VII.G.7 Application of Advanced Computer-Aided Engineering (CAE) Methods for Quality and Durability of Fuel Cell Components

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Objectives

- Accelerate implementation of fuel cell technologies.
- Improve fuel cell component development time, cost, and performance.
- Develop computer-aided engineering (CAE) processes that improve understanding of the effects of variation on fuel cell stack and component performance.
- Demonstrate fuel cell applications of integrating CAE methods with advanced design techniques.
- Transfer successful applications of advanced CAE tools and methodologies to the fuel cell industry.

Technical Barriers

This work has direct impact on overcoming technical barriers such as durability and cost and achieving DOE's technical targets of energy efficiency and specific power. This project specifically addresses items:

- A. Durability
- B. Cost (stack material and manufacturing cost)

of the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. This project is helping DOE meet its milestones under Fuel Cell Task 14.

Approach

- Work with fuel cell industry partners to apply CAE tools to address specific key technical barriers.
- Improve component reliability by applying robust design techniques for optimal solutions that account for variations in material properties, loads, and manufacturing processes.
- Develop reusable CAE models and processes that can be used by the fuel cell industry on future applications.
- Lower costs and development time by reducing the number of prototype components that are built and tested.
- Transfer the results of simulating the effects of variation in material properties, loads, and manufacturing processes on stack and component performance.

Accomplishments

- Robust Fuel Cell Stack: Demonstrated the probabilistic design methodology on a fuel cell stack and applied lessons learned to a number of stack designs.
- Manufacturing Process Improvement: Helped improve bi-polar plate manufacturing processes by modeling cathode and cooler plate ejection processes.
- Auto-Thermal Reformer (ATR): Improved ATR component designs by modeling the effect of thermal fatigue and various component placements/geometries on constituent flow distributions.
- Robust Seals: Determined alternative gasket and groove configurations of the cooler and cell interfaces to provide robust sealing.
- Hydrogen Generation Component Optimization: Used analysis to guide design changes of bi-polar plates and end-plates for improved strength.
- High-Temperature Stack: Developed innovative 3-D stack thermal/flow model used to conduct design parameter investigations and improve thermal performance.

Future Directions

- Project diversification with new partners and advanced CAE applications:
  – Focus on design for manufacturability and quality accounting for material, load, and manufacturing process variations with additional industry partners
  – Conduct carbon storage design space investigations and thermal analysis using probabilistic methods
- Transfer technology to the fuel cell industry through publication of successful CAE methods for fuel cell applications.
- Continued robust design optimization of high-temperature stack thermal design, gasket seals, and stack components.

Introduction

Enhancing performance and durability while reducing costs and compressing development schedules are top priorities for the fuel cell industry. Since the industry is relatively new, limited design rules, codes, standard practices, experience, and data are available to guide the design process. In particular, the industry has a limited understanding of the effects of variation caused by manufacturing, load conditions, and material properties on the performance of fuel cell stack components. The relationship between these variations and stack performance is critical for developing necessary design and manufacturing targets and specifications. In the past, industry has relied heavily on designer experience and rules of thumb, as well as on building and testing physical prototypes. These can be expensive and time-consuming approaches that do not necessarily lead to optimal solutions. Meanwhile, the availability, quality, and sophistication of CAE tools have continued to improve rapidly. At NREL, a team of engineers has been working with industry over the past several years to develop virtual prototyping methods that couple structural, thermal, and fluid flow simulations to variation techniques, advanced design optimization, and quality and performance goals. In the last two years, the NREL team has applied this expertise in collaboration with Plug Power to advance optimal design methodologies for fuel cells while reducing the number of physical prototypes and laboratory tests required. This collaboration is helping to overcome technical barriers, reducing fuel cell development time and costs, and driving innovation.

Approach

The first step in this process is to meet with potential industry partners to identify specific technical barriers that can benefit from these techniques. In FY 2006, NREL plans to initiate collaborations with additional fuel cell industry partners while continuing work with Plug Power. Next, NREL and the industry partners will develop project statements of work that define specific requirements, including design data, key input parameter distributions, experimental data, analysis methods, component performance measures, deliverables, and timelines. NREL will then build the necessary component models and analysis methodologies, perform the analysis, and present the results to the industry partner and DOE. Results will be validated using industry experimental information. Finally, processes developed under this project will be transferred to industry and published jointly with the industry partners.

Fuel cell manufacturers have identified several specific applications that address key technical barriers, including

- Optimization of coolant and constituent flow paths for improved thermal performance of high-temperature stacks
- Robust gasket designs and innovative new concepts for sealing of plate interfaces
- Sensitivity and probabilistic design to improve product development time by reducing the number of design prototypes
- Optimal packaging of fuel cell components.

Results

Over the previous two years, NREL has worked with fuel cell industry representatives to successfully apply advanced CAE techniques such as optimization, probabilistic design, and topology optimization to address specific fuel cell design hurdles. The application of these techniques has led to a number of innovations, including improved structural, thermal, and flow performance of fuel cell and ATR component designs. Several of the NREL design innovations have been implemented on existing fuel cell products. The analysis has also helped to improve product development time by reducing the number of component prototypes. Images from a few of these successful applications are shown in Figure 1. Currently, we are transferring successful design processes to our industry partner through targeted design seminars.

Three areas of notable accomplishments during FY 2005 include the development of

- Nonlinear modeling techniques for gasket seal optimization

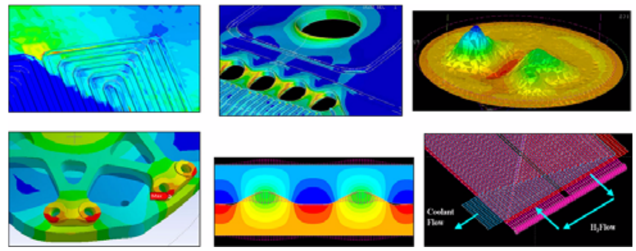

Figure 1. Images from Successful CAE Modeling Applications

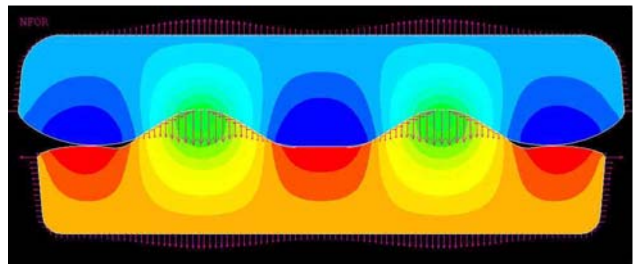

Figure 2. Stress Distribution of Compressed Gaskets

- New thermal modeling models for parameter sensitivity studies on thermal performance
- Topology optimization techniques used to optimize structural designs of end-plates and bi-polar plates.

Additional details on these accomplishments are provided in the following subsections.

Robust Gasket Seals

The objective of this project was to determine alternative gasket and groove configurations of the cooler and cell interfaces to result in robust sealing, which is defined as a design that achieves the required sealing force despite variations in material properties, load characteristics, and manufacturing tolerances. NREL's modeling effort involved developing a parametric, non-linear structural model of the gasket and gasket groove design. The parametric nature of the model allows for automatic reshaping of the gasket and groove geometry to assess the relative impact of the various geometric design parameters. The non-linear aspects of the model include hyperelastic material properties, large component deformations, and contact analysis. Figure 2 shows results from a stress analysis on a typical gasket seal under compression.

FY 2005 accomplishments for this project included:

- Developed a nonlinear, parametric gasket seal analysis model that accounts for variation in gasket and seal geometry, material properties, and loading.
- Developed a process to automatically perform parametric sweeps that identified the required shape and size of the gasket and groove that provides the required sealing force.
- Transferred the gasket analysis process to Plug Power.

Stack Thermal Model

The objective of this project was to develop a stack thermal model that will be used to assess thermal performance and assist in the development of improved heat transfer characteristics. This project involved coupling of Plug Power's electrochemical model with a thermal/fluid flow model developed by NREL. The electrochemical model is used to predict a non-uniform heat generation map. The heat generation map is then processed and applied to the thermal/flow model that predicts 3-D plate, fluid, and membrane temperatures. The membrane temperatures are fed back into the electrochemical model and the process is repeated until convergence is achieved. Figure 3 shows a flow chart of the overall process. The thermal/flow model uses pipe flow elements for rapid analysis of the 3-D stack's thermal performance. The modeling process also demonstrated the integration of design-of-experiments techniques to perform sensitivity studies on heat generation rates, fluid flow, bi-polar plate channel geometry, fluid properties, and plate thermal material properties.

FY 2005 accomplishments for this project included:

- Developed a modeling process that integrates 3-D thermal, flow, and current density simulations.
- Demonstrated the integration of CAE with design of experiments by conducting Taguchi screening of design parameters (flow rates, material properties, channel geometries, etc.) on temperature distributions and pressure drops.

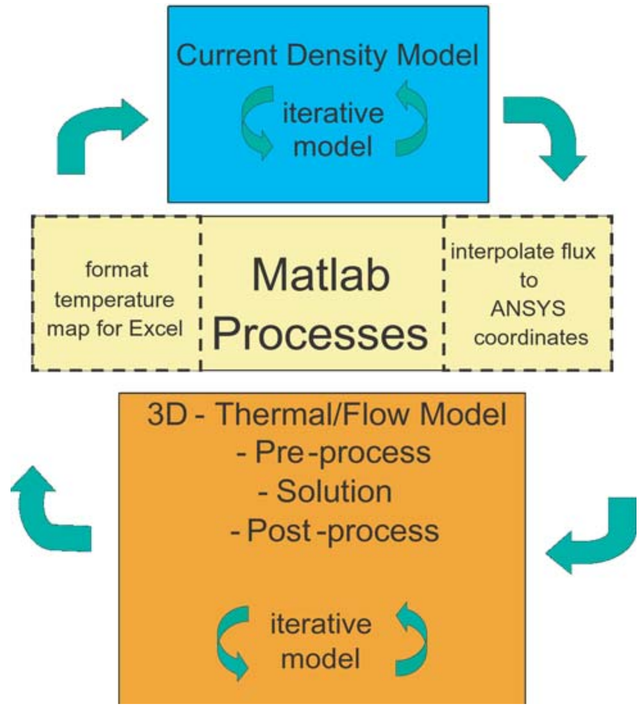

Figure 3. Thermal/Flow Analysis Process Flow Chart

- Modeled alternative coolant flow paths for improved thermal performance.

End-Plate and Bi-Polar Plate Structural Optimization

The objective of this activity is to develop analytical tools for the optimization of end-plate and bi-polar plate designs for reduced end-plate mass and improved membrane electrode assembly (MEA) and bi-polar plate loading characteristics. In this project, NREL demonstrated the application of topology optimization and rapid turnaround of finite element modeling to improve product development time and cost by reducing the number of physical prototypes that were built and tested. Topology optimization is a finite element optimization process that maximizes the structural stiffness of a component while reducing the mass. Structural stiffness of the end-plates can be important to stack manufacturing and performance, as non-uniform deflections are transmitted throughout the stack. These deflections can cause cracking of components during the assembly process as well as non-uniform compression of the MEA. Topology optimization was used to suggest optimal component shaping that

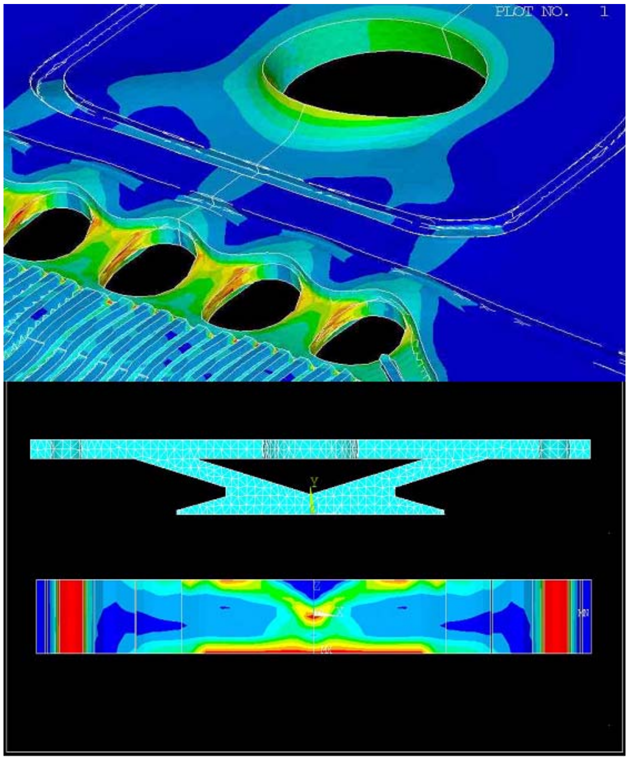

Figure 4. Bi-Polar Plate Stress Analysis and End-Plate Topology Optimization

achieves maximum stiffness while reducing component mass and volume. Figure 4 shows an image of a stress analysis performed on a bi-polar plate and one of the potential end-plate configurations derived from the topology optimization process.

FY 2005 accomplishments for this project included:

- End-plate analysis led to improved bolt pattern, end-plate, and bi-polar plate geometry to avoid plate cracking during assembly.
- Application of topology optimization resulted in new innovative design concepts.
- Rapid stress analysis reduced the number of component prototypes built and tested.

Conclusions

The fuel cell industry continues to rely heavily on designer experience and rules of thumb, as well as on building and testing physical prototypes. These can be expensive and time-consuming approaches that do not necessarily lead to optimal solutions. Meanwhile, the availability, quality, and sophistication of CAE tools have continued to improve rapidly. Over the past several years, NREL has demonstrated the application of a number of advanced CAE techniques that have helped guide fuel cell component design processes and reduced development time and cost. In collaboration with Plug Power, the NREL team has applied this expertise to advance optimal design methodologies for fuel cells while reducing the number of physical prototypes and laboratory tests required. This collaboration is helping to overcome technical barriers, reducing fuel cell development time and costs, and driving innovation.