Level-set Modeling Simulations of Chemical Vapor Infiltration for Ceramic Matrix Composites Manufacturing

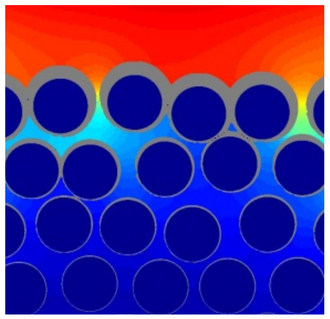
Ramanan Sankaran and Richard A. Lowden (Oak Ridge National Laboratory)

Chong M. Cha (Rolls-Royce Corporation)

HPC4 MANUFACTURING

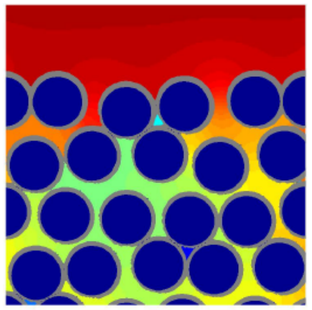
Motivation

Optimize Chemical Vapor Infiltration (CVI) of gas into an evolving porous medium and obtain a uniformly densified product. Produce a larger variety of gas turbine components amenable to Ceramic Matrix Composites (CMC) manufacturing.



Infiltration is poor, fast surface densification creates internal voids.

Vapor infiltration



Infiltration is good, but manufacturing time is too long.

Challenge

In CVI, the vapor needs to completely infiltrate and egress from an evolving, complex network of channels. The fluid network is initially characterized by the preform, which could be a 3-D weave shaped in large part like the gas turbine component itself. The flow network evolves as the solid matrix material is deposited, at times causing inaccessible pores. High porosity and lack of uniformity reduces manufacturing part yield.

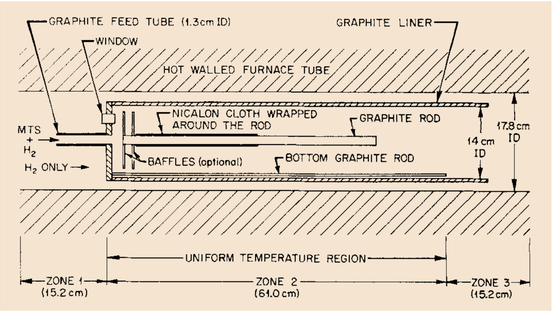
Approach

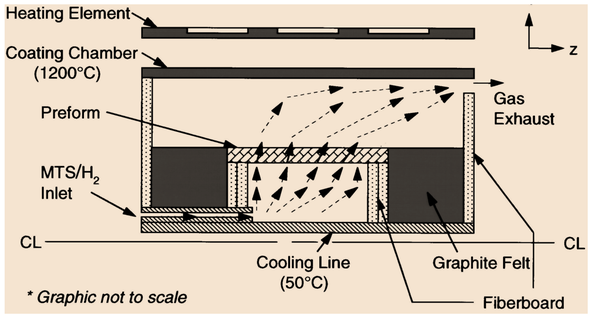
Direct numerical simulation (DNS) using level-set method is employed to track the growth of the solid phase through interface tracking. The numerical model accounts for the local effects on the surface growth due to finite rate chemical kinetics and Thiele modulus (Damkohler number).

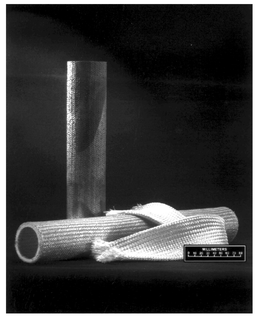
The DNS3D code developed by ORNL includes level-set and multi-component chemical kinetics capabilities. DNS3D has been programmed to be massively parallel and uses the Kokkos programming model for performance portability. Code demonstrated on many-core processors and GPU accelerators, such as the OLCF Titan system.

DOE CMC programs at ORNL

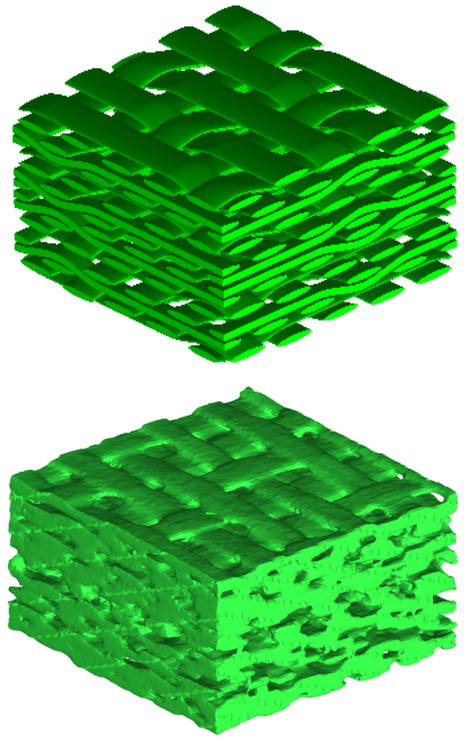
In the 1980s, ORNL pioneered forced-flow thermal gradient CVI (FCVI) to reduce the process time[1]. DOE's Continuous Fiber Ceramic Composite (CFCC) program ran from 1992 to 2002 and supported industrial development of CMCs







Configuration of the CVI reactors used in ORNL experiments. (Left) Isothermal CVI[2]. (Middle) Tubular forced CVI[3]. Photograph on the right shows a cloth sleeve, a rigidized preform and an infiltrated tube[3].



A validation case using a 5HS fiber weave before CVI (top) and after processing (bottom).

Objectives

Direct Numerical Simulations (DNS) using a high resolution interface tracking method will be conducted to study the evolution of the preform densification. Experimental cases progressing from simple to complex geometries will be simulated. ORNL's experimental data and the 5HS weave geometry data from Rolls-Royce will be used for validation.

Simulated results will be analyzed for global quantities such as porosity and tortuosity. Microstructural statistics associated with XCT data will also be compared. Sensitivity to flow parameters and kinetics will be evaluated. The validity of semi-empirical mean-field submodels used in the industry will be verified.

Benefits

Presently, CVI processing has largely been optimized by trial-and-error due to its high complexity. The optimization of CVI will be accelerated by simulations which show the porous structure evolution of the preform densification. HPC simulations will allow a much cheaper, virtual method to reduce CVI manufacturing time, for example, by evaluating multiple fiber weave geometries.

The high temperature capability of CMCs allow for smaller cores in gas turbine engines, which improves specific fuel consumption (SFC) due to a higher core pressure and/or larger bypass ratio. The reduced weight of CMC components also allows for lighter supporting structures, further reducing SFC. Total savings in SFC alone are estimated to be ~10%.

1. Caputo, A. J., W. J. Lackey, and D. P. Stinton. 1985. "Development of a New, Faster Process for the Fabrication of Ceramic Fiber-Reinforced Ceramic Composites by Chemical Vapor Infiltration."
2. Sheldon, B. W., and T. M. Besmann. 1991. "Reaction and Diffusion Kinetics During the Initial Stages of Isothermal Chemical Vapor Infiltration."
3. Probst, K. J., T. M. Besmann, D. P. Stinton, R. A. Lowden, T. J. Anderson, and T. L. Starr. 1999. "Recent Advances in Forced-Flow, Thermal-Gradient CVI for Refractory Composites."

*Images are not to scale.

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