PEM Fuel Cell Stack Development and System Optimization

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PEM Fuel Cell and Stack

A PEM Fuel Cell:

A PEM Fuel Cell Stack:
PEM Fuel Cell

• History of Development
  – GE (Gemini spacecraft, 1959-1982)
    > UTC-Hamilton Standard and Siemens AG (for the air-independent submarine, mid-1980s)
  – Ballard Power System Ltd. (1983, 1990s, …)
  – Many Others

• Core Technology
  – MEA (Membrane Electrode Assembly)
  – Stack

• Key Technical Problems of Stack/System Design
  – Heat Management
  – Water Management
  – Costs
Proof of Concept Fuel Cell E-Vehicles
Automotive Companies and Transit Authorities Using Ballard Fuel Cells

GM
Ford
DaimlerChrysler

BC Transit
Chicago Transit
Volkswagen

Honda
Nissan
Volvo

From other Manufacturers
PEM Fuel Cell Research at University of Victoria

• **Next Generation Fuel Cells for Transportation (NGFT) (1994~1999)**
  - Carried out in the *Institute for Integrated Energy Systems*
  - Jointly supported through a *Collaborative Research Grant* of 3.4 M by Natural Science and Engineering Research Council (NSERC) of Canada, British Gas Canada and Ballard Power Systems Ltd.

• **Research on Fuel Cell Powered Electrical Bicycles (2000 ~ ...)**

• **Etc.**
NGFT Fuel Cell Research

- **Research Groups:**
  - NGFT program
  - tubular-cell stack development
  - radiator stack development; low-cost fuel cell plate manufacturing; and fuel cell system design and optimization
  - new fuel cell membrane development
  - fuel cell modeling

- **Outcome:**
  - extensive new intellectual properties, transferred to Ballard
  - a large number of students and professionals who now play active roles in the fuel cell industry
  - a modern fuel cell research laboratory
Research on Fuel Cell Powered Electrical Bicycles

- To be carried out as a collaborative research program
  - Palcan Fuel Cell Ltd.
  - Innovation Center, National Research Council (NRC) of Canada
  - University of Victoria

- To focus on the development of
  - stack and system modeling, design and optimization tools
  - testing of fuel cell powered electrical bicycles and scooters
Types of Model
- Performance model
- Cost model
- Parametric solid models

Functions
- Identifying technology/cost challenges
- Component design optimization
- Integrated concurrent engineering design and system optimization

Modeled Subjects
- Fuel cell
- Fuel cell stack
- Ancillary devices
- Fuel cell system
Importance of Product Design

- Direct cost of design in product development: 5%
- Influence of design to the entire product cost: 70%
Quantitative Concurrent Engineering Design Using Virtual Prototyping-based Design Optimization

Quality

Cost  Lead-time
A Novel Transportation PEM Fuel Cell Stack Design
Tri-stream, External-manifolding, Radiator Stack (TERS)
Research Issues

• Virtual Prototyping Using Pro/ENGINEER
• Validation of Computer Modeling and Analysis Results
• Development of A Software Tool for Virtual-prototyping Based Design Optimization
• Concurrent Engineering Design through Multiple Objective, Global Optimization
Virtual Prototyping-based Design Optimization

- **Virtual Prototype Construction**
  - a parametric CAD model using Pro/ENGINEER

- **Virtual Prototype Testing**
  - built-in finite element analysis module for structure integrity, heat transfer capability and dynamics stability assessments
  - manufacturing planning module for production cost and manufacturability estimation; and
  - dedicated external software modules for measuring specific functional performance of the design.

- **Solution Method**
  - Adaptive Response Surface Method (ARSM)
Virtual Prototyping-based Design Optimization
Adaptive Response Surface Method (ARSM)

Virtual Prototyping

Computer Analysis and Simulation Tools -- Pro/E and Research Programs

Experimental Designs

Model Fitting

Global Optimization

Design Space Reduction

End Plate
Support Columns
 PEM Cell
Flow Field Plate
Optimal Design of the Key Component of TERS — Multi-functional Panels

Design Considerations

- Heat transfer
- Compensation of thermal and hydro expansion
- Electrical conductivity

Design Variables

- Fin Wavelength, $w$
- Thickness, $t$
- Panel height, $h$
- Surface texture
- Material
- Fin shape
Formulation of Design Problem

Objectives

Minimize | Panel Stiffness - Ideal Stiffness |
Maximize Outlet Temperature

Constraints

Maximum Air Flow Rate < Constant 1
Panel Deformation Percent Difference < 10%
Outlet Temperature > 320 K
Conductivity > Constant 2
Parameter Bounds
Validation of the Computer Model (Multi-functional Panels)

- **Heat Transfer**
  
  Mathematical Modeling +

- **Panel Stiffness**
  
  Virtual Prototyping +

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ARSM for Integration and Optimization
Modeling of the TERS Fuel Cell System

- H₂ Storage Tank
- H₂ Ejector
- H₂ Humidifier
- Air Humidifier
- Air, 25°C, 101.3 kPa
- Silencer Filtering System
- Compressor
- Pump
- De-ionizing Filter
- Water Storage Tank
- Knockout
- Knockout Air-Water
- H₂-Water
- Air to Environment
- Air, 25°C, 101.3 kPa
- Cooling Fan
- 0.5 Air to Environment
Optimization of the TERS Fuel Cell System

**Design Parameters:**
- five geometric parameters
- one operational parameter
- one system configuration parameter

**Design Objectives:**
- cost, power densities, efficiency and net power

**Design Constraints:**
- structure integrity and system size

**Integrated Concurrent Engineering Design:**

\[
\min_{X} f(X) = \min_{X} \left\{ \lambda_c \sum f_c(X) - \lambda_p \sum f_p(X) \right\}
\]
Results of Design Optimization

- **Multiple Functional Panel Design**
  - Panel thickness, $t$, dominants the stiffness; panel height, $h$, dominants the heat transfer capability;
  - Optimum at: $h=4$, $w=9$, $t=0.012$ (mm) with an ideal panel deformation of $0.0341$ mm under loads.

- **TERS Fuel Cell System Design**
  - Design considerations: cost, performance (net power, efficiency, power densities), structure integrity, and space constraints.
  - Increased system power density by 43%,
  - Reduced system costs by 16%, and
  - Obtained the global optimum of system design in hours.
Screen Printing Fuel and Oxidant Delivery Plate Manufacturing Method
Fuel Cell Fuel and Oxidant Delivery Plate
Screen Printing Fuel and Oxidant Delivery Plate Manufacturing Method
Major Research Targets

• **Process feasibility** – low cost manufacturing
  – build up the height and complex shape of flow channel walls
  – stencil material and automated stencil production process
  – tolerance control and process details
  – prototype, batch and mass production at ($2~5/plate)

• **Plate stability and zero contamination**
  – corrosive, humid & heated working conditions
  – ink base and ink ingredients (poster ink, conductive polymer, castable graphite, composite material, etc.)
  – printing process and post processing

• **Eliminating/reducing contact resistance**
  – wet assembly, laminated copper-graphite foils
Screen Printing Fuel and Oxidant Delivery
Plate Manufacturing Method

Test Station

Screen Printing Press

Test Station

Single Cell Test

Current density (amps/cm²)

Volts (V)

SP1

BC2

SP 2

Cell Temp = 75°C

Thum/H₂ = 85°C

Thum/air = 82°C

P gases = 30 psig

VH = 3.2 slpm

Vair = 2.0 slpm

Pb lead = 220 psig

Pt loading = 4 mg/cm²
Rapid Prototype Development of Fuel Cell Gas Delivery Plate Using Virtual Prototyping, Optimization and Screen Printing

- **Plate Structure Design & Optimization**
  - design of plate geometry
  - flow field layout and plate geometry (CFD & FEA) (30% more oxygen)
  - design of composite material property and composition (FEA, etc.)
  - testing of composite materials

- **Rapid Prototyping**
  - stencil making
  - plate making
  - fuel cell testing (23% more power)
Testing of New Composite Materials

- Resistivity
- SEM (Scanning Electronic Microscope) (microstructure)
- EDX (Energy Dispersive X-ray) (spectrum of active ions)
- DSC (Differential Scanning Calorimeter) (vapor evaporation)
- Fuel Cell Test (performance)
PEM Fuel Cell Research of Our Group at University of Victoria

- **Next Generation Fuel Cells for Transportation** (94~99)
  - Part of the IESVic CRD Grant by NSERC, British Gas Canada and Ballard Power Systems Ltd.
  - Four Related Areas:
    - Radiator Stack Design; Low Cost, Rapid Prototype Development of Fuel Cell Plates; Fuel Cell Stack and System Modeling; and Concurrent Engineering Design through Global Optimization.

- **Fuel Cell Powered Electrical Bicycles** (2000 ~ present)
  - Mathematical Modeling of the Fuel Cell Systems for Powering Electrical Bicycles and Scooters
  - Testing Methods and Procedures for Electrical Bicycles
  - Virtual Prototyping of Fuel Cell E-Bicycles and E-Scooters
A concept fuel cell powered bicycle built on a Rocky Mountain Bicycles RM6 full suspension bicycle.

Due to the front motorized drive, the power system can be easily fitted to any bicycle.
Fuel Cell and E-Bicycle Testing Facilities
Concept Fuel Cell Stack and E-Bicycle Design, Modeling and Analysis