Film Cooled Recession of SiC/SiC Ceramic Matrix Composites: Test Development, CFD Modeling and Experimental Observations

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41st International Conference on Metallurgical Coatings and Thin Films
San Diego, California
April 28- May 2, 2014

Acknowledgements

The work was supported by NASA Fundamental Aeronautics Programs, and Aeronautical Science Project.

The authors are grateful to

Janet Hurst and Mike Halbig in helpful discussions

Robert Pastel for assisting High Pressure Burner Rig Testing

Tiffani Casper and George R. Harpster for assisting the CAD drawings and CAD designs of the rig and test fixtures used for modeling

Abstract

In this paper, we describe a comprehensive film cooled high pressure burner rig based testing approach, by using standardized film cooled SiC/SiC disc test specimen configurations. The SiC/SiC specimens were designed for implementing the burner rig testing in turbine engine relevant combustion environments, obtaining generic film cooled recession rate data under the combustion water vapor conditions, and helping developing the Computational Fluid Dynamics (CFD) film cooled models and performing model validation. Factors affecting the film cooled recession such as temperature, water vapor concentration, combustion gas velocity, and pressure are particularly investigated and modeled, and compared with impingement cooling only recession data in similar combustion flow environments. The experimental and modeling work will help predict the SiC/SiC CMC recession behavior, and developing durable CMC systems in complex turbine engine operating conditions.

Outline

- **Recession of SiC/SiC and Environmental Barrier Coatings in Combustion Environments**

- **Development of Simulated High Pressure Burner Rig Testing**
  - Achieving high pressure and high velocity
  - High Temperature film cooling

- **Experimental Observed Recessions under Impingement and Film Cooled Conditions for SiC/SiC in Simulated Testing**

- **Development of 3-Dimensional (3D) Computational Fluid Dynamics (CFD) Modeling and Tools for Burner Rig Simulated Recession Testing**

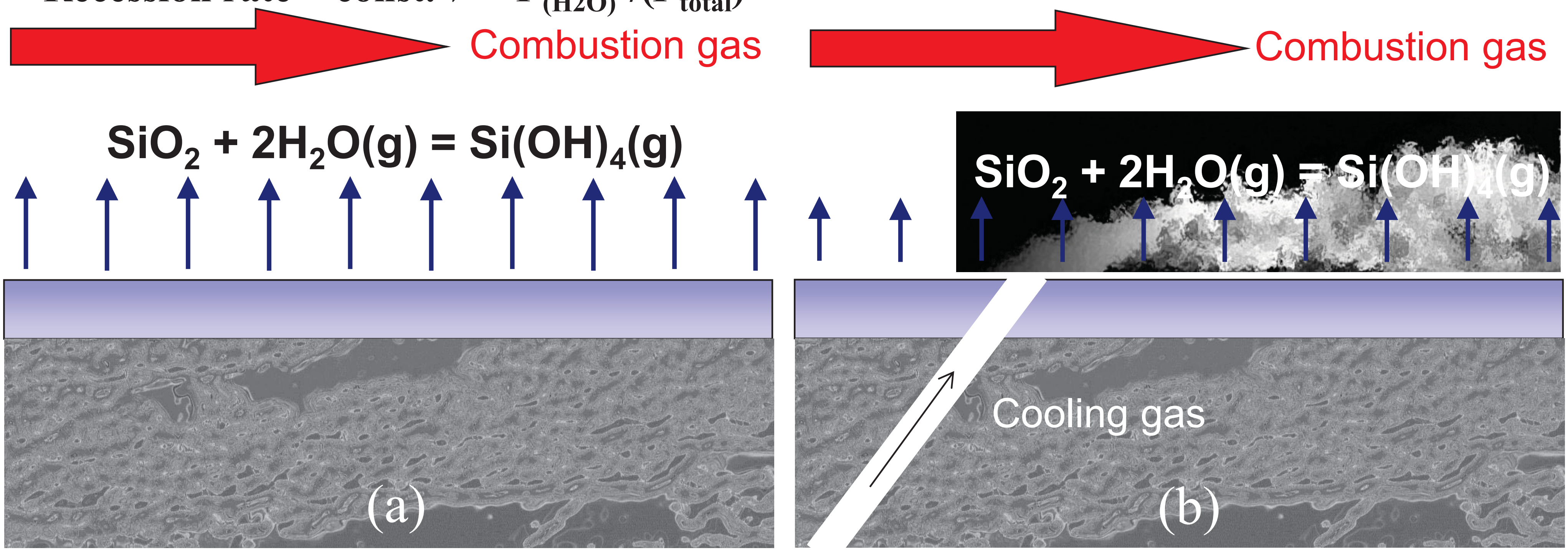
- **Film Cooled Recession of SiC/SiC**
  - CFD Models
  - Experimental Measurements

- **Summary**

SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

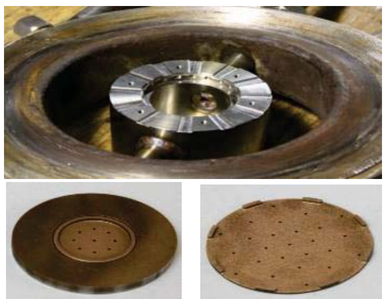
- **Recession of Si-based Ceramics**
  (a) convective; (b) convective with film-cooling
- **Advanced rig testing and modeling** (coupled with 3-D CFD analysis) to understand the recession behavior in High Pressure Burner Rig
  - Work primarily supported under the ERA Combustor and FAP Supersonics projects

Recession rate = const. $V^{1/2} P_{(H2O)}{}^{2}/(P_{total})^{1/2}$

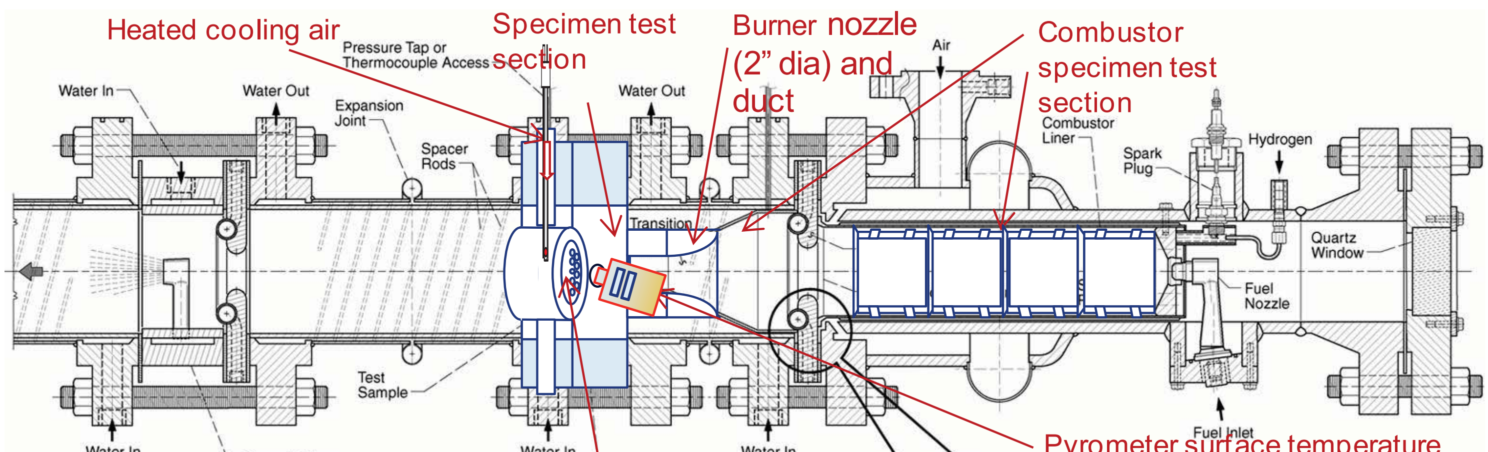
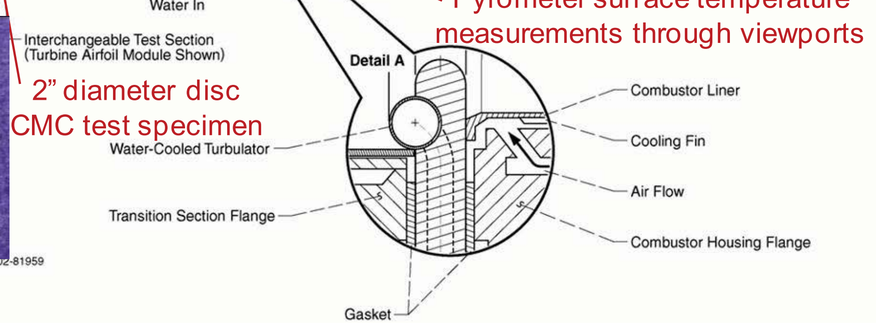


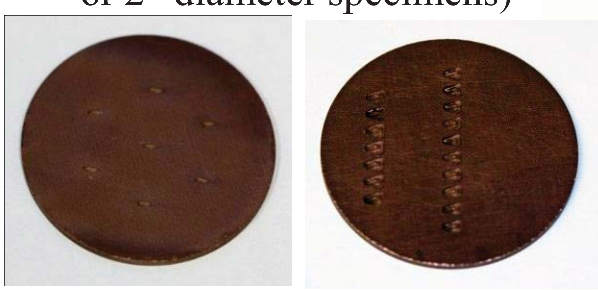
Experimental: Development of Advanced High Temperature Impingement and Film Cooling Testing Approaches

- Jet fuel & air combustion with mass air flow 1.5-2.0 lb/s and gas temperature up to 3000°F (1650°C)
- Improved pressure to 16 atm by added cooled exhaust air and improved liner cooling configurations
- Significantly improved burner gas velocity by incorporating advanced internal nozzles (up to 850 m/s combustion gas velocity in the turbine testing section)
- Adjustable testing pressures from 4 to 16 atmospheres independent controls of sample temperature, testing pressure, and gas velocity
- Incorporated advanced air preheater for 800-1200°F cooling air for high temperature film cooling
- Designed 2” diameter film cooled specimens for model development and validation

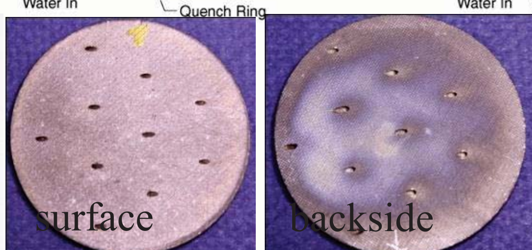


High heat flux cooled CMC-EBC tests (accommodate 1” or 2” diameter specimens)



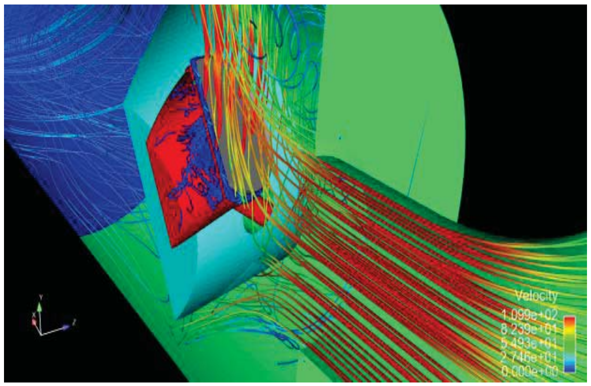
Film cooled 7 and 17 hole CMC specimens



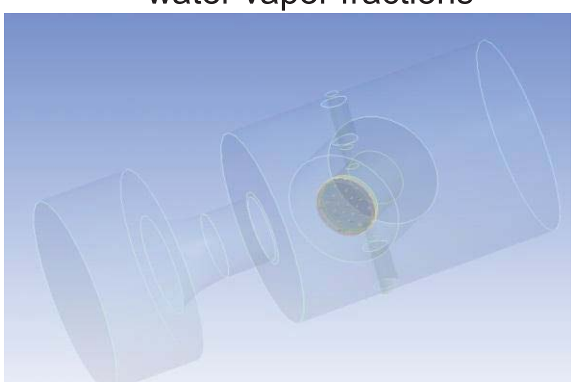
Tested 10-hole film cooled CMC specimen

3 Dimensional (3D) CFD Modeling Approaches

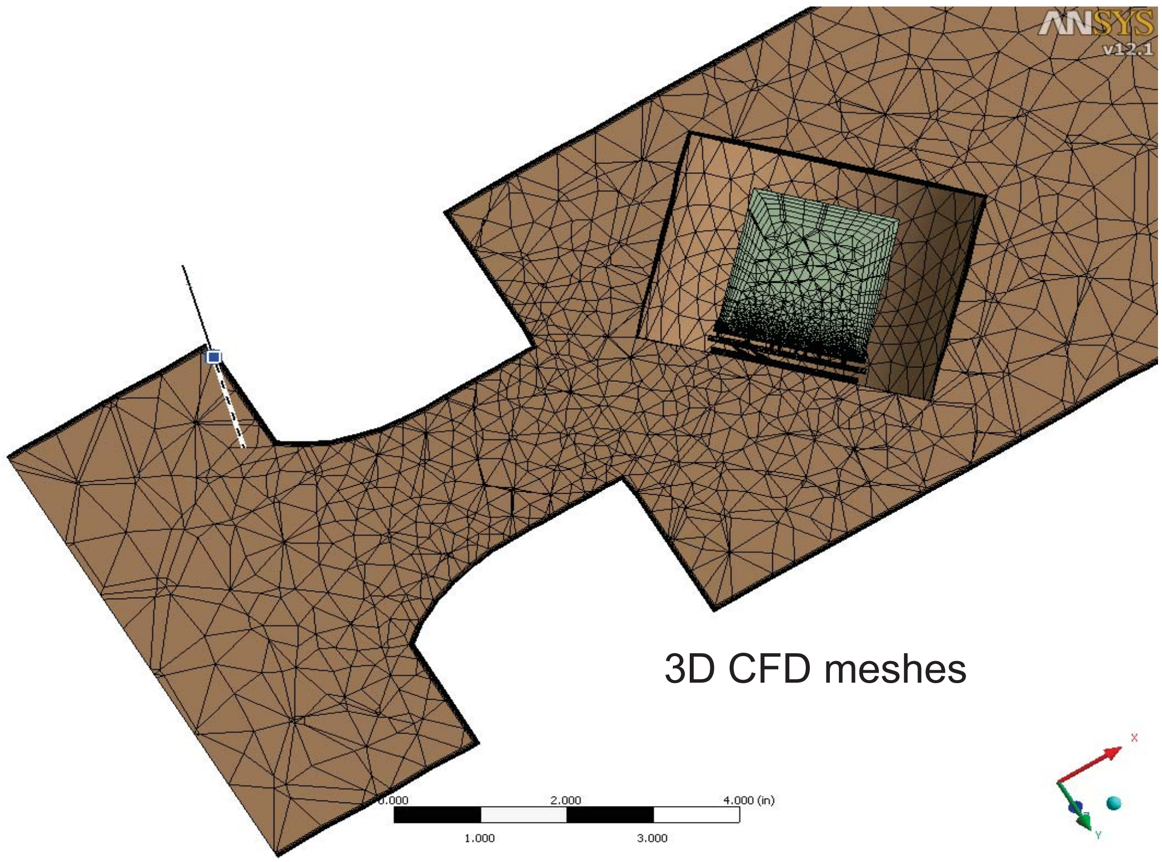
– Emphasize the cooling and jets flow interactions, temperature and water vapor contents
  - CFD model input – Combustion gas, mass air flows, pressures, boundary conditions, and specimen configurations
  - CFD model output: heat transfer coefficients, heat fluxes, velocity, and temperatures
  - The work aiming at predicting CMC-EBC recession



The CFD modeling of film cooled CMCs included cooling hole subelements, and water vapor fractions



3D CFD models of NASA impingement and film cooled CMC-EBC specimens

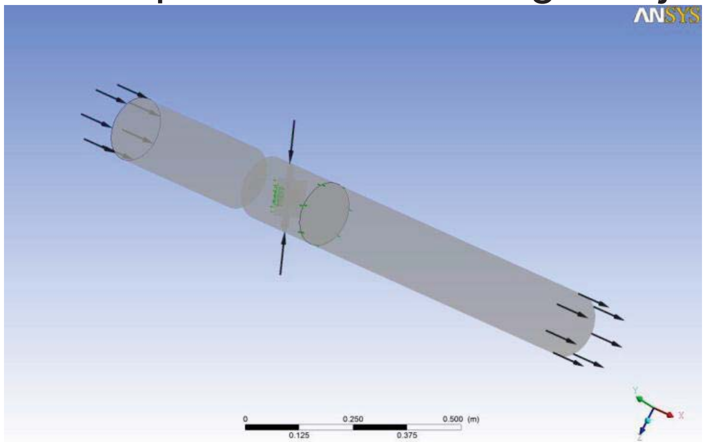


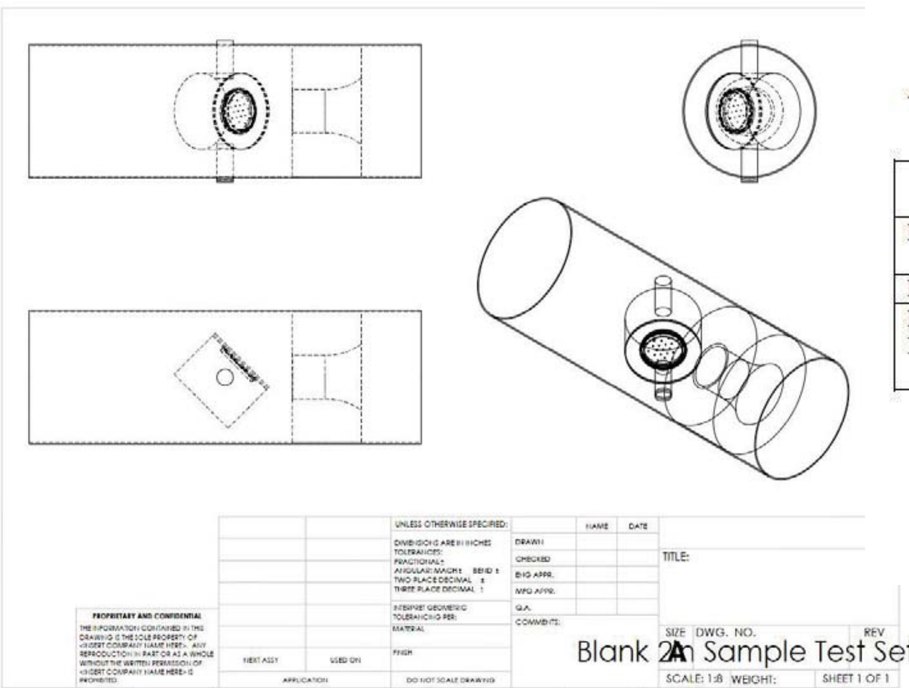
3D CFD meshes

Meshes

CFD Modeling Approaches for SiC/SiC Film Cooling - Continued

– Emphasize the cooling and jets flow interactions, temperature and water vapor contents





Main Inlet: JET-A Fuel Combustion (Real Gases)
OF Ratio (Mass) = 0.045
800 Deg F Cooling Air (Real Gas)
7 and 10 Hole Configurations With Sample Heat Transfer
1.5 in Nozzle Diameter
Manifold Flow Rate Total (2*0.01) lbm/s
Combustion Flow Rate 1.7 lbm/s
Thermal Model of Sample Included

A CFX model was created of a 7 and 10 hole SiC/SiC specimen under the following conditions:

TABLE 3.a: CFX Input Run Summary for 7 and 10 Hole Specimens

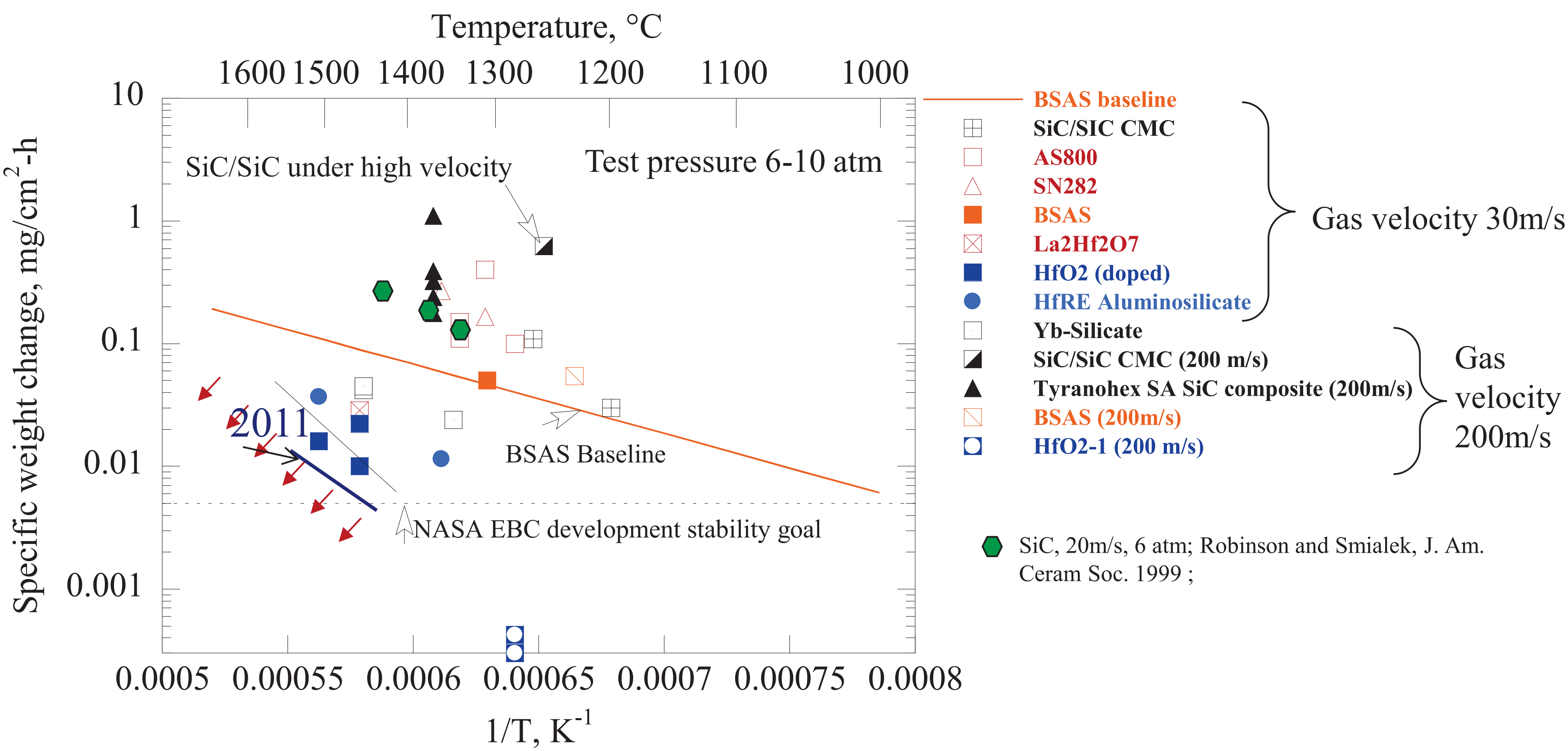
	TEMPERATURE	PRESSURE	FLOWRATE	CONSTITUENTS/MASS FRACTION
MAIN INLET	200 Deg F	Calculated	1.4 lbm/sec	Jet-A/0.043 O_2/0.223
MAIN OUTLET	Calculated	200 psi	Calculated	Calculated
MANIFOLD INLET	800 Deg F	Calculated	2.0*1.0E-2 lbm/sec	Air

TABLE 3.b: MESH INFORMATION

	NUMBER OF ELEMENTS FLOW MODEL	NUMBER OF ELEMENTS THERMAL MODEL
7 HOLE MODEL	4715517	1158266
10 HOLE MODEL	4714761	1158230

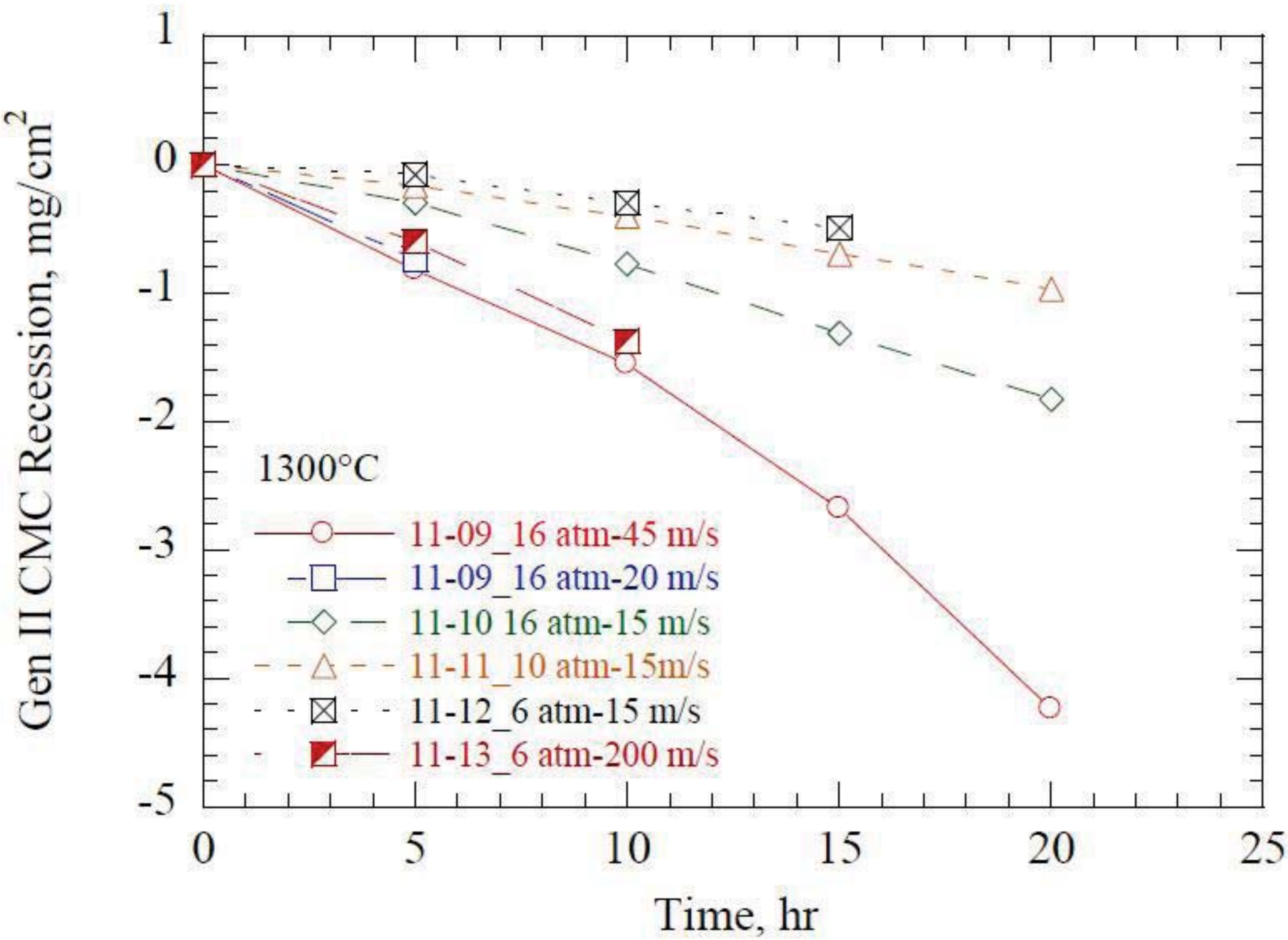
Environmental Stability and Recession Weight Loss of SiC/SiC and Selected Environmental Barrier Coating Materials Measured in NASA High Pressure Burner Rig

— CMC and EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environment



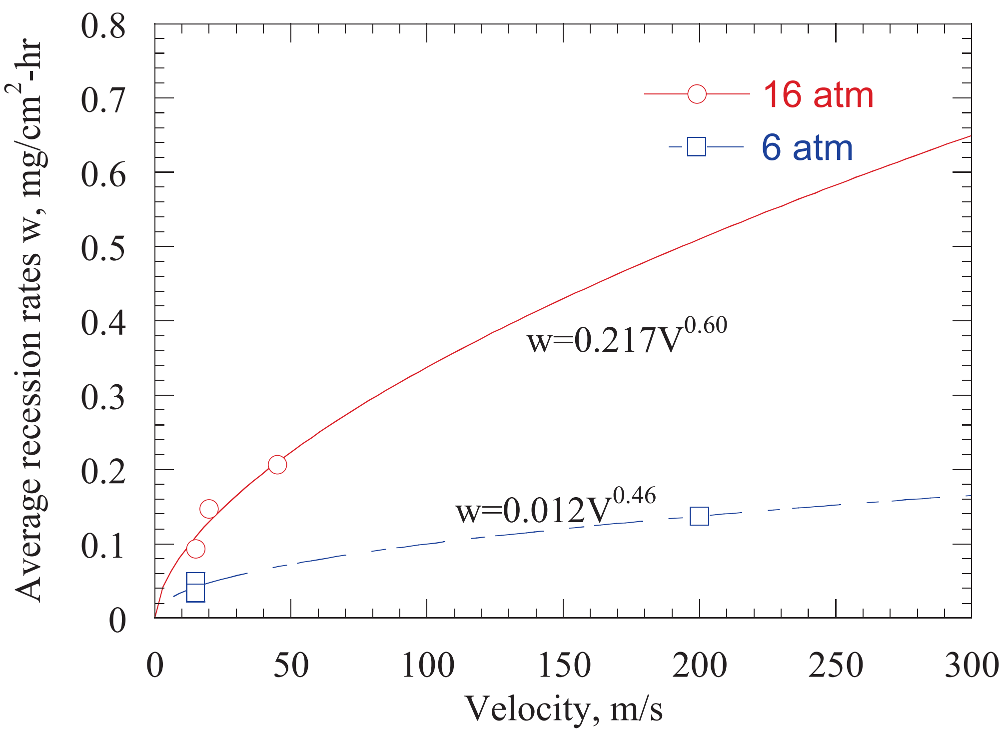
Recession of Generation II Prepreg SiC/SiC Ceramic Matrix Composites Determined in High Pressure Burner Rig under Impingement Cooling at High Pressure and High Velocity

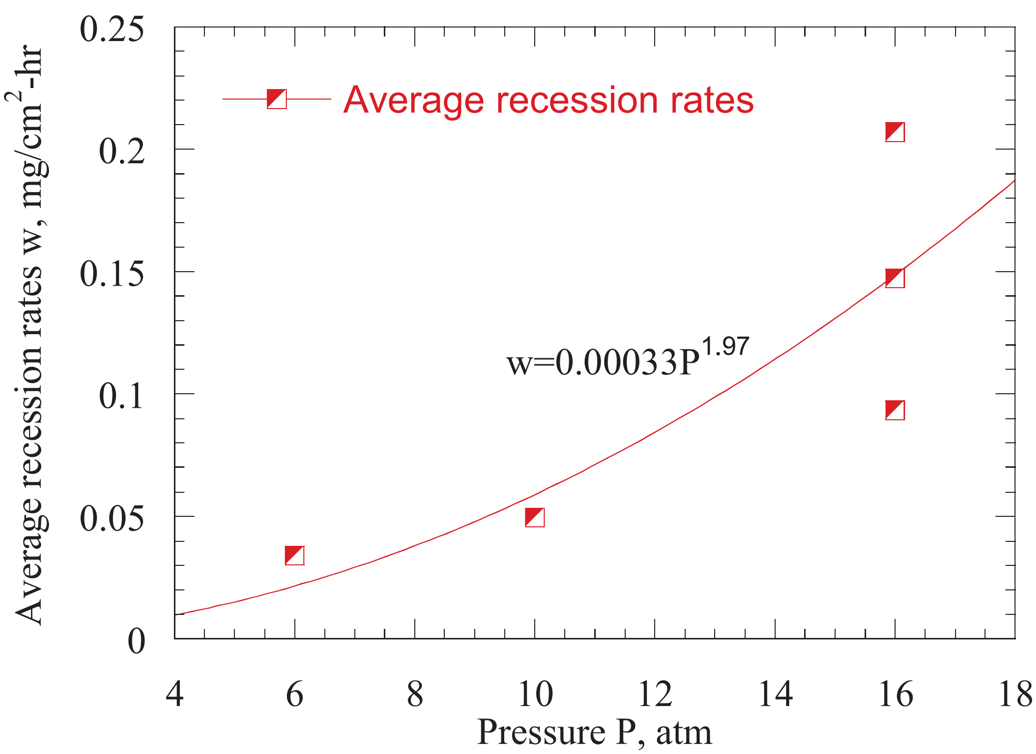
– The velocity and pressure dependence of the recession rates of SiC/SiC determined under high pressure burner rig



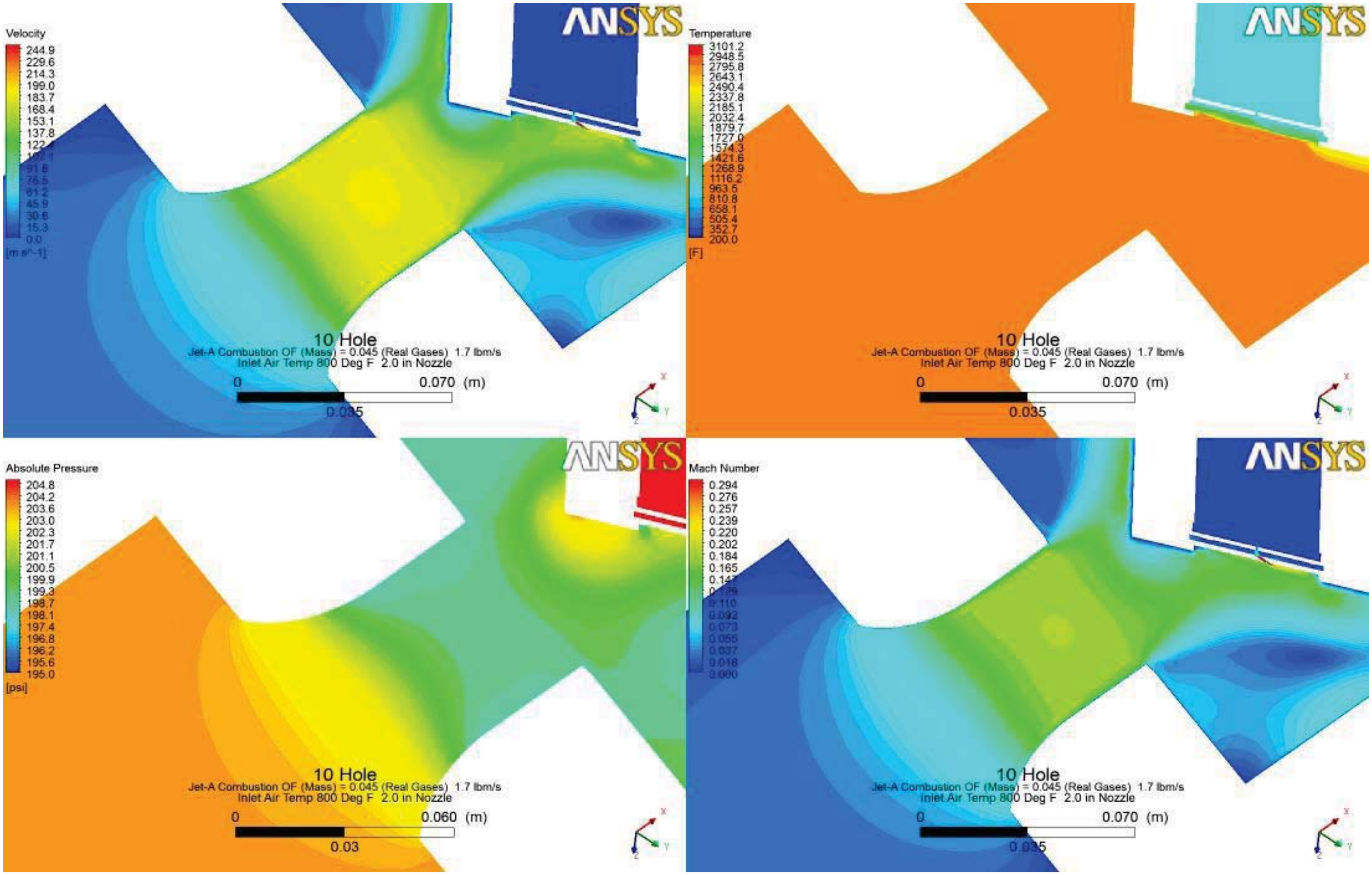
Recession of Prepreg SiC/SiC Tested in High Pressure Burner Rig under Impingement Cooling

– The velocity and pressure dependence of the recession rates of SiC/SiC determined under high pressure burner rig testing conditions



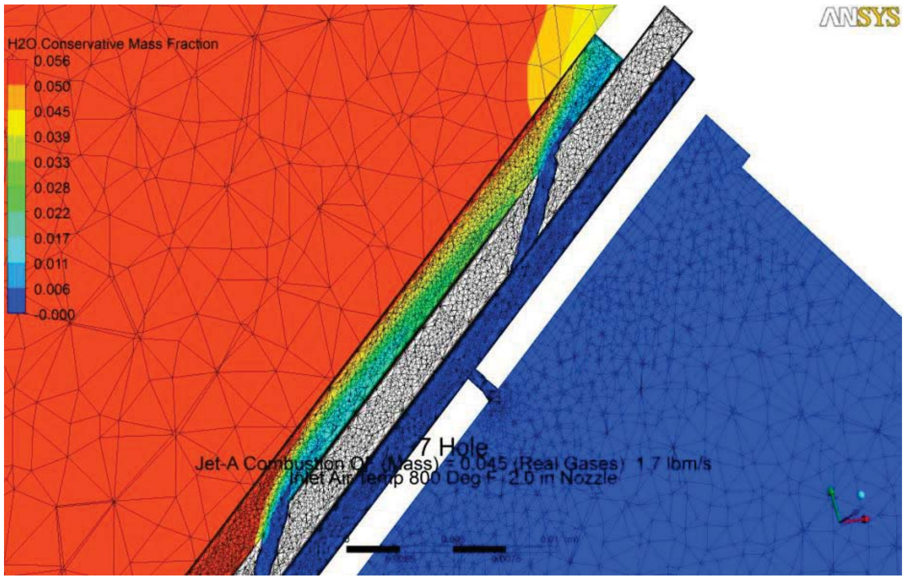


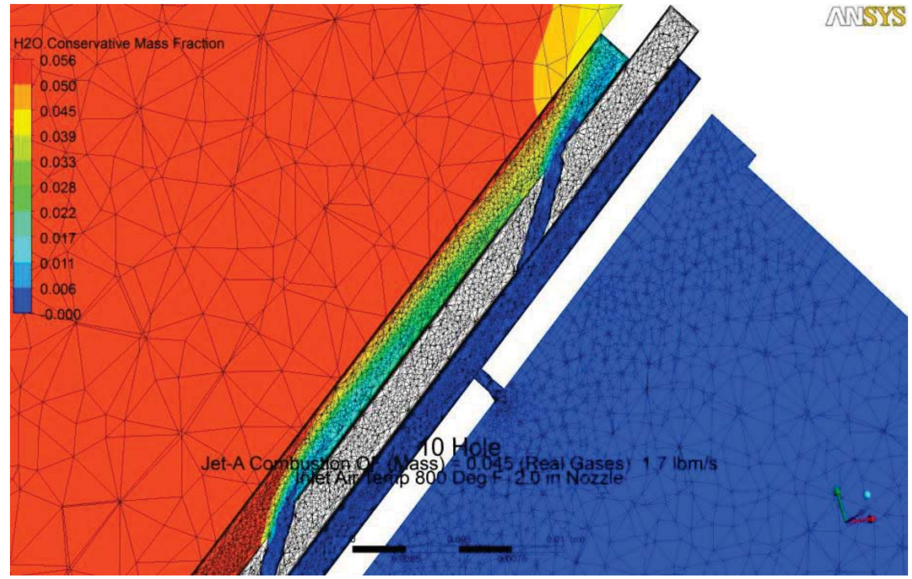
CFD Modeling of Velocity, Temperature, Pressure, Mach Number of a 10 hole Film Cooled Specimen

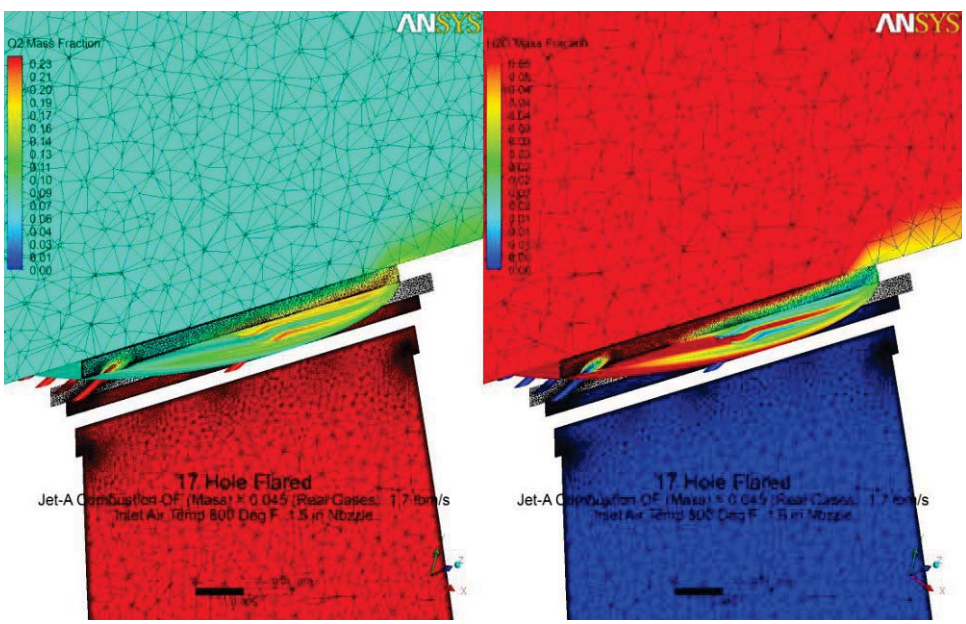


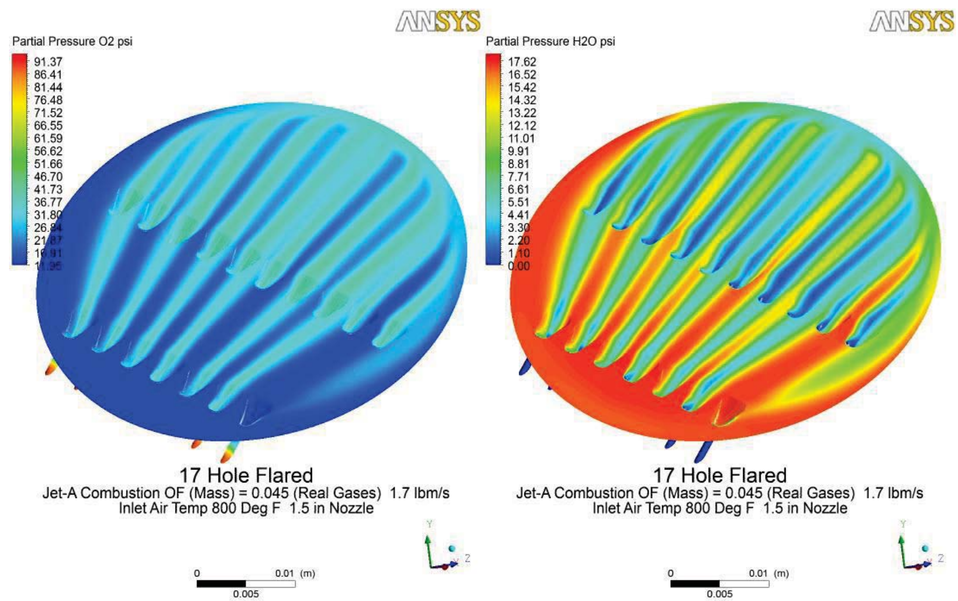
Modeled Mass Fraction H_2O in Various Specimen Configurations

– Reduced water contents under high pressure burner rig film cooled testing conditions

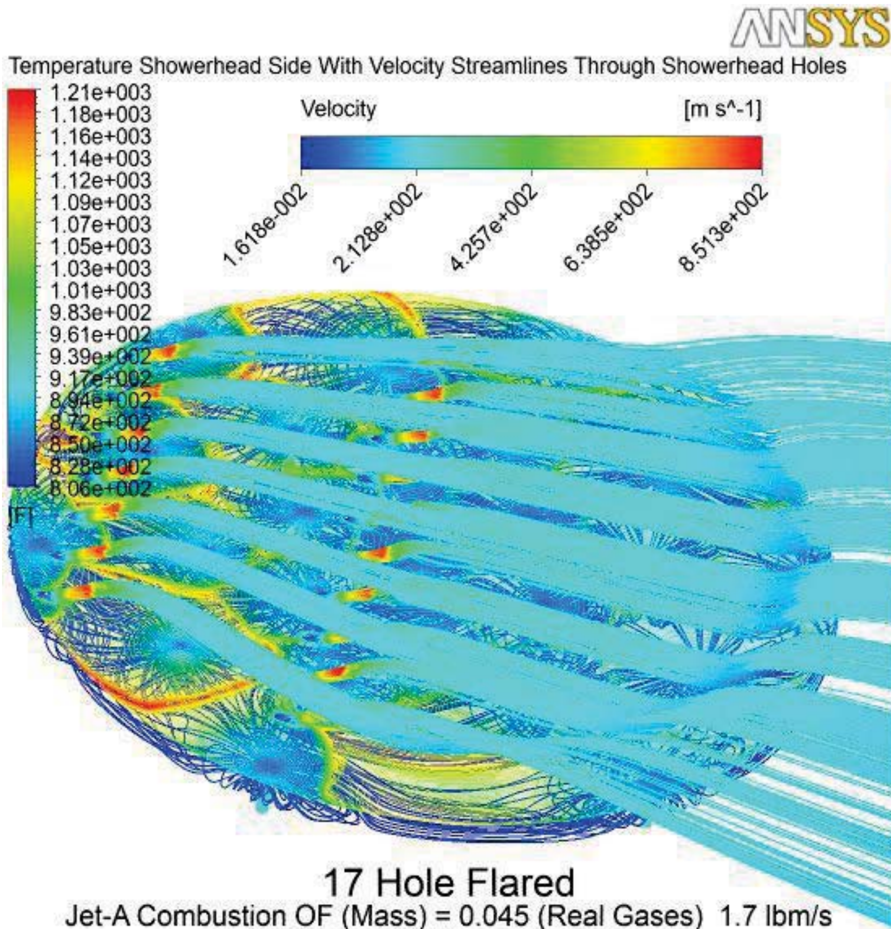




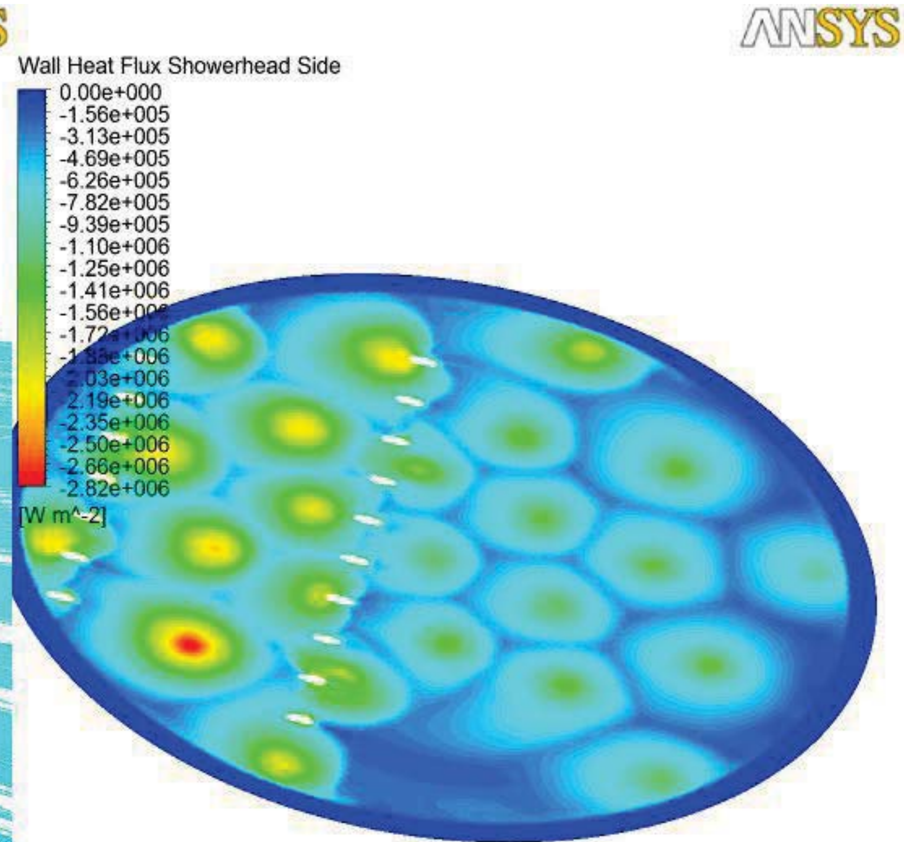




Velocity and Heat flux of Expanded Jets Specimens



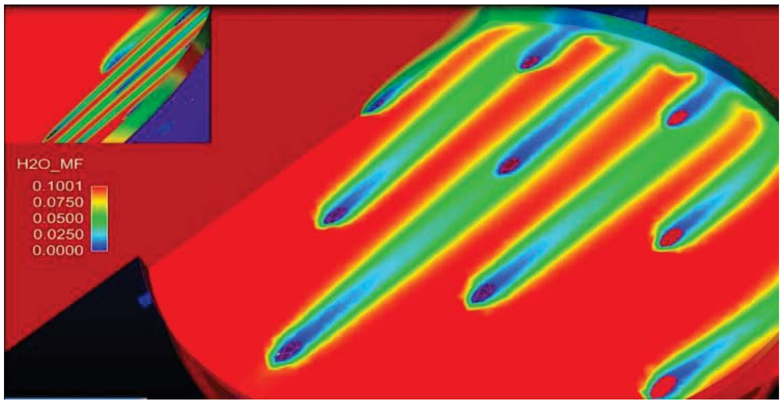
17 Hole Flared
Jet-A Combustion OF (Mass) = 0.045 (Real Gases) 1.7 lbm/s
Inlet Air Temp 800 Deg F 1.5 in Nozzle



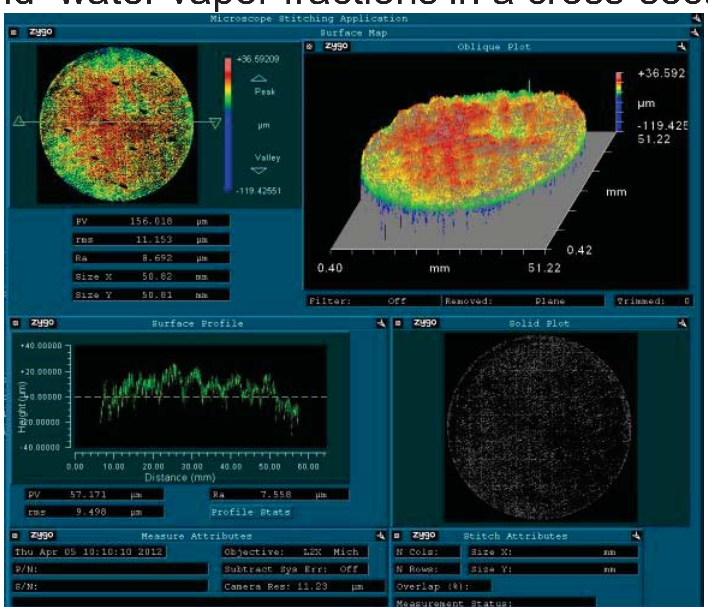
17 Hole Flared
Jet-A Combustion OF (Mass) = 0.045 (Real Gases) 1.7 lbm/s
Inlet Air Temp 800 Deg F 1.5 in Nozzle

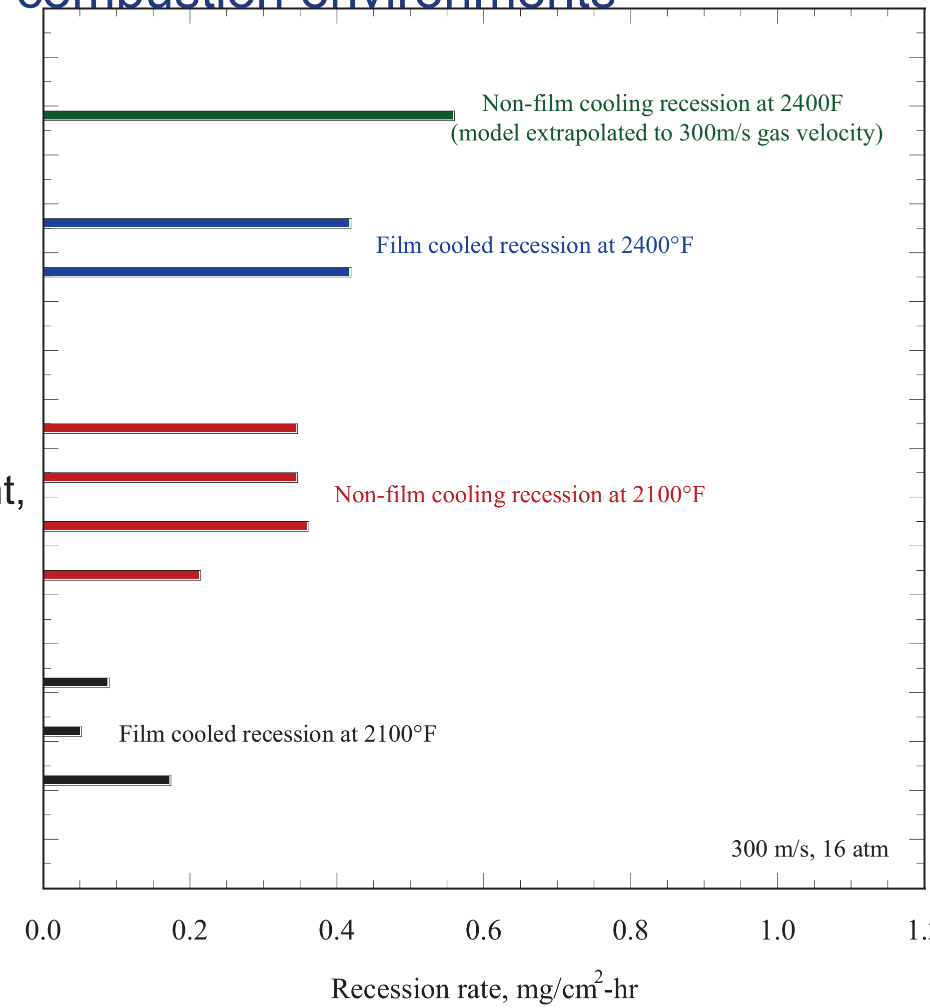
High pressure Burner Rig Film Cooled Tested Specimens – Recession Comparisons

- Reduced recession in film cooling
- Potentially improve EBC-CMC stability in combustion environments



The CFD modeling of a film cooled CMC 10 hole subelement, and water vapor fractions in a cross-section view





High temperature recession kinetics for film-cooled and non-film cooled SiC/SiC specimens tested at NASA High Pressure Burner rig

Summary

– **Advanced high pressure high velocity impingement and film cooled testing approach developed in simulated rig combustion conditions**
  - Achieved 16 atm, 300 m/s velocity, and heated cooling air capable testing at 1316°C (2700°F)

– **Recessing of Generation II Prepreg SiC/SiC CMC determined in rig simulated environments**
  - Determined velocity and pressure dependence of the SiC/SiC of impingement cooled recession
  - Determined recession of various hole configuration specimens
  - Film cooled recession specimens showed reduced surface recession

– **3D CFD models developed for simulated film cooling testing**
  - Comprehensive modeling helps understand film cooling flow, heat transfer and water vapor content
  - CFD model validated through experiments