VII.H.9 PEM Fuel Cell Freeze and Rapid Startup

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Objectives

- Establish a fact-based strategy for rapid startup of proton exchange membrane fuel cells (PEMFCs) from sub-freezing temperatures.
- Investigate the existing proposed solutions to rapid startup of PEMFCs.
- Use system analysis and other tools to aid in evaluating and identifying strategies.
- Aid in developing fuel cells that startup at –20°C in 30 seconds or less.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- A. Durability
- D. Thermal, Air and Water Management
- J. Startup Time/Transient Operation

Technical Targets

Performance Measure	2010	2015
Rapid Startup of PEMFC to 90% Rated Power from –20°C	30 sec	< 30 sec
Max Startup/Shutdown Energy from -20°C (20°C)	5 (1) megajoules (MJ)	5 (1) MJ

Approach

- Collect data/information through literature search and collaborations.
- Conduct a detailed patent search and document the findings.
- Perform energy analysis to bracket energy/power requirements for startup.
- Participate in the DOE fuel cell freeze workshop.
- Use component/system models to evaluate merits of various solutions from fuel efficiency and other factors within a vehicle.

Accomplishments

- We found over the last six years that many patents, more than published articles, have been issued on fuel cell freeze and rapid startup. The majority of proposed concepts/solutions in these patents are from a system level perspective.
- We analyzed and categorized these major patents categories: Water Removal, Keep-Warm, and Thaw/Heating methods.
- We performed preliminary energy analysis of some of these solutions.
- We found that freeze protection and rapid startup strategies should be initiated at shutdown, by removal of water from the fuel cell system at shutdown.
- We found that keep-warm methods do not allow the system to freeze. This method is effective for short-term storage and/or for mild sub-freezing temperatures, but could be an inefficient approach for long-term storage.
- Thawing/heating methods require high power and humidification at startup but may not consume much energy.
- Some combinations of different technologies could be the most promising to address rapid startup.

Future Directions

- Use system and component tools to evaluate and define various strategies for rapid cold startups.
- Evaluate the impact of weather pattern and location on the choice of freeze protection and rapid startup solutions.
- Perform more rigorous evaluation for the freeze start technologies and methods by modifying and using a commercial 3-D PEMFC code.
- Perform system-wise analysis for the possible combinations of promising technologies.
- Partner with industry to evaluate and implement and new approaches and use National Renewable Energy Laboratory (NREL) unique capabilities to aid industry in developing solutions.

Introduction

The inherent presence of water in PEMFC systems creates a problem when vehicles using these power sources are parked in sub-freezing ambient weather conditions. Freeze/thaw cycles could create two issues: Damage - a durability issue for the fuel cell system (e.g., related to internal ice expansion and damage to the cells); and Rapid Startup - a convenience problem for vehicle users if a long warm-up period or large energy input is required before the vehicle could be driven. The objective of the FY 2005 fuel cell freeze and rapid startup research at NREL is to establish a fact-based strategy for coping with these freeze-related issues. We employ our research expertise and relations with industry partners to investigate potential approaches for achieving DOE's fuel cell freeze-start technical targets using system and component analysis tools to analyze, investigate, and develop specific solutions.

Approach

For the first year of this effort, the foundation of our approach was to conduct a thorough literature search to investigate techniques being pursued by experts in the field working to develop a PEMFC cold start strategy. This search helped indicate the subset of strategies and specific techniques deserving of detailed energy and power analysis. Our modeling and analysis have helped to bracket the requirements for sub-freezing startup and evaluate the merits of various proposed solutions. We also sought to maintain our interaction with others in the field by presenting and receiving feedback on our findings. We have also investigated the use and expansion of commercially available modeling tools to enhance available analysis capabilities at both the cell and system levels.

Results

We collected data and information through collaboration and a comprehensive literature and patent search. After mapping and analyzing the over 1,300 fuel cell freeze-related patents from the past 17 years, we arrived at a tabulation of the 177 most relevant patents. Next, we created a solution category chart (see Figure 1). In addition to water removal at shutdown, the proposed solutions could be categorized into two main strategies according to whether the system uses energy during vehicle parking or mostly at vehicle startup. The successful implementation of either strategy requires development of supporting technology groups.

The first, the so-called keep-warm method, does not allow the system to freeze. With this strategy, the system consumes energy/fuel in order to remain above a certain threshold temperature. Our analysis showed that this method is effective for short-term parking and/or for mild sub-freezing vehicle storage temperatures. The energy/fuel consumption requirements, however, are highly dependent on these difficult-to-predict parking time and ambient temperature variables. Supporting technologies for the keep-warm method include system insulation, use of a continuous low-power energy source (from a battery, fuel cell itself, or burning hydrogen), and sensing and control for energy/fuel management during heated parking (for example, turning on and off the fuel cell stack to provide both heating the fuel cell (due to its waste heat) and charging the on-board battery. The fuel cell could also be run intermittently since it creates both waste heat and electricity.

The method of thawing/heating at start does not use energy/fuel during vehicle parking. This technique instead requires energy to warm up the system quickly so it requires high power at system startup. Supporting technologies include water removal from the fuel cell system shut-down, re-humidification at system start, ice management in the system components, and design of the thawing/heating power source.

Analysis of the supporting keep-warm technologies included investigation of the insulation often used around freeze-prone system components. Figure 2 shows the comparison of fuel cell stack temperature variation for different insulation cases when the vehicle is stored at –20°C. The insulation greatly influences the time for the stack to cool from 80°C (normal operating temperature) to 5°C (selected threshold temperature). Insulation, therefore, helps significantly reduce keep-warm energy requirements, but also carries additional volume and weight penalties, which adversely impact vehicle performance, installed power requirements, and cost.

Figure 3 compares the required energy for the keep-warm method using one-inch of insulation and the thaw at start method using no insulation (which assumes the system is started from the given cold-soaked temperature). The calculations for each

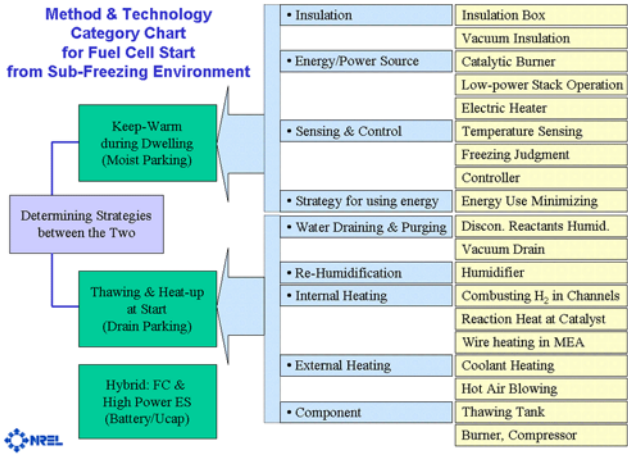

Figure 1. Solution Category Chart for PEMFC Freeze Startup from Patent Categorization

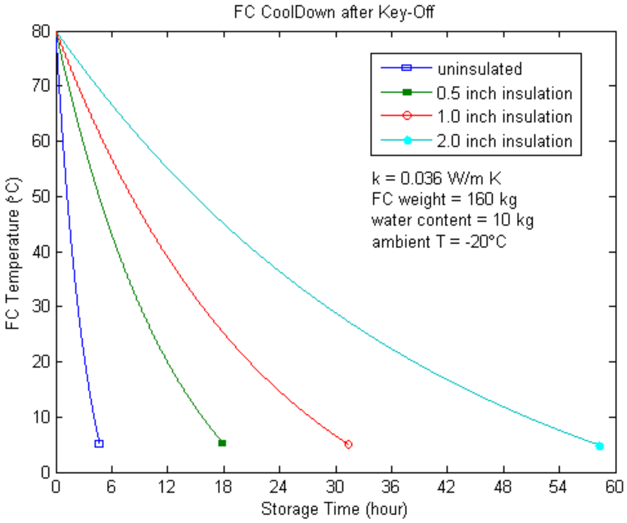

Figure 2. FC Cool-Down after Key-Off

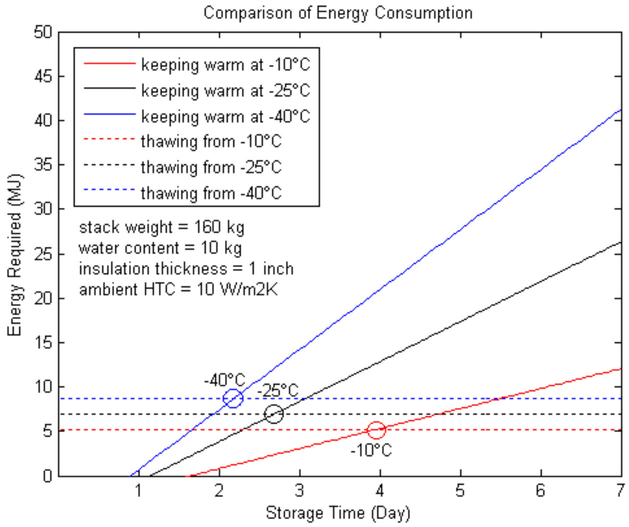

Figure 3. Energy Consumption Comparison between Keep-Warm and Thaw at Startup Methods

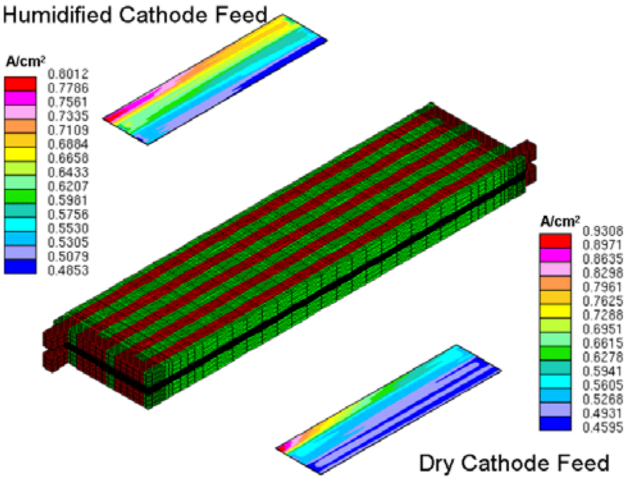

Figure 4. Five-channel serpentine flow field PEMFC mesh and current density contours for humidified vs. dry cathode feed case.

method apply only to the fuel cell stack, and assume uniform stack temperatures. For each case there is a crossover point on the order of days where the energy requirements of the keep-warm method surpass the constant energy requirement for the thaw at start method. Water is often removed from the stack at shutdown (such as by air purging, vacuum evaporation, or discontinuation of reactant humidification) in order to minimize thawing energy requirements. Upon startup, however, stack performance depends greatly on effective re-humidification.

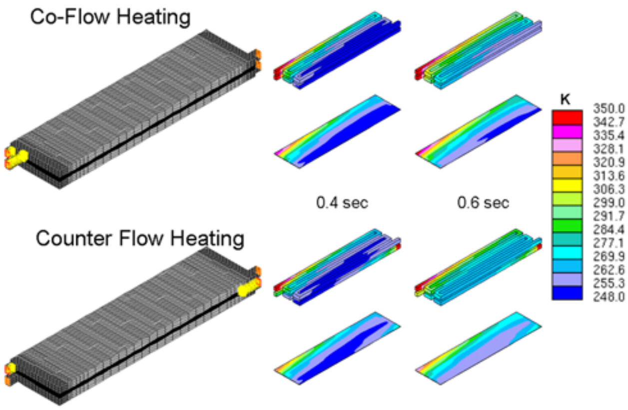

Figure 5. Comparison of Hot Air Heating Model Results for Co-flow and Counter Flow heating: Meshes and temperature contours of channels and MEAs at 0.4 sec and 0.6 sec.

After evaluating several commercial software packages for modeling variable humidity FC reactant flows, we selected the PEMFC module in StarCD (developed by CD-adapco and the University of South Carolina). Figure 4 shows the StarCD mesh for a five-channel serpentine flow field PEMFC. Current density contours at the membrane electrode assembly (MEA) are also presented for a humidified feed case (average density of 0.61 A/cm^2) and for a dry cathode feed case (average of 0.55 A/cm^2). StarCD also proved useful for simulating one method for internal stack heating using high temperature air (typically greater than 90^{o}C) produced as a result of the compression process in the fuel cell system's air compressor. Figure 5 presents the results for initially flowing hot air over each side of a MEA cold soaked at –25^{o}C. The model features include transient multi-stream flow, porous media flow and conjugate heat transfer. We plan to modify and this PEMFC code for further investigating freeze solutions.

Summary

- We systematized the many approaches to PEMFC vehicle freeze protection and rapid cold startup by investigating and categorizing 177 relevant patents.
- We developed a Matlab-based simulation program to calculate energy, power, and temperature-time performance for the keep warm and rapid thaw at start methods.

- We analyzed the impacts of insulation, heating, water drainage, de-humidification, and heated reactant flow as they related to each of these methods.
- We investigated several fuel cell modeling software packages and selected StarCD as the most appropriate for adapting to freeze problems and then evaluating freeze-related solutions from both a systems and cell perspective.
- We have presented on our findings and interacted with others working on fuel cell freeze issues at the February 2005 DOE Fuel Cell Freeze Workshop.
- Our analysis indicates that a combination of several strategies will provide the most promising solution to the fuel cell freeze problem. However, we recognize that the added complexity of multiple approaches may increase the operation and installation costs of the system.

FY 2005 Publications/Presentations

1. Pesaran, A.; Markel, T.; Kim, G.; Wipke, K. (2005) "Fuel Cell Freeze Startup and Landscape of FC Freeze Patents." Presented at *DOE Workshop on Fuel Cell Operations at Sub-Freezing Temperatures*. Phoenix, AZ. February 1, 2005.
2. Pesaran, A.; Kim, G.; Markel, T.; Wipke, K. (2005) "Fuel Cell Vehicle Systems Analysis (Fuel Cell Freeze Investigation)." Poster presentation at Hydrogen and Fuel Cell Infrastructure Technologies Program Review. Washington, DC. May 24, 2005.