Ceramic Matrix Composites for H_2 Combustion

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Abstract

Gas turbine engines for power generation are under transition to hydrogen-based combustion systems to achieve net-zero or net-negative carbon emissions. A transition to hydrogen-based fuel combustion must also coincide with other technological advancements in gas turbines. The significantly higher energy content and lack of greenhouse gas emissions characteristic of hydrogen fuel make it an attractive alternative to traditional fossil fuels. However, the increased flame temperature and chemical corrosivity introduced by the water vapor generation of hydrogen combustion pose a risk to the materials used in current gas turbine engines. Furthermore, the small molecule size of hydrogen subjects existing metallic materials to hydrogen embrittlement and increase the risk of dangerous fuel leaks. In this project, we explore the viability of ceramic matrix composites (CMCs) as an alternative to traditional metallic superalloys in hydrogen combustion environments. Yttria-Stabilized Zirconia (YSZ) ceramic oxide fibers are first treated with a YSZ-based rigidizing process and then used as reinforcements for various polymer ceramic precursors, and the composites are subjected to multiple polymer infiltration and pyrolysis (PIP) cycles. A hydrogen torch testing rig is designed and used to impart a high heat flux hydrogen flame on the CMCs, and the insulation performance is analyzed. The CMCs are also used to line the inside of a hydrogen combustion chamber to evaluate their performance in a gas turbine engine environment. The CMCs are characterized pre- and post- hydrogen combustion exposure, and the preliminary results show that the CMC material exhibits robust performance and desirable damage response behavior. Numerical models are employed to validate experimental data and further understand the behavior and properties of the CMCs.

Introduction

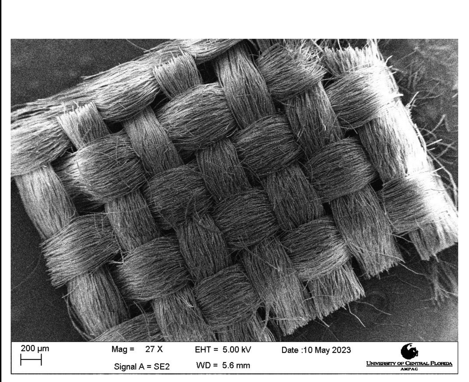
Elevated combustion temperatures and chemical corrosion caused by water vapor byproduct generation are among many challenges posed by the switch from fossil fuels to hydrogen in gas turbine engines. Specifically, the adiabatic flame temperature of hydrogen is approximately 250ºC higher than that of natural gas. Today, nickel- and cobalt-based alloys are used at temperatures up to around 1,100ºC, close to their melting temperature (~1,200ºC). As such, the eventual transition to hydrogen fuel relies heavily on the development of materials that can withstand increased combustion temperatures. Furthermore, the combustion of hydrogen with oxygen produces high amounts of water vapor, which can create an oxidizing and chemically corrosive environment detrimental to currently used metallic components. This project proposes the use of YSZ/SiCN CMCs produced via the PIP method in components for H_2 combustion environments due to their outstanding thermal and oxidation resistance, high customizability via additives and coatings, relative ease and low cost of manufacturing.

Material Selection

Ceramic Yields of Various Ceramic Precursors

Ceramic Precursor	Resulting Ceramic	Ceramic Yield (Literature)	Ceramic Yield of Precursor (Experimental)
SPR-688	SiOC	65-85%	79.08%
SMP-10	SiC	72-78%	73.02%
Durazane 1800	**SiCN**	**80-90%**	**82.45%**

- When selecting ceramic precursor, factors such as ceramic yield, workability, and thermal performance were considered.
- Durazane 1800 (Merck Group) was chosen as the precursor for its superior ceramic yield and lower viscosity (better infiltration of porous preform) while providing similar thermal stability.



Yttria Stablized Zirconia (YSZ) Ceramic Fiber (Zircar Zirconia, Inc.)	
Melting Point, ºC	2590
Porosity, %	87
Excellent stability in corrosive and oxidizing atmospheres	
High porosity allows for easy saturation with rigidizer and ceramic precursor	

Nominal Chemical Composition	
ZrO_2	90%
Y_2O_3	10%

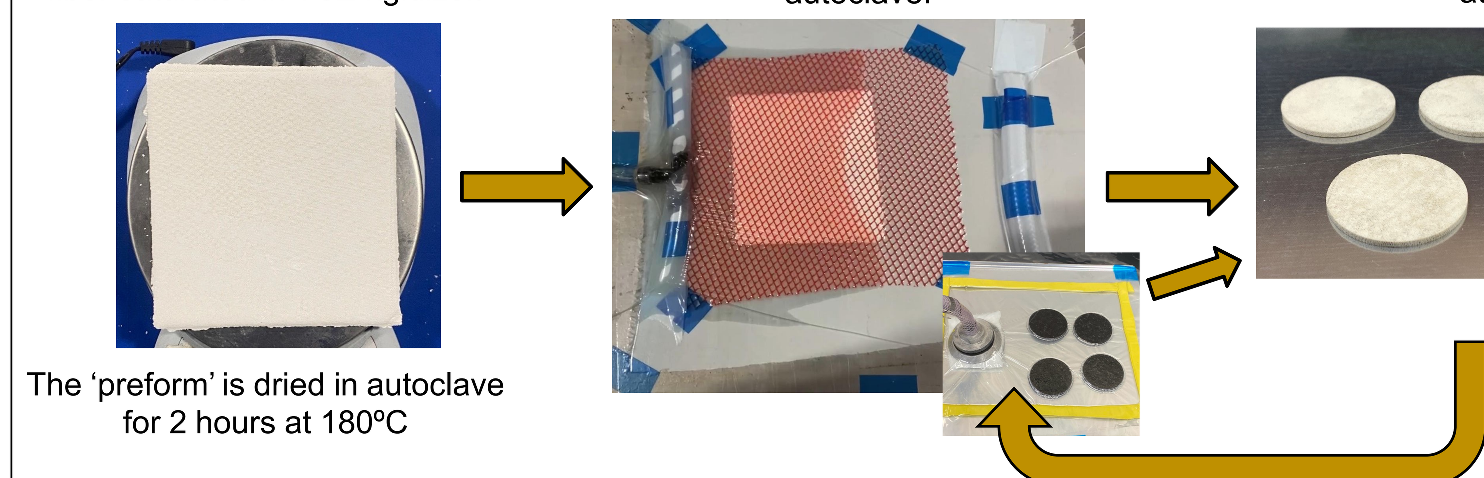
- Zirconium Oxide Rigidizer (Zircar Zirconia, Inc.) contains sub-micron particles of YSZ in a zirconium acetate aqueous solution.
- Used in fabrication to provide dimensional stability and mechanical strength to laminates while increasing YSZ content.

CMC Fabrication

Fabrication process begins by creating a YSZ 'preform' consisting of 8 layers of YSZ fiber saturated in YSZ rigidizer.

The preform is saturated with ceramic precursor through vacuum infusion and cured in autoclave.

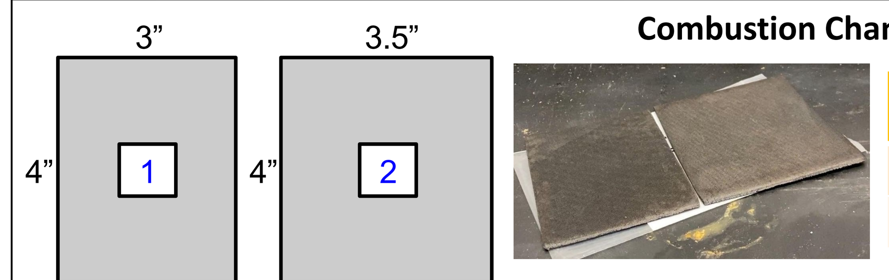
'Green body' is waterjet cut to desired shape and pyrolyzed at 950ºC for 2 hours in N_2 atmosphere.



The 'preform' is dried in autoclave for 2 hours at 180ºC

Resulting CMC is reinfiltrated with ceramic precursor and pyrolyzed once more.

Combustion Chamber Test Panels

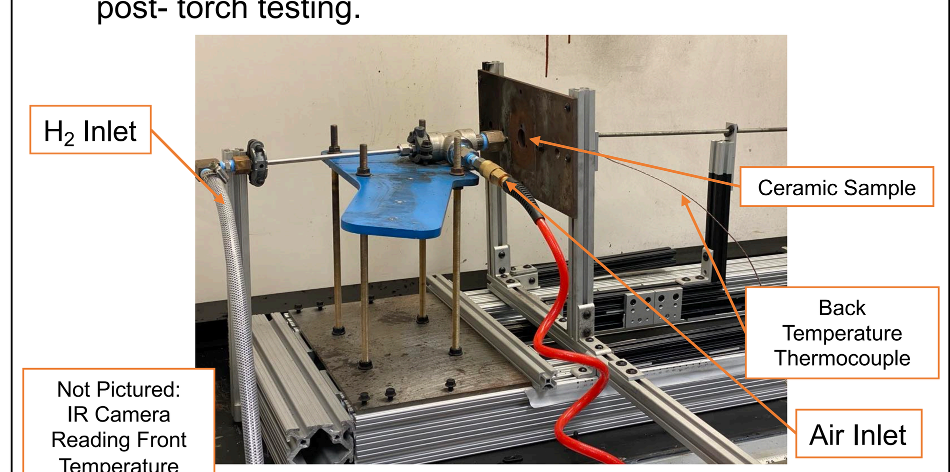


Panel	Ceramic Yield (1st cycle)	Ceramic Yield (2nd cycle)	Percent by mass of YSZ	Percent by mass of SiCN
#1	70.55%	78.57%	82.25%	17.75%
#2	60.01%	80.87%	82.73%	17.27%

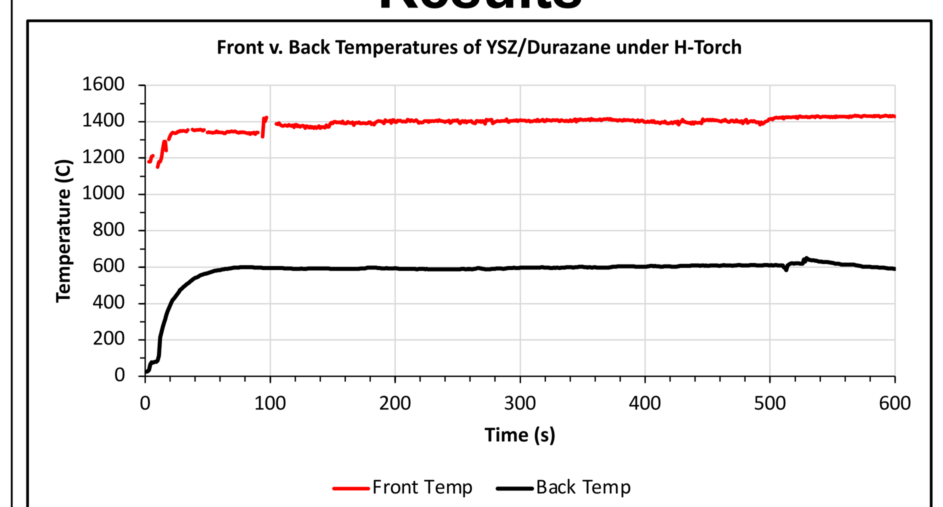
H_2 Torch Test

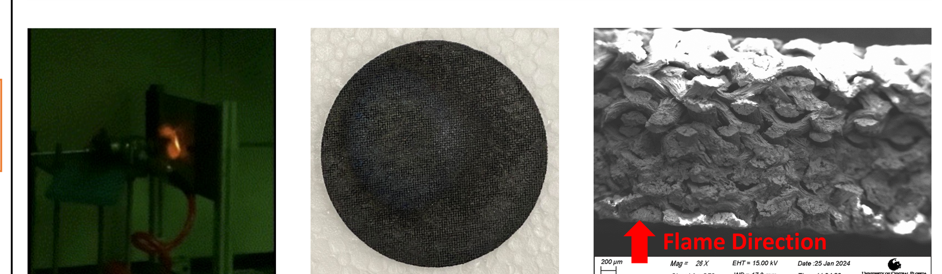
Experimental Setup

- Exploring acute damage of hydrogen flame and CMC response.
- Heat flux of 183 W/cm² imparted at 20 mm from torch tip for 10-minute test duration.
- Samples were characterized via SEM and EDS pre- and post- torch testing.



Results

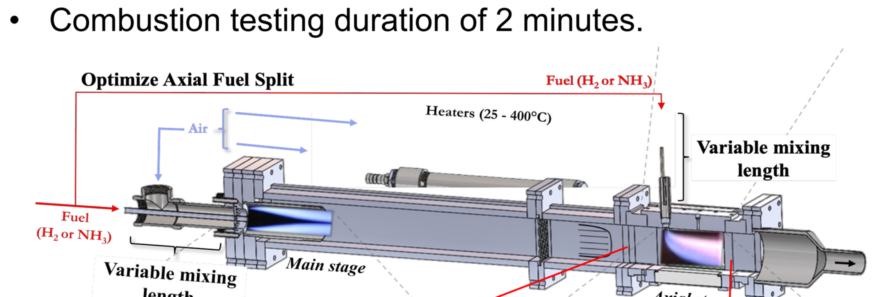


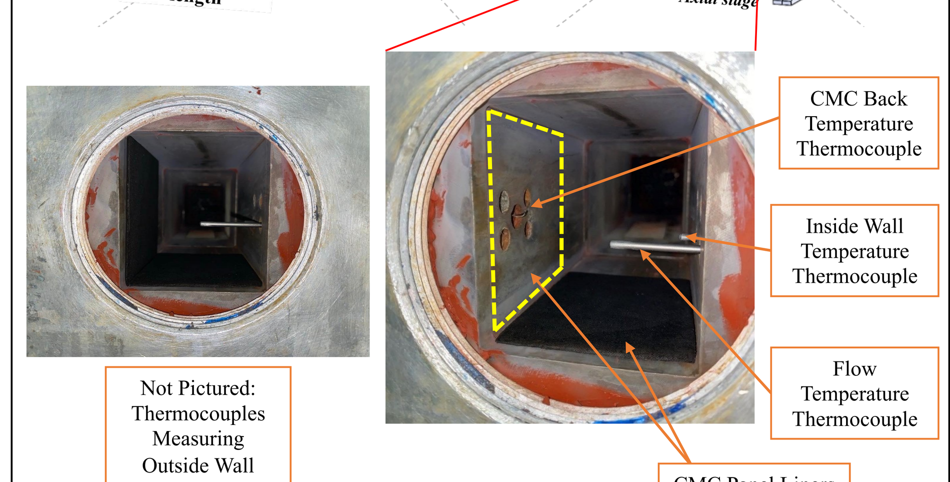


H_2 Combustion Engine Test

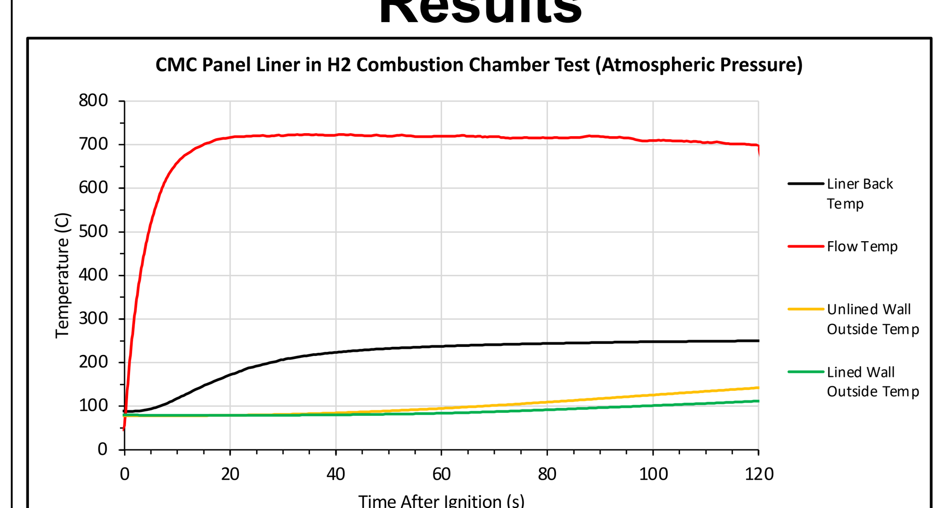
Experimental Setup

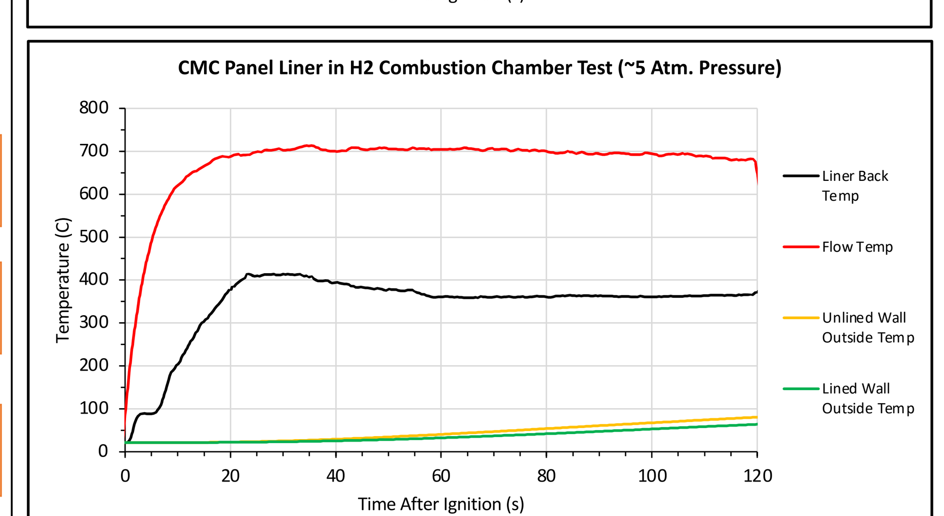
- Preliminary testing, targeting low temperatures (~700ºC) at atmospheric and pressurized conditions.
- Investigating effects of hydrogen flame traveling parallel to CMC (as opposed to through-thickness as in torch test).
- Combustion testing duration of 2 minutes.



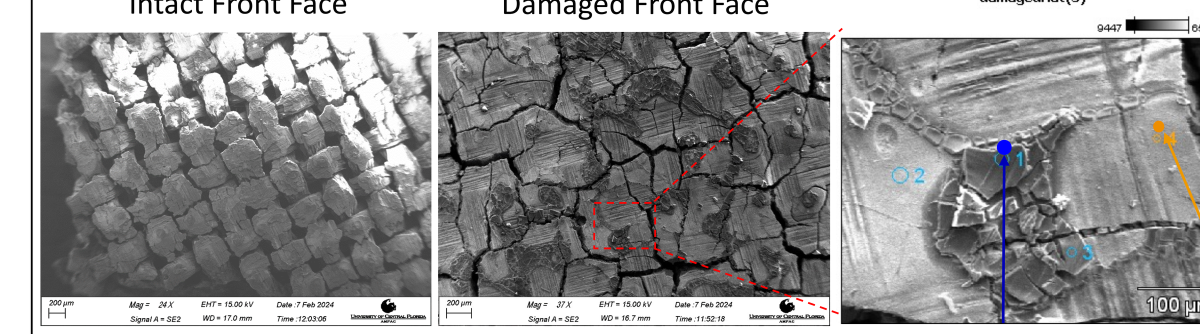


Results





Material Characterization



- Gaps in matrix become filled after torch exposure.
- Formation of protective oxide plaques (SiO_2) due to passive oxidation: $2SiC(s) + 3O_2(g) \rightarrow 2SiO_2(s) + 2CO(g)$
- Large increase in Oxygen content in post-damage.

Element	Weight %	Atom %
C K	14.8	28.1
N K	0.0	0.0
O K	29.6	42.2
Si K	27.1	22.0
Zr L	27.8	7.0

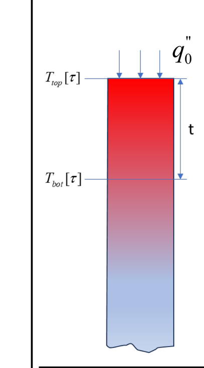
Element	Weight %	Atom %
C K	8.1	15.5
N K	0.0	0.0
O K	41.5	59.5
Si K	21.8	17.8
Zr L	28.6	7.0

Element	Weight %	Atom %
C K	4.8	8.6
N K	4.6	6.9
O K	32.0	42.4
Si K	55.1	41.7
Zr L	0	0

Element	Weight %	Atom %
C K	6.4	16.4
N K	2.7	5.8
O K	27.4	52.5
Si K	5.4	5.9
Zr L	58.0	19.4

- YSZ fibers become exposed after hydrogen flame attack.
- Oxygen and Silicon are distributed throughout surface, with higher concentrations on plaque-like structures.

FE and ML Modeling



1D Transient analytical solution for given heat flux

$$T(t,\tau) - T_0 = \frac{q_0'' t}{k}\left(\frac{1}{\sqrt{\pi}}\frac{1}{t/(2\sqrt{\alpha\tau})}e^{-\frac{t^2}{4\alpha\tau}} - \left(1 - erf\left[\frac{t}{2\sqrt{\alpha\tau}}\right]\right)\right)$$

$\alpha = k_3 / \rho\gamma \quad (m^2/s)$

t -- specimen thickness

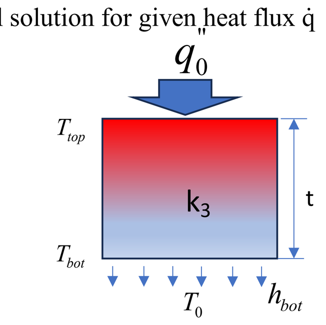
τ -- time elapsed

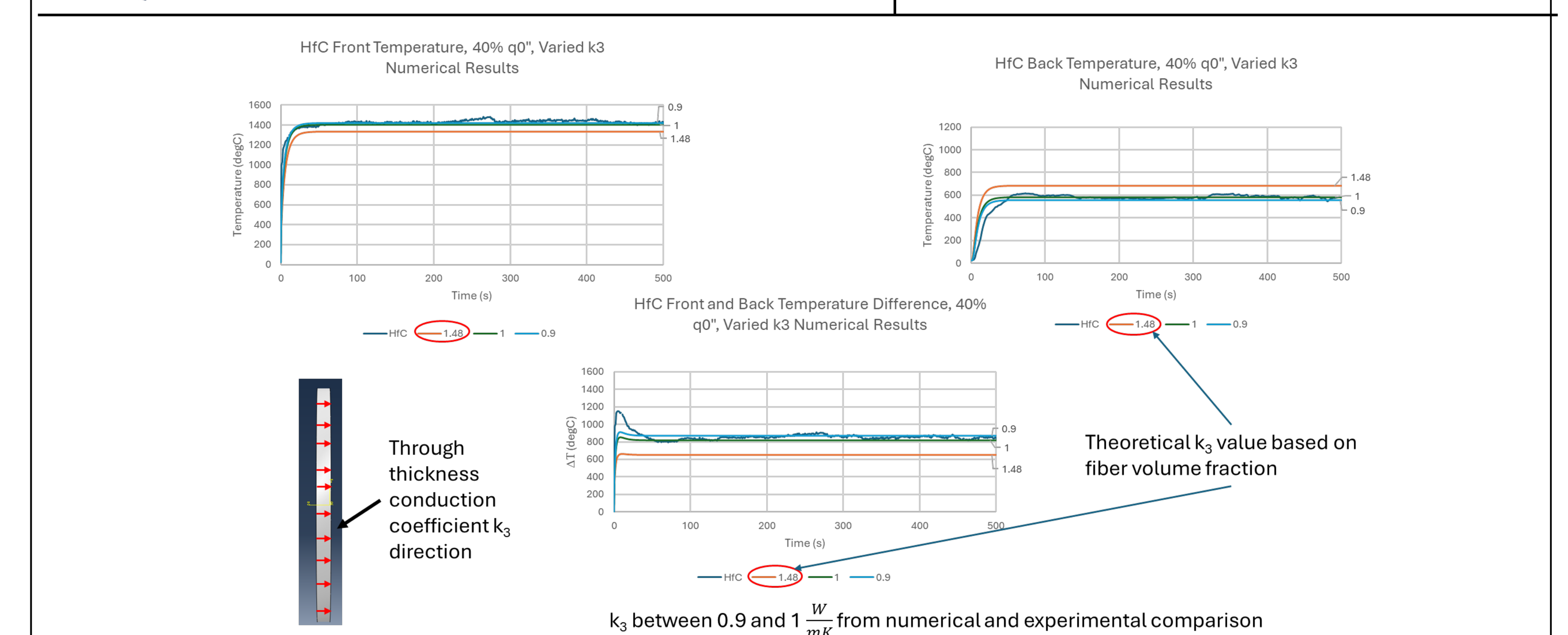
1D Steady-state analytical solution for given heat flux $\dot{q}''$

$$T_{bot} = \frac{q_0''}{h_{bot}} + T_0$$

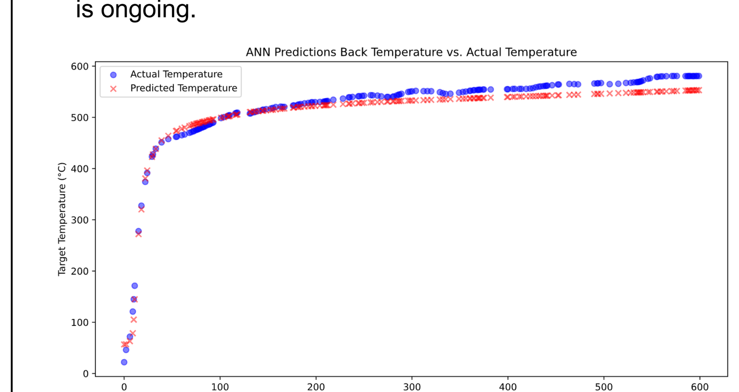
$$T_{top} = \frac{q_0''}{k_3/t} + \frac{q_0''}{h_{bot}} + T_0$$

$$T_{top} - T_{bot} = \frac{q_0''}{k_3/t}$$





- Numerical modeling of torch test data used to match experimentally measured T_{top} and T_{bot} to determine absorbed heat flux q_0'', through-thickness conduction coefficient k_3, and specific heat γ.
- Difference between theoretical and experimental values could be caused by voids in specimen filling with water vapor, determination is ongoing.



Model Name	MAPE	RMSE	MAE	R^2 Score
LASSO	25.94%	69.28	34.10	0.4166
Random Forest	12.84%	41.15	31.88	0.7941
Gradient Boosting	6.97%	25.44	16.91	0.9213
Extreme Gradient Boosting	6.98%	26.45	17.64	0.9150
Deep Artificial Neural Network	**3.92%**	**16.45**	**14.07**	**0.9671**

- Machine learning techniques are being explored to predict the ablation performance of the CMCs based on manufacturing parameters, saving time and resources needed to determine optimal material formulations.

Conclusions & Future Work

- The proposed CMC formulation and processing technique show promise for use in H_2 combustion environments.
- Direct H_2 flame exposure at high heat flux resulted in minimal damage to the CMCs, and post-damage characterization shows favorable behavior by way of Silica (SiO_2) formation.
- The reduced insulation effectiveness of the CMCs at higher pressures suggest the need to further densify the material through more PIP cycles, reducing porosity and increasing thermal performance.
- A full-sized CMC combustion liner will be manufactured using the material formulation presented, and larger timescale testing will be conducted to investigate long-term H2 combustion effects and viability.

Acknowledgements

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