Optimal Design and Operation of Solid Oxide Fuel Cell Systems for Small-scale Stationary Applications

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Overall Objective

Develop methods for:

Optimal Design and Operation of
Solid Oxide Fuel Cell Systems for
Small-scale (<10 kW) Stationary Applications

Methodology

Integration of cell- and system-level modeling with balance of system models; optimization

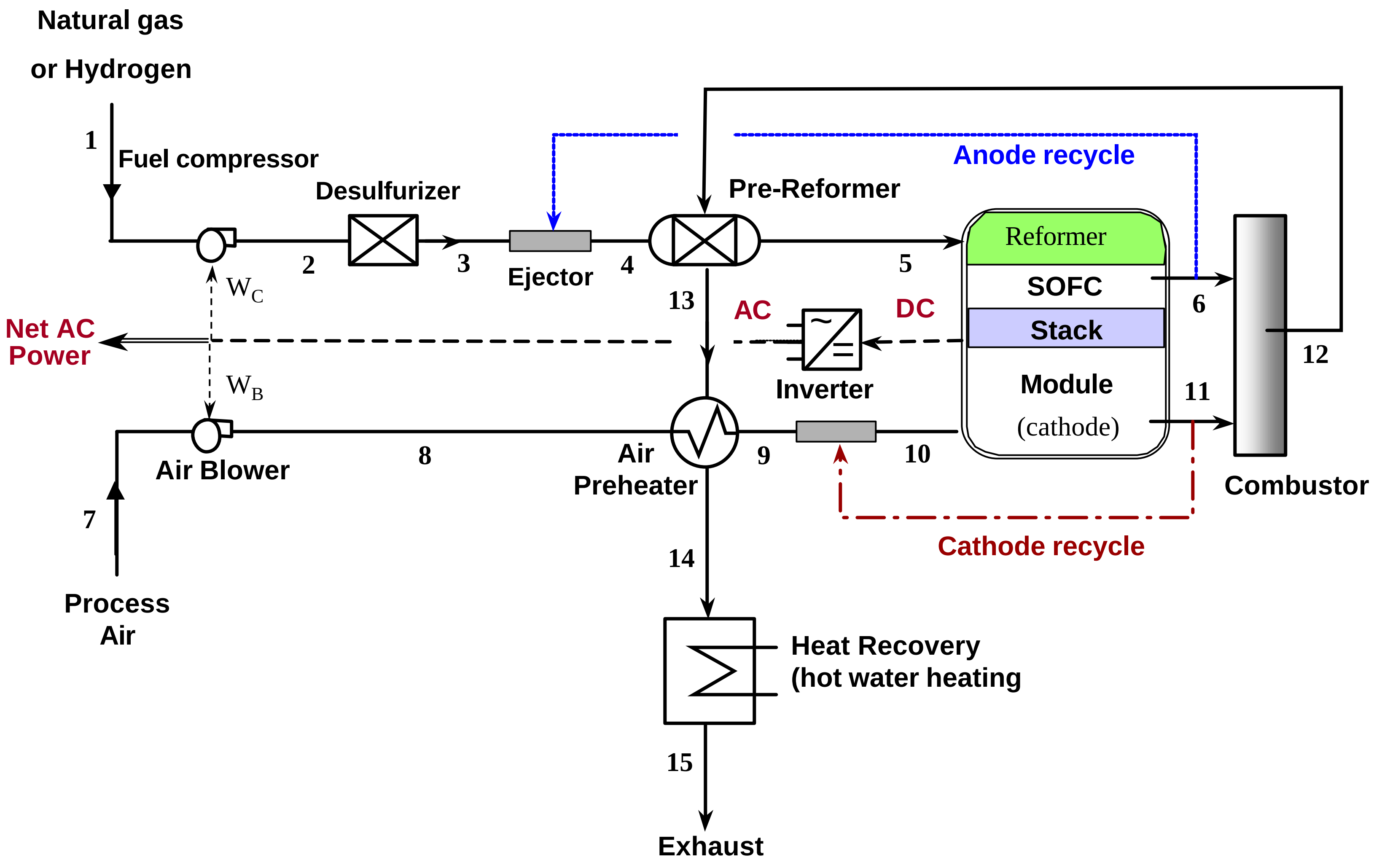
Publication

Robert J. Braun, Ph.D thesis, Univ. of Wisconsin, 2002
Energy Center Wisconsin Report 207-R

Simulation Platform
EES – Engineering Equation Solver

- Solves up to 10,000 simultaneous non-linear algebraic and differential equations
- Built-in thermodynamic and transport property data for many fluids
- Provides parametric studies, plots, optimization, regression, uncertainty analyses, unit checks
- Supports graphical and numerical input/output
- Also used for HYDROGEMS (Research Council of Norway)

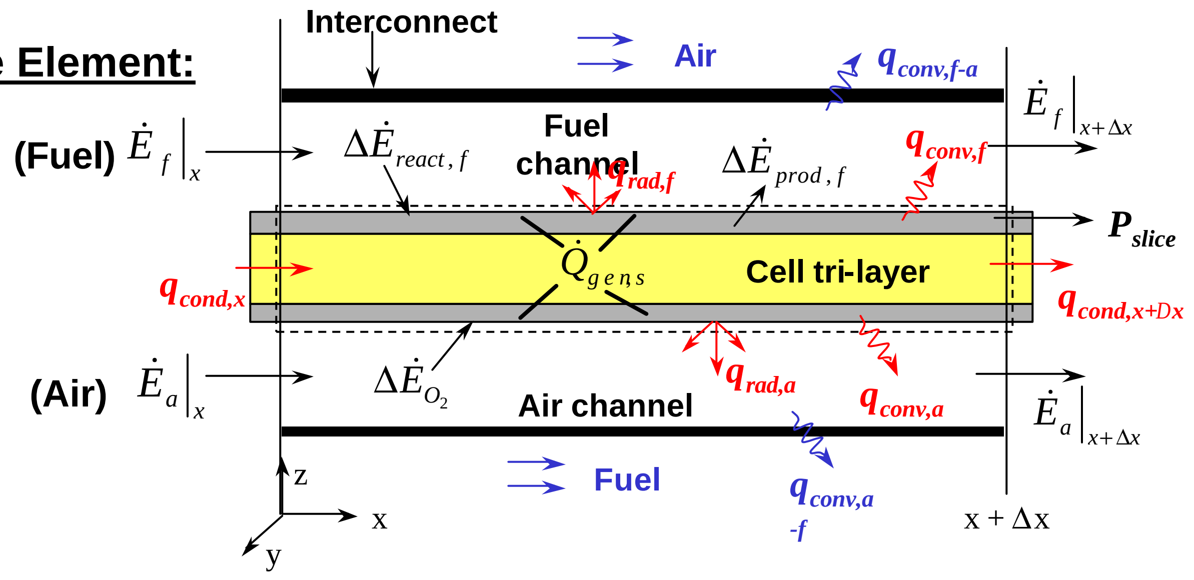
Schematic of General System



Cell Model: 1-D axial discretization

- Mass Transfer (related to current density)
- Heat generation due to reaction and ohmic dissipation
- Conduction, convection, and radiation heat transfer
- Pressure drop due to friction, flow acceleration
- Resolves temperature profiles and gradients, current distributions, gas compositions, and power
- Validation: **IEA SOFC Benchmark (5-8 organizations)**

Slice Element:



All conservation equations (mass, energy, potential) are coupled

Balance of System Component Modeling

Component Types:

- Fuel pre-reformer
- Blower, compressor, pump
- Heat exchangers, boiler
- Recycle jet pump/ejector
- Inverter
- Hot water storage tank

General:

- Mass, Momentum, and Energy Balances
- Boundary Conditions
- Property Relations
- Performance Characteristics

Part-load:

$$(UA) = (UA)_{ref}\left(\frac{\dot{m}_{gas}}{\dot{m}_{gas,ref}}\right)^{0.80}$$

$$\Delta P_{sys} = \Delta P_{ref}\,(\dot{V}_{gas}/\dot{V}_{ref})^2$$

Cost Modeling

Life Cycle Costs

$$COE^{*} = \underbrace{\frac{(\overbrace{R_F}^{\text{capital recovery factor}} \cdot \overbrace{C_{sys}}^{\text{system cost}} + \overbrace{M_C}^{\text{maintenance}})}{C_F}}_{\substack{\text{capital and maintenance cost} \\ C_F \text{ = the electric capacity factor}}} + \underbrace{\frac{\overbrace{F_c}^{\text{fuel cost}}}{h_{sys,e}}}_{\text{fuel cost}} - \underbrace{\frac{\overbrace{F_{th} \cdot e_H}^{\substack{\text{fractional} \\ \text{energyavailable} \\ \text{for cogneration}}} \cdot F_c}{h_{sys,e} \cdot h_R}}_{\substack{\text{thermal energy credit} \\ \text{for cogeneration systems}}}$$

Capital Costs (Scaling)

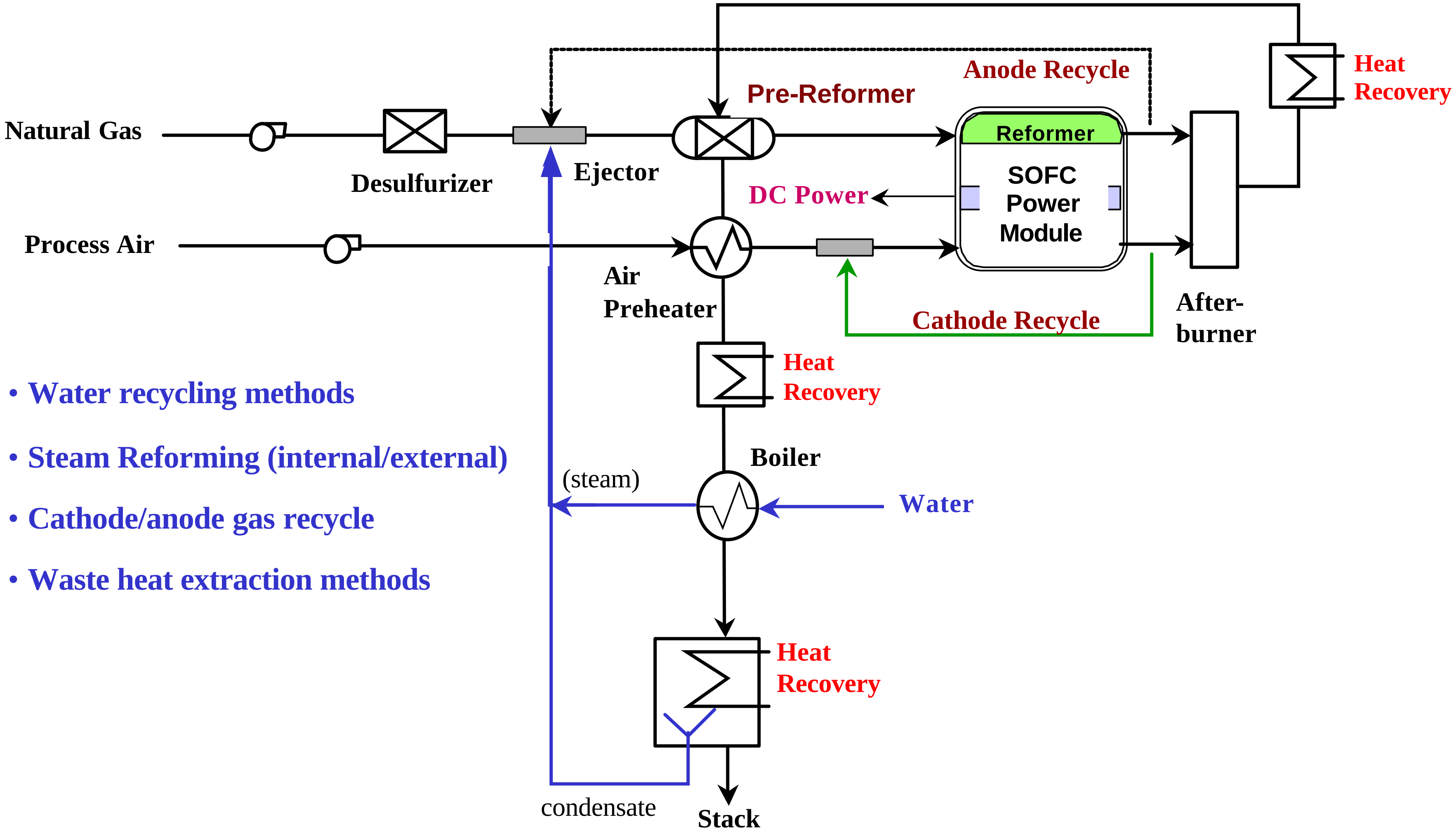
$$C_{new} = C_{ref} \cdot \left(\frac{S}{S_{ref}} \right)^{m}$$

Cost Assumptions:

- 2001 US$
- Plant Life = 20 years
- Stack Life = 5 years (1/3 salvage)
- Discount rate = 20%
- O&M = $0.005/kWh
- Production level = 0.2 –2.5 GW/yr
- Stack cost = $450/kW (large quantity)
- System Cost: $1,200-2,200/kW (10-1 kW)

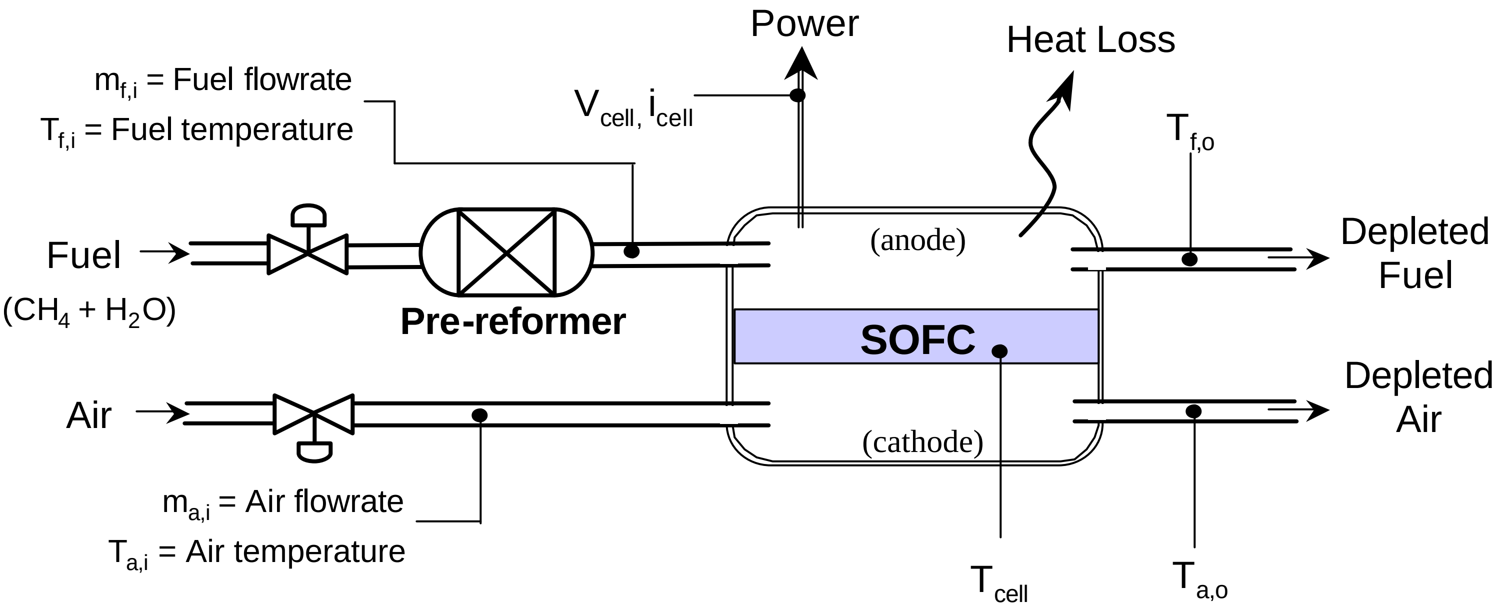
** Based on Ellis and Gunes, ASHRAE Transactions, vol. 108, Pt.1, 2002*

Process Design Options



- Water recycling methods
- Steam Reforming (internal/external)
- Cathode/anode gas recycle
- Waste heat extraction methods

SOFC Operating Control



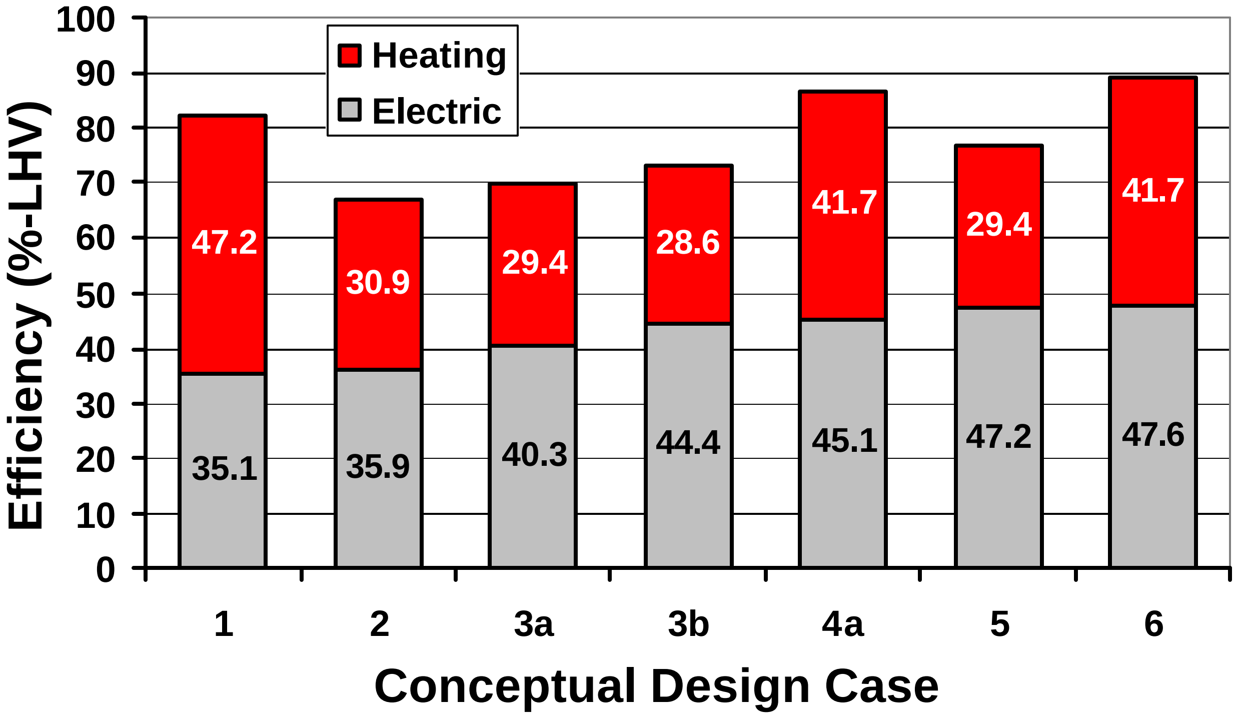
Control 'knobs':

- Fuel flowrate
- Air flowrate

Control methods:

1. Constant fuel utilization and temperature
   $m_{f,i} = f(U_f)$ and $m_{a,i} = f\,(T_{cell}$ or $DT_{air})$
2. Constant cell voltage and temperature
   $m_{f,i} = f(V_{cell})$ and $m_{a,i} = f\,(T_{cell}$ or $DT_{air})$
3. Constant feed flow
   $U_f = f(m_{f,i}, j_{cell})$ and $T_{cell} = f\,(m_{a,i}, j_{cell})$

Model Results: Efficiency Comparison



1 Hydrogen

2 Ext. Ref

3 50% Int. Ref (IR)

4 100% IR, AGR

5 100% IR, CGR

6 100% IR,
AGR-CGR

Cases 4 and 6 most efficient (and least total *system* cost)

Hydrogen system less efficient due to:

- Larger blower parasitic
- Larger (20%) fuel energy input to deliver the same current

Conclusions: Influence of Cell Parameters

- Constant fuel utilization and cell temperature control provides the most operational flexibility
- Independent control of fuel and air flow rates is best for meeting power and stack temperature constraints.
- Cell temperature is strongly correlated with cell performance
- Regulation of cell temperature is affected by the ratio of cell heat generation to the cooling air stream thermal capacitance rate
- Internal reforming increases system efficiency

Conclusions: System Design

- Hydrogen-fueled SOFC systems ? **lower** system efficiencies
  - Larger (20%) fuel energy input to deliver the same current
  - Larger blower parasitic
- Recycle exhaust gases for max. efficiency and lowest cost
- Optimal cell voltage, fuel utilization, and temperature parameters can be selected using minimization of life cycle costs
- Design guidelines for stationary SOFC systems
  - Design systems for multi-family dwellings
  - Size system based on annual hourly average electric load
  - Operate the system in a base-load configuration
  - Cogenerate domestic hot water with thermal storage