Matrix-Stabilized Combustion Technologies to Enable Ultra-Low Emission Combustion in Aviation Gas Turbines

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Overview

- The innovation and impact: Why matrix-stabilized combustion for aviation gas turbines?
- Research issues and challenges
- Technical approach
- Results and accomplishments
  - Theoretical analysis and feasibility
  - Durability tests
  - Development of advanced diagnostics
  - Computational modeling and assessment of novel PMB-concept
- Conclusions and main findings
- Distribution/Dissemination
- Next steps

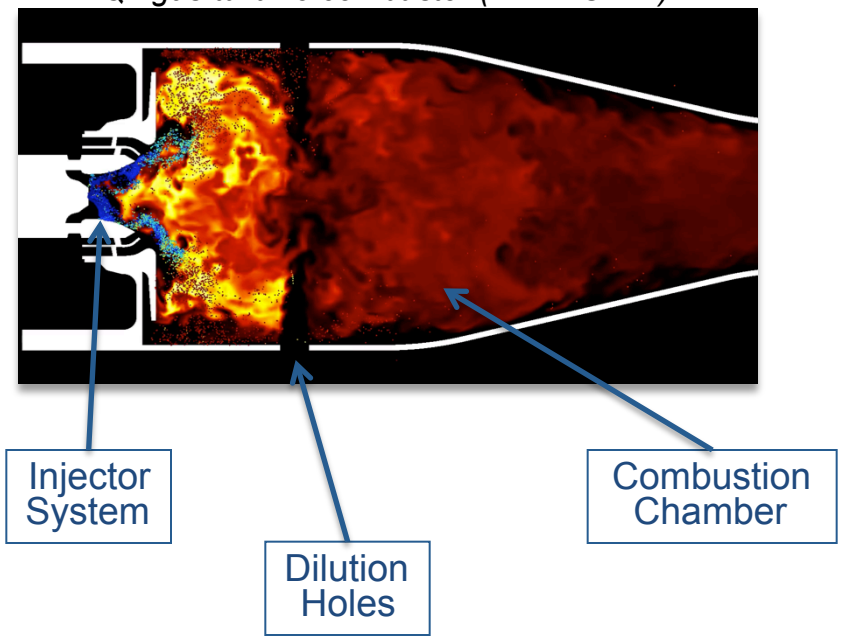
Leading Edge Aeronautics Research for NASA (LEARN)

- Identify innovative concepts and novel solutions resulting from a multi-disciplinary, multi-institutional teamed approach to explore novel concepts and processes with the potential to create new capabilities in aeronautics research; thrust areas
  - Ultra-efficient commercial vehicles
    - Pioneer technologies for big leaps in efficiency and environmental performance
  - Transition to low-carbon propulsion
    - Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Proposed Innovation

Enable the utilization of matrix stabilized combustion as an advanced low-emission fuel-flexible combustion strategy for gas turbine engines

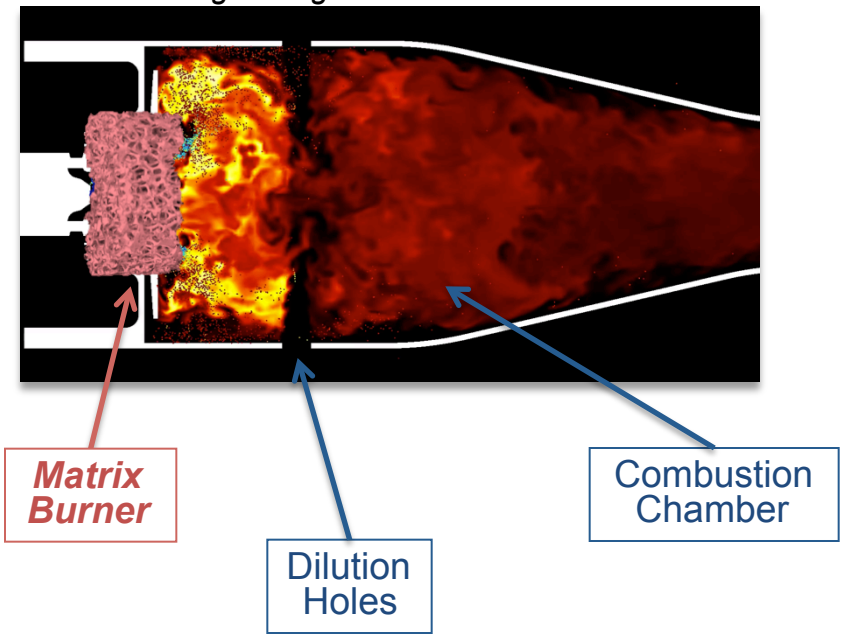
RQL gas-turbine combustor (AFRL/URDI)



Proposed Innovation

Enable the utilization of matrix stabilized combustion as an advanced low-emission fuel-flexible combustion strategy for gas turbine engines

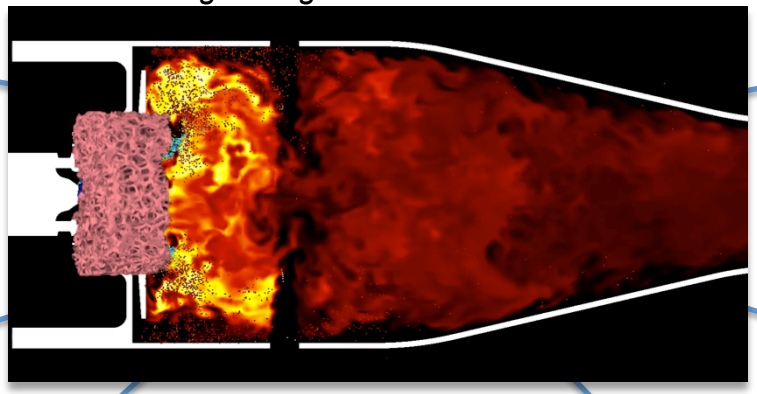
PMB-integrated gas-turbine combustor



Proposed Innovation and Impact

Potential advantages of porous-media combustion for gas-turbine engines

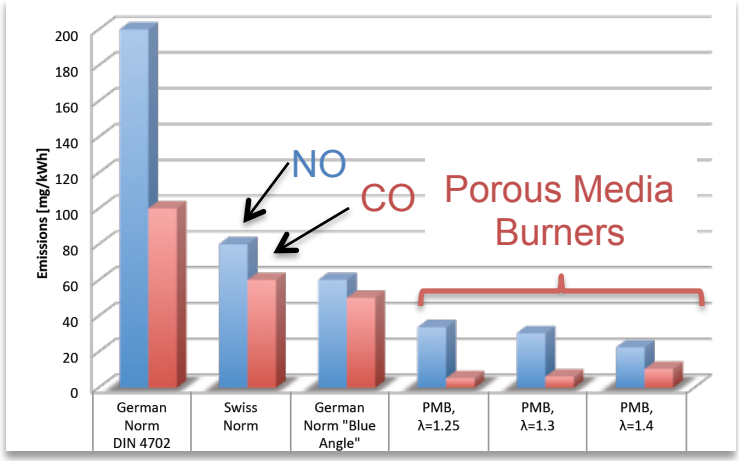
PMB-integrated gas-turbine combustor

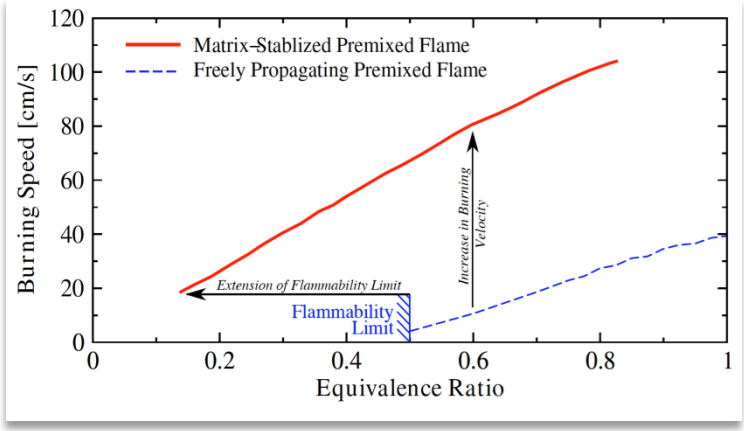


- Extended power modulation
- Reduction in CO and NO
- Combustion of ultra-lean fuel/ air mixtures
- No thermo-acoustic instabilities
- Low noise emission
- Fuel-flexible operation

Innovation and Impact: Why Porous Media Combustion?

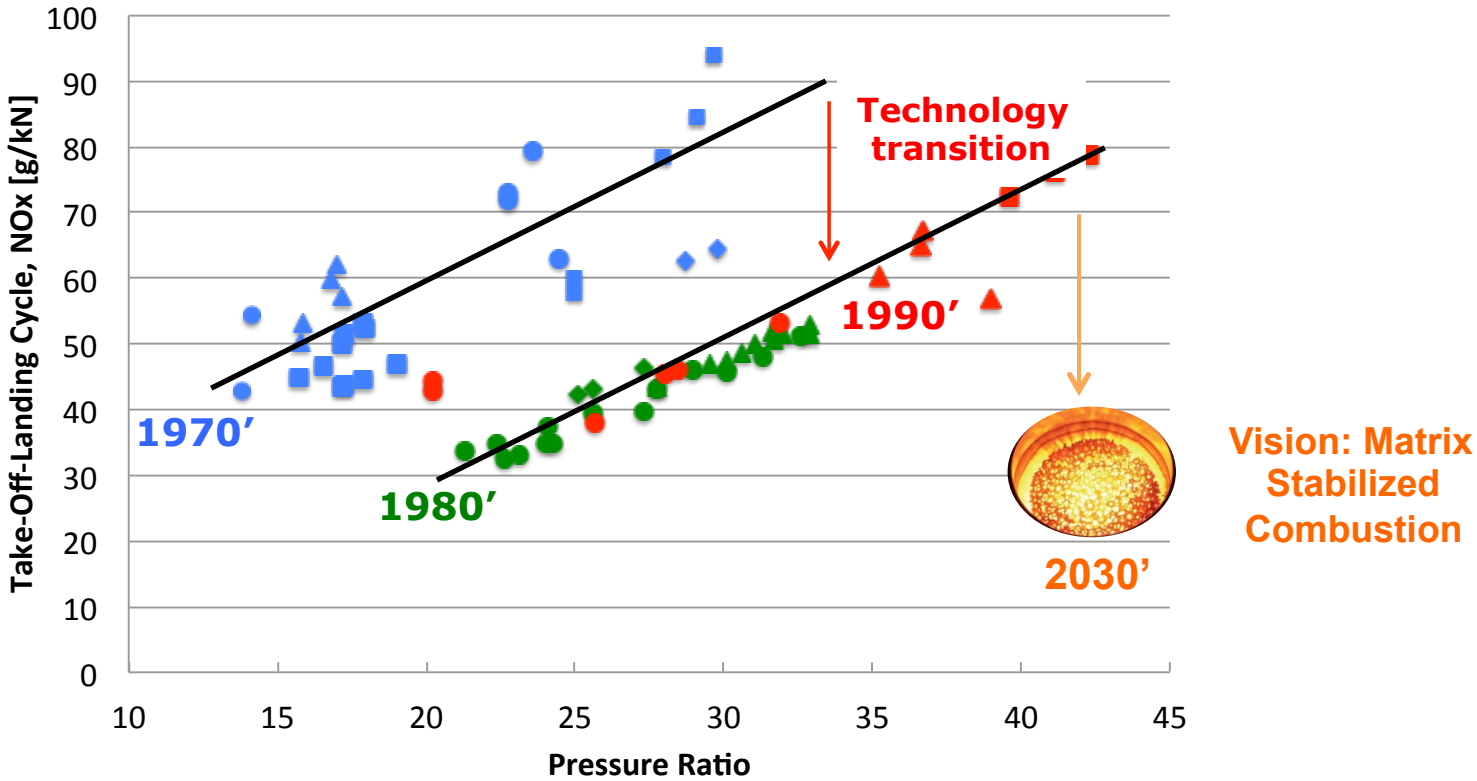
- Advantages of matrix-stabilized combustion
  - Significant reductions of CO and NO, down to sub-ppm levels
  - Extension of operating envelope to ultra-lean fuel/air mixtures
  - Robust operation with flexible, renewable, low-caloric, and hydrogen-containing fuels
  - Extended power-modulation and considerably higher power densities
  - No thermoacoustic instabilities and reduced noise emissions





Innovation and Impact: Why Porous Media Combustion?

Enable the utilization of matrix stabilized combustion as an advanced low-emission fuel-flexible combustion strategy for gas turbine engines

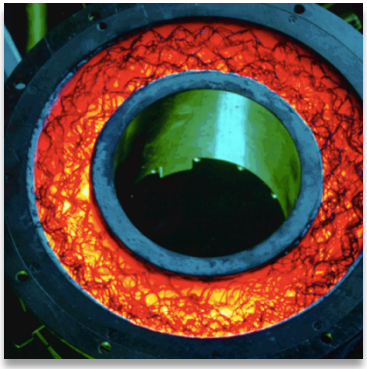


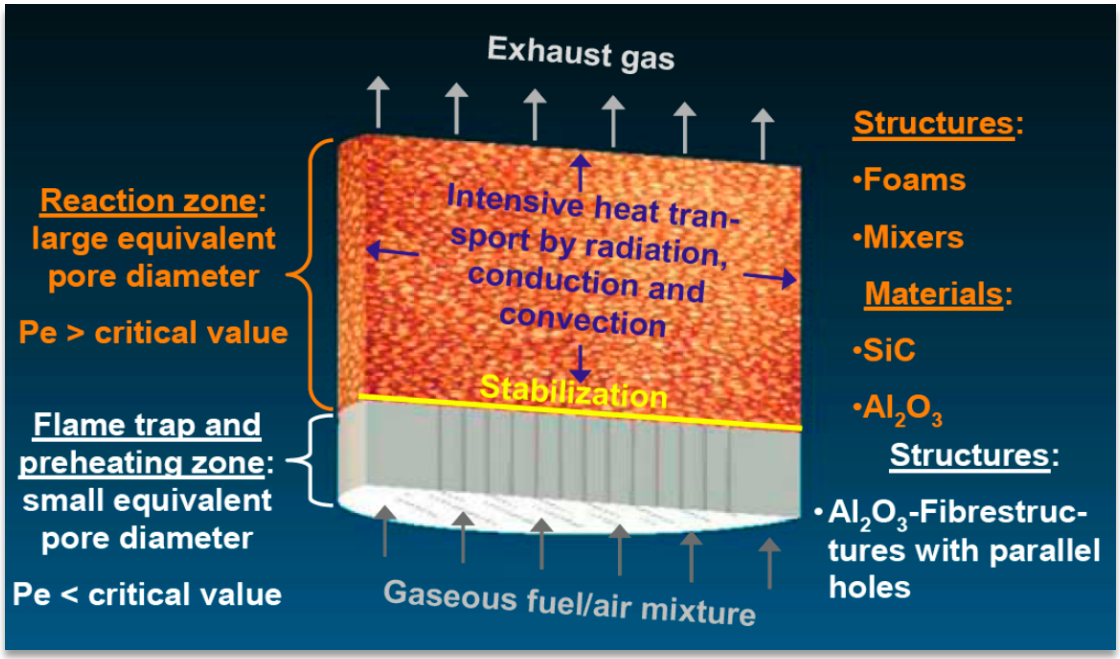
MATRIX-STABILIZED COMBUSTION

Operating Principle

What Is Porous Media Combustion?

- Porous media combustion involves heterogeneous interactions amongst gases and solid matrix
- Combustion is facilitated inside heat-conducting porous media (SiC, Alumina, Zirconia) to achieve internal heat-recuperation and excess-enthalpy utilization
- Stability achieved via pore-scale quenching mechanism

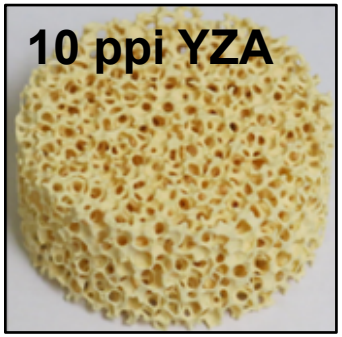


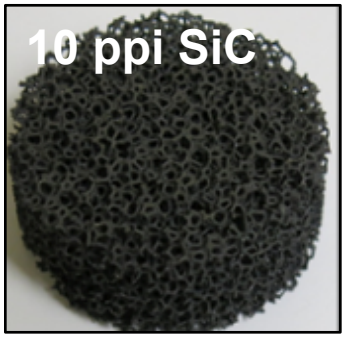


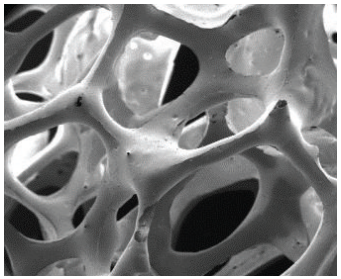
Challenges in Enabling PMBs for Gas-Turbine Combustors

- Common PMB-design: Two-zone burner
  - Flame-stabilization by thermal quenching
- Material properties and durability

Property	Alumina (Al2O3)	Silicon Carbide (SiC)	Metal Alloys (ZrO2)
Max. Temperature use	✔	✔	✔
Thermal Expansion	✔	✖	✖
Thermal conductivity	✖	✔	✖
Thermal stress/shock resistance	✖	✔	✖
Emissivity	✖	✔	✔✖
Application		Combustion zone	Preheat zone







Challenges in Enabling PMBs for Gas-Turbine Combustors

Burner performance

- Pressure drop
- Flame stability and operating range
- Durability: cyclic modulation, long-time stability

Advanced diagnostics techniques

- Non-intrusive and non-destructive measurement techniques

Theoretical limitations

- Fundamental understanding of heterogeneous combustion physics
- Analysis of coupling processes between combustion, fluid dynamics, and heat transfer

Computational modeling

- Absence of high-fidelity physics based models
- Integrated burner-design optimization

Project Plan and Technical Approach

Objectives

1) Develop modeling capabilities and advanced diagnostics to enable fundamental characterization of heterogeneous combustion in PMBs
2) Perform life-cycle tests to demonstrate feasibility of using matrix-stabilized combustion for low-emission and ultra-efficient aviation propulsion systems
3) Evaluate novel PMB concepts to achieve improved performance

STANFORD ENGINEERING

Develop computational models for simulation of heterogeneous combustion, and optimization of porous matrix

STANFORD SCHOOL OF MEDICINE

Develop non-intrusive X-Ray CT diagnostics to obtain 3D measurements of temperature and flame structure in porous matrix

ALZETA CORPORATION

Experimentally characterize emissions, stability, durability and performance of porous media burners

Research Team

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Diagnostics)

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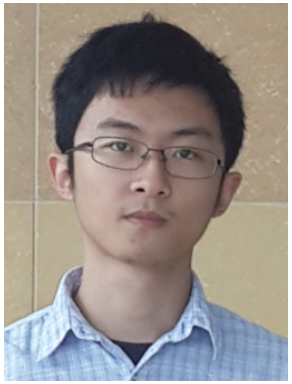

Tonghe Wang
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(XCT Reconstruction)

Michael Werer
High-school student
(PMB Topology)

PMB-INTEGRATION

Evaluate feasibility of integrating PMBs into aviation gas-turbine engines

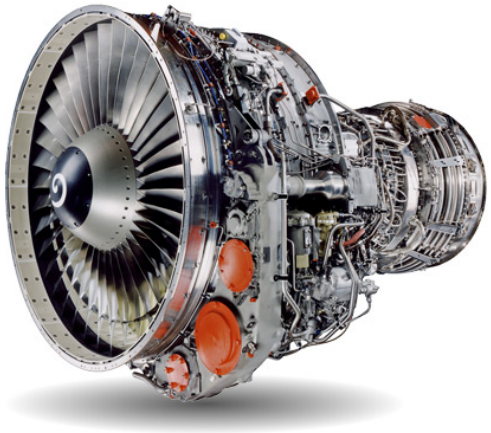
PMB Integration

Objective

- Perform system analysis for PMB integration into gas-turbine engine

Engine configuration: **CFM56**

- Rated thrust: 89kN; Cruise: 22.5kN
- Combustor-pressure drop: 3%
- Installation: B737-300/400/500
- Operating condition: cruise @ 35,000ft



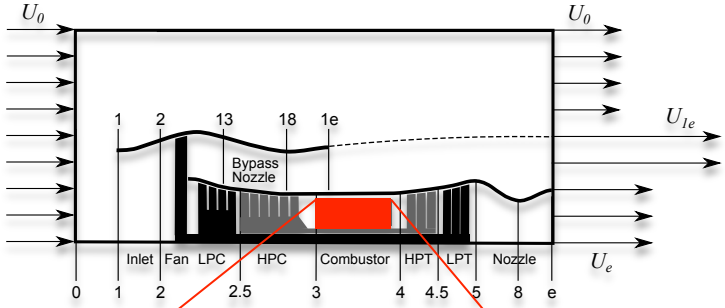
Approach

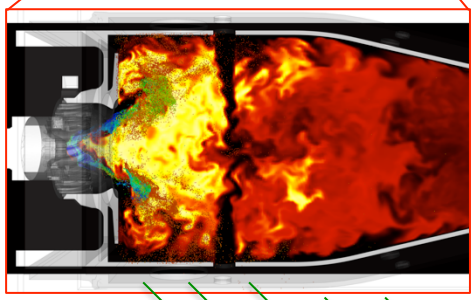
- Brayton-cycle analysis to evaluate mass-flow rate
- Evaluate design-modification to utilize advantages of PMB

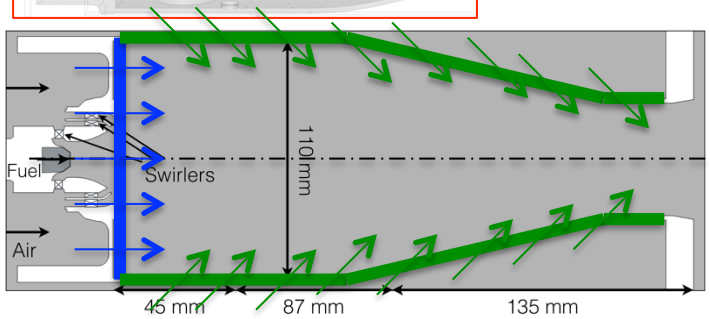
PMB Integration

- Results (Brayton-cycle analysis)
  - Combustor inlet temp: 600 K
  - Combustor exit temp: 1600 K
  - TSFC = 5.4g/kN-s
  - $\eta_{th} = 0.64$
  - Evaluate burner area of combustor sector from FAA referee rig

Representative mass flux through total combustor area:
5.1 kg/m²s

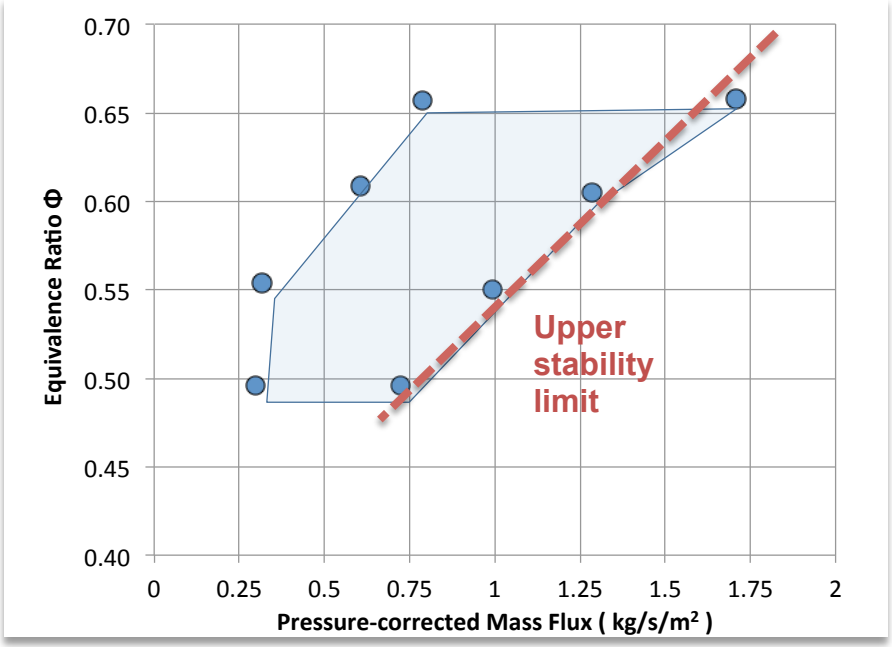






PMB Integration

- Measurements of PMB-stability show that mass-flow rates are within **factor of three** of required mass-flux rate at CFM56-cruise conditions



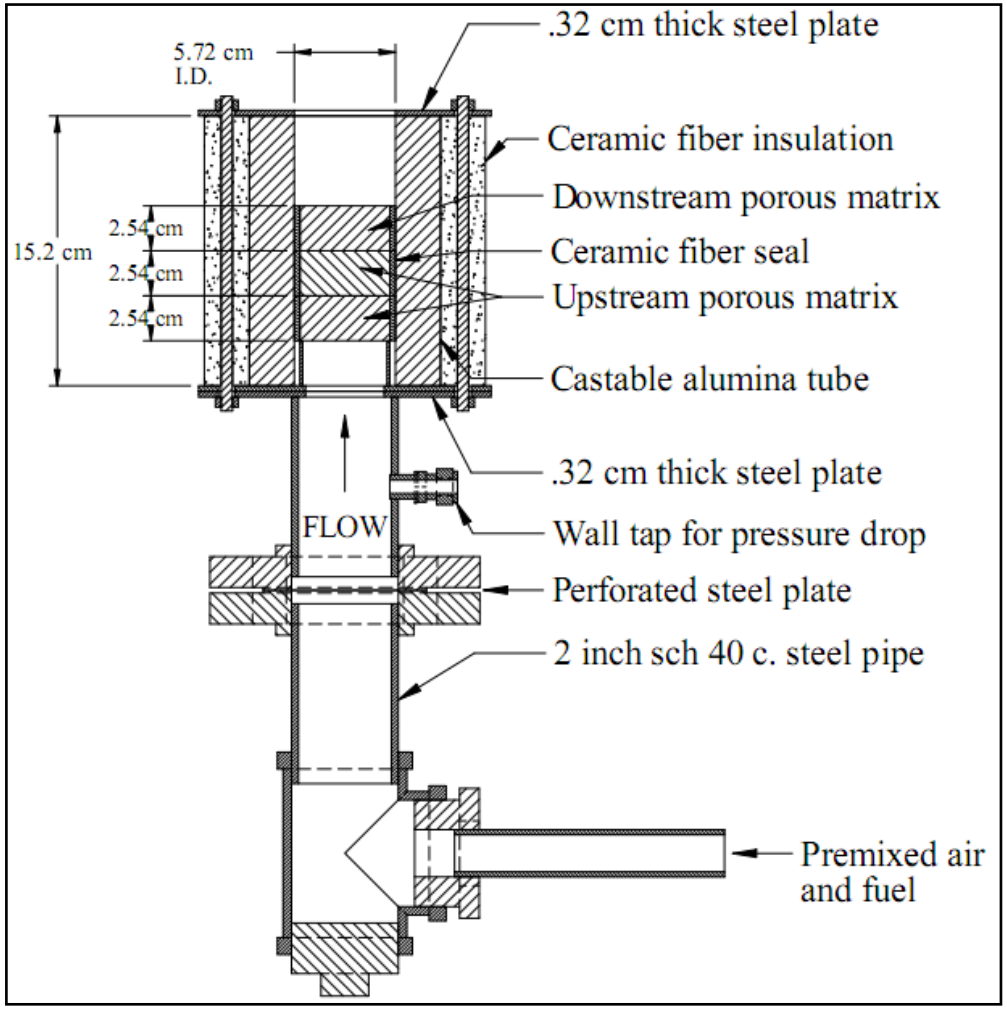
- Main findings
  - PMB integration appears feasibility
  - Further benefits are achievable by exploiting heat-recuperation
  - Improved PMB-design concepts are required to extend stability conditions

PMB PERFORMANCE TESTS

Objectives

- Measure performance of porous media
  - Range of stability (mass flux, equivalence ratio)
    - Wide range (max/min > 2)
    - Adequate mass flux
    - Low equivalence ratio
  - Pressure drop
    - Low pressure drop ($\Delta P/P_0 < 3\%$)
  - Emissions (CO, NOx)
    - Low emissions (< 5 ppmv corr to 15% O2)
- Evaluate durability of porous media
  - Continuous operation (**419 hours**)
  - On/off cycling operation (**1229 cycles**)

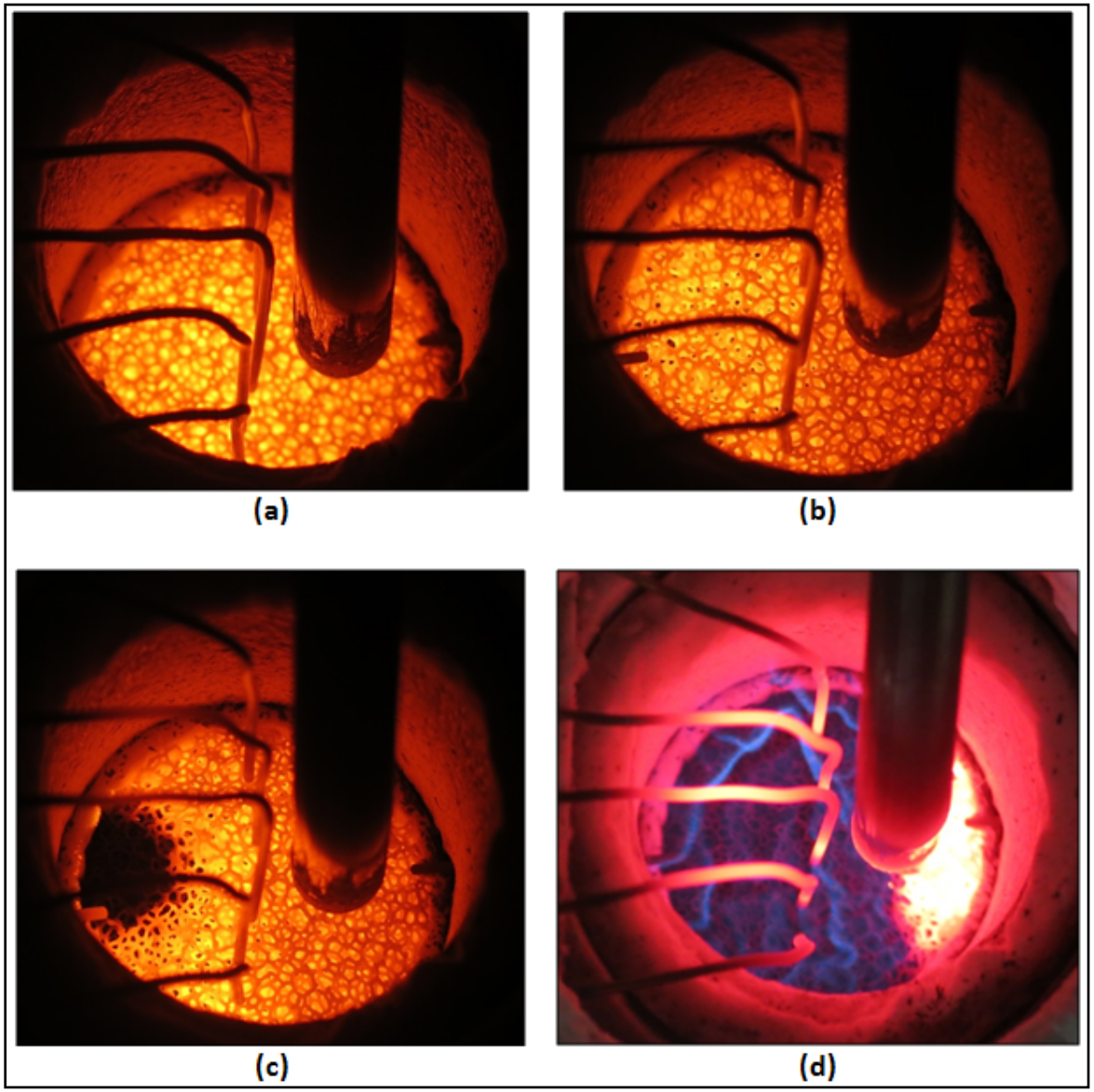
Cross-Section of Test Rig



Performance Test Matrix

Matrix of Tests of Stability Limits of Porous Media								
Series	Upstream Porous Media				Downstream Porous Media			
	Material	Pore size	Length	Diameter	Material	Pore size	Length	Diameter
		ppc	cm	cm		ppc	cm	cm
1	SiC	26	5.1	5.1	SiC	3.9	2.5	5.1
2	YZA	24	5.1	5.1	SiC	3.9	2.5	5.1
3	YZA	16	5.1	5.1	SiC	3.9	2.5	5.1
4	YZA	16	5.1	5.1	YZA	3.9	2.5	5.1
5	YZA	16	5.1	5.1	SiC	1.2	2.5	5.1
	Notes:							
	1)	For each series, Φ was varied from 0.5 to 0.65, and mass flux varied from 0.1 to 1.0 kg/s/m^2, within limits of stability.						

Stability Limit: Flame Lift Off



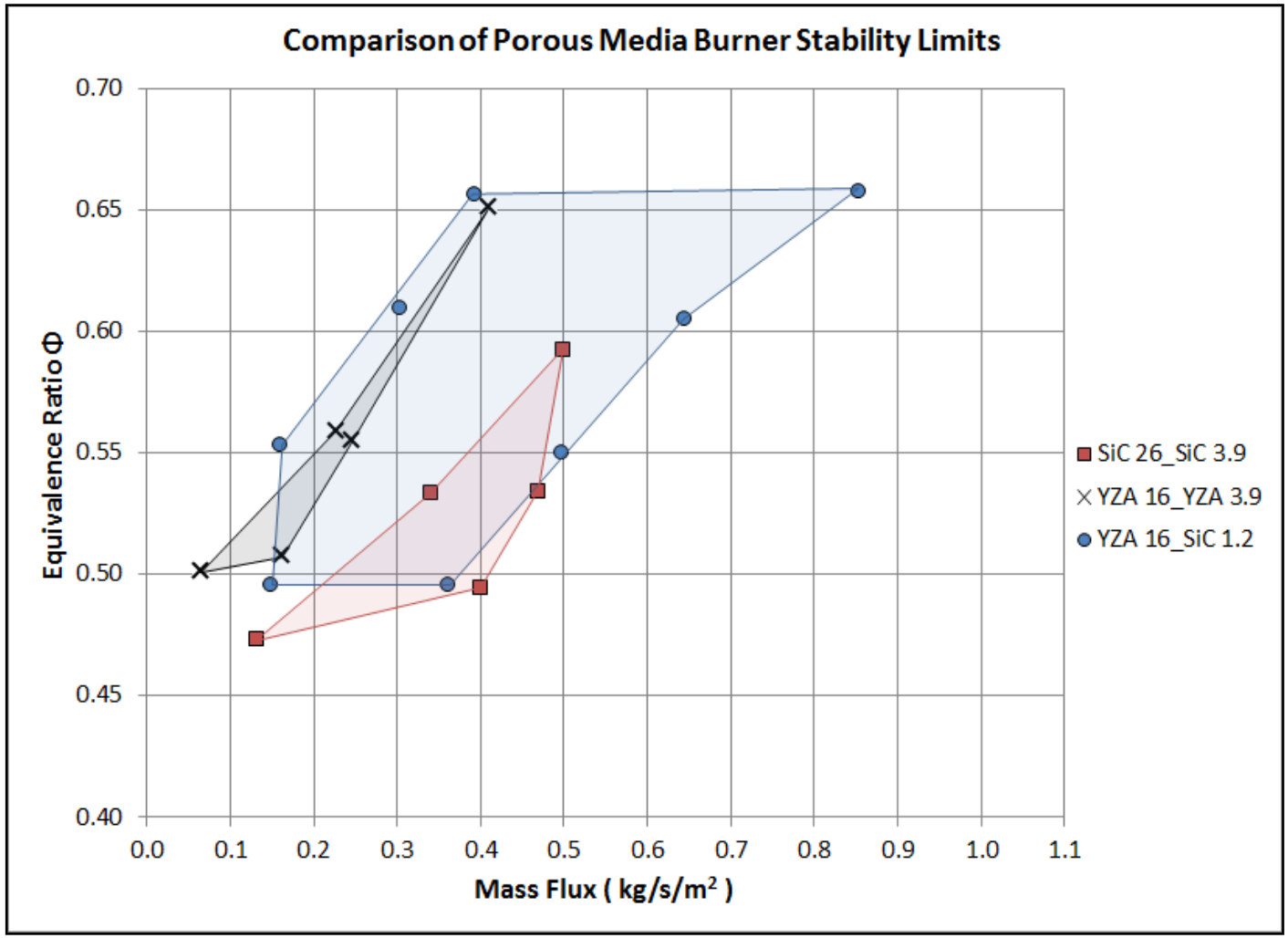
(a) Flame-front anchored at interface.

(b) Flame-front approaching top surface on left side.

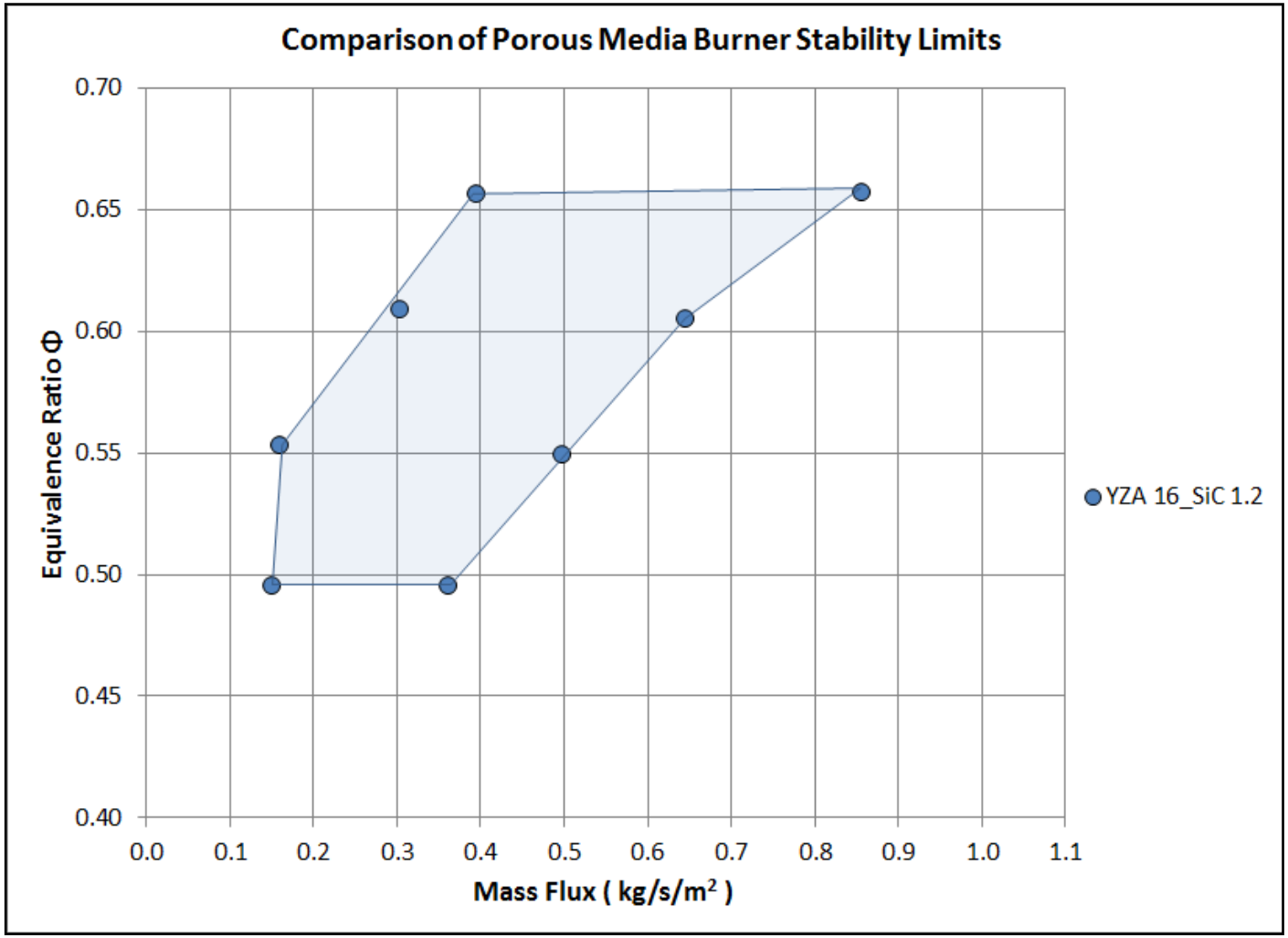
(c) Cold premix has reached surface.

(d) Complete lift-off imminent.

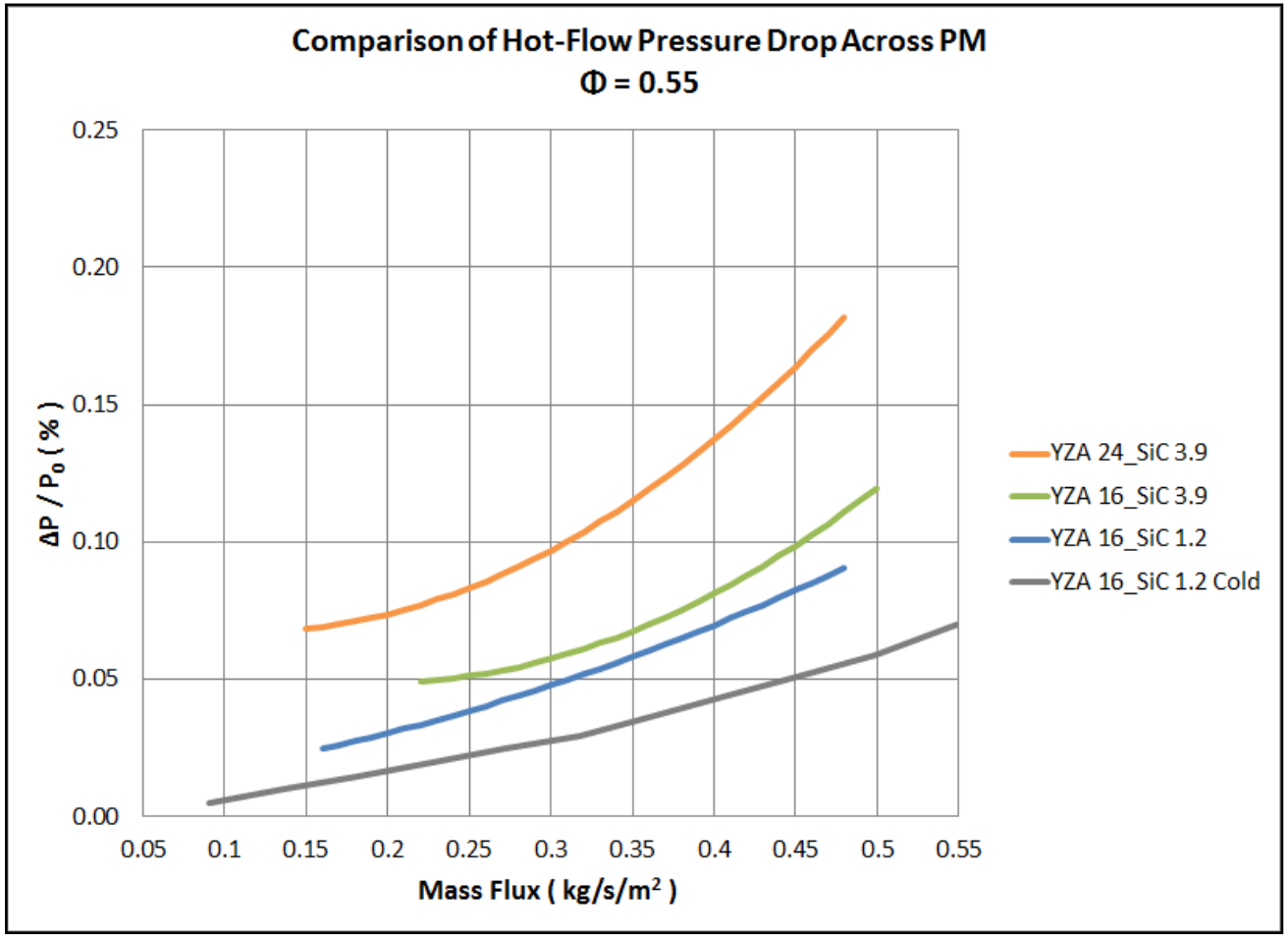
Operational Stability Map



Operational Stability Map



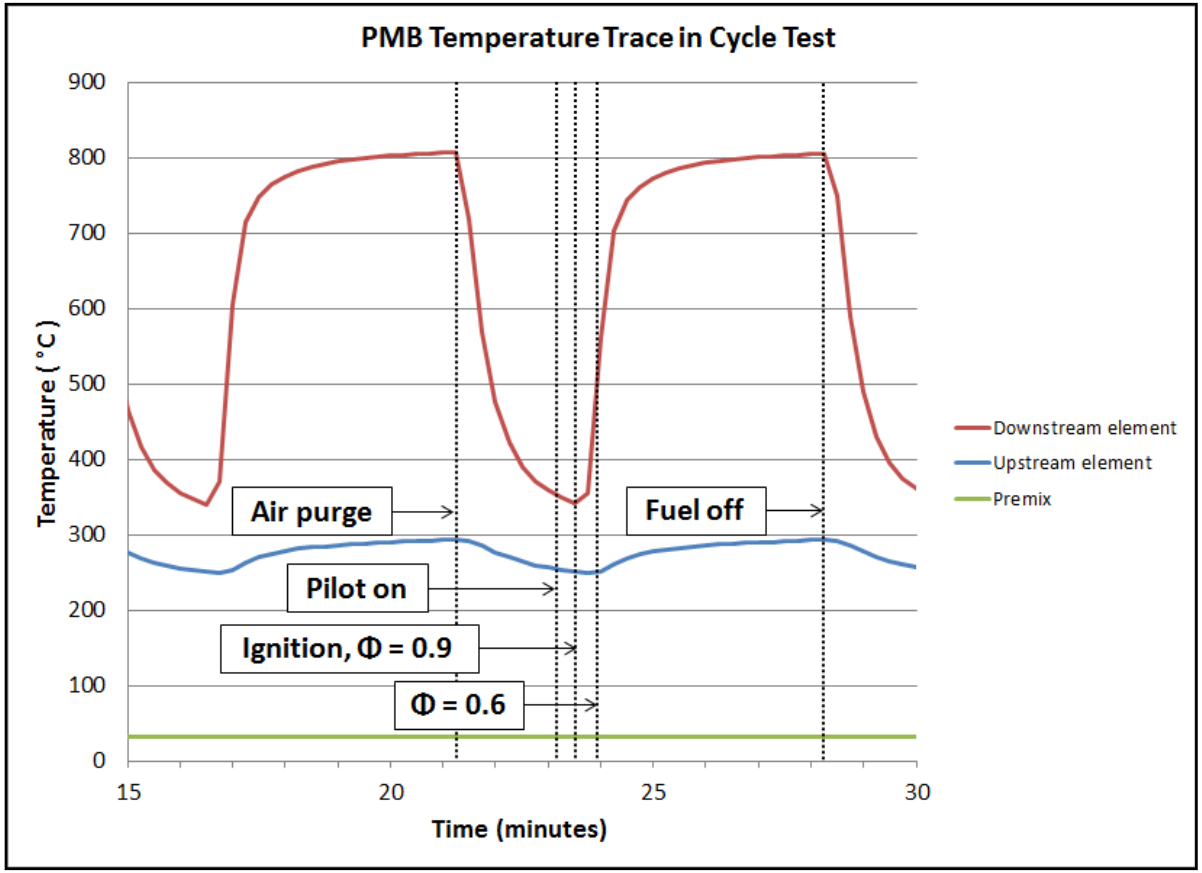
Hot-Flow Pressure Drop



➔ Acceptable pressure drop (<1%) for investigated operating conditions

Life-Cycle Test

Performed 1229 cycles of on/off operation to mimic engine start/unstart conditions



Durability Test Summary

Continuous Test	Start	End	Change
• Hours of operation	0	419	419
• Sample weight (g) ○ YZA 1 ○ YZA 2 ○ SiC	 41.88 37.25 18.90	 41.87 37.21 17.46	 0.01 0.04 1.44
• Cold $\Delta P/P_0$ (%) at design conditions, 51 slpm cold flow rate	0.039%	0.039%	0
• Fired $\Delta P/P_0$ (%) at design conditions, 0.51 kg/m^2/s at phi = 0.6	0.076%	0.076%	0
• Appearance	Figure 19	Figure 20	

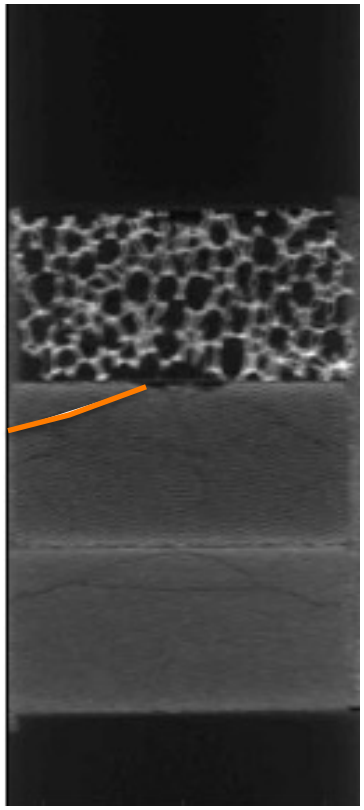
No apparent performance loss or significant deterioration of YZA after 419 hours continuous testing; SiC shows some spallation

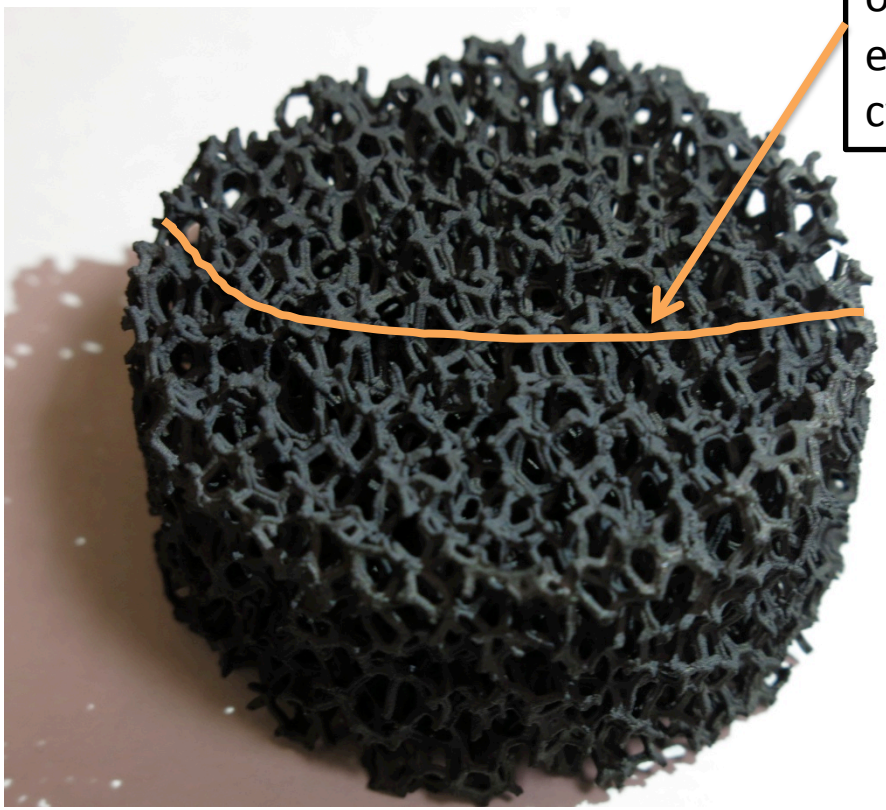
Cycle Test	Start	End	Change
• Cycles of operation ○ 5 min fired, 2 min purge	0	1229	1229
• Sample weight (g) ○ YZA 1 ○ YZA 2 ○ SiC	 41.87 37.21 17.46	 41.85 37.20 17.35	 0.02 0.01 0.11
• Cold $\Delta P/P_0$ at design conditions (%)	0.039%	0.039%	0
• Fired $\Delta P/P_0$ at design conditions (%)	0.074%	0.074%	0

Excellent performance of Zirconia-based porous matrix; SiC-matrix more brittle → advanced manufacturing

SiC Element After Cycle Test

Use X-ray computed tomography and micro-CT for rapid evaluation of matrix integrity





Approx. location of fissure in SiC element after cycle tests

Main Findings

- Established test-protocol for long-time durability tests
  - 419 hours continuous test
  - on/off life cycle tests

- Evaluated PMB-performance
  - Pressure drop → well below 0.5% for all conditions
  - Stability regime → ratio between max/min mass flux = 2.6
  - Emissions (CO, NO) → well below required values
  - Durability → cracking of struts and spalling in SiC element

- Series 5 showed best performance (pressure drop, stabilization)
  - 16 ppc YZA for flash-back preventer
  - 1.2 ppc SiC for flame holder

DEVELOPMENT OF X-RAY COMPUTED TOMOGRAPHY DIAGNOSTICS

XCT Diagnostics for PMB Analysis

Challenges: Limited PMB diagnostics

- Limited optical access
- Heterogeneous environment
- Thin reaction zones
- Thermal/non-intrusive diagnostics

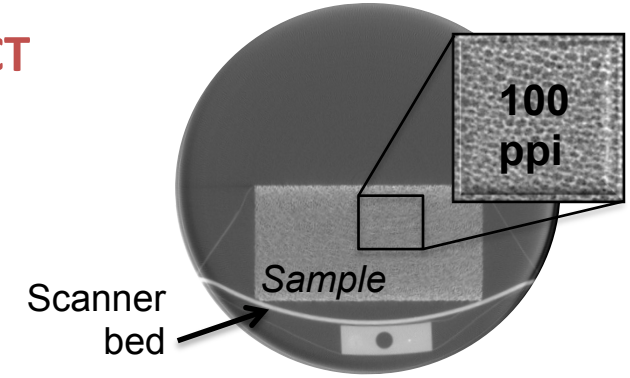
Objective: Develop X-ray computed tomography for volumetric diagnostics of PMBs; characterize

- Temperature field and flame structure
- Inhomogeneous combustion
- Topology of porous structure

XCT Diagnostics for PMB Analysis

Extract topology of porous foams using **Micro-CT**

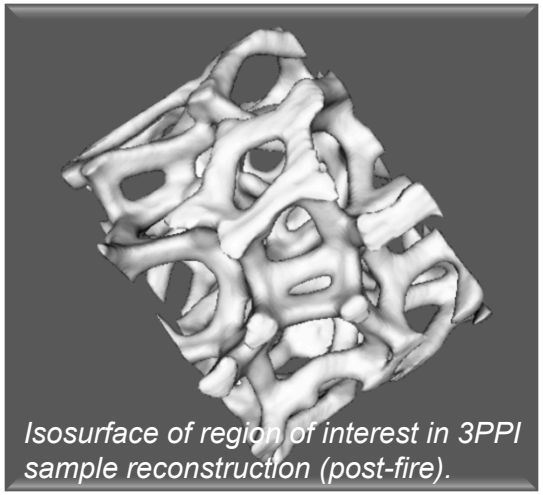
- eXplore Locus RS150 GE Micro-CT Scanner
- Volumetric Conebeam
- FOV: 7cm transaxial and 4 cm depth
- Spatial resolution: **48µm**
- Maximum energy: 150kV



Central slice of CT reconstruction

Reconstruction of PM-topology for

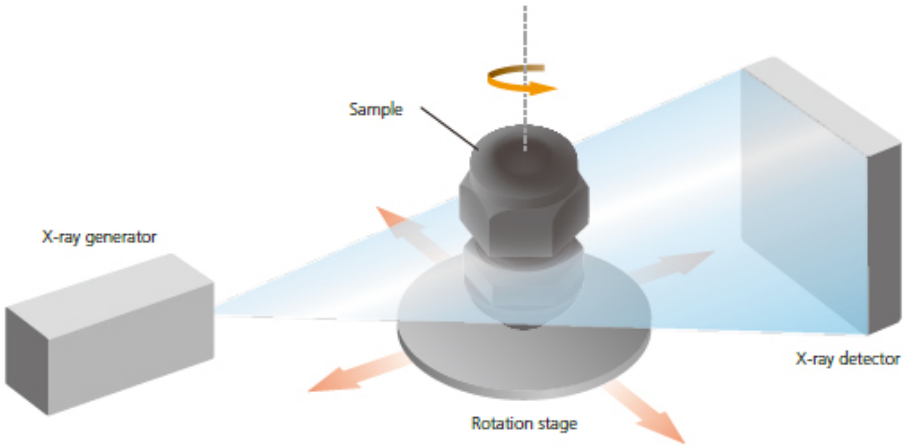
- CFD simulations
- Fracture identification
- Evaluation of matrix properties (dispersion, porosity)



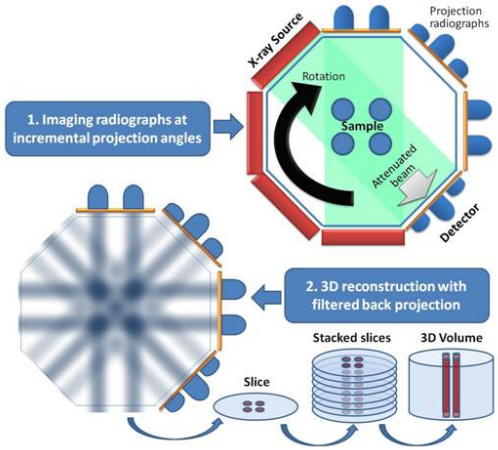
Isosurface of region of interest in 3PPI sample reconstruction (post-fire).

XCT Diagnostics for PMB Analysis

- XCT: non-intrusive 3D imaging technique through absorption of electromagnetic radiation

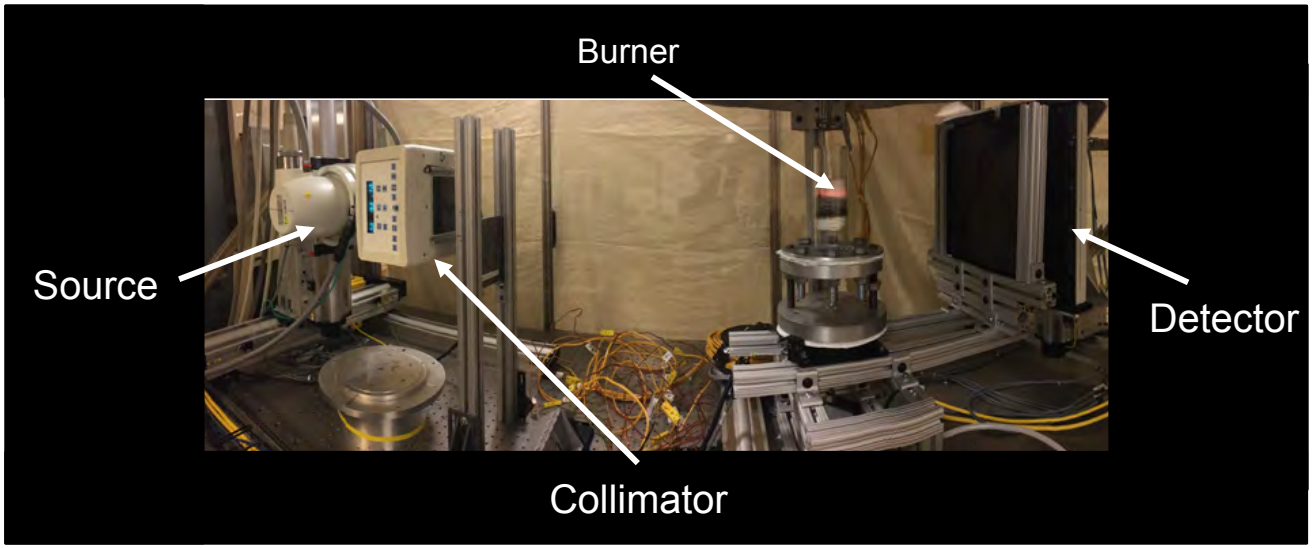


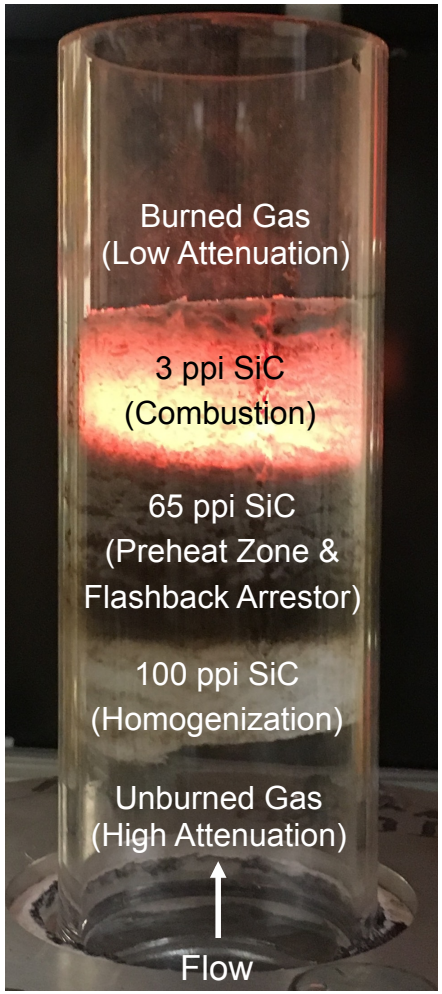
- Main advantages
  - Easily accessible diagnostics
  - High-view number (~1000 scans)
  - Straightforward setup
  - Applicable to optically inaccessible media (PMBs)
  - Advanced reconstruction for quantitative analysis



PMB XCT Experiment: Setup

- Designed+fabricated PMB integrated with XCT rotary unit
- Establish stable CH4/O2/Kr within PMB on tabletop XCT
- PMB setup: 100-65-3 PPI SiC stack with pore-quenching stabilization
- XCT-parameter: 60 kVp, 50mA, 1200 projections





PMB XCT Diagnostics Development

Diagnostics developments

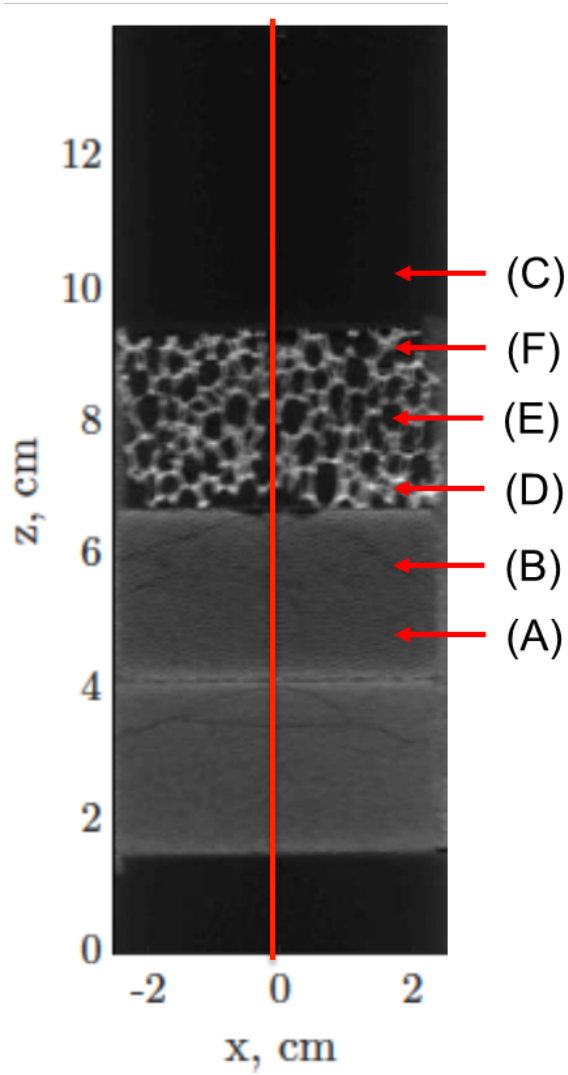
- Overcome contrast differences between gaseous combustion products, solid matrix, and burner housing
- Beam hardening correction
- Employed and developed advanced reconstruction techniques to enhance signal/noise ratio
  - FPB (Filtered back-projection) averaged over 6 acquisitions
  - Iterative techniques: SART (Simultaneous algebraic reconstruction technique) and PWLS (Penalty-weighted least-square)
- Thermo-couple instrumentation for cross-verification
- Infer temperature from absorption through ideal gas law

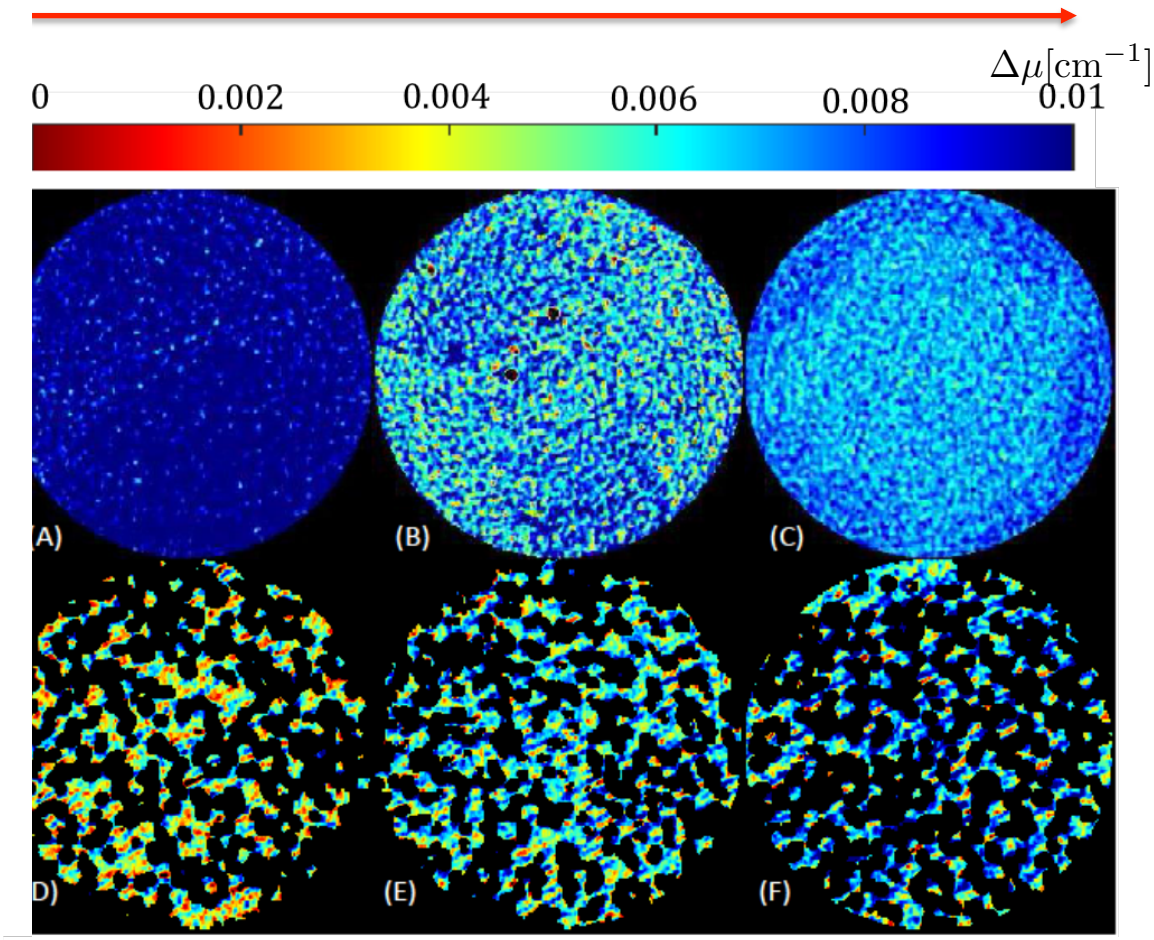
$$\Delta\mu = \xi_{\mathrm{Kr}}\rho_{\mathrm{Kr}} = \xi_{\mathrm{Kr}}\frac{p\,X_{\mathrm{Kr}}\,W_{\mathrm{Kr}}}{\mathcal{R}T} \quad \rightarrow \quad \boxed{T = \frac{p\,X_{\mathrm{Kr}}\,W_{\mathrm{Kr}}\,\xi_{\mathrm{Kr}}}{\mathcal{R}\Delta\mu}}$$

Linear attenuation ($\Delta\mu$)

Mass attenuation (ξ_{Kr})

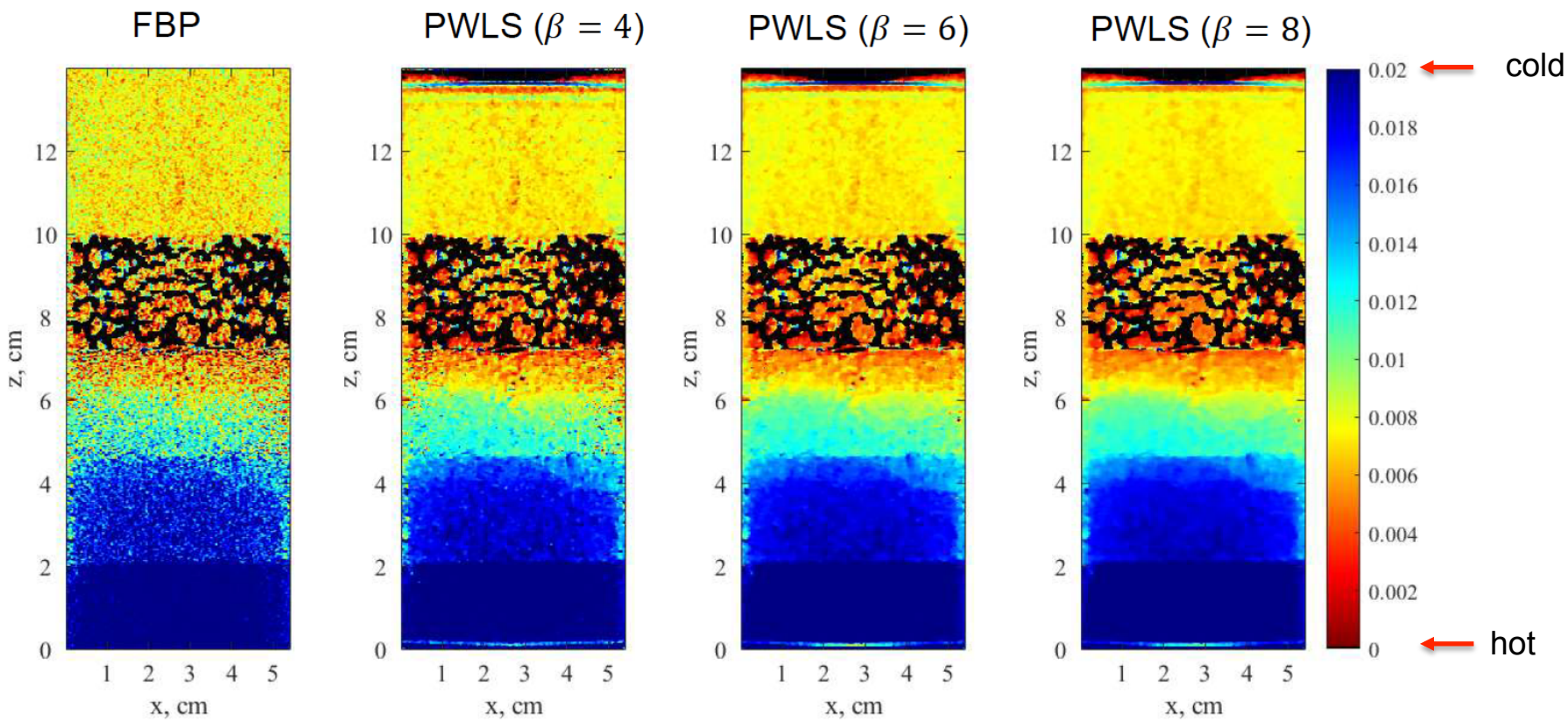
PMB XCT Diagnostics: Results





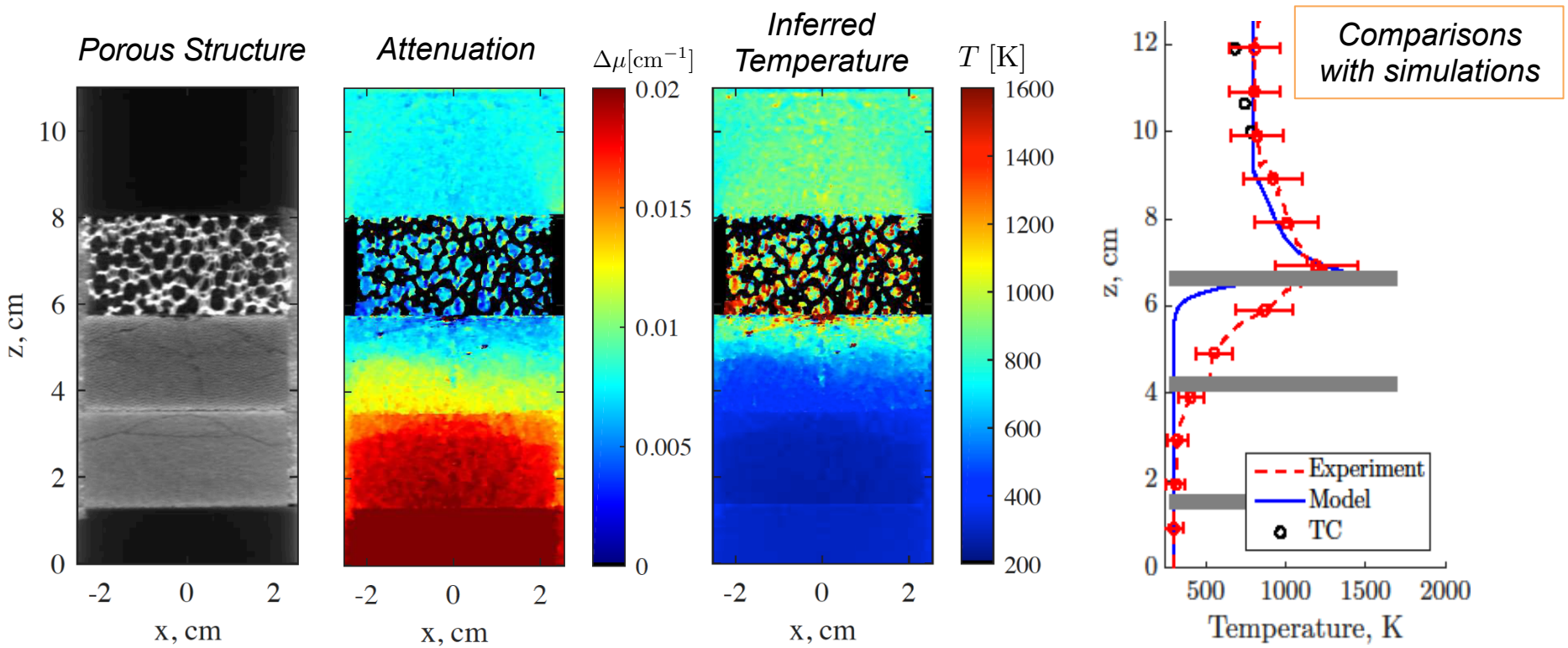
PMB XCT Diagnostics: Results

Image reconstruction



Solid structures are masked in black

PMB XCT Diagnostics: Results



Main Findings

- Developed XCT for 3D visualization of gas-phase attenuation fields in PMBs
  - Flame structure visualization inside PMBs through radiodense inert
- Developed advanced reconstruction techniques to increase SNR and correct for beam-hardening
  - Enable rapid 3D temperature measurements

COMPUTATIONAL MODELING

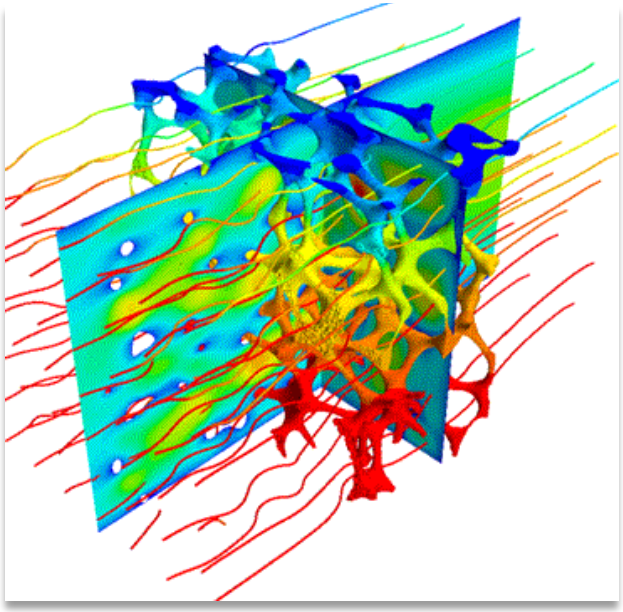
Development of computational models for design-concept analysis and PMB-performance assessment

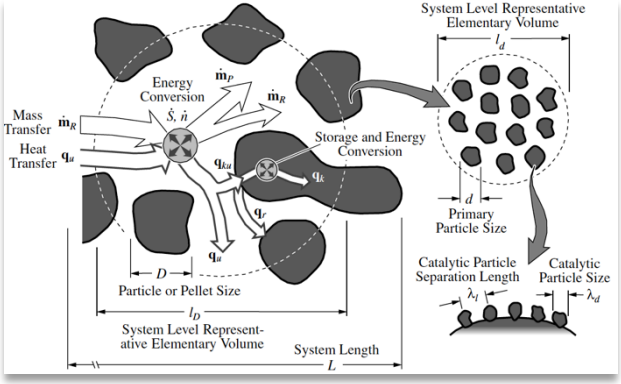
Objective

- Complement experimental and diagnostics efforts through computational modeling for
  - Validation
  - PMB-performance analysis: pressure drop, emissions, stability boundaries
  - PMB Design optimization

- Challenges
  - Large range of length scales
  - Complex/anisotropic geometry
  - Solid/gas coupling

- Our approach: volume-averaged method
  - Represent effects of pore-scale variations by effective transport coefficients





Technical Approach: Two-zone model

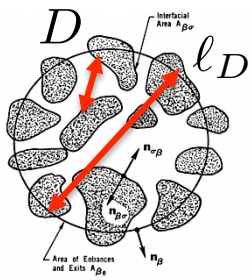
Scale separation

$$D < \ell_D < L$$

Pore scale — *Representative volume element* — *Device scale*

$$\rightarrow \epsilon = \frac{V_{pore}}{V}$$

Porosity



Pore-averaged governing equations

Mass conservation:

$$\frac{\partial(\rho_g \epsilon)}{\partial t} + \frac{\partial(\rho_g u \epsilon)}{\partial x} = 0$$

Species conservation:

$$\rho_g \epsilon \frac{\partial Y_i}{\partial t} + \rho_g \epsilon u \frac{\partial Y_i}{\partial x} + \frac{\partial}{\partial x}(\rho_g \epsilon Y_i V_i) - \dot{\omega} W_i \epsilon = 0$$

Energy conservation:

Heat release

$$\rho_g \epsilon C_g \frac{\partial T_g}{\partial t} + \rho_g \epsilon C_g u \frac{\partial T_g}{\partial x} + \epsilon \sum_{i=1}^{n} \rho_{g,i} C_{g,i} V_i Y_i \frac{\partial T_g}{\partial x} + \epsilon \sum_{i=1}^{n} \dot{\omega}_i h_i W_i - \frac{\partial}{\partial x}(k_{g,eff} \epsilon \frac{\partial T_g}{\partial x}) + h_v (T_g - T_s) = 0$$

Convection

Solid temperature:

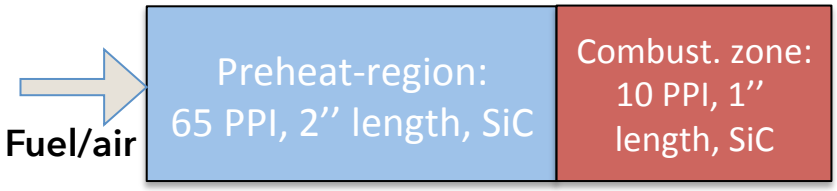
$$\rho_s C_s \frac{\partial T_s}{\partial t} + \frac{\partial}{\partial x}(\lambda_s \frac{\partial T_s}{\partial x}) + \frac{dq}{dx} - h_v (T_g - T_s) = 0$$

Radiation *Convection*

Compute pressure drop from Darcy's law with Forchheimer extension

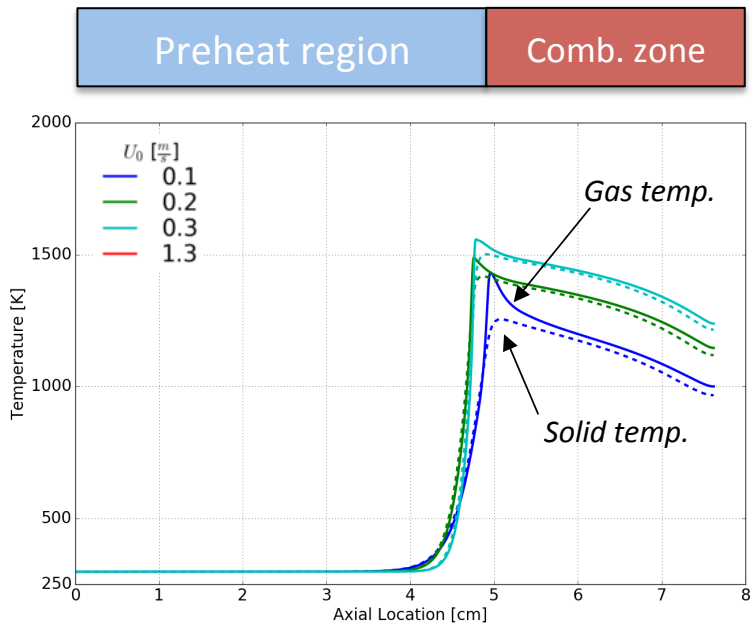
Results and Burner-Design Analysis

- Two-zone step-profile PMB
  - Conventional PMB-design
  - Employed in experiments and diagnostics efforts



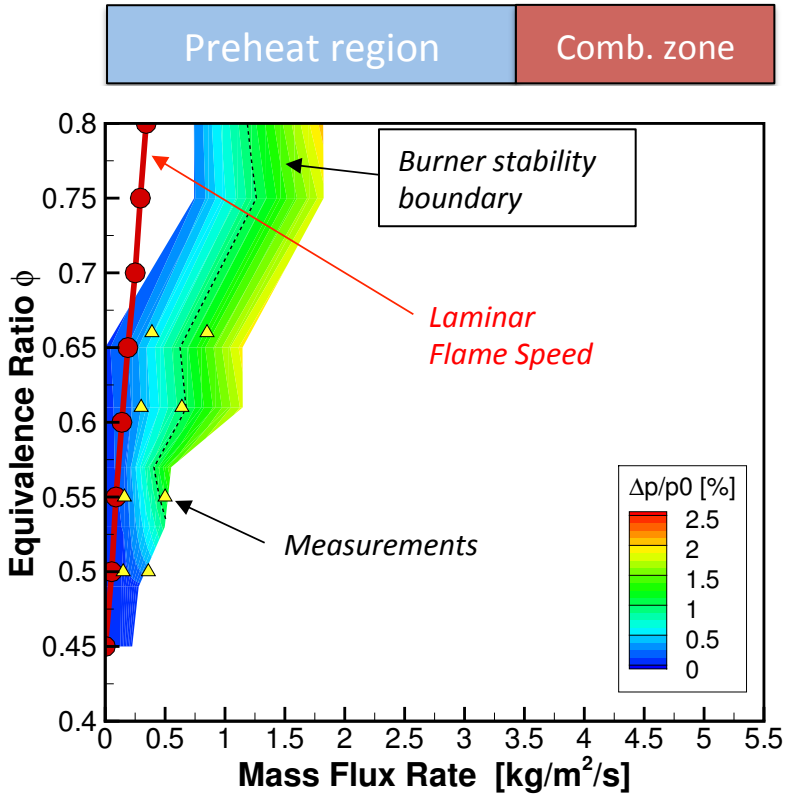
Results and Burner-Design Analysis

- Two-zone step-profile PMB



Results and Burner-Design Analysis

- Two-zone step-profile PMB



Main Findings

- Developed volume-averaged model for design-analysis and performance characterization of PMBs
- Through computational modeling, identified new PMB-concept that exhibits significantly increased stability range and lower pressure drop compared to conventional two-zone step-profile PMBs
- New PMB concept achieves required mass-flow rates necessary for integration in gas-turbine engines!

CONCLUSIONS AND MAIN CONTRIBUTIONS

Conclusions and Main Contributions

- Performed system analysis to demonstrate feasibility of PMB-integration into gas-turbine engine
- Performed life-cycle tests to evaluate performance, stability and durability of PMBs (>400 hours continuous run, >1000 on/off cycles)
- Developed advanced non-intrusive XCT diagnostics for volumetric evaluation of flame-structure inside porous matrix
- Performed design-optimization to identify new PMB-concept having significantly higher stability range at lower pressure drop

DISTRIBUTION/DISSEMINATION

Distribution/Dissemination

Publications and Proceedings

- J. Dunnmon, S. Sobhani, T. W. Kim, A. Kovscek, and M. Ihme, "Characterization of scalar mixing in dense gaseous jets using X-ray computed tomography." Experiments in Fluids, 56, 193, 2015
- J. Dunnmon, S. Sobhani, M. Wu, R. Fahrig, and M. Ihme, "An investigation of internal flame structure in porous media burners using X-ray computed tomography." Proceedings of the Combustion Institute, 2016, under review.
- J. Dunnmon, M Wu, Y. Xia, S. Sobhani, R. Fahrig, and M. Ihme, "3-D flame characterization via X-ray computed tomography." International Conference on Theoretical and Applied Mechanics, August, 21-26, 2016, Montreal, Canada.
- M. Wu, J. Dunnmon, Y. Xia, W. Hinshaw, N. Pelc, A. Maier, R. Fahrig, and M. Ihme, "X-ray computed tomography of flame structure in porous media burners." 4th International Conference on Image Formation in X-Ray Computed Tomography, July 18-22, 2016, Bamberg, Germany.

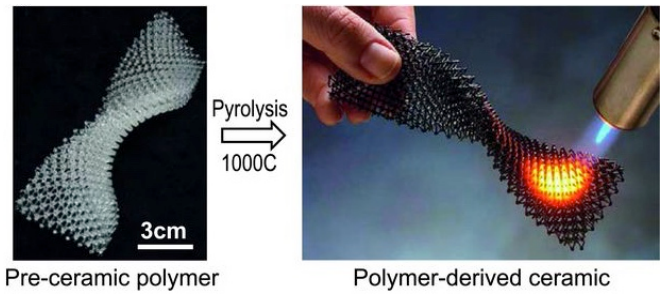
Conferences

- J. Dunnmon, S. Sobhani, W. Hinshaw, R. Fahrig, and M. Ihme, "High-energy X-ray absorption diagnostics as an experimental combustion technique." American Physical Society, Division of Fluid Dynamics, Nov. 22–24, 2015, Boston, MA
- S. Sobhani, J. Dunnmon, M. Werer, M. Ihme, "Coupling micro-CT with computer simulations to analyze dispersion in porous media." American Physical Society, Division of Fluid Dynamics, Nov. 22–24, 2015, Boston, MA
- J. Dunnmon, S. Sobhani, W. Hinshaw, R. Fahrig, and M. Ihme, "High-Energy X-ray for visualizing flame structure within a porous media burner," Thermal and Fluid Sciences Affiliates Conference, Feb. 3-5, 2016, Stanford, CA.

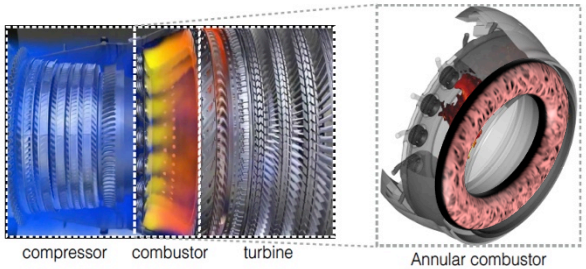
NEXT STEPS

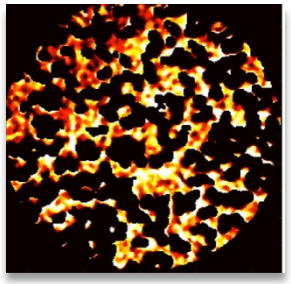
Next Steps

- New burner concept
  - Advanced manufacturing of tailored matrix structures
  - Experimental investigations and detailed modeling



- Evaluate performance and durability at aviation-relevant conditions
  - Life-cycle test of continuous stabilization PMB
  - Operating with liquid fuels and pressurized conditions (8 bar, 600K preheat temperature)



- Computational modeling and theoretical analysis
  - Combustion regime-diagram for heterogeneous combustion
  - Pore-resolved modeling of PMBs

- XCT-diagnostics
  - Advanced reconstruction techniques
  - Application to time-dependent flames
  - Validation data for pore-resolved models
  - Pore-topology extraction through use of micro-CT