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AUTOMOTIVE CONFERENCE 2023
Korea

The Modeling of Fuel Cell System Using Simscape

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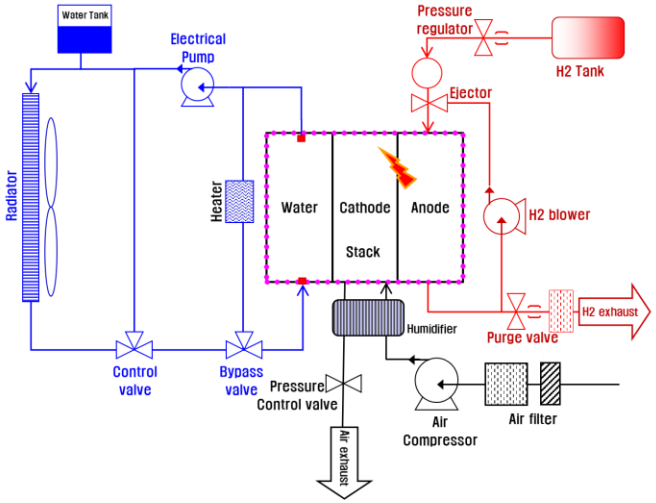
Project Overview

Review of the possibility of building a fuel cell system analysis model through Simscape for modeling of physical systems within the Simulink environment

- Understanding fuel cell vehicles
- Fuel cell system main components
  - Stack: To product electricity from H_2&O_2 chemical reaction
  - Fuel process system(FPS): To supply hydrogen
  - Air process system(APS): To supply oxygen
  - Thermal management system(TMS): To manage the temperature of FC
- Through the deep engagement process of Mathworks

Fuel cell system diagram



What Is Fuel Cell System?

Fuel cell system is power-generating devices that operate by directly taking out electricity through the **electrochemical reaction of hydrogen and oxygen**, from air, **making water and completing the cycle**.

Fuel Cell System

Hydrogen + Oxygen → Energy + Water

Internal Combustion Engine

Gasoline + Oxygen → Energy + Water ***+ CO2 + CO***

Electricity Is More Useful Than Heat

Combustion

- Energy = Heat (100%)

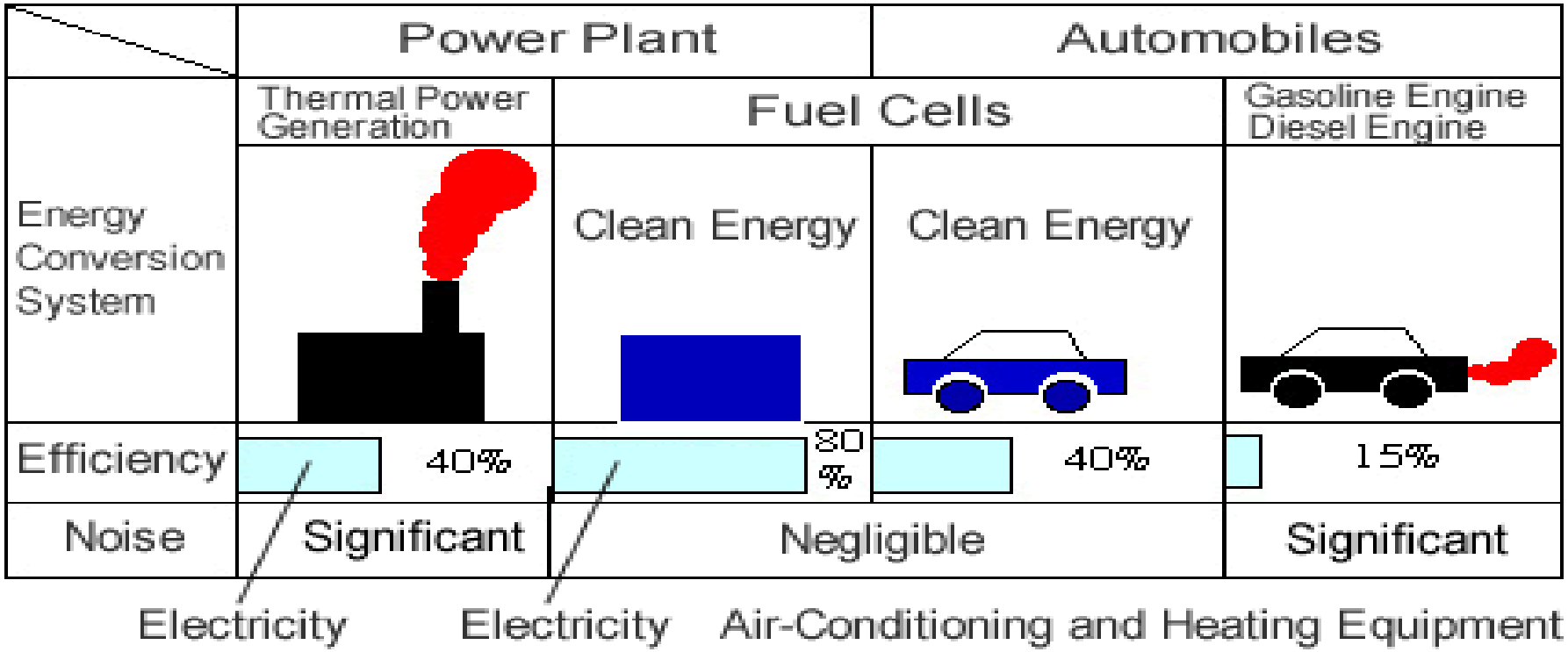
Fuel Cell

- Energy = Heat (50%) + Electricity (50%)

Energy Conversion Efficiency

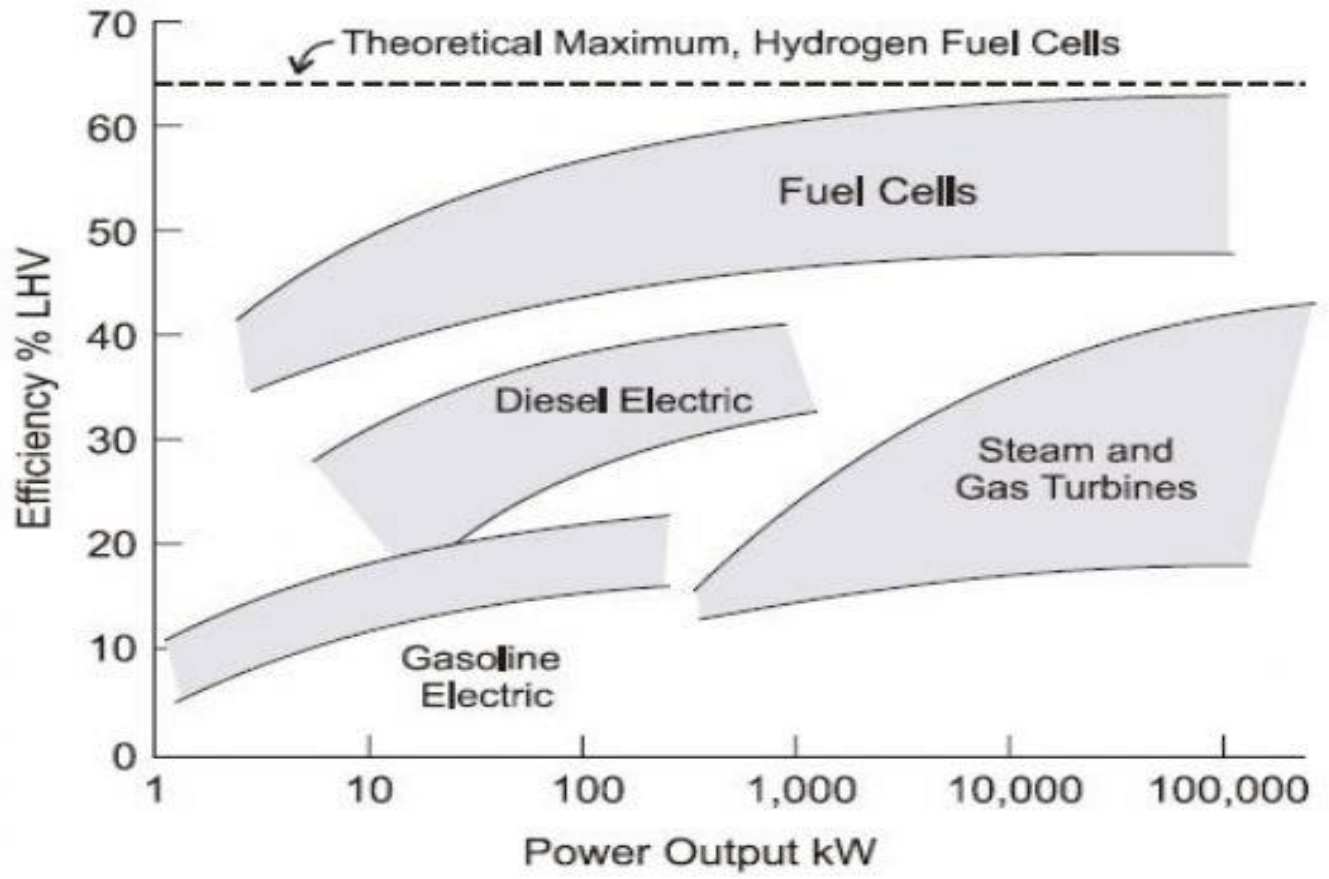
Heat → Mechanical (20 %)
Heat → Electrical (15 %)

Electrical → Mechanical (80%)
Electrical → Heat (100%)



Source : http://www.fcgroup.yamanashi.ac.jp/en/fuel-cell/index.html

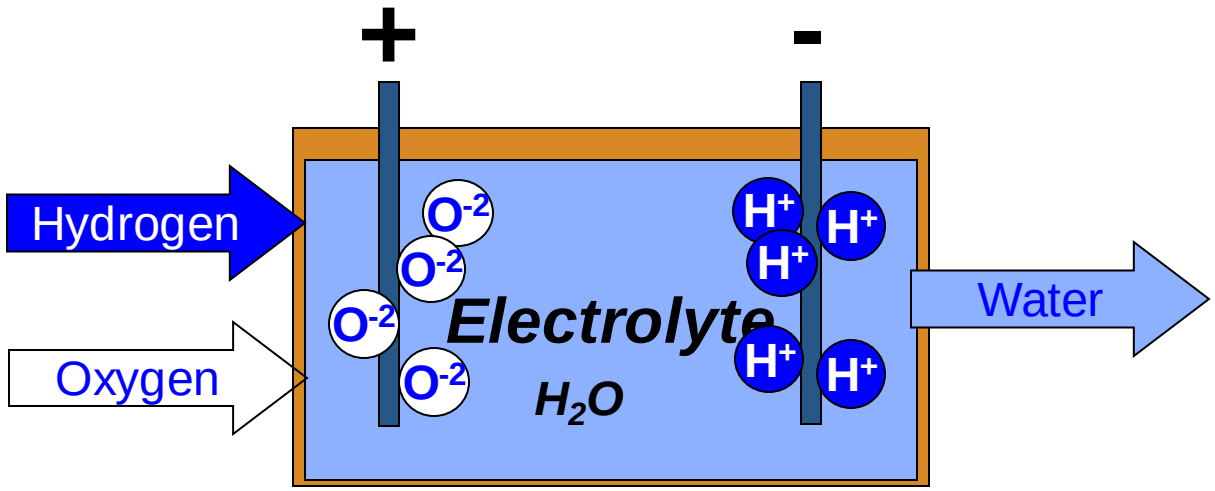
Efficiency Comparison



Efficiency Comparison (www.micro-vett.it)

Source : http://www.ags-energy.com/html/efficiency-g3.html

Fuel Cell Is Like a Battery



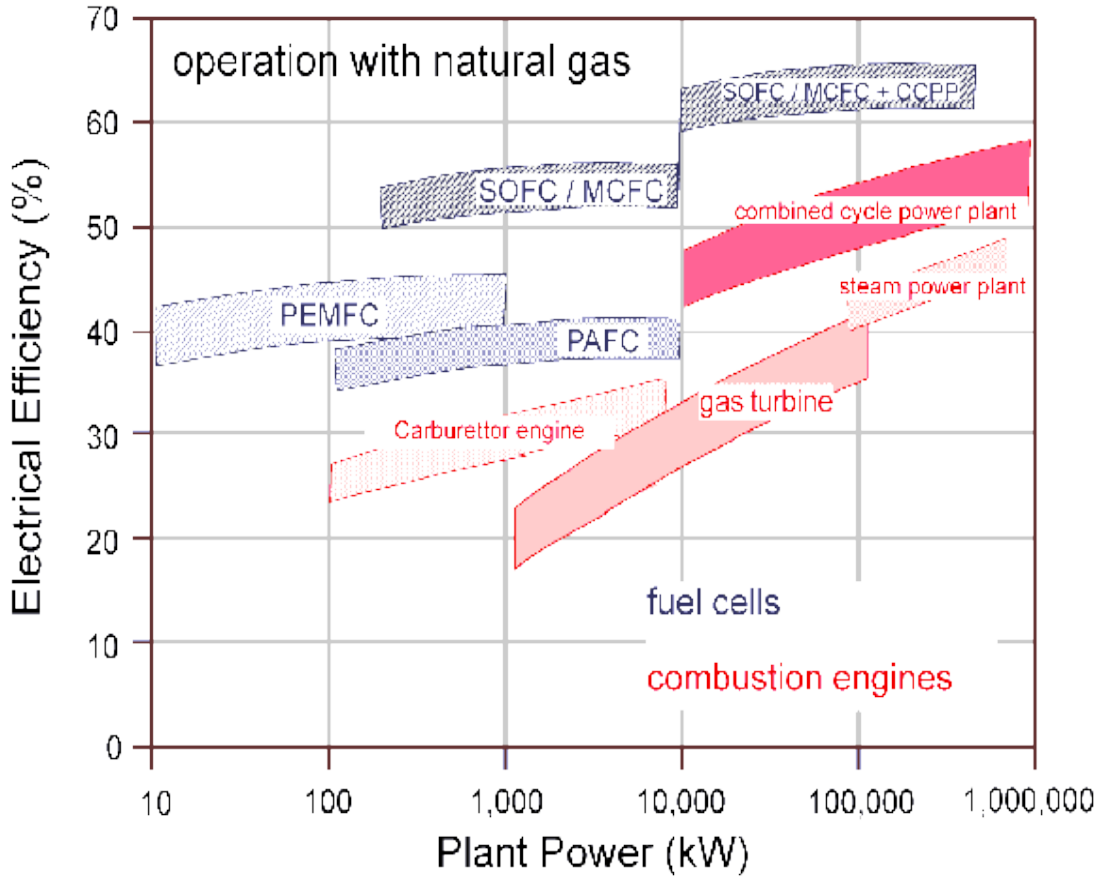
A Hydrogen Fuel Cell

Unlike a battery in that it is an open system with fluid flow

Type of Fuel Cell

Fuel Cell Type		Electrolyte	Operating Temperature	Electrical Efficiency	Fuel Oxidant	Energy Output
AFC	Alkaline Fuel Cell	Potassium hydroxide solution	Room temperature to 90°C	60-to-70%	H^2 O^2	300W-to-5KW
PEMFC	Proton Exchange Membrane Fuel Cell	Proton Exchange Membrane	Room temperature to 80°C	40-to-60%	H^2 O^2, Air	1KW
DMFC	Direct Methanol Fuel Cell	Proton Exchange Membrane	Room temperature to 130°C	20-to-30%	CH^3 OH , O^2 Air	1KW
PAFC	Phosphoric Acid Fuel Cell	Phosphoric Acid	160-to-220°C	55%	Natural gas, bio gas, H^2 O^2, Air	200KW
MCFC	Molten Carbonate Fuel Cell	Molten mixture of alkali metal carbonates	6200-to-660°C	65%	Natural gas, bio gas, coal gas, H^2 O^2, Air	2MW-to-100MW
SOFC	Solid Oxide Fuel Cell	Oxide ion conducting ceramic	800-to-1000°C	60-to-65%	Natural gas, bio gas, coal gas, H^2 O^2, Air	100KW

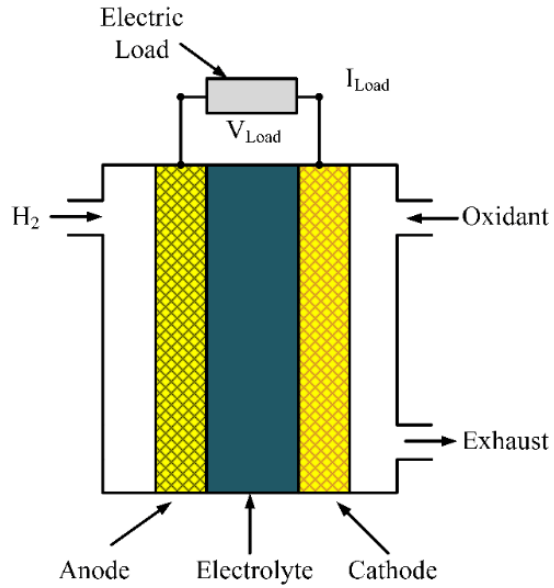
Source: h-tec, SAE International



Source : http://www.fcgroup.yamanashi.ac.jp/en/fuel-cell/index.html

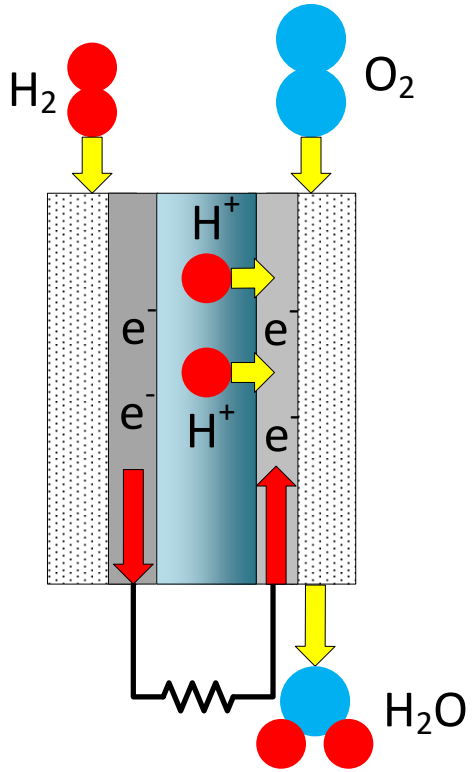
Why Polymer Electrolyte Membrane Fuel Cell(PEMFC)?

- Electrification megatrend
- Advantages
  - Lower emissions than conventional fuel
  - Better fuel economy than conventional fuel
  - Easier scalability than other systems
  - Lighter than batteries for same power
- Disadvantages
  - Costs are higher
  - Pure H_2 storage and transport is challenging
  - Impurities can degrade system
- Open area – lots of investment!



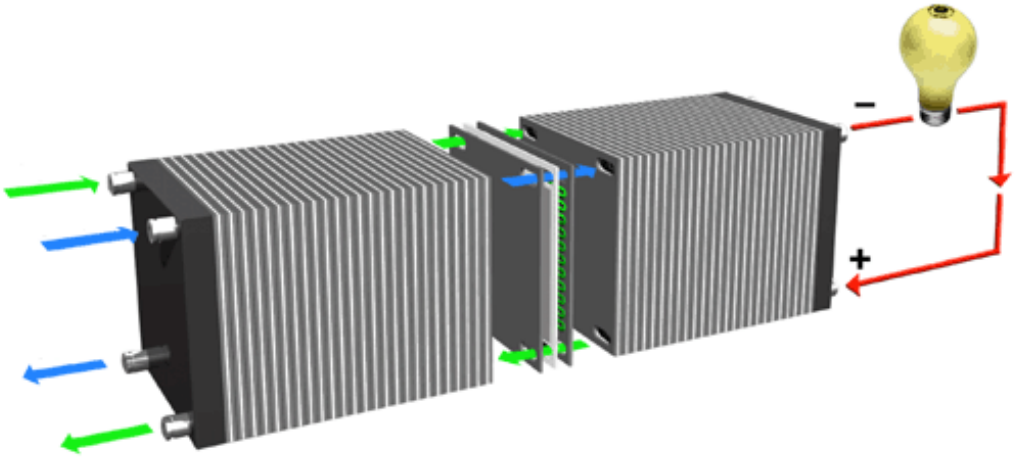
What Is a PEM Fuel Cell?

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + heat + electricity$$



- Anode → oxidizes H_2
- Cathode → reduces O_2
- Conducting layers → transport electrons
- Polyelectrolyte Membrane (PEM) → transport H^+
- Liquid cooling channels → temperature control

- Electrical characteristics
  - V_{max} ~ 1.25 volts
  - i ~ 1-2 A/cm^2
  - Cells are “stacked” in series to get higher voltage



Hyundai's Fuel Cell Technology

- Hyundai has long developed FC technology, and now is getting meaningful achievements
- Through experience in FCEV development, Hyundai is pioneering the hydrogen mobility market

1998 Initiated Fuel Cell Development

2000 First Developed FCEV model (Santa Fe-based)

2013 1st Generation FCEV (ix35 Fuel Cell) "The world's 1st mass production"

2018 2nd Generation FCEV (NEXO) "Superior range and energy efficiency"

2020 Commercial FCEV (XCient FC truck) "The world 1st mass produced FC truck" (Elec City FC bus) "Mass produced FC bus"

2022 High-performance concept FCEV (N vision 74) " The Most advanced FCEV"

Latest Achievements

- Over 25,000 NEXO sold to the global market

FC Stack	95 kW
Motor	113 kW
H2 Tank Capacity	6.33 Kg
Drive Range	666 km

- 47 trucks exported to Switzerland / 27 trucks to Germany BMDV[1]
- 1,600 trucks to be exported to Switzerland by 2025

FC Stack	180 kW
Motor	350 kW
H2 Tank Capacity	32 Kg
Drive Range	400 km

- 241 buses in domestic market ('22 target sales : 300)
- Successful test drive in Munich, Germany (Jun. 2022)

FC Stack	180 kW
Motor	300 kW
H2 Tank Capacity	34 Kg
Drive Range	474 km

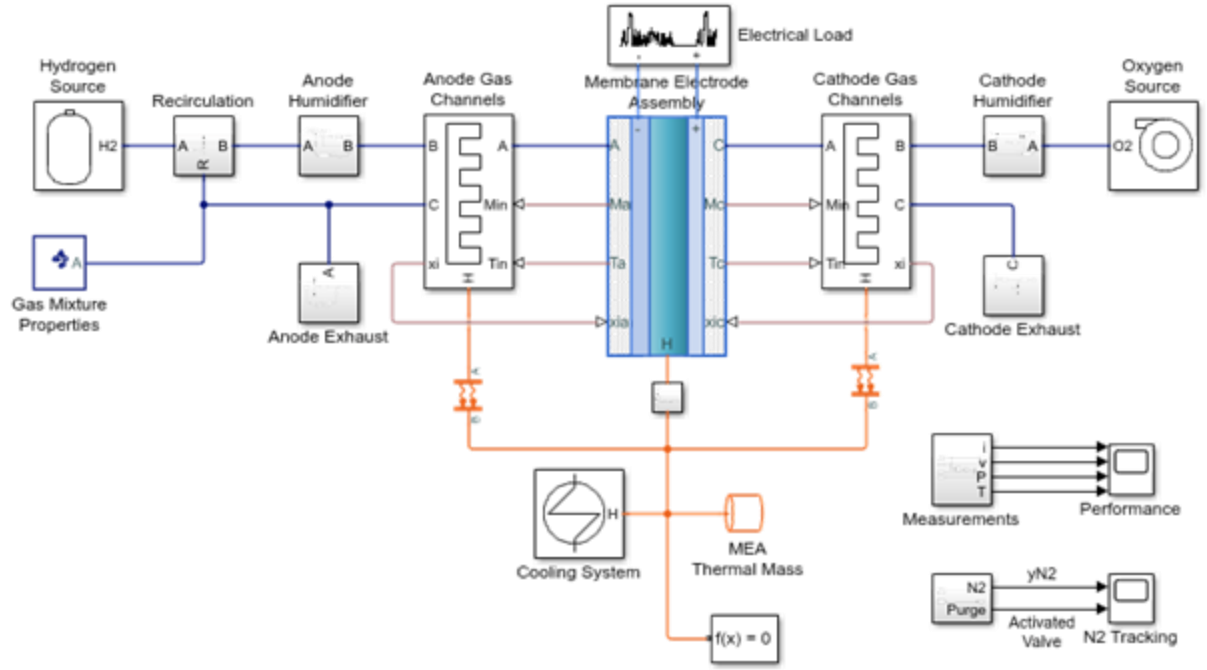
[1] Federal Ministry for Digital and Transport

Project Goals and Challenges

Building of a model that reliably predicts fuel cell performance and efficiency

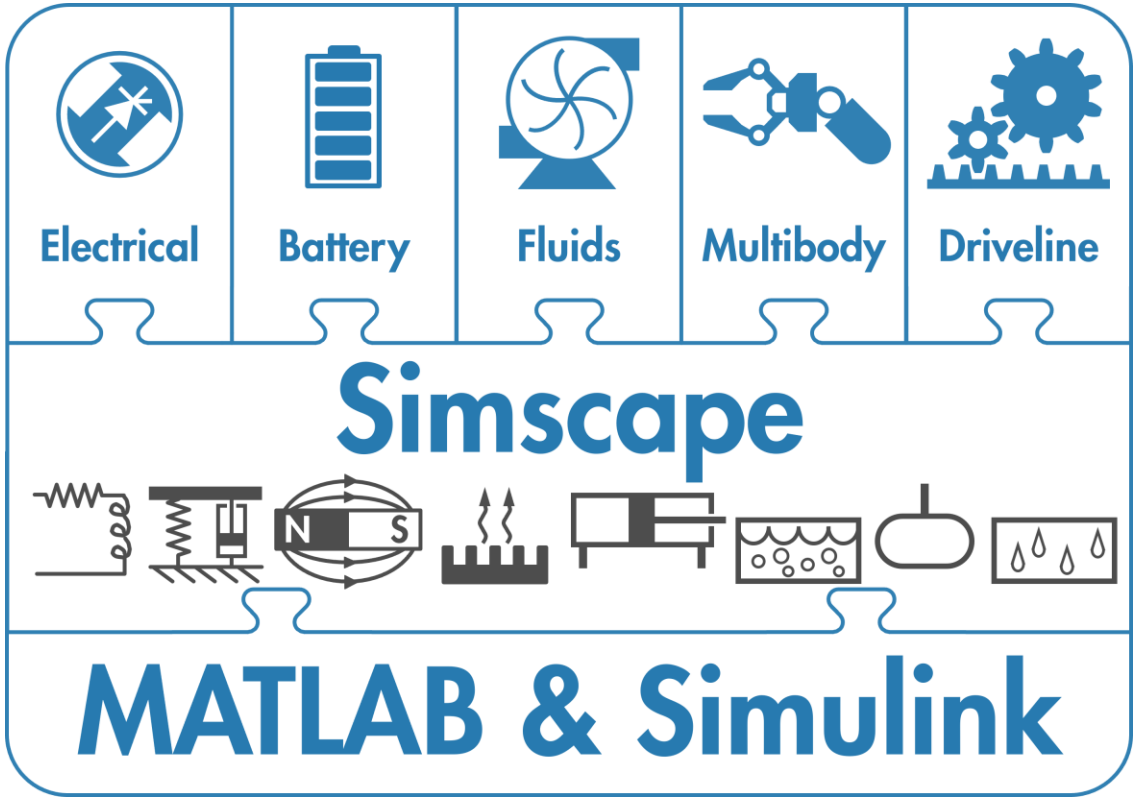
- Addition of physical phenomena that affect a fuel cell reaction
- Construction of models for main component comprising the fuel cell system
- Ensuring of compatibility among components in the system

Existing Simscape model for fuel cell system

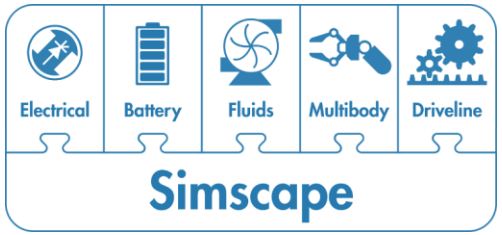


Simscape Products

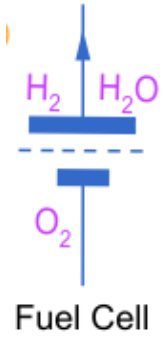
- Simscape platform
  - Foundation libraries in many domains
  - Language for defining custom blocks
    - Extension of MATLAB
  - Simulation engine and custom diagnostics
- Simscape add-on libraries
- Simscape Language for customization

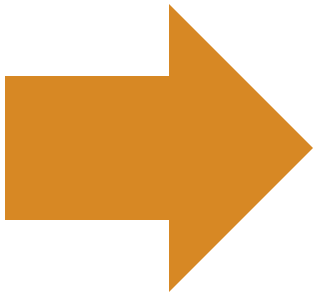


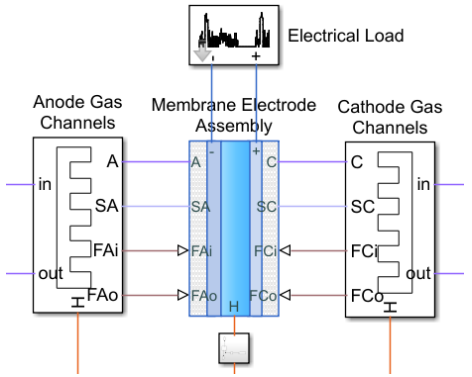
Supported Fluids Domain in Simscape Environment



- Simscape provides libraries that let you include only the physical effects you need





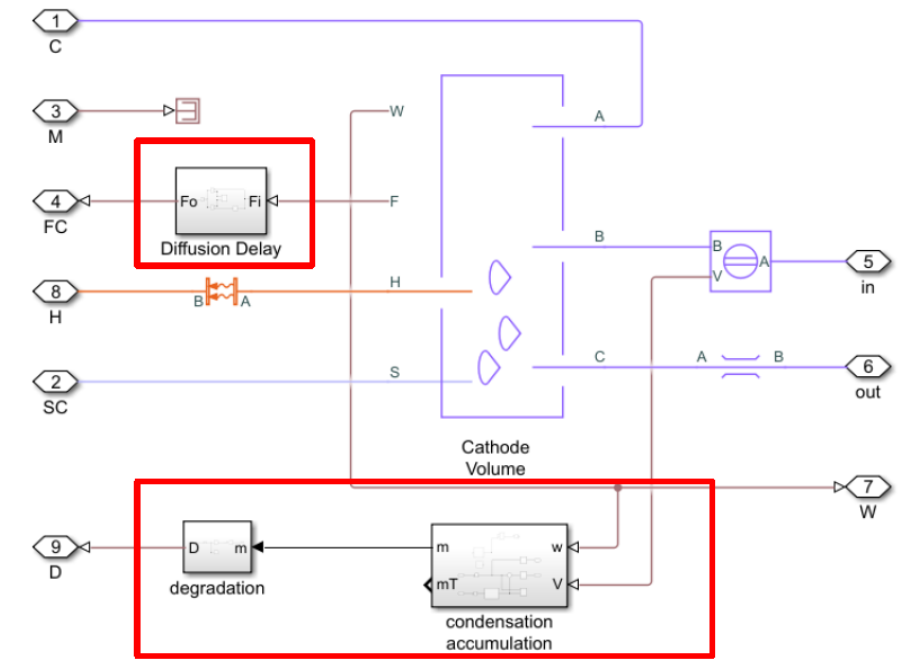


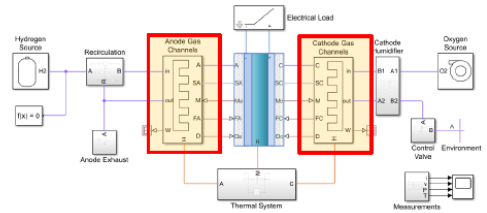
How did we get there and leverage Mathworks (1)

Improvement of physical phenomena in the stack

- Gas diffusion between anode & cathode through membrane
  - Diffusion coefficient depending on the material property
- Diffusion through GDL & water condensation in GDL
  - Behavioral model without modeling the volume and mass in GDL
  - Assumed liquid water removal as a function of air flow
- GDL blockage & effective area
  - Residual water not removed by air flow may reduce effective stack area

Cathode side in the stack



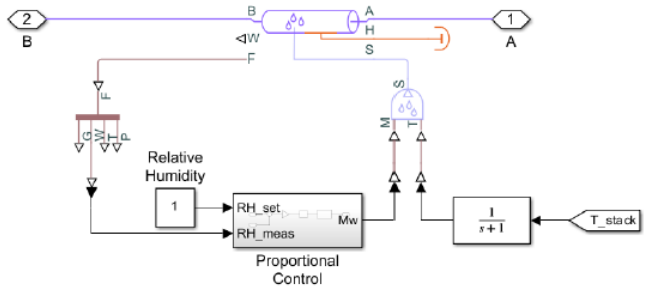


How did we get there and leverage Mathworks (2)

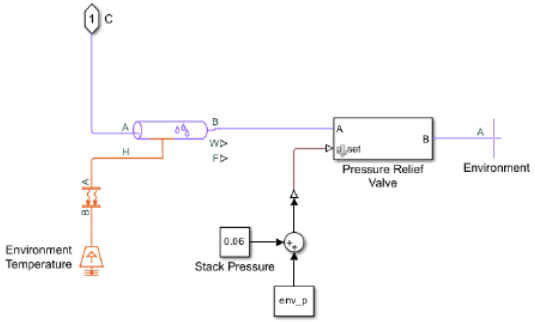
APS component models

- Humidifier
  - Modifying the model to be humidified using stack drain vapor
- Air compressor
  - Implementation of flow map and efficiency map as lookup tables
- Air intercooler and Pressure control valve
  - Newly added component models
  - Hot air cooling from air compressor
  - Control to maintain pressure setpoint

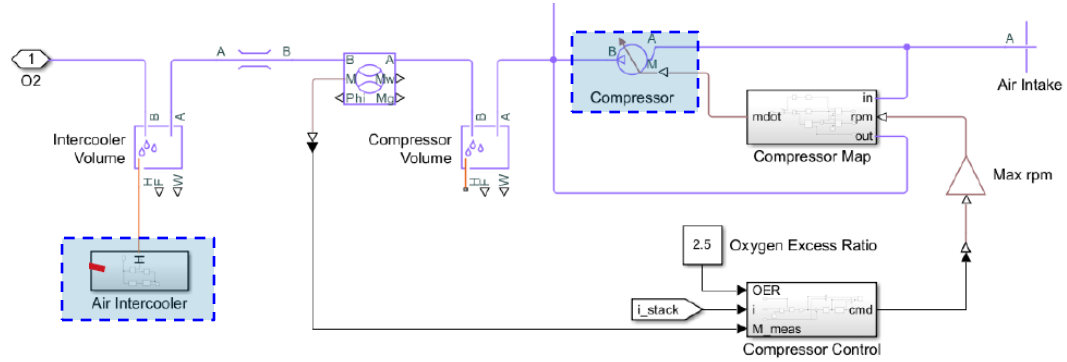
Humidifier



Pressure control valve



Air intercooler and Compressor



How did we get there and leverage Mathworks (3)

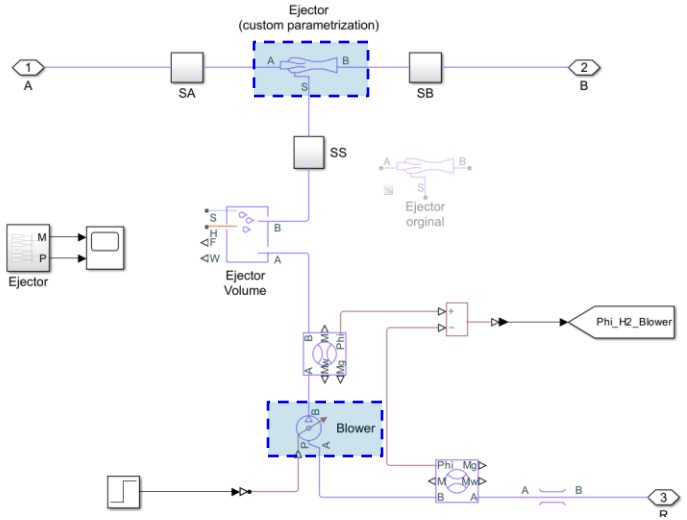
FPS component models (1)

- Ejector
  - Newly added component models
  - Tuning parameters simultaneously with Parameter Estimator App.

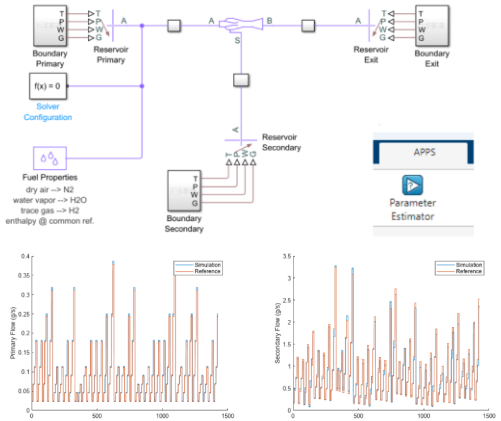
- Recirculation blower
  - Map-based model
  - More sophisticated equations for the corrected speed and mass flow

$$\tilde{m} = m\frac{\sqrt{T/T_{st}}\cdot\sqrt{R/R_{st}}}{(P/P_{st})\cdot\sqrt{\gamma/\gamma_{st}}} \quad \text{and} \quad \tilde{N} = \frac{N}{\sqrt{T/T_{st}}\cdot\sqrt{R/R_{st}}\cdot\sqrt{\gamma/\gamma_{st}}}$$

Ejector & Recirculation Blower



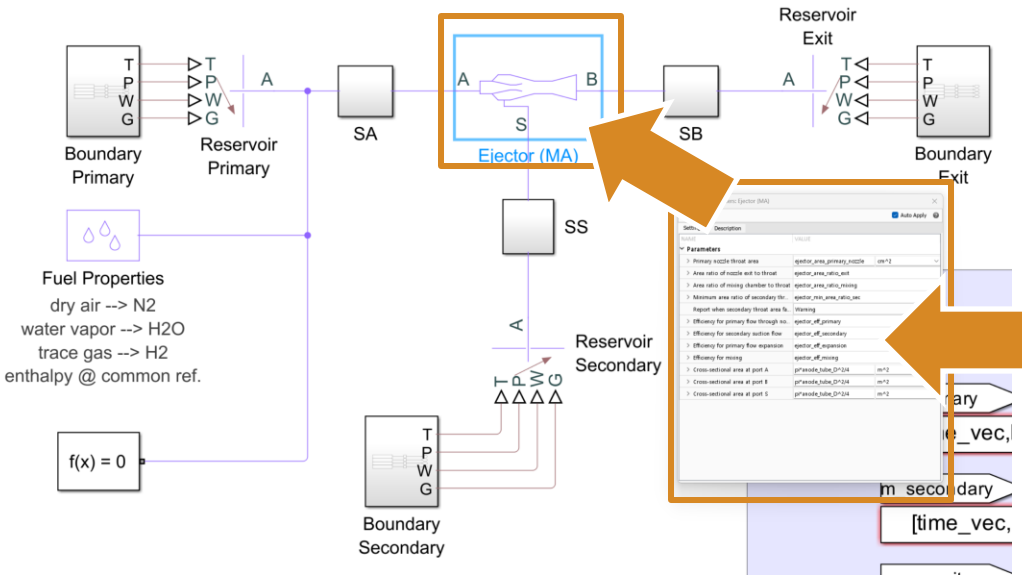
Ejector modeling with Parameter Estimator

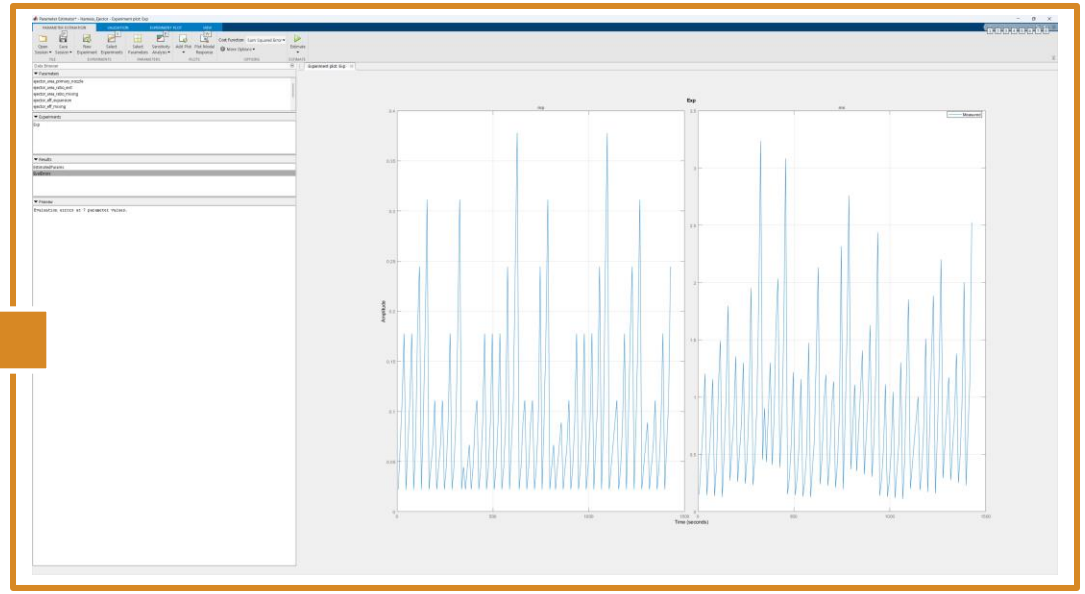


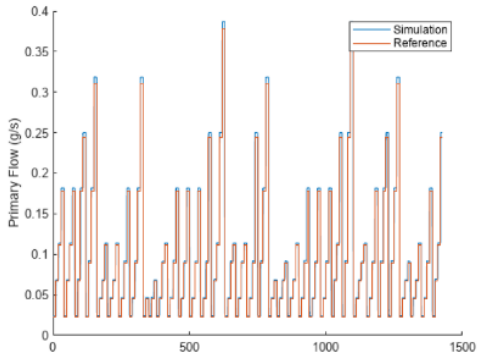
Ejector model

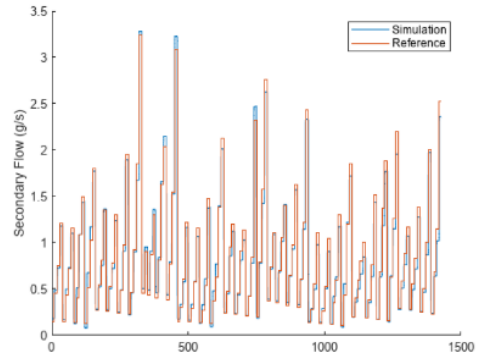
Parameter Estimator ★ Response Optimizer ★ Sensitivity Analyzer

– Unknown parameters of ejector model are estimated using Experiment data





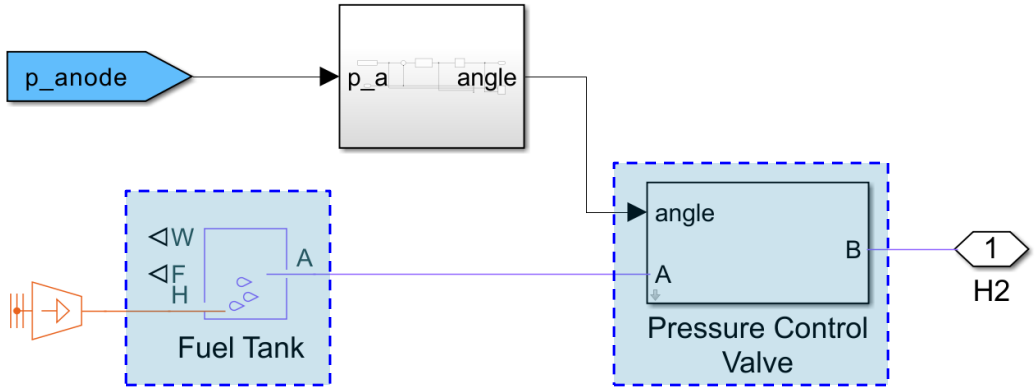




How did we get there and leverage Mathworks (4)

FPS component models (2)

Hydrogen tank & Control valve



- Hydrogen tank
  - Prescribed temperature boundary condition
  - Parameters: tank volume, initial pressure & temp.
- Hydrogen control valve
  - Local restriction block + lookup table
  - Lookup table translates the opening angle to an effective opening area
  - Controlled to maintain anode pressure

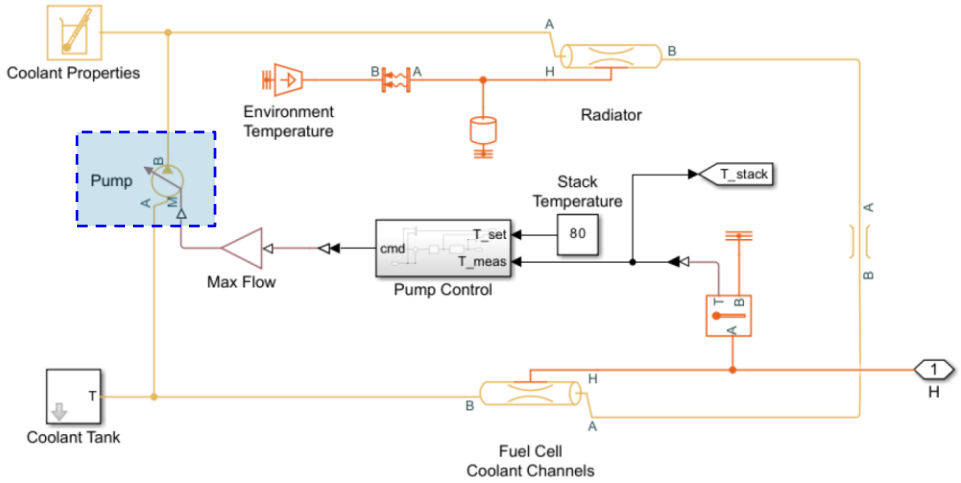
How did we get there and leverage Mathworks (5)

TMS component models

- Improved thermal network model for the components of stack
  - Conduction through different layers
  - Separate thermal masses for each component in stack

- Pump
  - Option to use 2D lookup tables for parameterization
  - Script to convert pressure rise and efficiency data

TMS & Pump

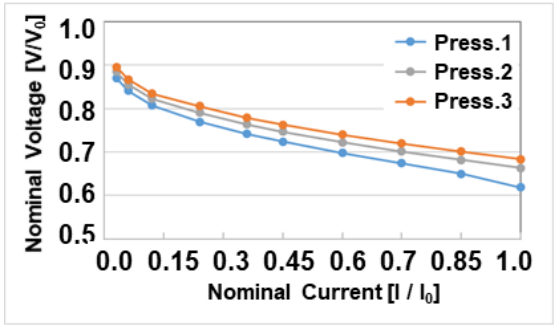


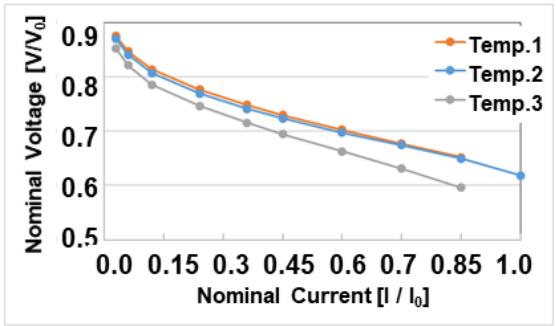
Achievement and Outlook

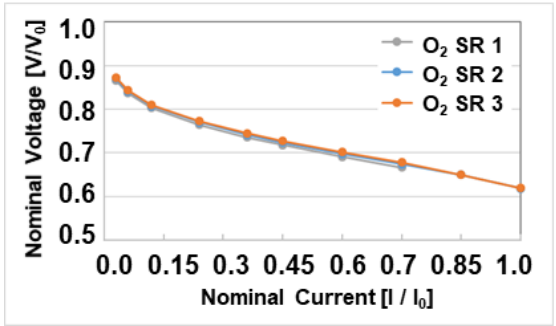
Check for compatibility and appropriateness after configuring the system with each component

- No error in a system simulation under various conditions
- Confirmation of similar tendencies in comparison of fuel cell performance with existing data
  - Anode&Cathode pressure
  - Coolant temperature
  - Oxygen SR(stoichiometric ratio)

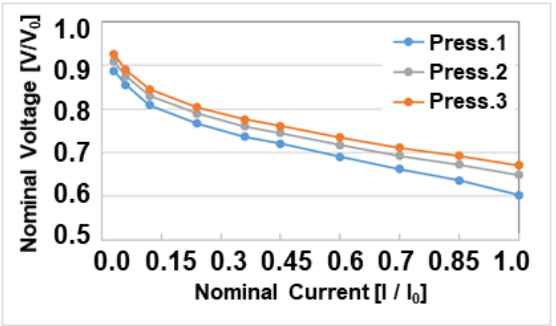
HMC model

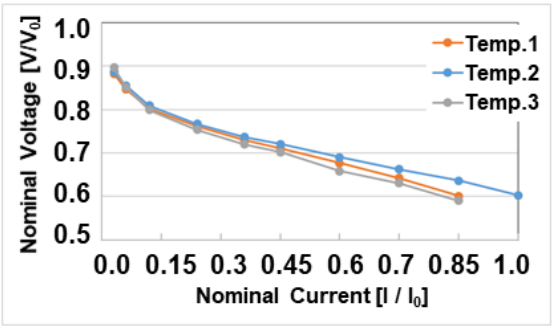


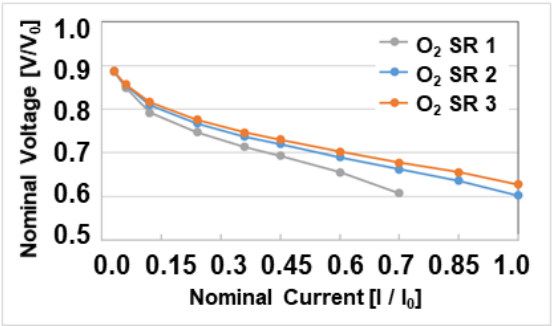




Simscape model



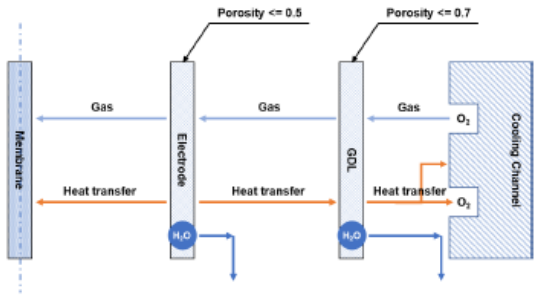




Further Details on Solutions Adopted

Consultant project promotion for further model development

- Stack
  - Gas blockage from condensed water in porous components such as GDL & electrode
  - More detail heat transfer mechanism in channel, GDL, CL with separated layer configuration



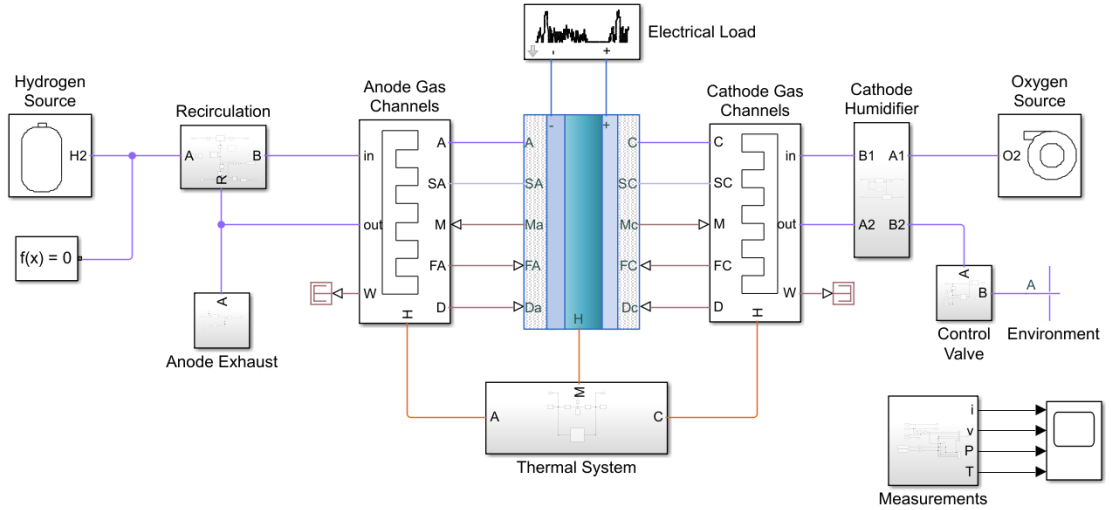
- System
  - Modeling to simulate gas compositions with multi-species

Concluding Remarks

Development of the appropriate model for fuel cell system through Simscape

- Active technical support with outstanding technical skills
- Work cooperation with the vehicle side through the enhanced fuel cell system model

Developed Simscape model for fuel cell system



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