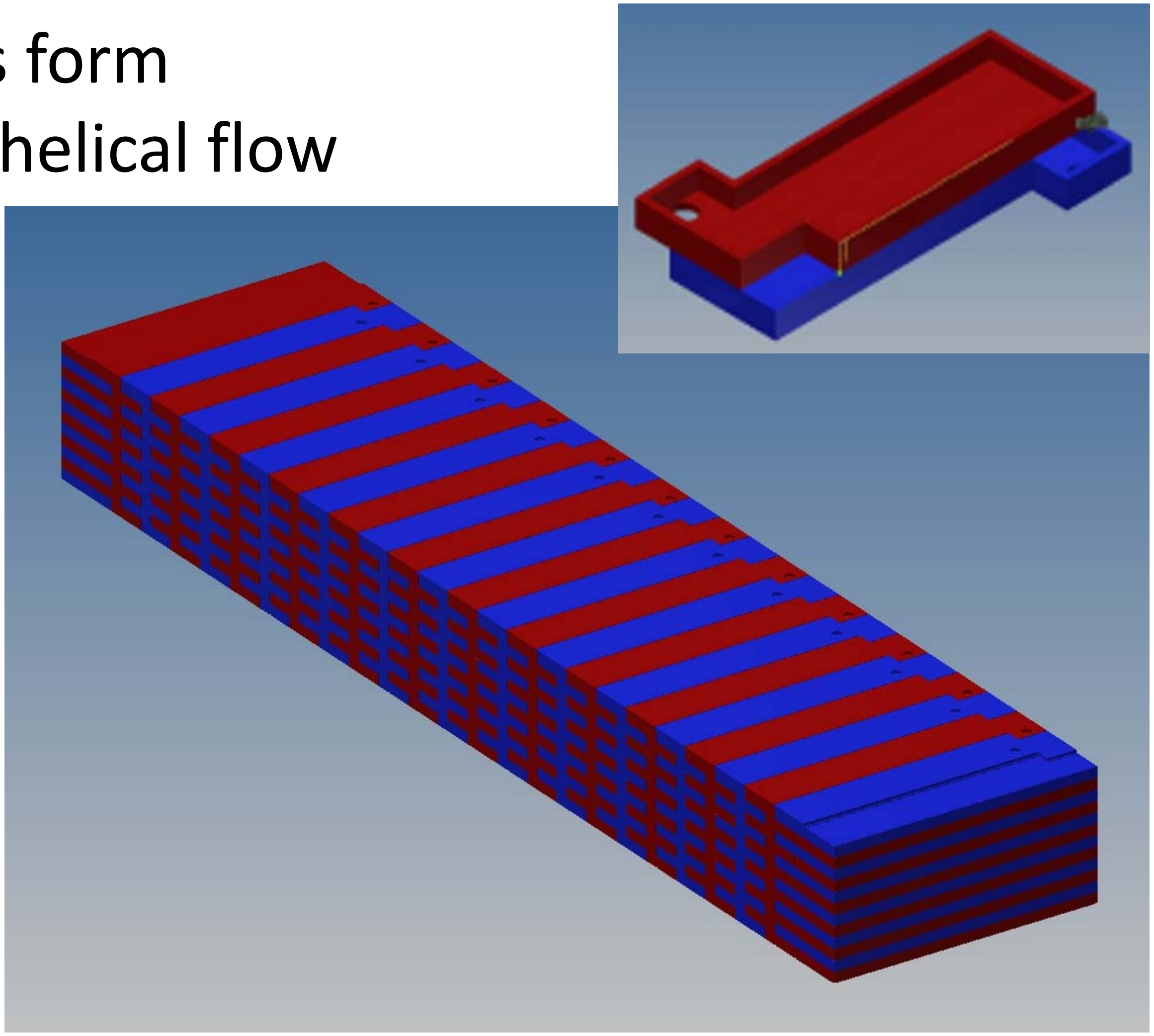
Heat Exchanger Conceptual Layout

- Modular segments form overlapping quasi-helical flow paths.
- Design allows to add or remove segments according to flow, pressure drop, or heat exchange rate requirements.

- ***Patent Pending: U.S. Provisional Patent Application US62/040,559***



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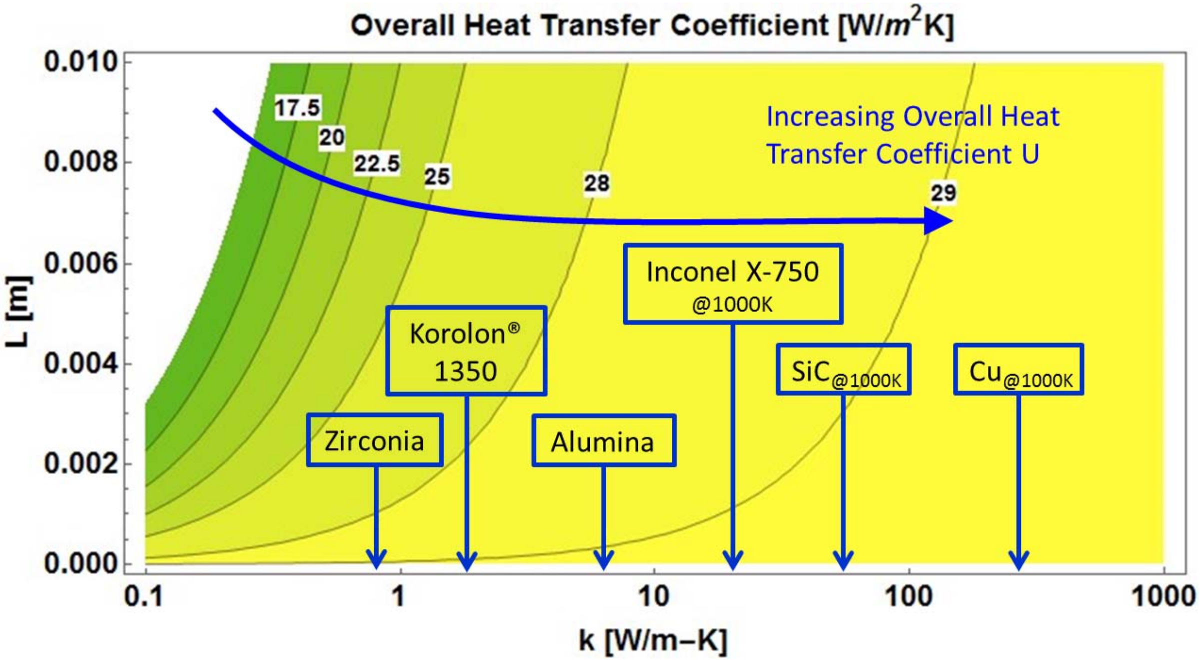
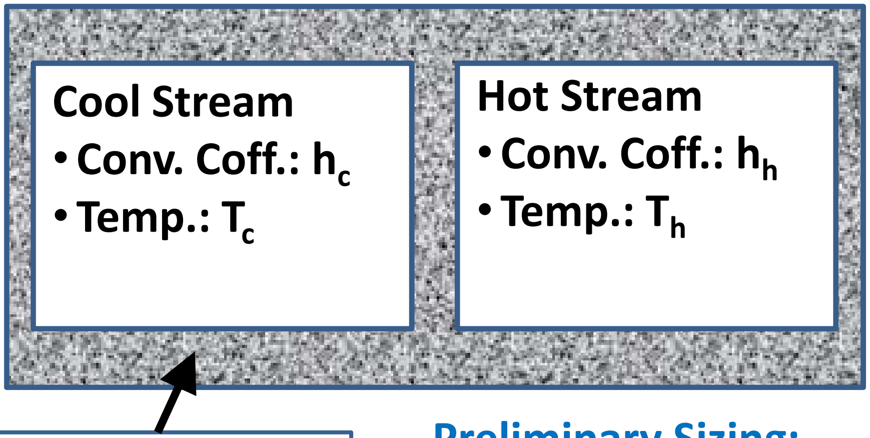


Thermal Criterion for Material Selection

MATERIAL SELECTION

Parametric Study for Design Optimization

Basic Heat Transfer Element



Cool Stream
- **Conv. Coff.: h_c**
- **Temp.: T_c**

Hot Stream
- **Conv. Coff.: h_h**
- **Temp.: T_h**

Walls:
- **Thickness: L**
- **Conductivity: k**

Preliminary Sizing:

	Heat Trans. Coeff.
Cool stream	50.2551 W/(m^2 K)
Hot stream	68.8445 W/(m^2 K)

Heat transfer between flows:

$$q = U\ A\ \Delta\mathrm{T} = \frac{A\ (T_h - T_c)}{\frac{1}{h_h} + \frac{L}{k} + \frac{1}{h_c}}$$

Overall Heat Transfer Coeff.:

$$\Rightarrow U = \frac{1}{\frac{1}{h_h} + \frac{L}{k} + \frac{1}{h_c}}$$

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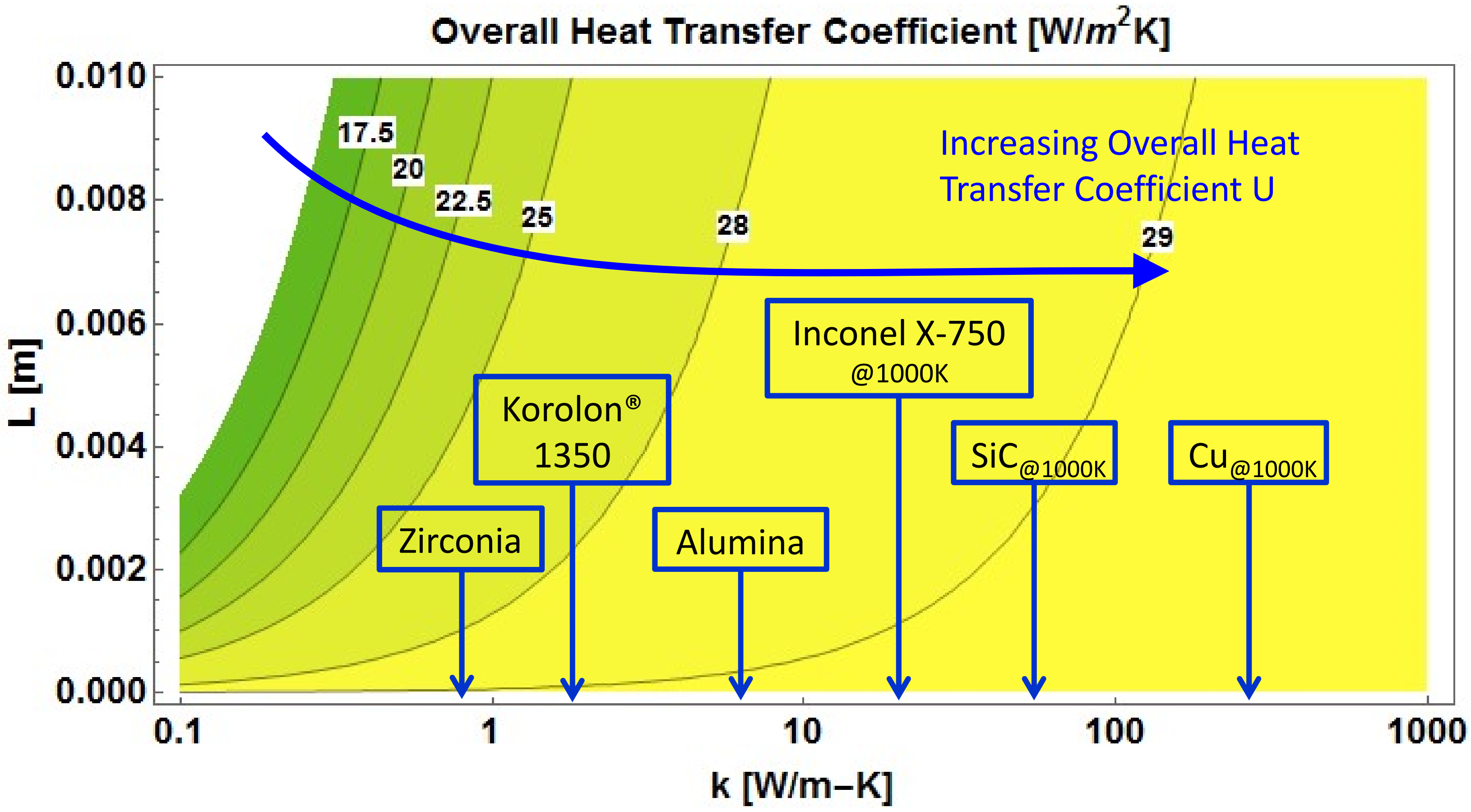
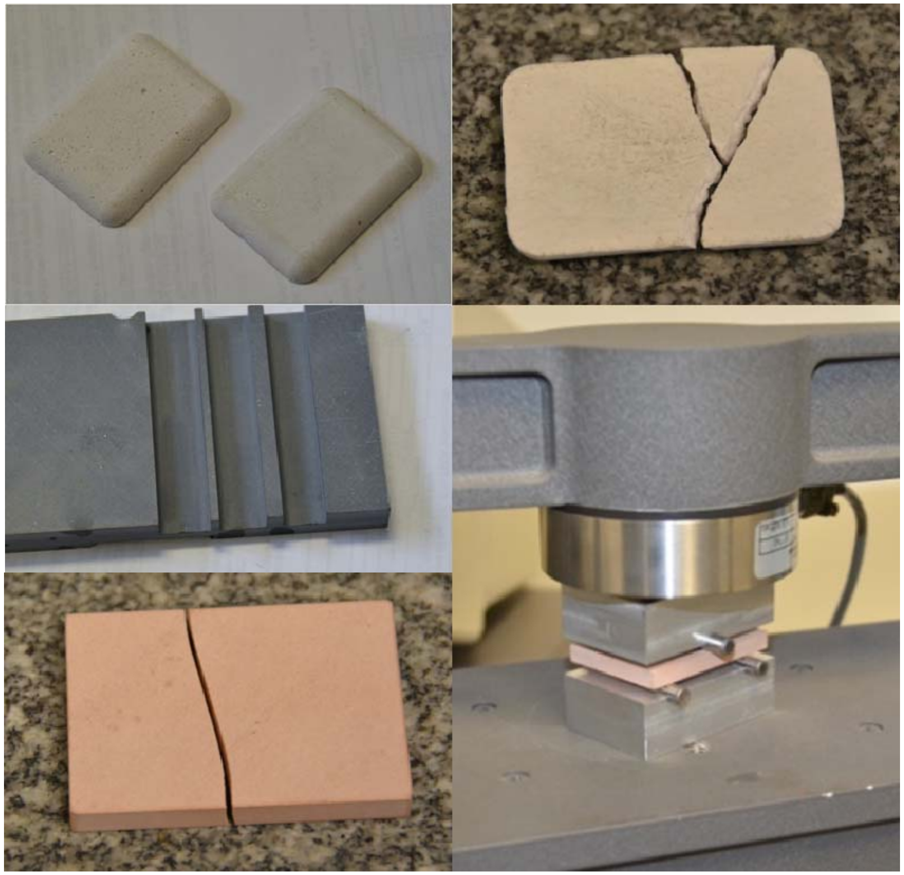
Effect of Wall Thermal Conductivity



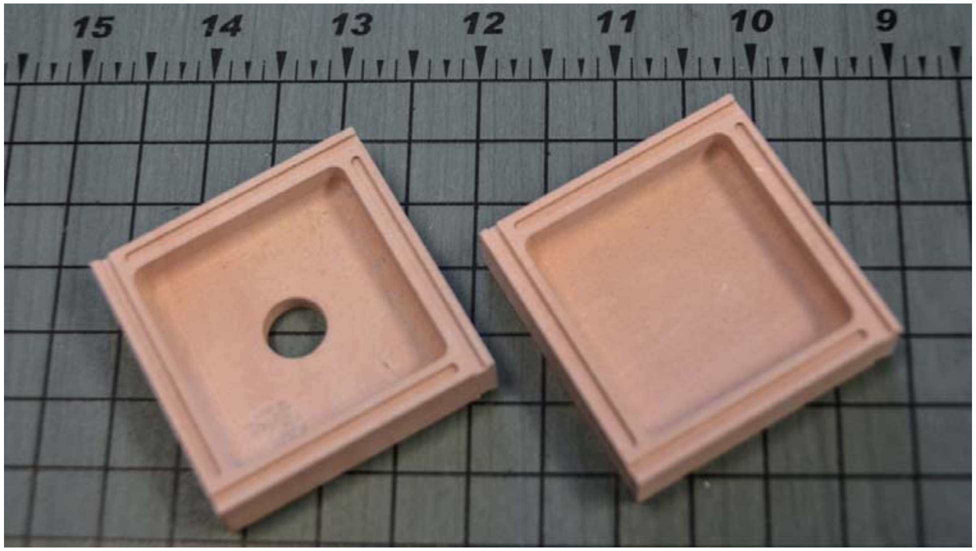
At SOFC operating conditions and practical wall thickness (L < 0.005 m), the walls behave as thermally thin, and the overall heat transfer coefficient is nearly *independent of wall conductivity,* therefore, the choice of material is irrelevant.

Choice Based on Ease of Fabrication

- Explored several commercially-available materials
  - Castable/Moldable
  - Green-State Machinable
  - Fired-State Machinable
- Fabricated and tested samples



Component Fabrication Testing



- Material Selected: Alumina-Silicate Green-State Machinable
  - Mechanical properties achieved after firing
    - Thermal Cond.: k = 1.45 W/m-K
    - Density: ρ = 2350 kg/m3
    - Flexural stress: s = 69 Mpa
    - Thermal expansion: ε = 4.9 $10^{-6}/^{o}C$
    - Geometric tolerance: 1%

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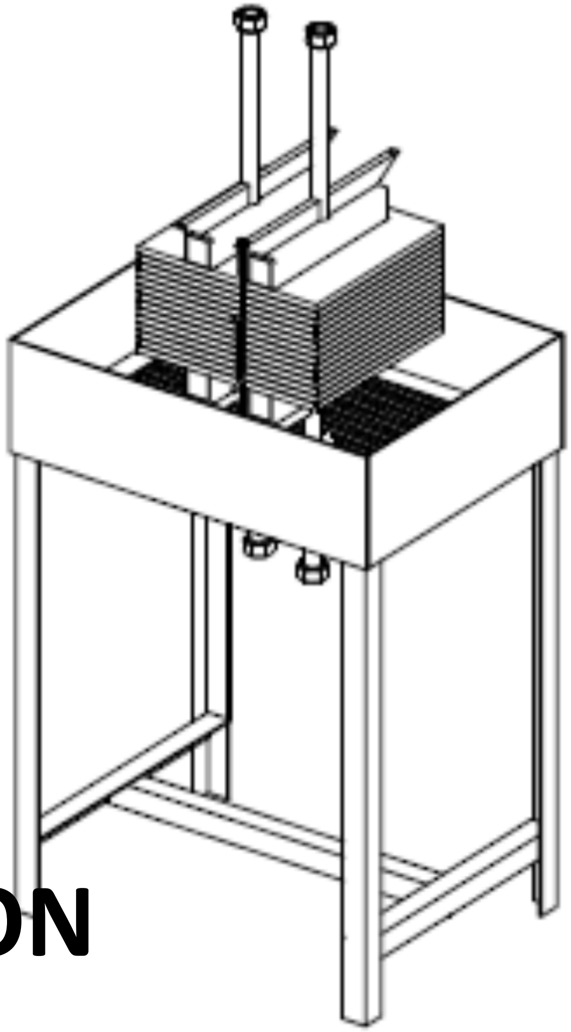
Sizing, Design, and Fabrication

PROTOTYPE INTEGRATION



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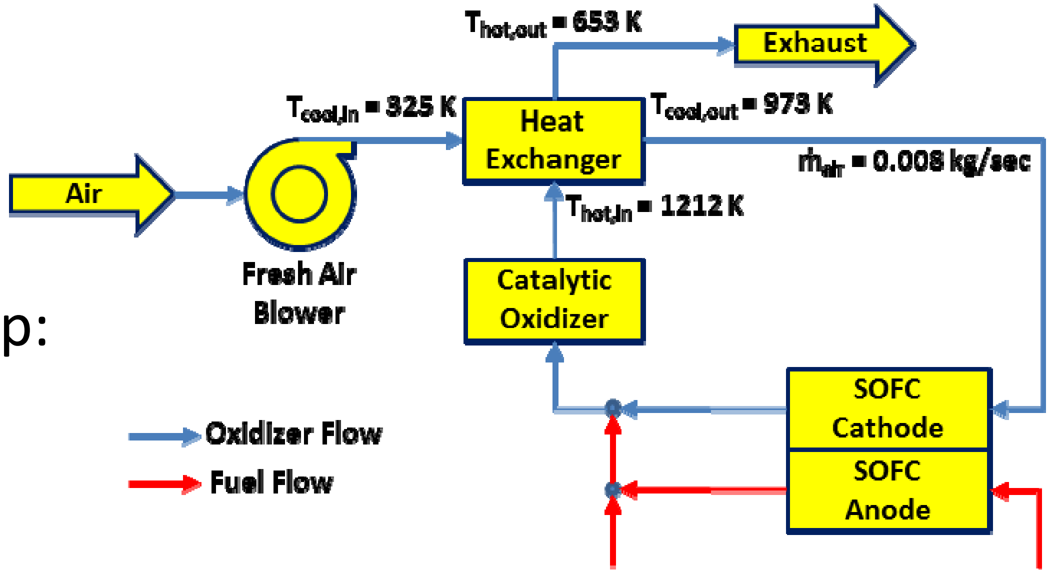
5 kW Prototype Operating Conditions

- $\dot{m}$ = 8 g/sec (1 lbm/min)
- Required Heat Transfer:
  - $Q = \dot{m}\, c_p\, (Tair_{out} - Tair_{in})$ □ 5.2 kW
- Total Allowable Pressure Drop:
  - $\Delta P_{tot} < 0.5$ psi



$T_{hot,out} = 653$ K

Exhaust

$T_{cool,in} = 325$ K

Heat Exchanger

$T_{cool,out} = 973$ K

$\dot{m}_{air} = 0.008$ kg/sec

Air

$T_{hot,in} = 1212$ K

Fresh Air Blower

Catalytic Oxidizer

SOFC Cathode

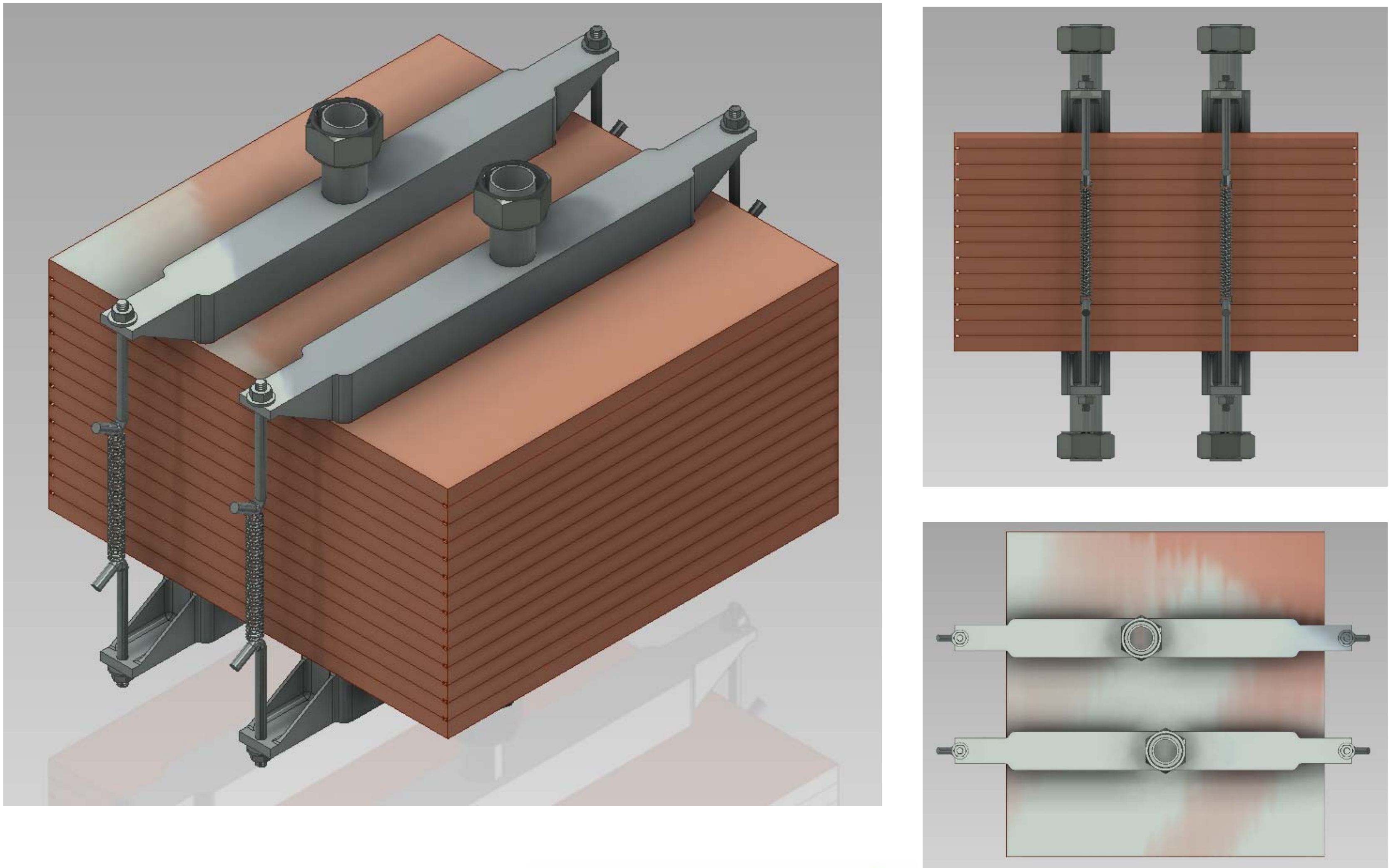
SOFC Anode

Oxidizer Flow

Fuel Flow

- **With all temperatures pre-determined, the effectiveness is constrained to be ε = 73%**

MiTi® Cathode Air Preheater



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Repeating Unit

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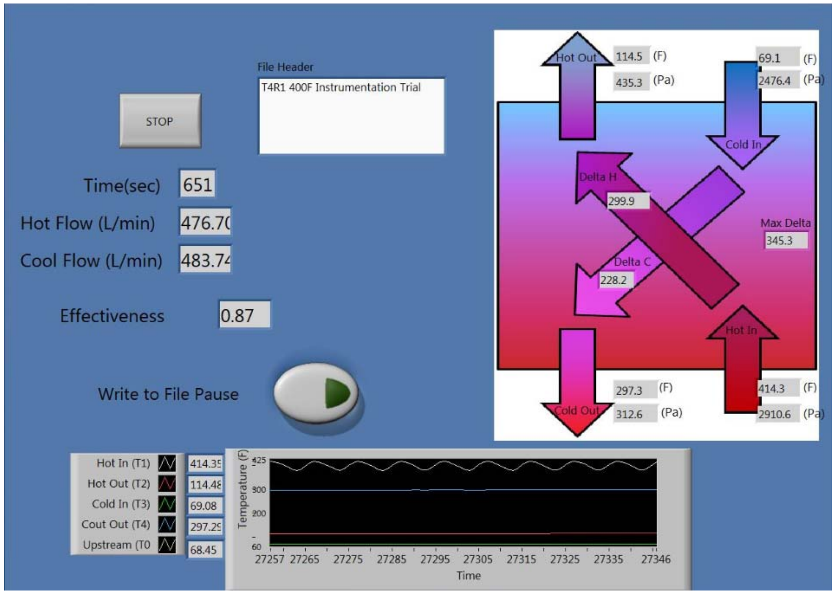
Ceramic Heat Exchanger



File Header: T4R1 400F Instrumentation Trial

Time(sec) 651

Hot Flow (L/min) 476.7

Cool Flow (L/min) 483.74

Effectiveness 0.87

Hot Out 114.5 (F) 435.3 (Pa)

Cold In 69.1 (F) 2476.4 (Pa)

Delta H 299.9

Max Delta 345.3

Delta C 228.2

Cold Out 297.3 (F) 312.6 (Pa)

Hot In 414.3 (F) 2910.6 (Pa)

Hot In (T1)	414.35
Hot Out (T2)	114.48
Cold In (T3)	69.08
Cout Out (T4)	297.29
Upstream (T0	68.45

Effectiveness and Pressure Drop Tests

PROTOTYPE PERFORMANCE TESTING

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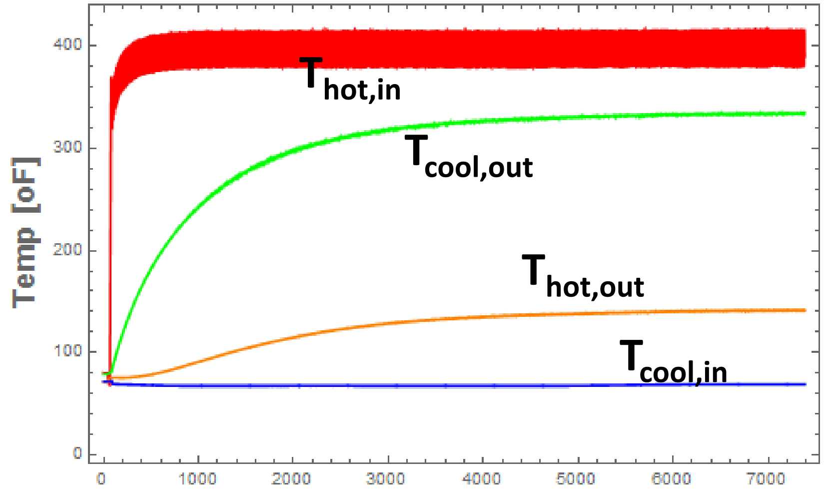
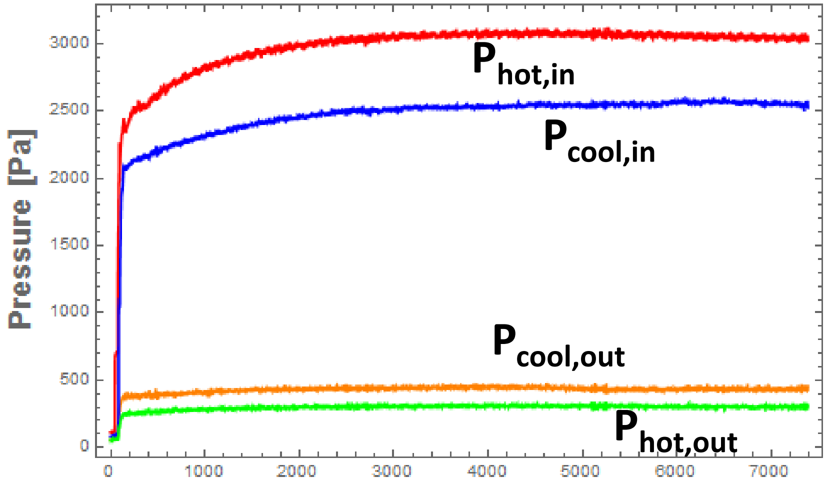
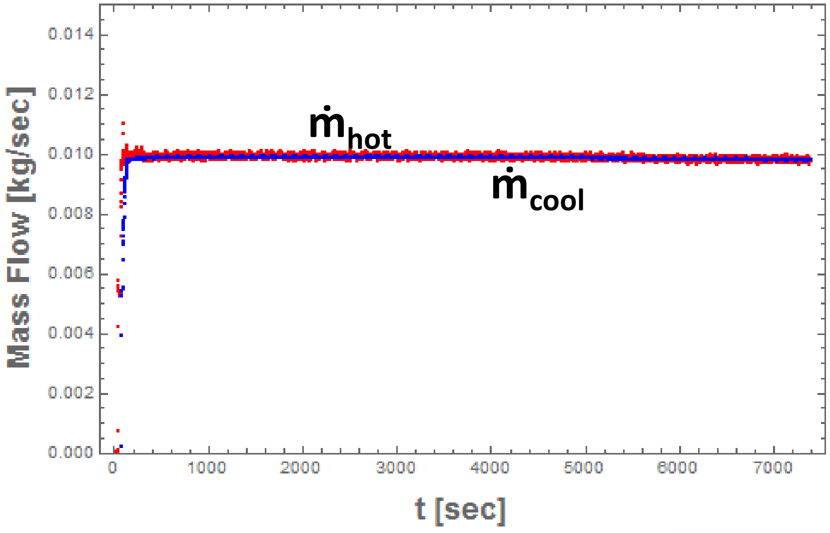
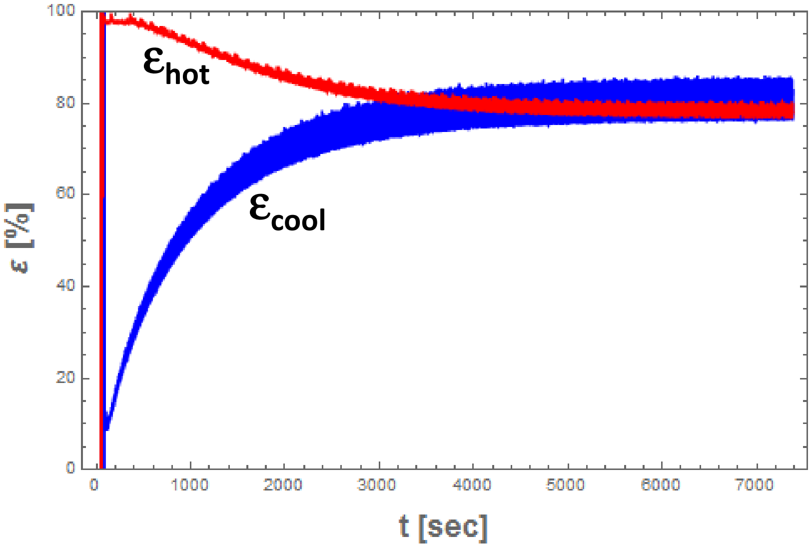
Testing: Typical Raw Data

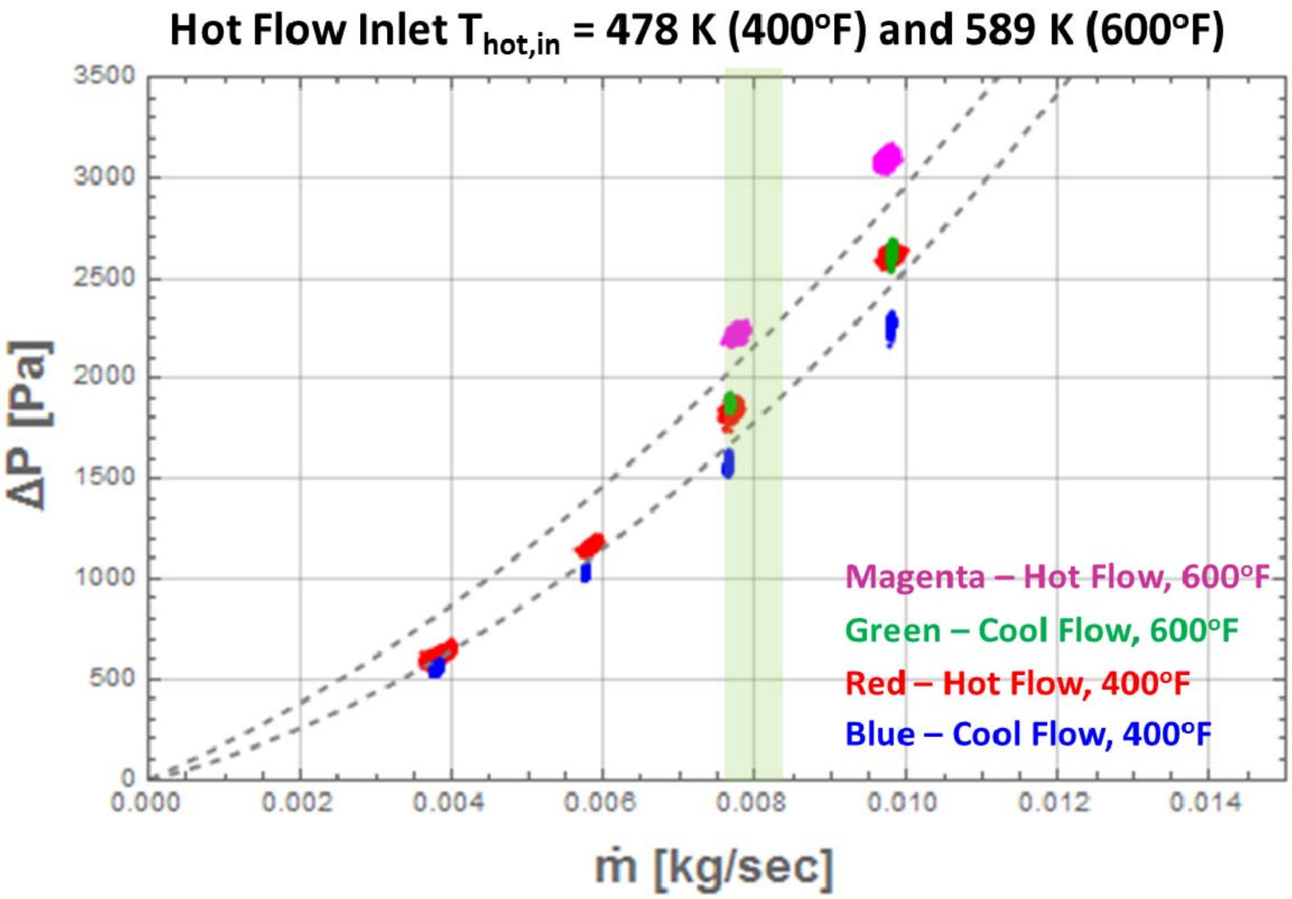

Thermocouple Data Vs. Time


Pressure Data Vs. Time


Mass Flow Rate Vs. Time


Effectiveness Vs. Time

Pressure Drop vs. Mass Flow



Total ΔP at operating condition around 3440 Pa (0.5 psi)

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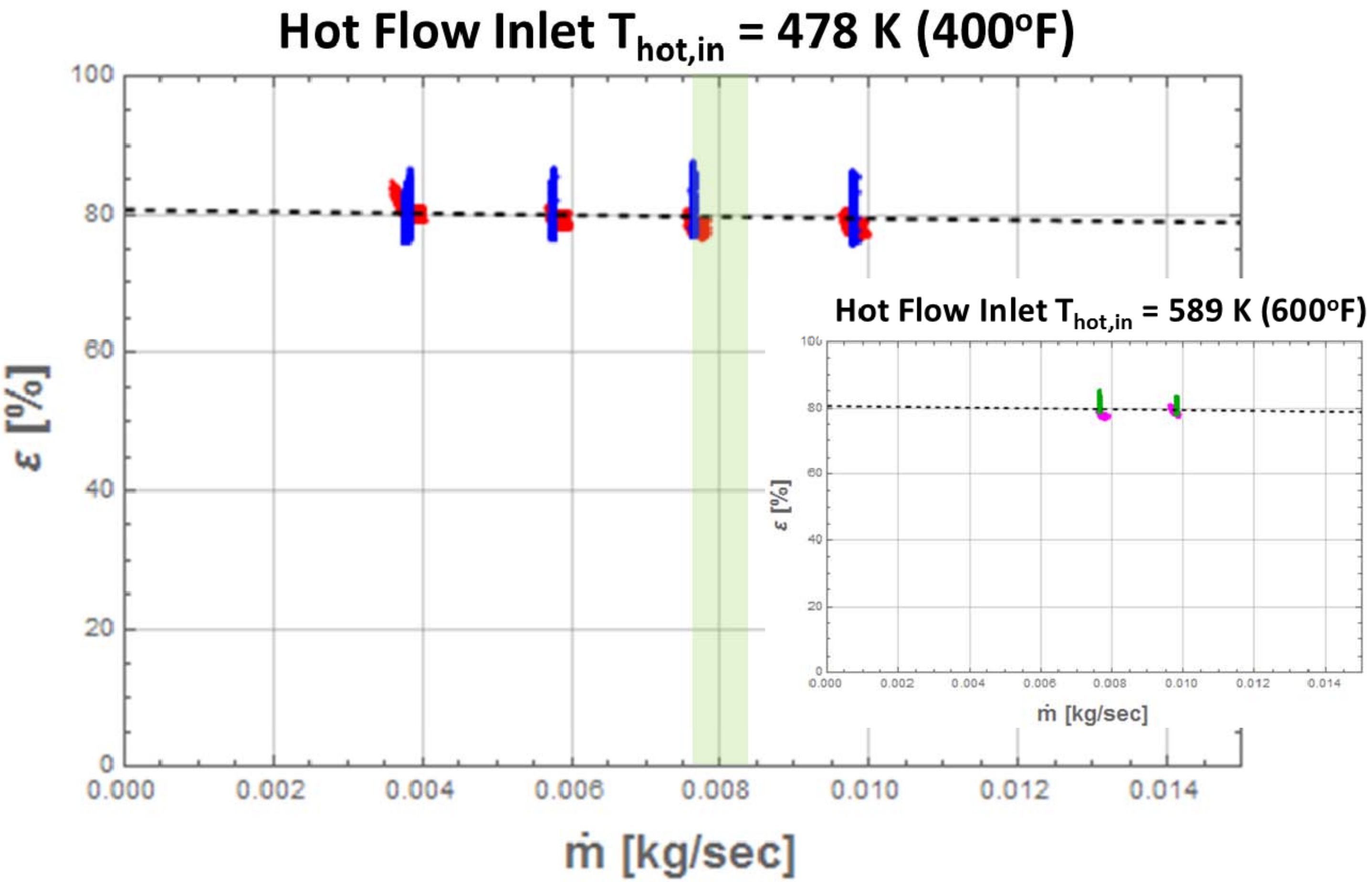
Effectiveness vs. Mass Flow



ε 80%, independent of operating condition!

Closing Remarks

- Successfully Designed and Prototyped Ceramic Heat Exchanger for Fuel Cell Application
  - Modular Design Allows Great Flexibility for Application-Specific Performance Matching
- Immediate Next Steps:
  - Conclude Preliminary Parametric Testing
  - Test in Fuel Cell Environment
- Future Steps
  - Improve Manufacturability
  - Integrate to Actual Fuel Cell

Acknowledgements

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- We also acknowledge the technical advice provided by Dr. Hossein Ghezel-Ayagh and his team at Fuel Cell Energy, Inc.

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Questions and Discussion

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