Comprehensive Modeling and System Interactions in Planar SOFC Power-Conditioning System

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SECA Core Technology Program Review Meeting

Jan 27, 2005 **Florida**

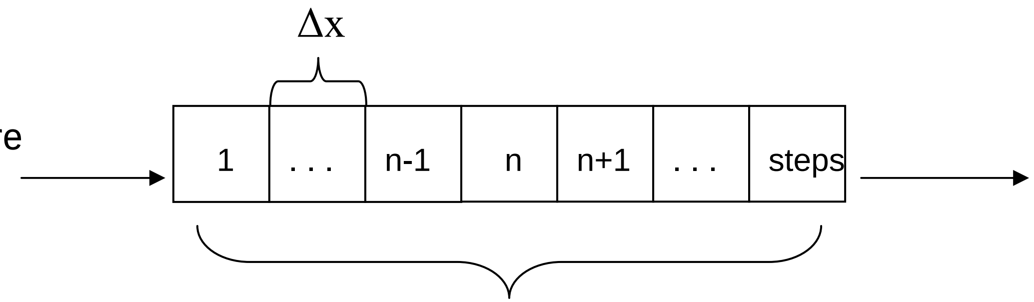
Overview

- Pre-Analysis Efforts
  - Comprehensive Planar SOFC (PSOFC) 1D and 2D Modeling
  - Model Validation
  - Power-Electronics Modeling
  - Fully-controlled BOPS Modeling
  - Comprehensive System Modeling
- Interaction Results and Analysis
  - Load Power Factor
  - Load Transients
- Conclusion
- Future Works

Modeling

1D PSOFC Model

Inputs
- Feed temperature
- Current
- Molar flows and compositions (Fuel, air)
- Cell geometry
- Stack size



Variables calculated for n = 1…steps at each time include: temperature and stream flows.

Outputs
- Temperature
- Operating Voltage
- Molar flows and compositions (Fuel, air)
- Power Output

- Fuel cell model run in Simulink via an embedded Matlab function.
- Finite difference method used to approximate transient parameters.
- Model returns position dependent variable values as well as outflow values.
- Interfaces with BOPS model in Simulink to form complete system.
- Radiation boundary applied to exit boundary.
- Co-flow setup between fuel and air streams.

Model Characteristics

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- Inlet fuel stream is a reformed methane stream.
- Each step (control volume) along the fuel cell is treated as having homogenous properties throughout.
- Shift equilibrium is applied to each control volume along the fuel cell.

<u>Shift Equilibrium Calculation</u>

$$K_p = \frac{(p_{CO_2} + x) \cdot (p_{H_2} + x)}{(p_{CO} - x) \cdot (p_{H_2O} - x)}$$

$$K_p = e^{-dG_o / RT} \qquad dG_o = f(T)$$

<u>Equilibrium Composition</u>

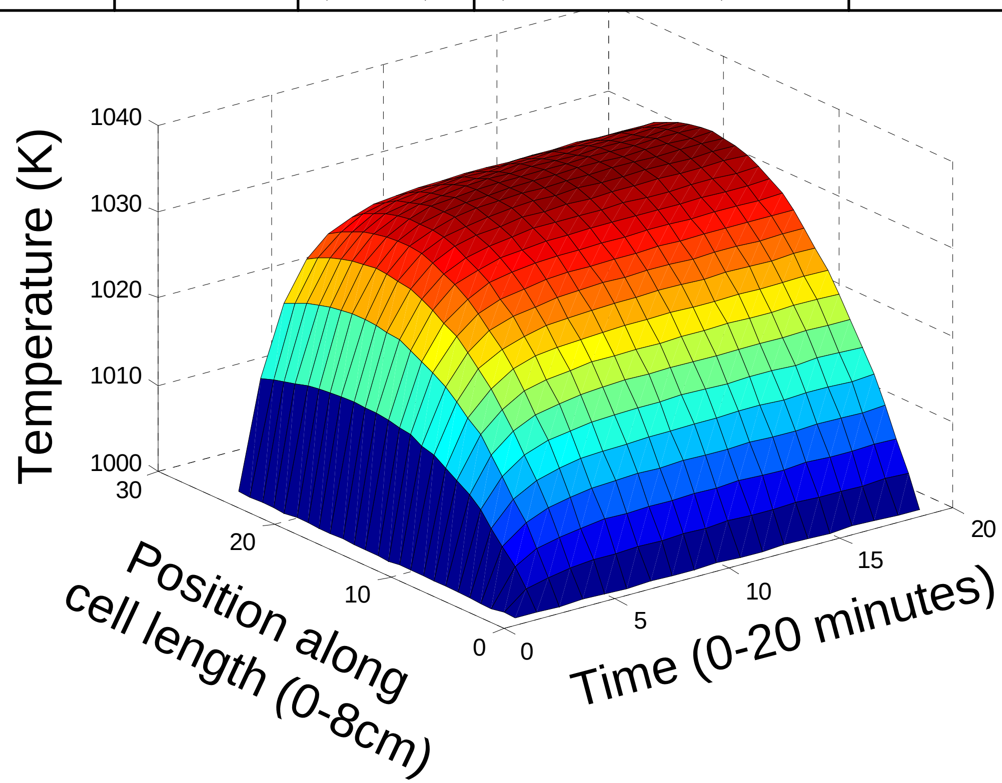
$$p_{H_2} = p_{H_2} + x \qquad p_{CO} = p_{CO} - x$$

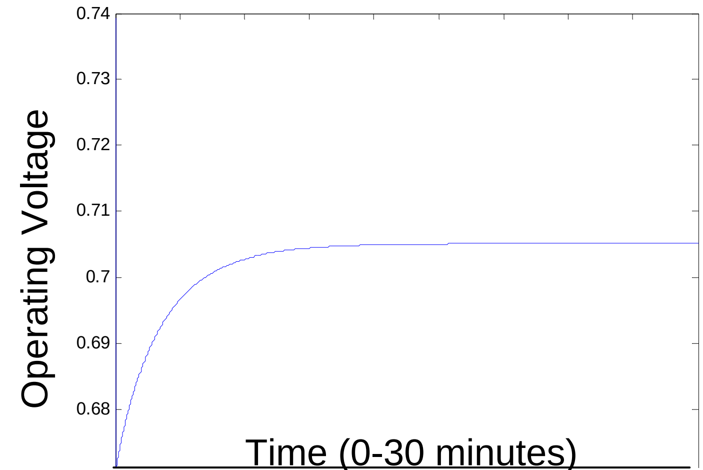
$$p_{CO_2} = p_{CO_2} + x \qquad p_{H_2O} = p_{H_2O} - x$$

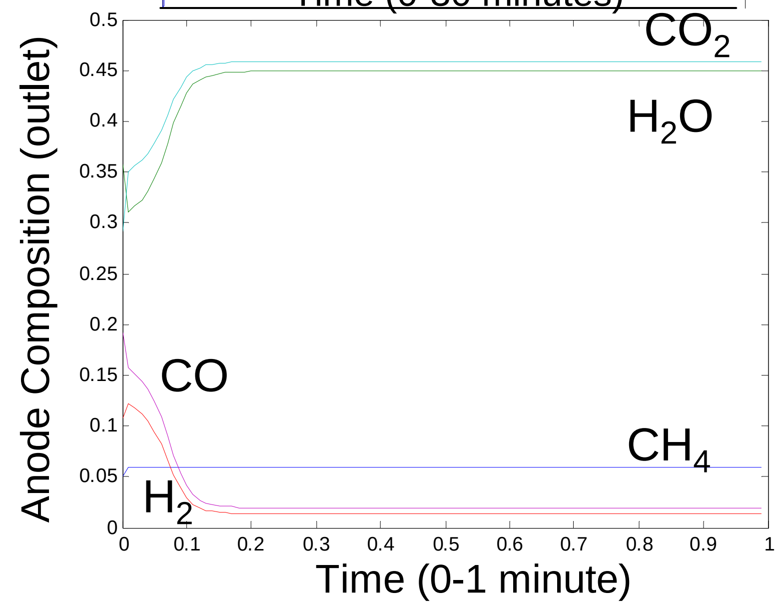
1D Model Results

Inlet Conditions

Air Flow (mol/s)	Fuel Flow (mol/s)	Air Comp (O_2, N_2)	Fuel Comp (CH_4, H_2O, CO, CO_2, H_2)	Feed temp (K)
8.87e-4	7.76e-4	(.21, .79)	(.05, .45, .2, .2, .1)	1000

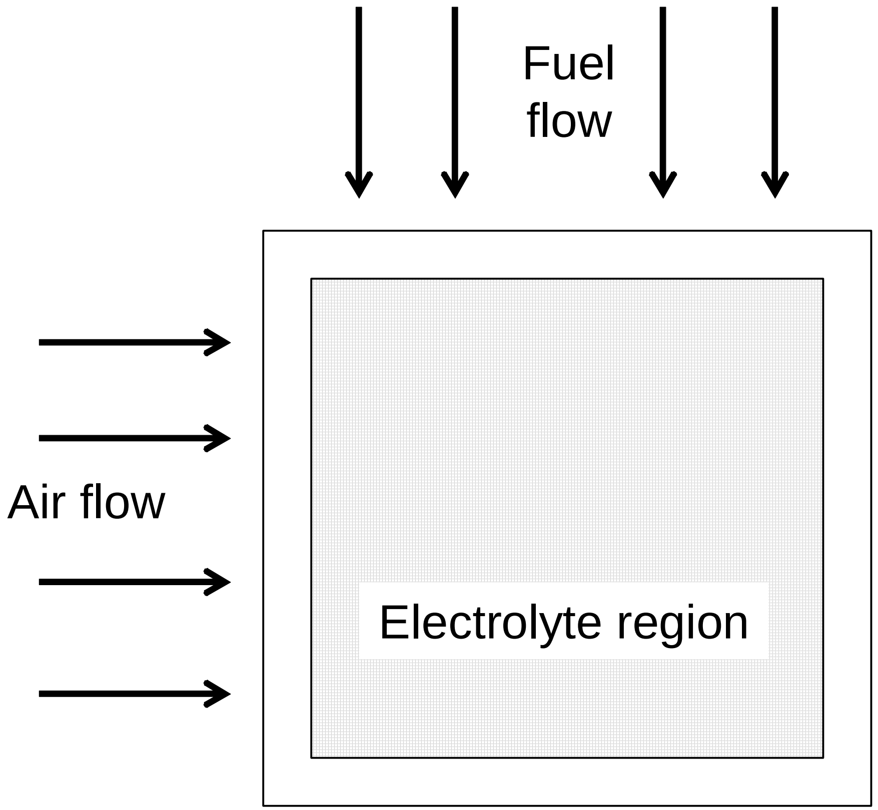




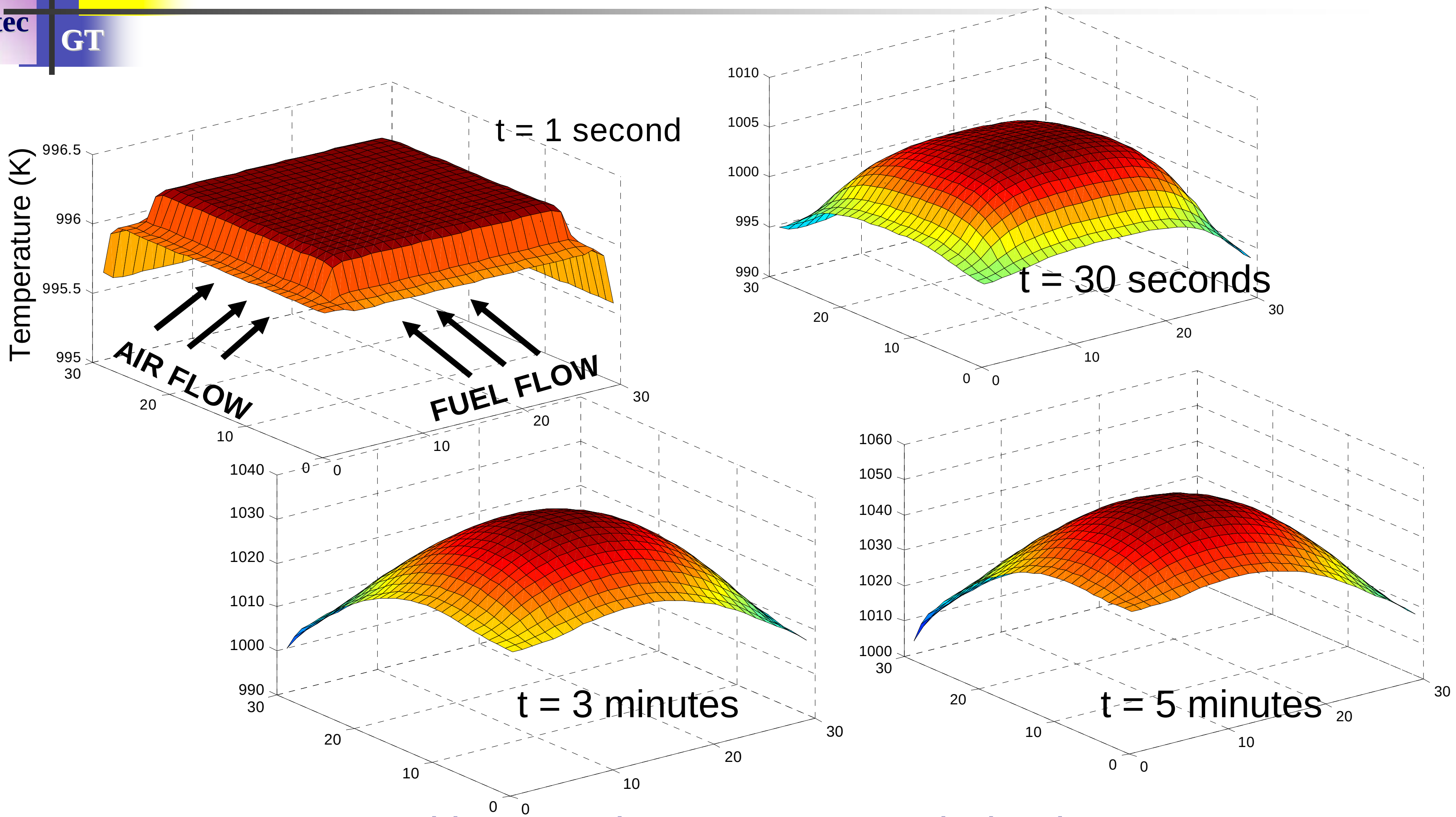


2D SOFC Model

- Same input and output variables as 1D model.
- Model returns variable values at outputs as well as across entire fuel cell surface.
- Radiation boundary applied to each exit stream boundary.
- Cross-flow setup between fuel and air streams.
- Includes an inactive seal area around active electrolyte region.



2D Model Results



Tracking transient temperature behavior

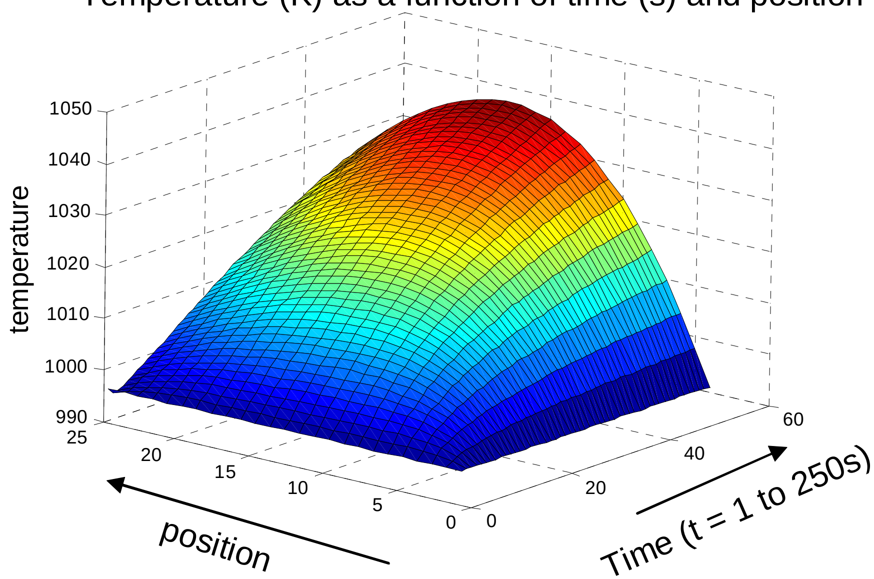
1D vs. 2D Model Comparison

Inlet Conditions

Air Flow per cell (mol/s)	Fuel Flow per cell (mol/s)	Air Comp (H_2O, O_2, N_2)	Fuel Comp (CH_4, H_2O, CO, CO_2, H_2)	Current per stack (A/stack)	Feed temp (K)
3.7e-4	1.81e-4	(.069, .196, .74)	(0.006, .31, .07, .08, .54)	15	996

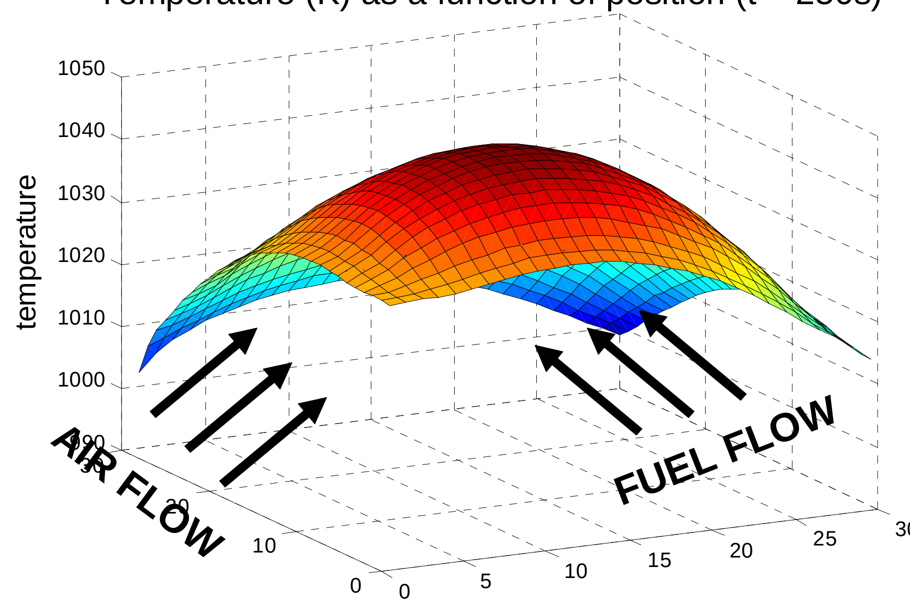
Temperature (1D Model)

Temperature (K) as a function of time (s) and position

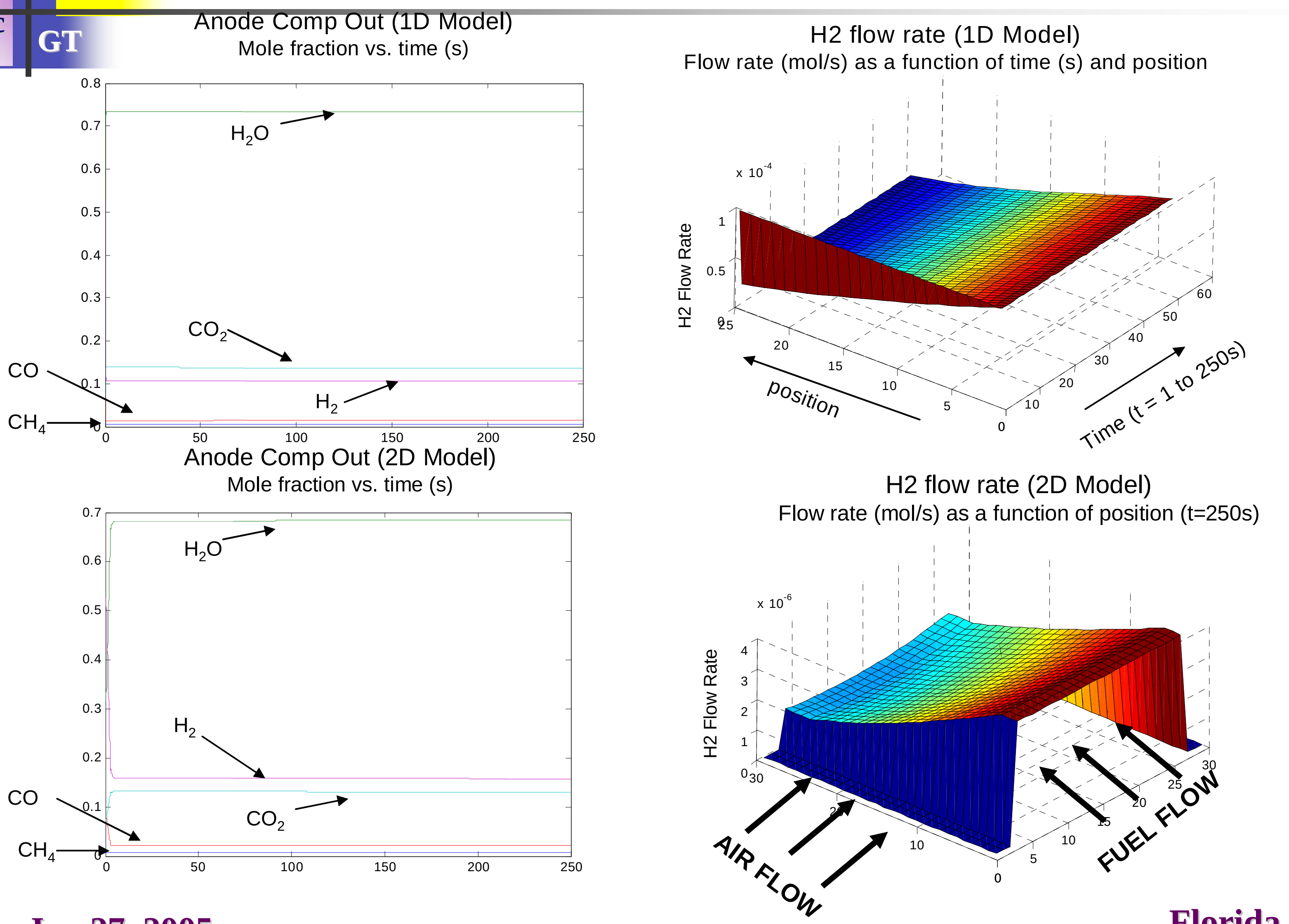


Temperature (2D Model)

Temperature (K) as a function of position (t = 250s)

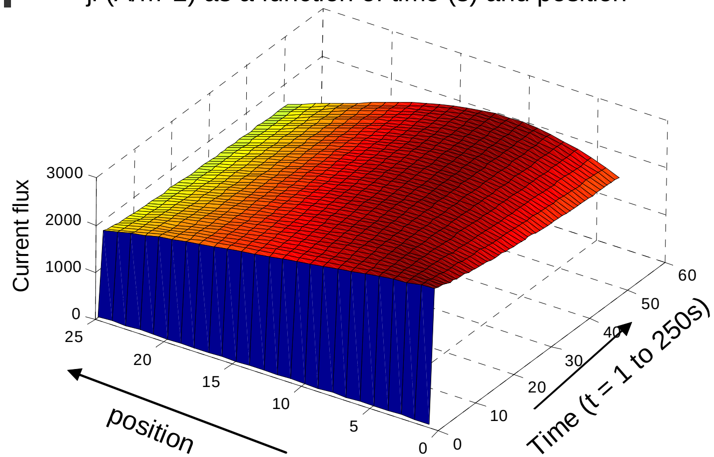


1D vs. 2D Model Comparison

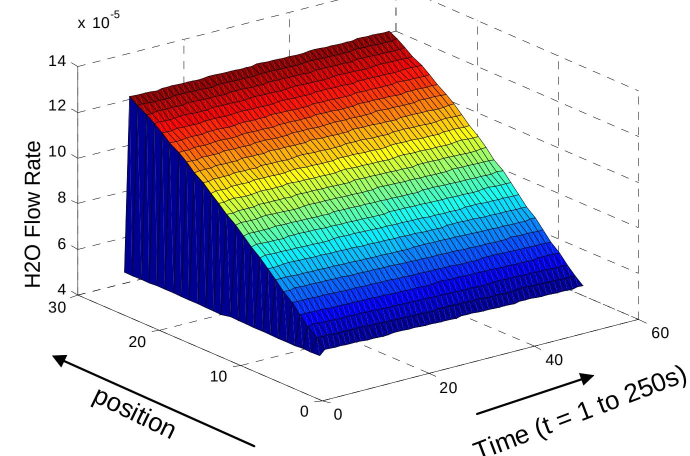


1D vs. 2D Model Comparison

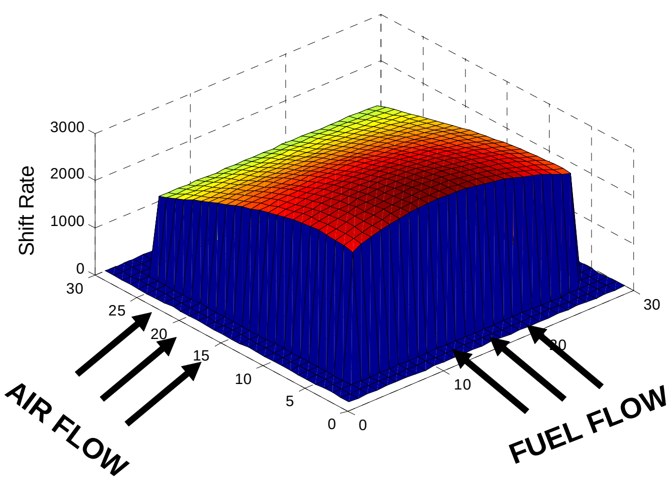
Current Flux (1D Model)
ji (A/m^2) as a function of time (s) and position



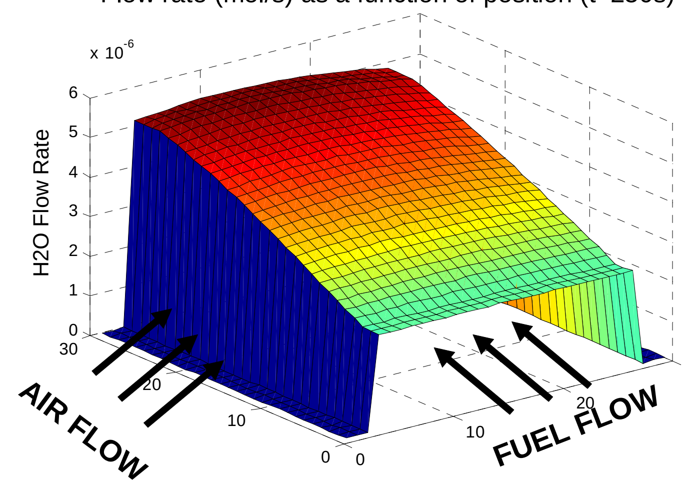
H2O flow rate (1D Model)
Flow rate (mol/s) as a function of time (s) and position



Current Flux (2D Model)
ji (A/m^2) as a function of position (t=250s)

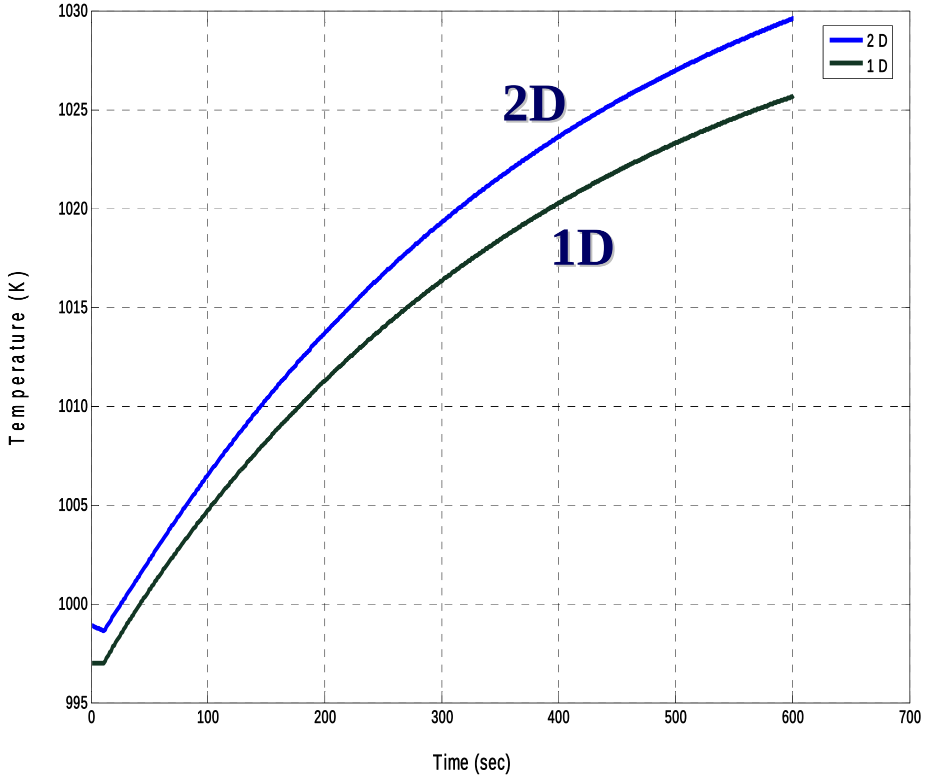


H2O flow rate (2D Model)
Flow rate (mol/s) as a function of position (t=250s)



1D vs. 2D Model Comparison with Load-Transient

- 600 seconds of system simulation needs
  - ~ 3.5 hrs for the 2 D Model
  - ~ 1.5 hrs for the 1D model

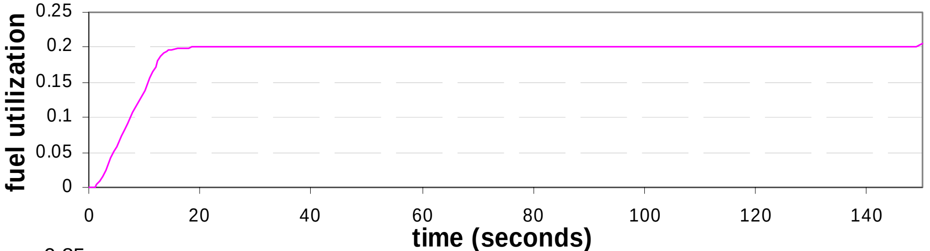


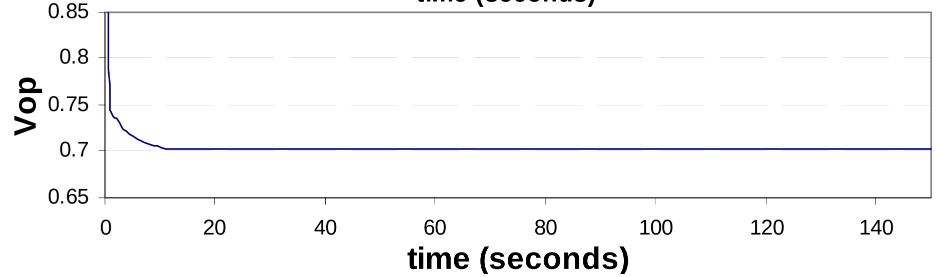
Adjusting Model Configurations

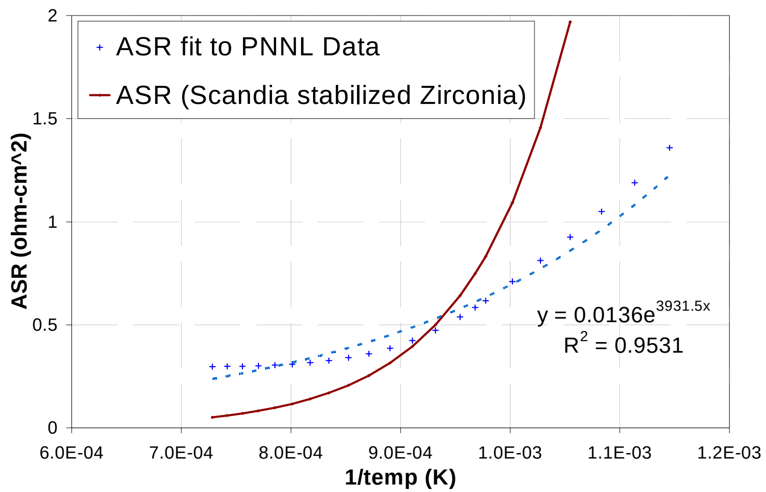
- Modified SOFC 2D fuel cell model for operating configurations provided by PNNL:
  - Isothermal operating conditions
  - User inputs for stream flow rates, compositions, and temperatures provided
  - Single cell set-up

- ASR fit to material data from PNNL model.

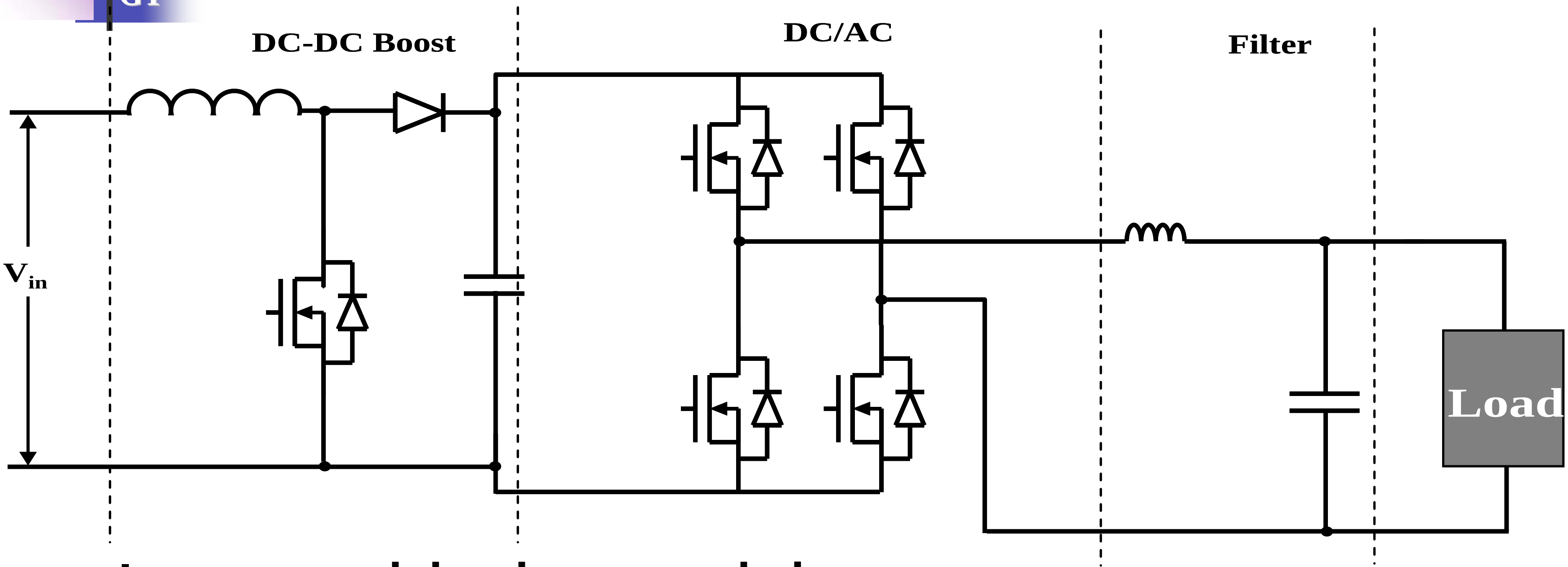
- Comparable results demonstrated between PNNL model and modified SOFC model.







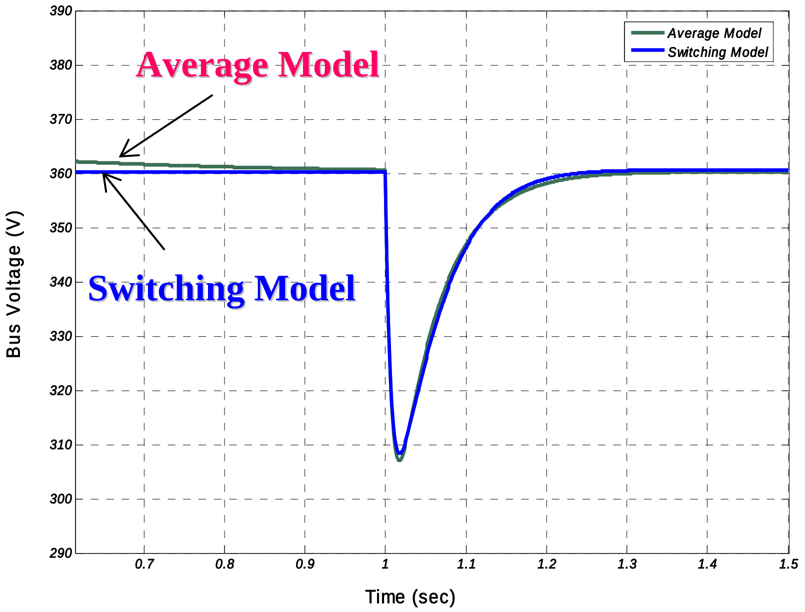
PES Switching Model



- Issues with the model
  - Switching discontinuity
  - Stiff system with nonlinearities

PES Average Model

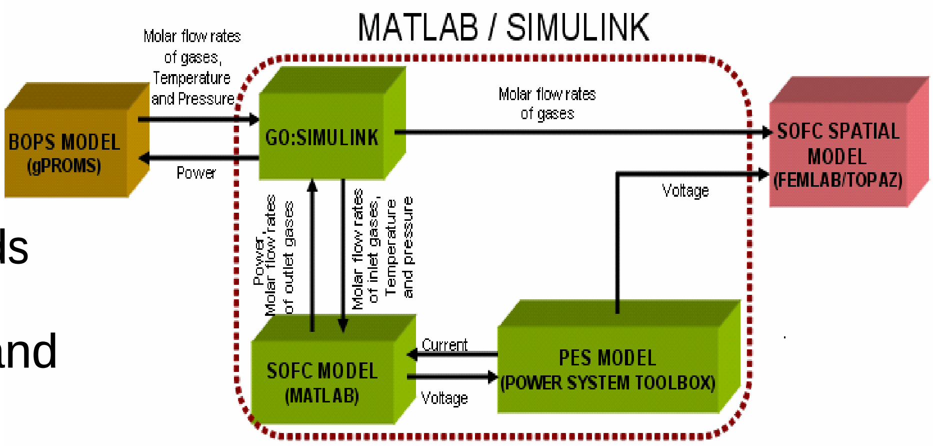
- Need
  - Simpler Configuration
  - Faster Computation and guaranteed convergence with fairly larger time-steps
- Cons of the modeling approach
  - Prediction of nonlinearity and chaos
- Comparison and significance
  - 1.5 sec of system simulation using
    - **Average Model → 5 sec**
    - **Switching Model → 540 sec**
  - Significant decrease in simulation time with appreciably high accuracy



Response comparison during load transient

Comprehensive System Model

- Modeling Issues
  - Bulky BOPS model in gPROMS needs an gO:Simulink interface for data transfer between Matlab/Simulink and gPROMS.
  - Integrity of data exchange between individual subsystems running at their individual pace on their own platforms
  - Need of order reduction of models
    - PSOFC : 1D vs 2D and 2D vs 3D model
    - PES : Switching to Average model
    - BOPS : Lookup table model



Simulation Issues

- Problems with Convergence
  - In the PSOFC model, which behaves similar to a current-controlled voltage source, the current information is unavailable at the start of the simulation (t = 0)
  - Infinite sampling time
    - The PSOFC model by default assumes a infinite sample time and hence needs to be triggered at a particular rate to proceed with the simulation
- Simulation Time
  - 1 sec of complete system simulation takes 1 million CPU (parallel processor-based Intel Xeon) seconds.

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Resolution of Simulation Issues

- SOFC Model Changes to resolve convergence at the PSOFC and PES interface at t = 0
- Multiple sampling rates
  - For PES-BOPS interface to enhance simulation speed
- Rate transition blocks
  - Ensure data integrity at multiple sampling rates
- Solver algorithm
  - Ode23tb
    - Solving crude error tolerances to solve stiff differential equations with algebraic loops.
- BOPS reduced-order polynomial fit model
- BOPS comprehensive lookup table model (*in progress*)

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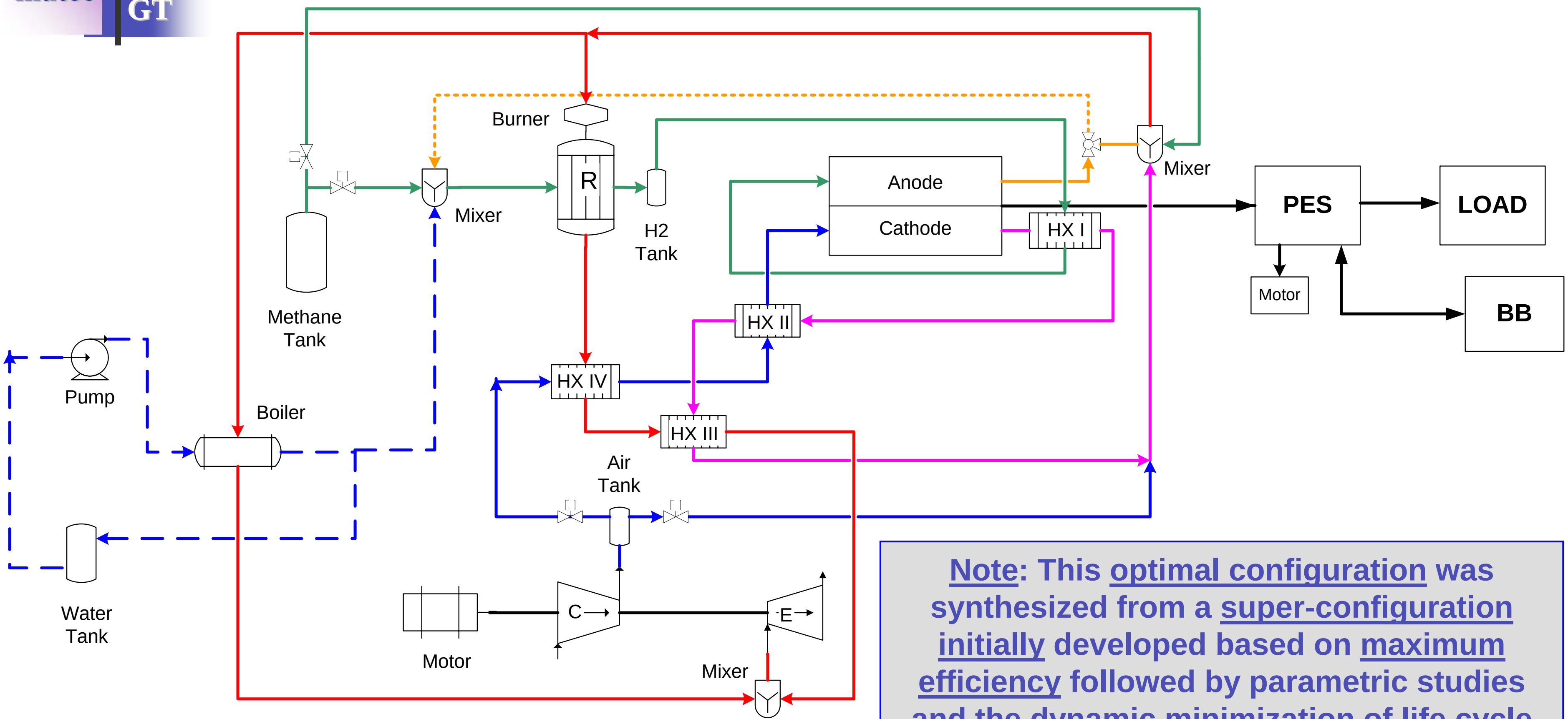
BOPS Optimization

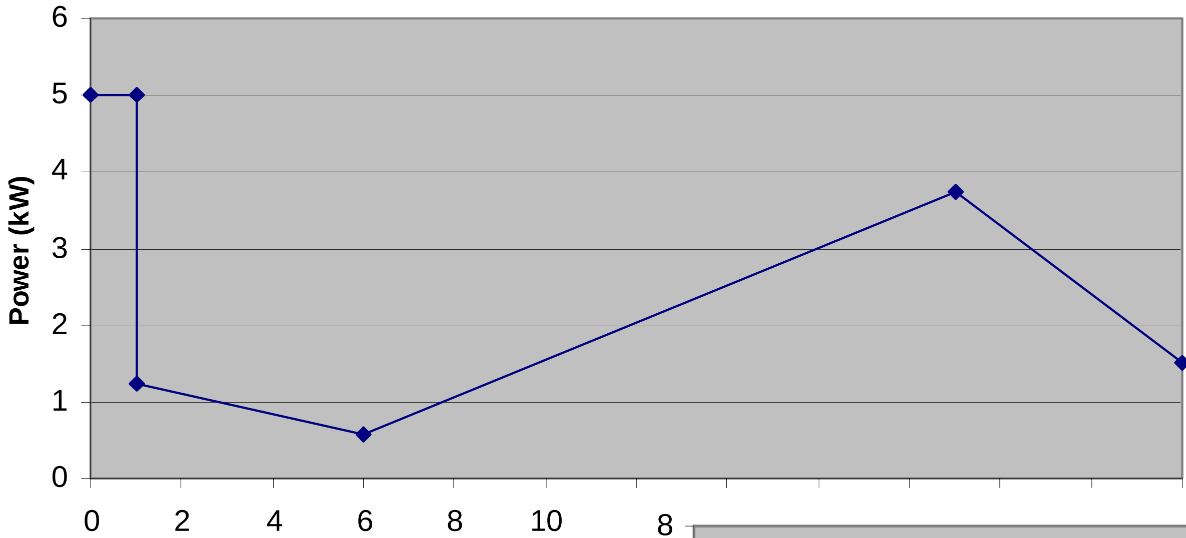
BOPS Optimum Configuration



Note: This optimal configuration was synthesized from a super-configuration initially developed based on maximum efficiency followed by parametric studies and the dynamic minimization of life cycle costs to arrive at the subset seen in this schematic; this synthesis/design was carried out optimally taking into account the dynamic operational control of the system.

Note: This configuration has been optimally synthesized/designed to respond in the shortest time possible to all transients.

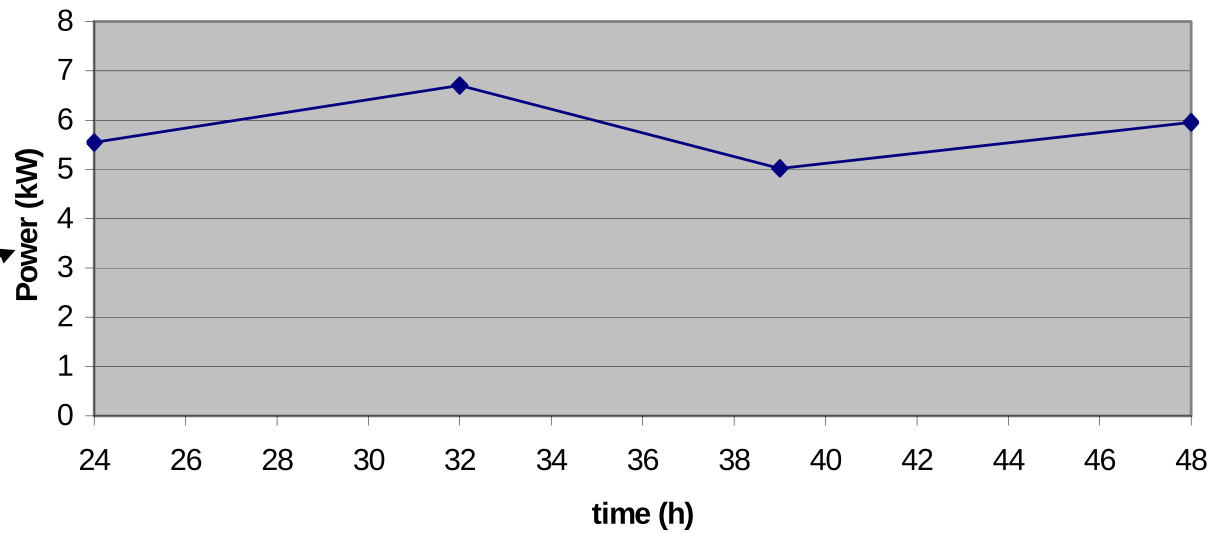
Residential Load Profiles



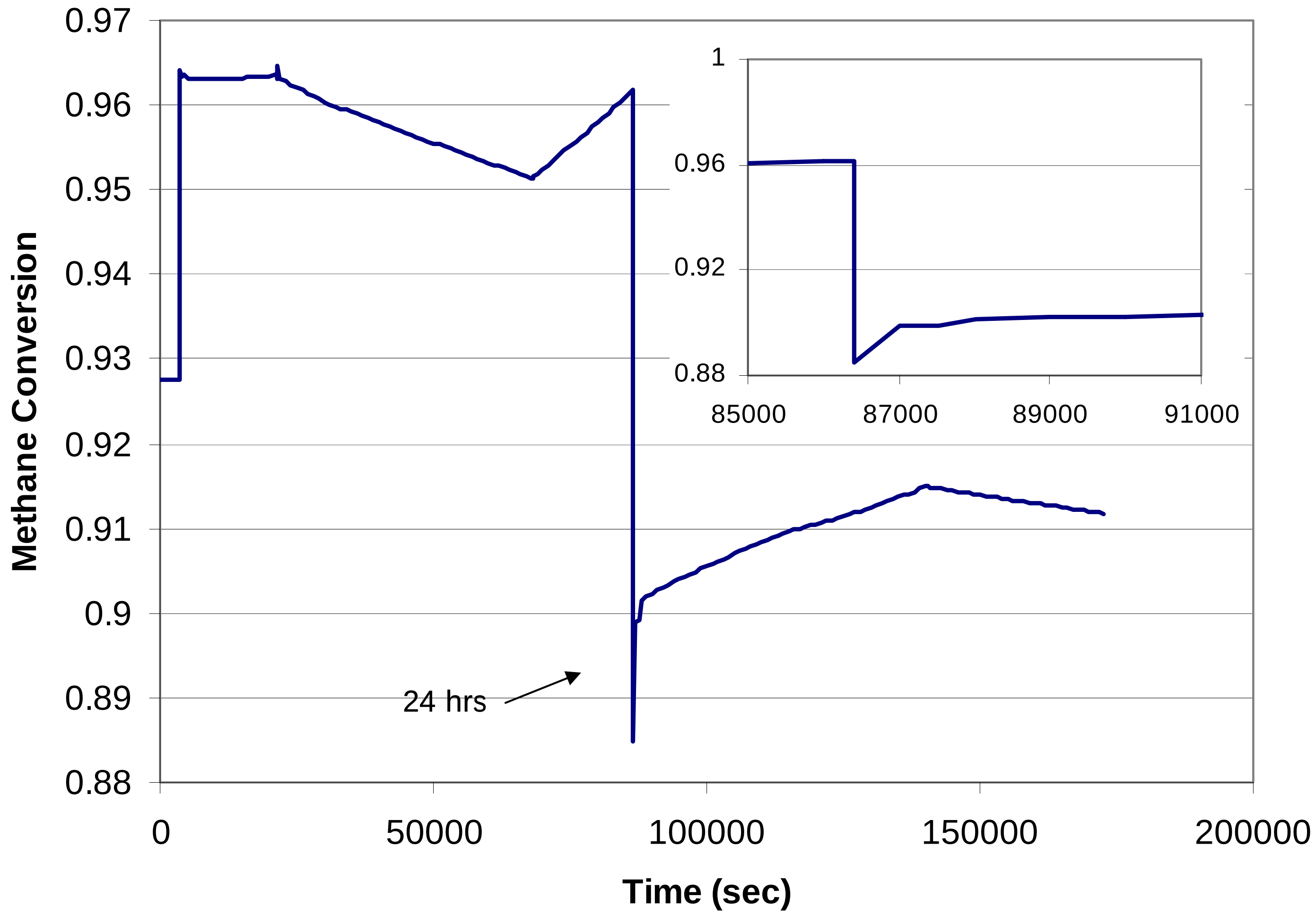
<u>Summer Profile</u>:
Approximated load profile. Cooling Day in Atlanta, Georgia Occurs on 07/11

<u>Note</u>: The system is <u>optimally synthesized/designed</u> using these two profiles back to back; the synthesis/design accounts for <u>optimal dynamic operation</u> and <u>control.</u>

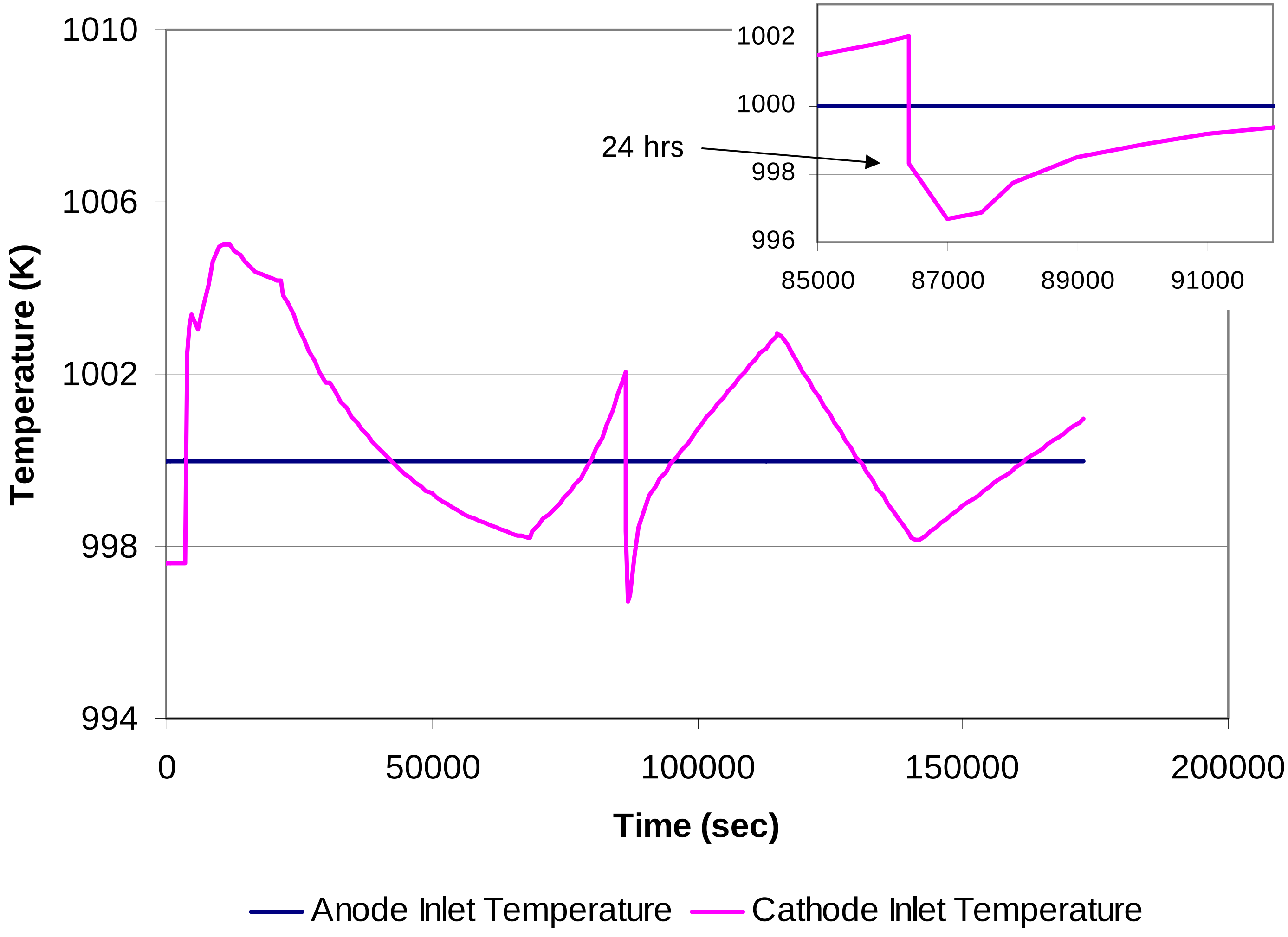
<u>Winter Profile</u>:
Approximated load profile. Heating Day in Atlanta, Georgia Occurs on 01/12



Optimum Transient Response over Entire Load Profile



Optimum Transient Response over Entire Load Profile



Optimum Transient Response over Entire Load Profile

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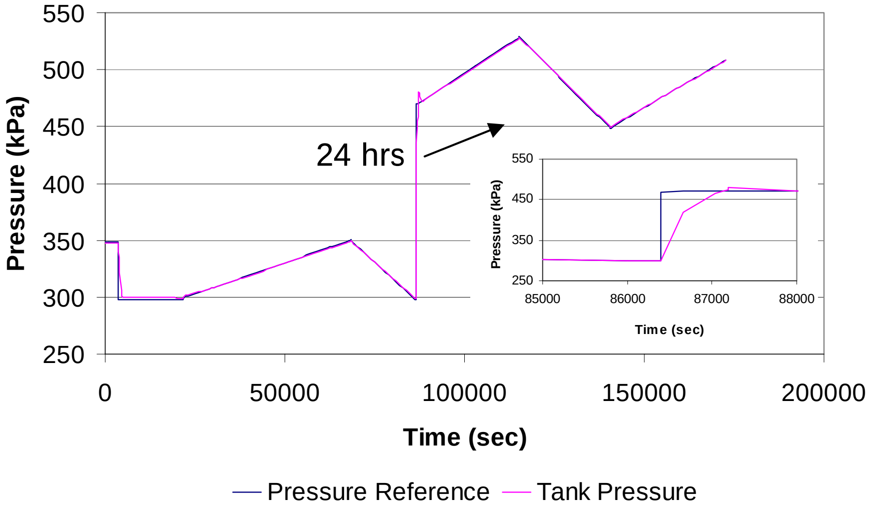
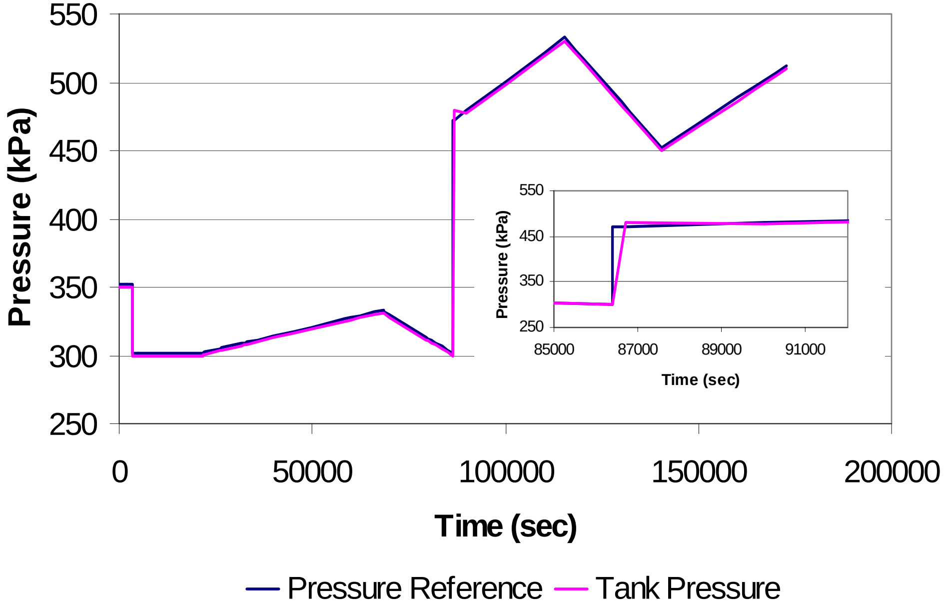
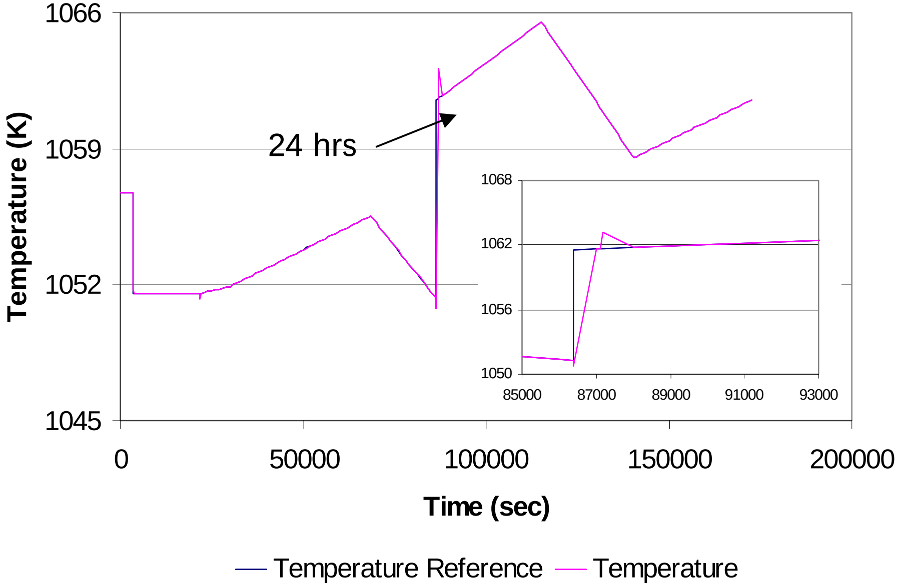


Air tank pressure dynamic response.

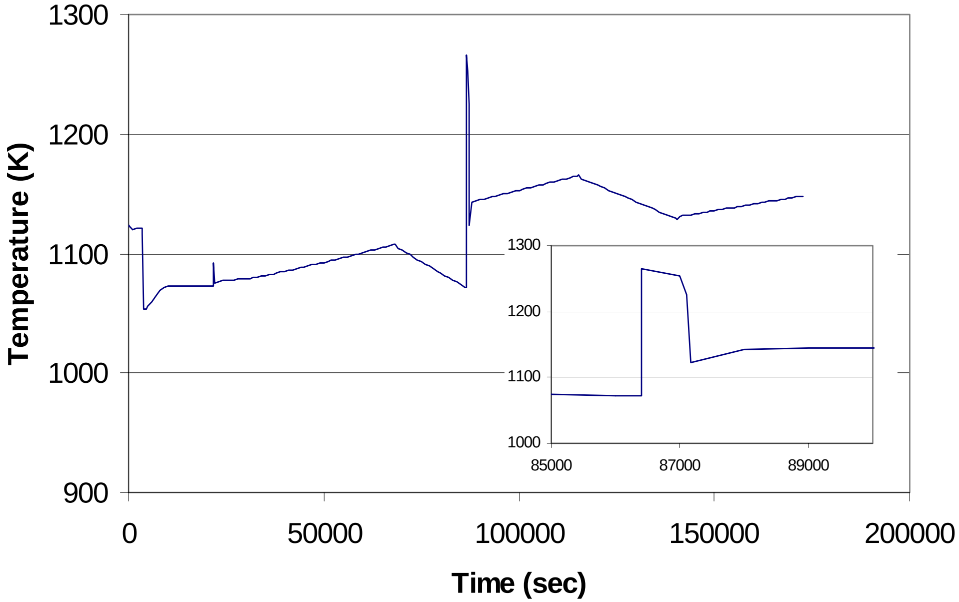
Hydrogen tank pressure dynamic response.



Optimum Transient Response over Entire Load Profile



Optimum steam-methane reformer reformat exit temperature (state variable) dynamic response.



Optimum steam-methane reformer hot gases inlet temperature (control variable) dynamic response.

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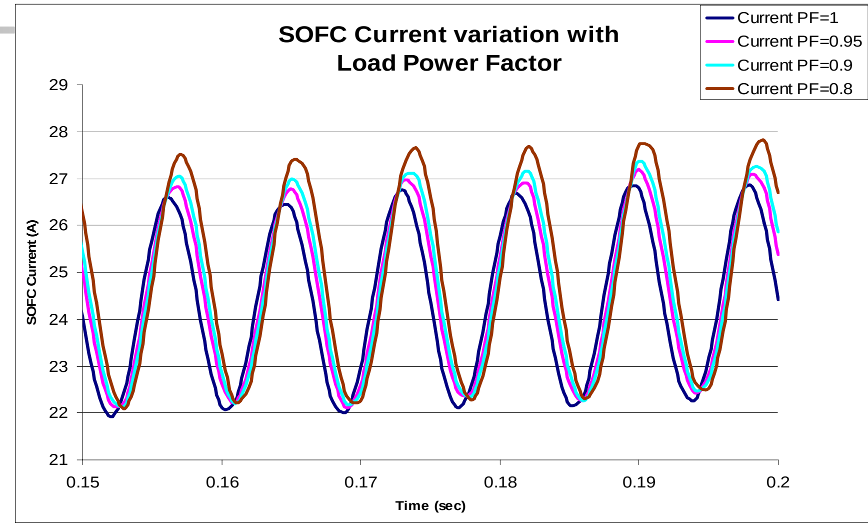
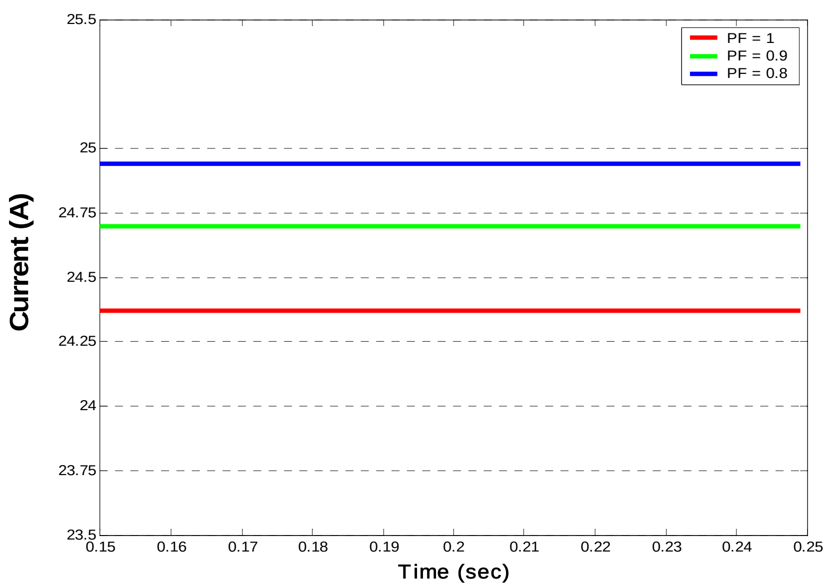
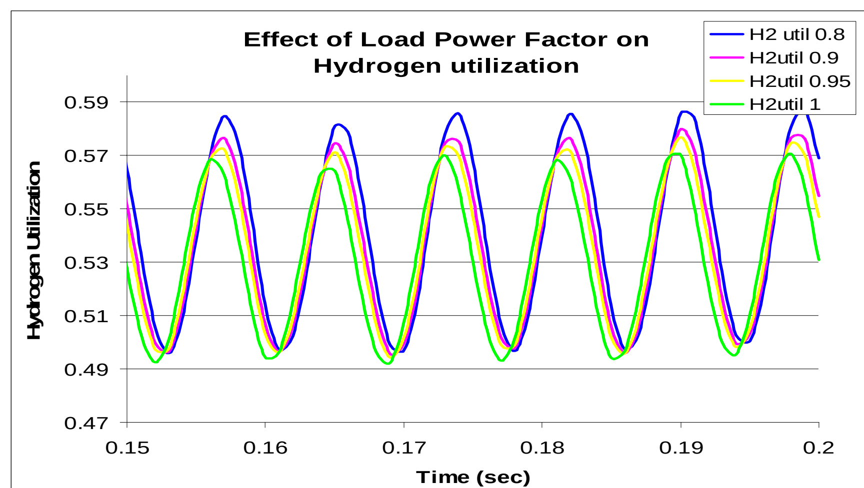
Interaction Analysis

Effect of Load Power Factor

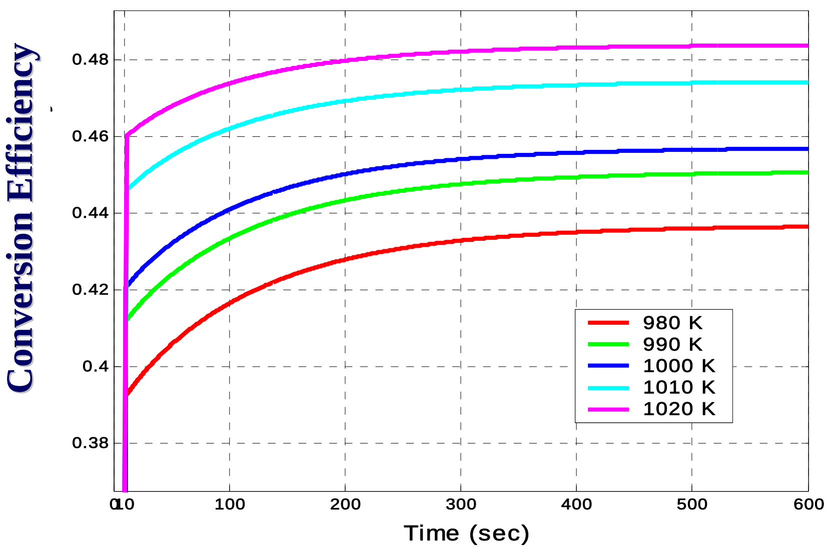
- The lower the load power factor
  - The higher is the SOFC stack current and current ripple
  - The higher is the hydrogen utilization

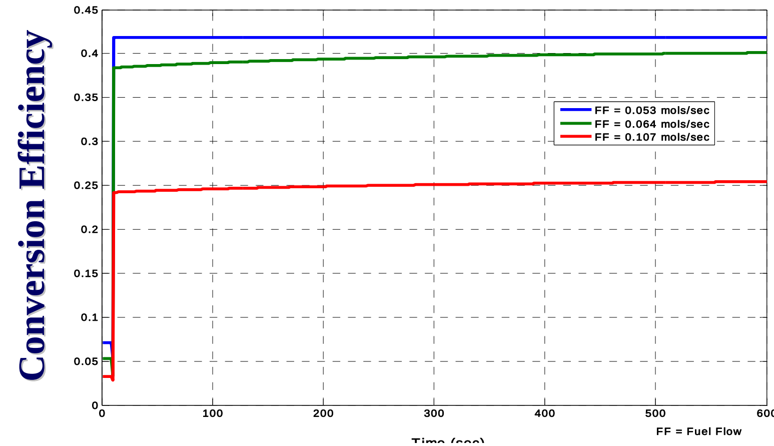


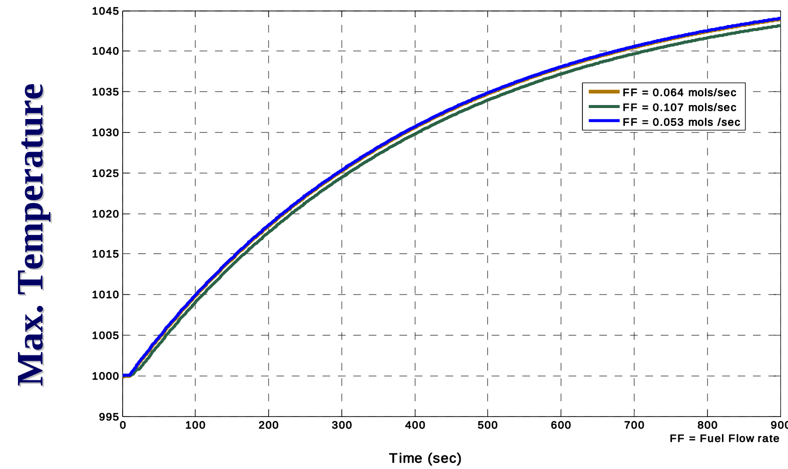




Impacts of Parametric Variations on the Effects of Load Transient

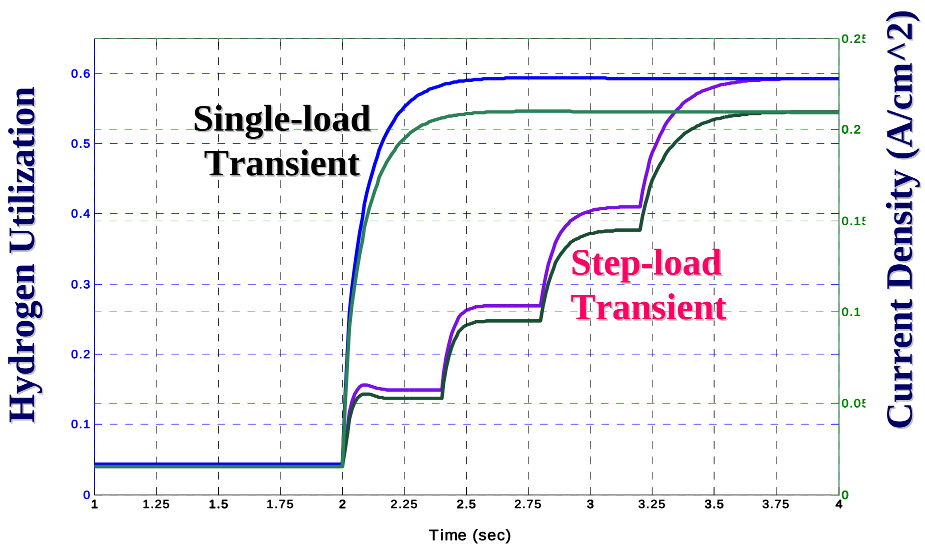


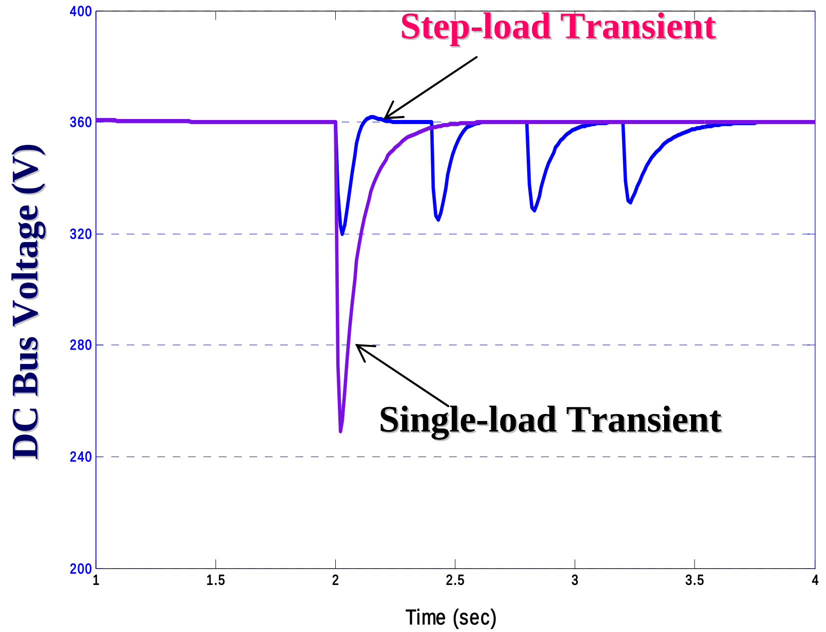




- Operating temperature increase
  - ASR decreases exponentially with increase in the temperature
  - Lesser potential drop
  - Higher efficiency
- Fuel flow rate increase
  - Slight decrease in the temperature
  - Decrease in the efficiency

Effect of step-load transient vs. single-load transient





- Step-load transient leads to
  - Significant reduction in the drop of the DC bus voltage
  - Reduction in increase of the hydrogen utilization and current density during the transient
    - Reduction in the battery size

Conclusion

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- **1D PSOFC model appears to be a good choice to study the load transient effects to reduce computation time without compromising accuracy. But, to accurately study the characteristics including thermal stress, temperature, strength, and the reliability prediction should be based on the PSOFC 2D model;**
- **On a similar note, the state-space averaged model of PES is better suited for the study of load-transient effects from computational efficiency standpoint;**
- **Fully-controlled BOPS model may accurately emulate the actual system but, for spatio-temporal studies on a basic PC, a reduced-order lookup-table model based on the comprehensive model is a more effective choice;**
- **Step-load transients as compared to single load-transient reduces the harmful effects on the SOFC and improves the performance of the PES, which may lead to reduction in the sizes of energy-buffering components (e.g., battery or PHT) and hence, the cost and weight of the power system.**

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Future Works

- Build a complete look-up table model for the BOPS to enhance faster and accurate simulation
- Experimental validation of the obtained simulation result on a PSOFC stack
- Investigate the electrical feedback effects on the material properties of the PSOFC and prediction of life of the PSOFC
- Build an optimal hybrid controller for the PSOFC system to optimize the stack performance while enhancing the reliability of the PSOFC