Webinar and demo:
Empowering Hydrogen Energy with Real-Time Simulation and HIL Testing of Multi-Energy Systems

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AGENDA

- Background on multi-energy flow simulation
- Review of our hydrogen system models
- Case demo in RSCAD FX software
- Q&A

Note: No primer on our technology today – check out our introductory videos on Youtube

About RTDS Technologies

- Headquarters in Winnipeg, Canada
- Pioneered real-time power system simulation in the 1980s
- The RTDS Simulator is the industry standard for real-time simulation and closed-loop testing, used by utilities, manufacturers, research and educational institutions, and consultants worldwide
- Learn more at www.rtds.com or the large library of videos on the RTDS Technologies YouTube channel

Upcoming Event:
North American Applications & Technology Conference

May 6 – 8, 2025 in Chicago

- Program will include many user presentations and presentations on new features from RTDS staff
- Tour of ComEd's state-of-the-art Grid Integration and Technology Lab facility
- Everyone welcome; not limited to customers located in North America
- **Register as an attendee and/or a presenter at http://rtds.com/atc2025**

Webinar Presentation:
Empowering Hydrogen Energy with Real-Time Simulation and HIL Testing of Multi-Energy Systems

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AGENDA

- Introduction
- Multi Energy Flow Simulations
- Hydrogen System Models
- Applications
- Demonstration
- Q&A

Introduction

Hydrogen (H_2) Energy

- H_2 is considered as one of the best energy carriers for the future
  - Environment friendly attributes
  - High conversion efficiency
  - Versatility to store, transport, and deliver energy from other sources
- The impact of H_2 in power systems is becoming increasingly important
- Hydrogen technologies still remain in the early stages of development and grapple with certain limitations
  - Lack of efficient and diverse energy conversion technologies
  - Lack of efficient and cost-effective storage mechanisms
  - Electrical supply problems

Introduction

Multi-Energy Systems

- Integrates different types of energy sources (e.g., electricity, heat, and H_2) to optimize energy generation, storage, and consumption in a cohesive, flexible way
- Core Components:
  - Energy Sources: e.g., Renewables and storage systems (batteries, hydrogen)
  - Energy Conversion: Systems that convert one form of energy into another (e.g., power-to-H_2)
  - Energy Distribution: Multi-sector networks to transmit/distribute energy (electricity, heating, H_2)
- Benefits:
  - Energy Efficiency: Optimized coordination between energy sources
  - Grid Stability: Enhanced flexibility in managing variable renewable sorces
  - Cost Reduction: Decreasing costs by using the most appropriate energy source at any given time
  - Energy Security: Diversified energy mix reduces dependency on a single energy source
  - Storage Solutions: Enables advanced energy storage solutions

Multi-Energy Simulation of H_2 Systems

Multi-Energy Simulations of H_2 Systems

MEF Modeling of H_2 System Components

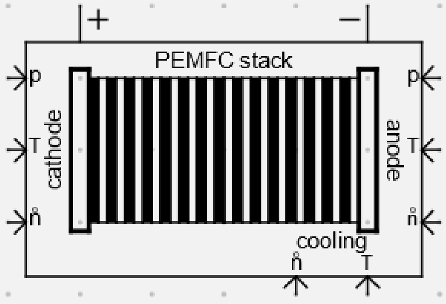
- Capability to simulate electrical behavior and the thermodynamic behaviors
- Energy conversion devices are modeled as power system components in RSCAD and interfaced to the electrical network using their equivalent circuits
- Auxiliary components are modeled as control component in RSCAD
- The thermodynamics and mass transport of these components account for four compounds:
  - Two phase fluid: H_2O
  - Ideal gases: H_2, O_2, N_2
- It is assumed that H_2, N_2, and O_2 exist as ideal gases
- H_2O may be present in both the gas and liquid phases
- Thermodynamic properties are approximated using polynomials

	H_2O	H_2	N_2	O_2
Gas/Vapor	✓	✓	✓	✓
Liquid	✓	×	×	×
Minimum Temperature	200 K	62 K	200 K	200 K
Maximum Temperature	6000 K	1000 K	6000 K	6000 K

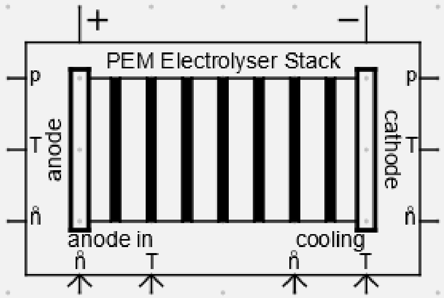
Multi-Energy Simulations of H_2 Systems

H_2 System Components

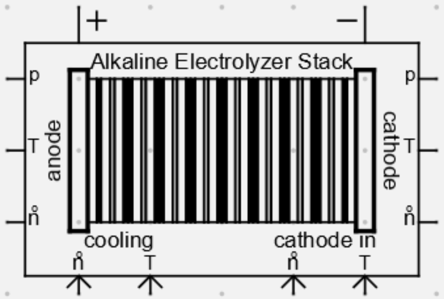
- PEM fuel cell
- PEM electrolyzer
- Alkaline electrolyzer
- Storage tank
- Gas compressor
- Fluid Mixer
- Fluid property calculator



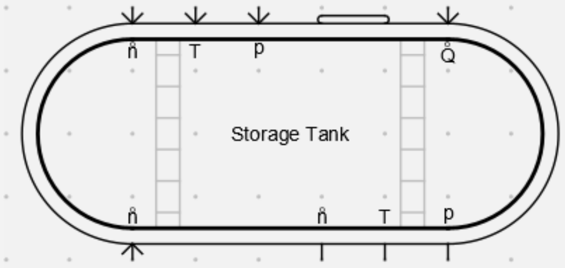
PEM Fuel Cell Stack



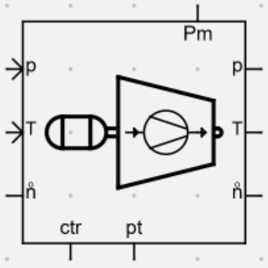
PEM Electrolyzer Stack



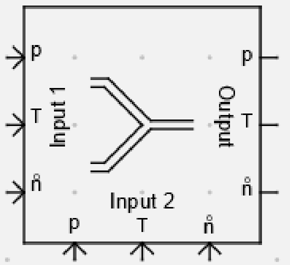
Alkaline Electrolyzer Stack



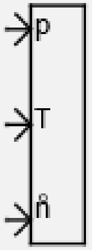
Storage Tank



Gas Compressor



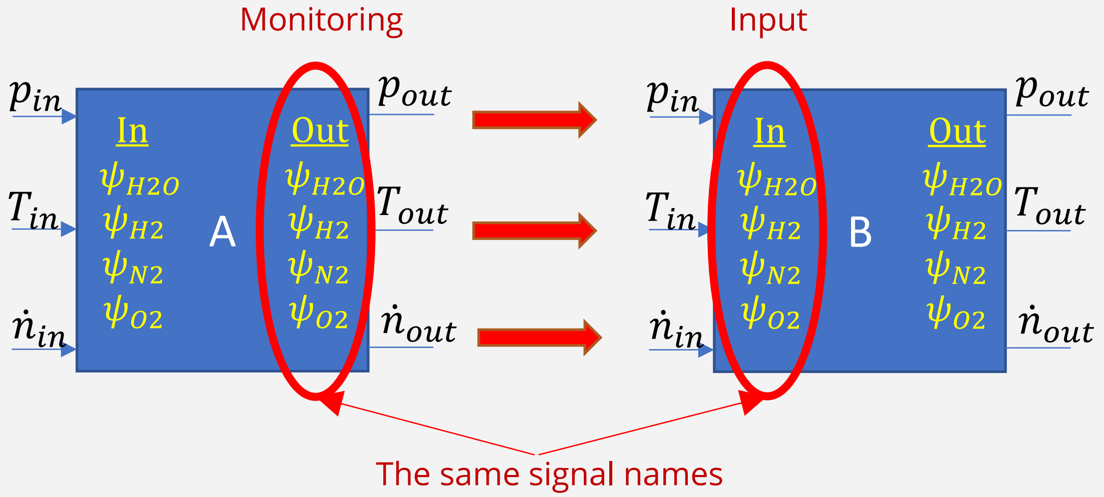
Fluid Mixer



Fluid Property Calculator

Multi-Energy Simulations of H_2 Systems

Component Connection



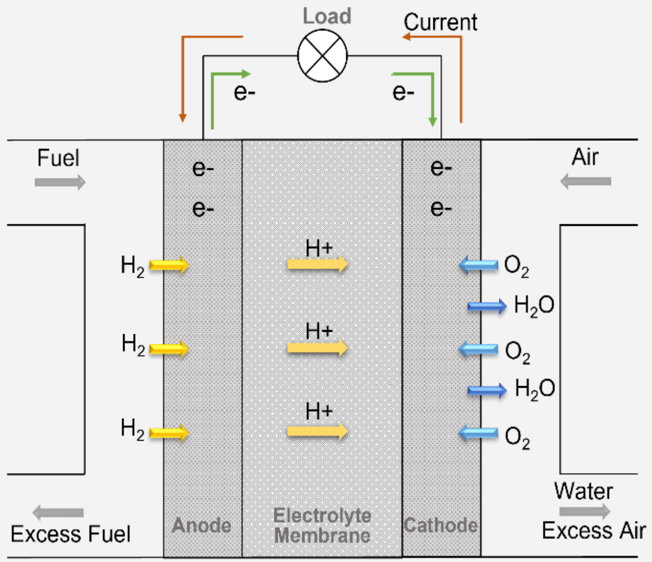
- Simulation of a H_2 systems is based on a modular approach
- Flow based models
- Ports to provide pressure, temperature, and molar flow rate
- Input molar fractions are specified

Hydrogen System Models

PEM Fuel Cell (PEMFC) Stack

Working Principle

- A fuel cell consists of an anode, a cathode, and a polymer electrolyte membrane (PEM)
- Anode input: Hydrogen
- Cathode input: Oxygen or Air
- The PEM has a low resistance to positive ions; hence, it allows H+ ions (protons) to pass through while blocking electrons
- Electrons are forced through an external circuit, creating a direct current from cathode to anode
- Number of fuel cells are connected in series and/or parallel to achieve a desired voltage and power



Anode: $H_2 \rightleftharpoons 2H^+ + 2e^-$

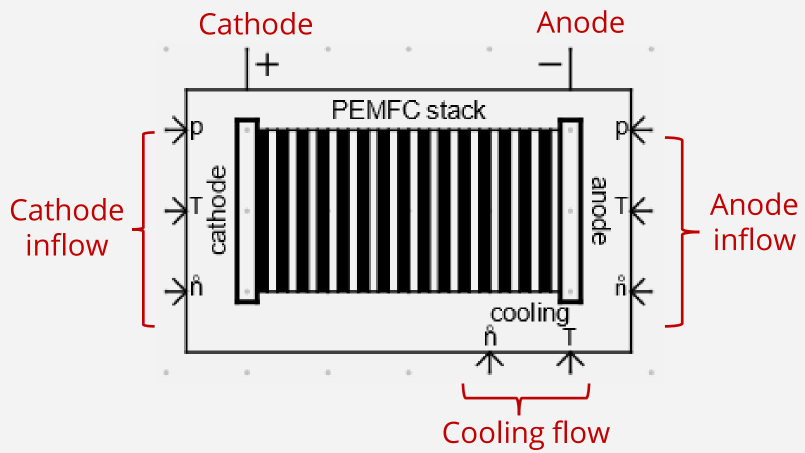
Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightleftharpoons H_2O$

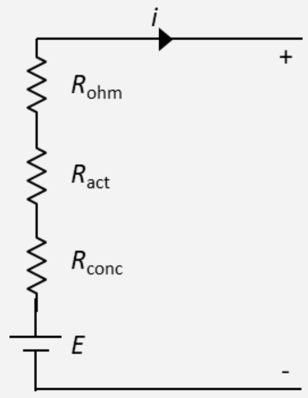
Overall: $H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O$

PEM Fuel Cell (PEMFC) Stack

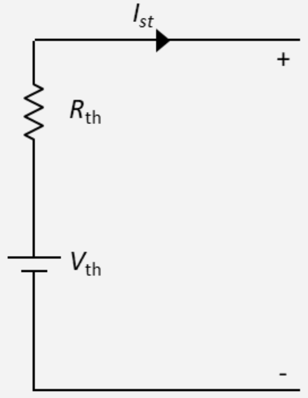
Model and Features

- The electrical model consists of four voltage components:
  - Nernst (reversible) voltage, E
  - Activation voltage loss, R_{act}
  - Concentration voltage loss, R_{conc}
  - Ohmic loss, R_{ohm}
- Model features include:
  - H_2 and O_2 supply and utilization
  - Fuel starvation
  - Anode and cathode pressures
  - Membrane water content
  - Cooling system and stack temperature





Single fuel cell

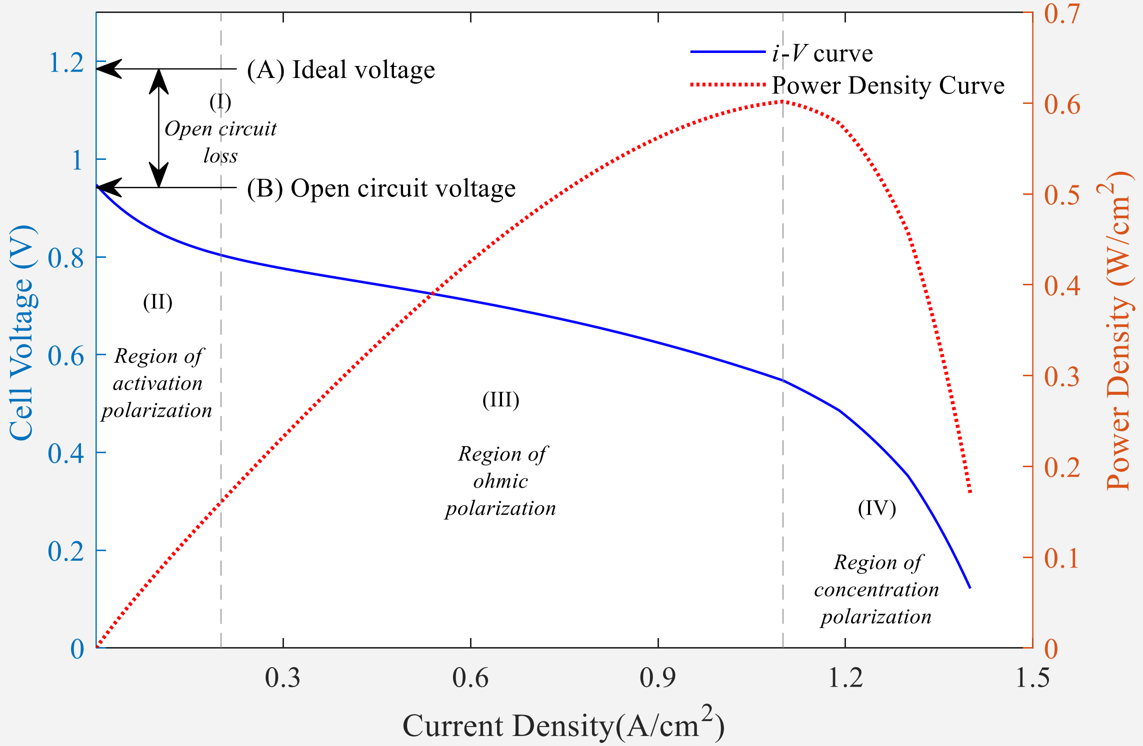


Fuel cell stack

PEM Fuel Cell (PEMFC) Stack

Characteristic Curves

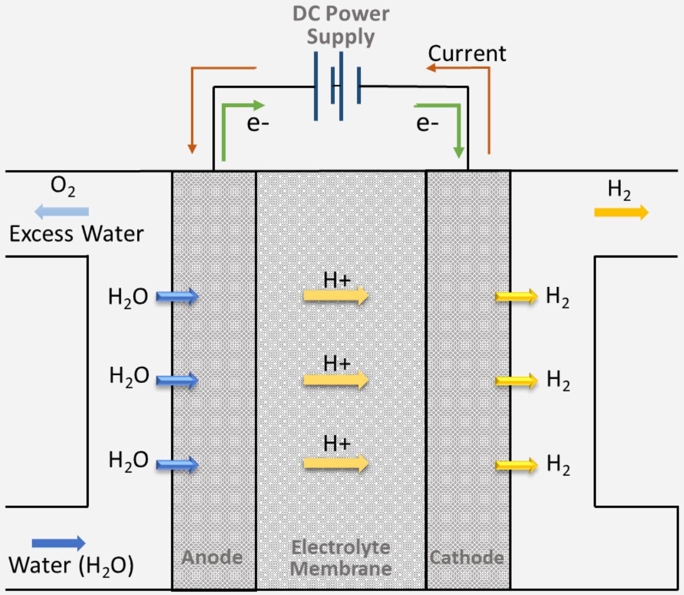
- Polarization Curve: cell voltage vs. current density
- Power Density Curve: power per unit area of the fuel cell vs. current density
  - (A) – Reversible voltage (~1.2 V)
  - (B) - Open circuit voltage (0.9 V – 1.0 V)
  - Region (I) - Open circuit voltage losses (0.2 V to 0.3 V)
  - Region (II) - Region of activation polarization
  - Region (III) - Region of ohmic polarization
  - Region (IV) - Region of concentration polarization
- Typical operating range: 0.6 V - 0.7 V



PEM Water Electrolyzer (PEMWE)

Working Principle

- A DC power source is connected between two electrodes
- Water (H_2O) is supplied to the anode where it is decomposed into protons and electrons while generating O_2
- Protons travel via membrane to the cathode side
- Electrons are forced to the cathode side through the external circuit by the voltage difference
- In the cathode, hydrogen ions and electrons are recombined to form H_2 gas



Anode: $H_2O \rightleftharpoons 2H^+ + 2e^- + \frac{1}{2}O_2$

Cathode: $2H^+ + 2e^- \rightleftharpoons H_2$

Overall: $H_2O \rightleftharpoons H_2 + \frac{1}{2}O_2$

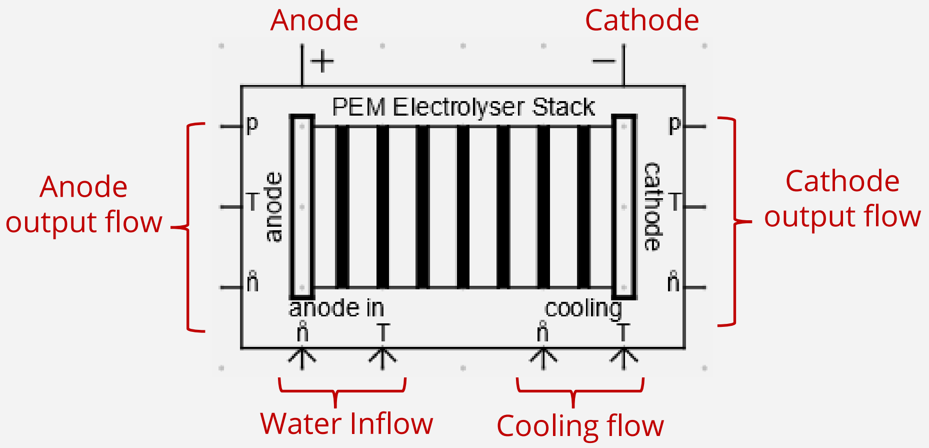
PEM Water Electrolyzer (PEMWE)

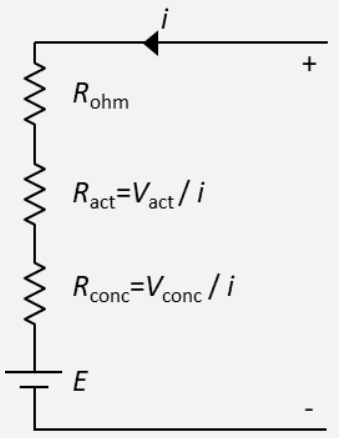
Model and Features

- The same equivalent circuit as PEM fuel cell
- Current in opposite direction
- Fully wet membrane humidity is assumed.
- Water consumption:

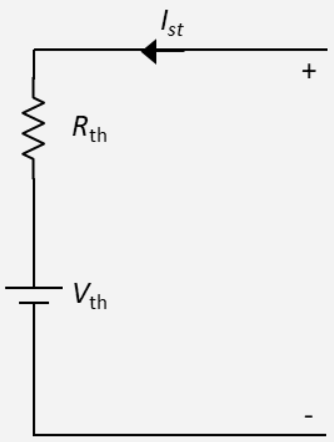
$$\dot{n}_{H2O,an} = N_s \frac{I}{2F}$$

- The same features as the PEMFC model





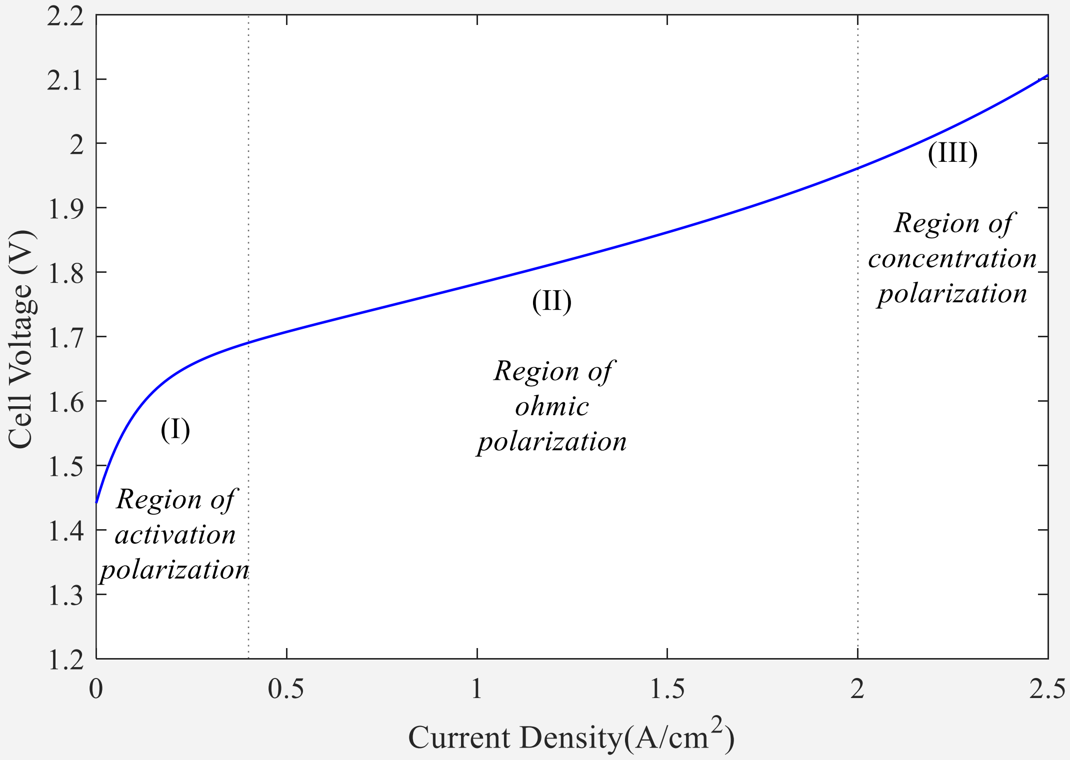
Single electrolysis cell



Electrolyzer stack

PEM Water Electrolyzer (PEMWE)

Characteristic Curve



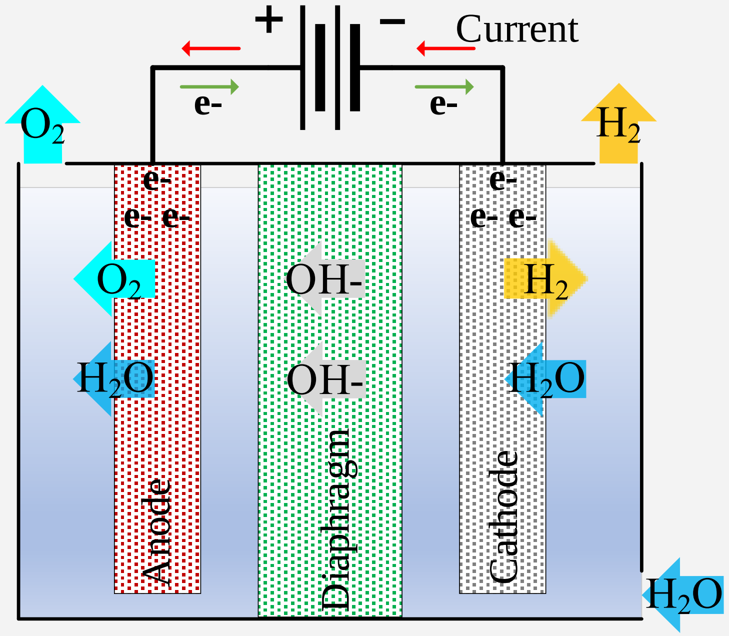
- Region (I) - Activation polarization region
- Region (II) - Ohmic polarization region
- Region (III) - Concentration polarization region

- Typical operating voltage: 1.6 V to 2.0 V
- Typical cell current density: 0.6 A/cm^2 and 2.0 A/cm^2

Alkaline Water Electrolyzer (AWE)

Working Principle

- Two electrodes, separated by a diaphragm, are submerged in a KOH/NaOH electrolyte solution. The cell is given a continuous water supply mixed with KOH/NaOH
- A DC source is connected between two electrodes
- Cathode: Water reacts with incoming e^-, forming H_2 and OH^-
- The OH^- ions move through the electrolyte to the anode
- Anode: OH^- decomposes into O_2 and water, releasing electrons
- Electrons are forced to the cathode side through the external circuit by the voltage difference



Cathode: $2H_2O + 2e^- \rightleftharpoons H_2 + 2OH^-$

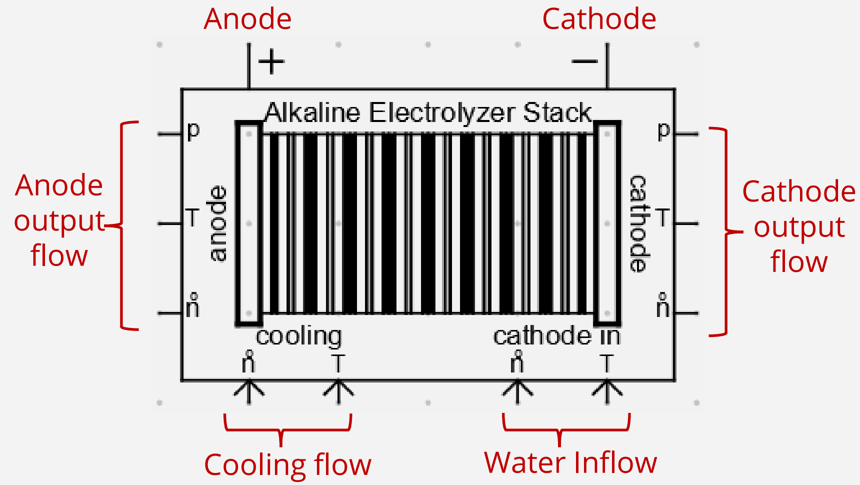
Anode: $2OH^- \rightleftharpoons \frac{1}{2}O_2 + H_2O + 2e^-$

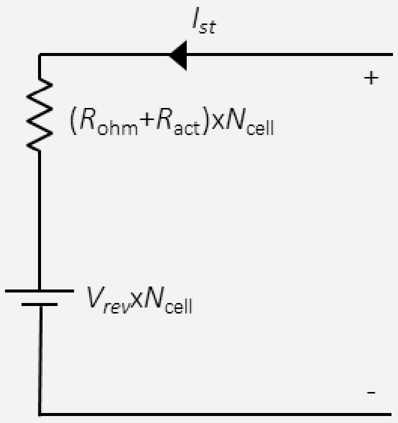
Overall: $H_2O \rightleftharpoons H_2 + \frac{1}{2}O_2$

Alkaline Water Electrolyzer (AWE)

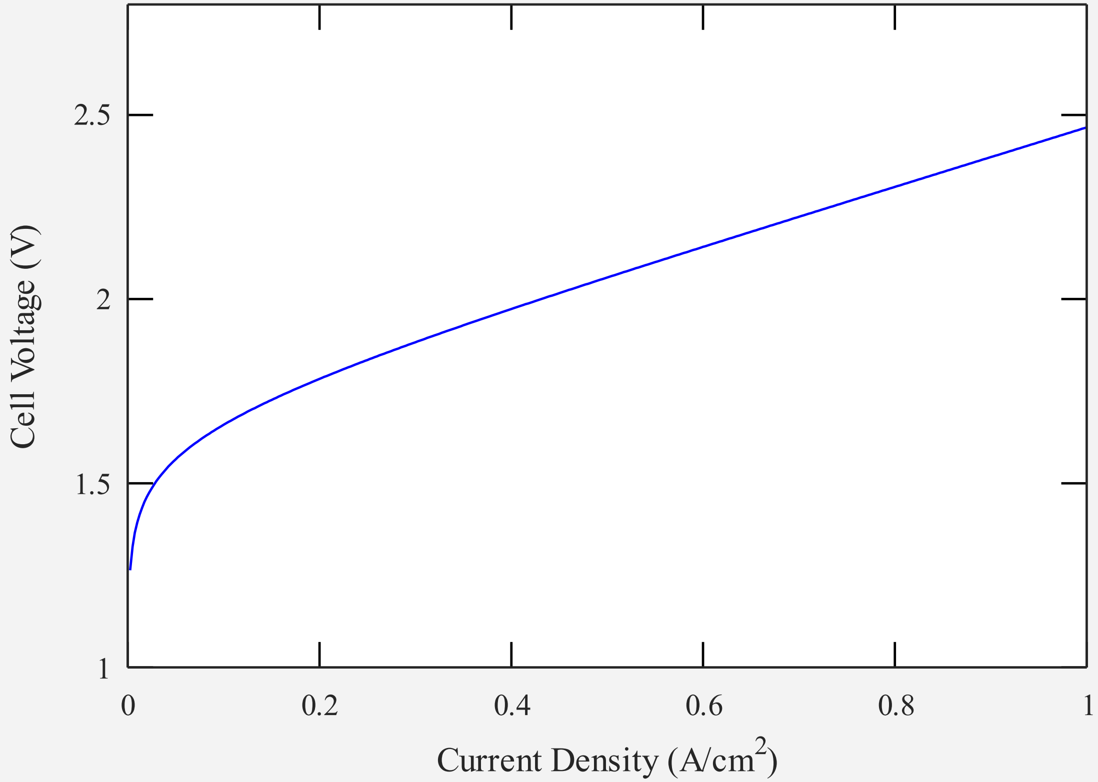
Model and Features

- The same features as the PEM water electrolyzer
- Mass transport losses were ignored
- Alkaline solution: KOH or NaOH



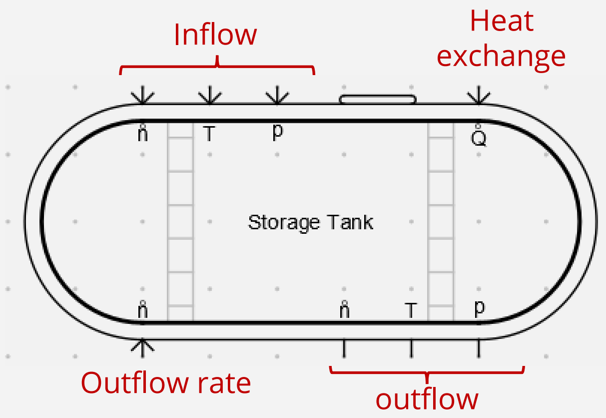


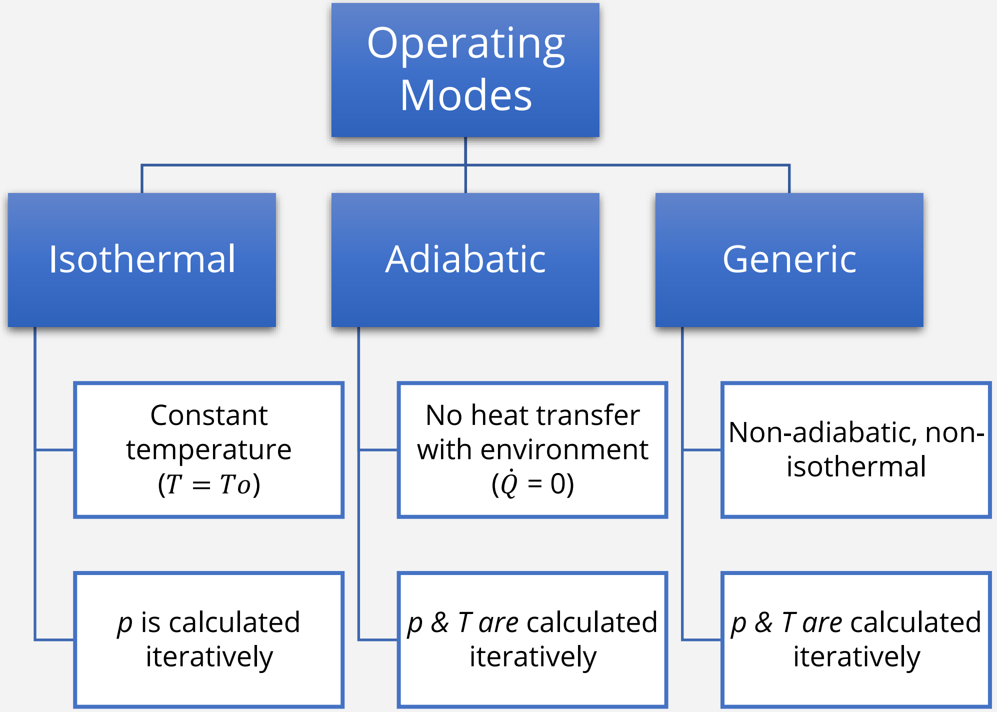
AWE stack



Gas Storage Tank

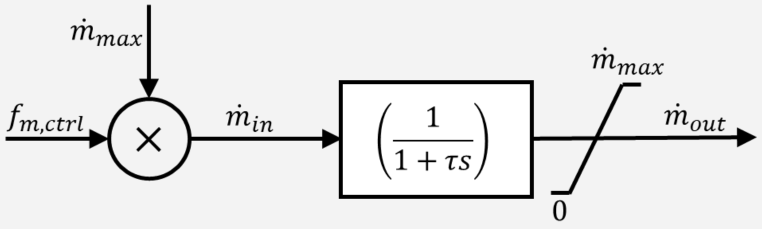
- Represents the behavior of a storage unit that can hold or supply compressed gases
- Three operating modes
- Fully simulate the dynamics of internal variables such as pressure, temperature, and mass of stored gases
- Iterative algorithm are used for dynamic calculations

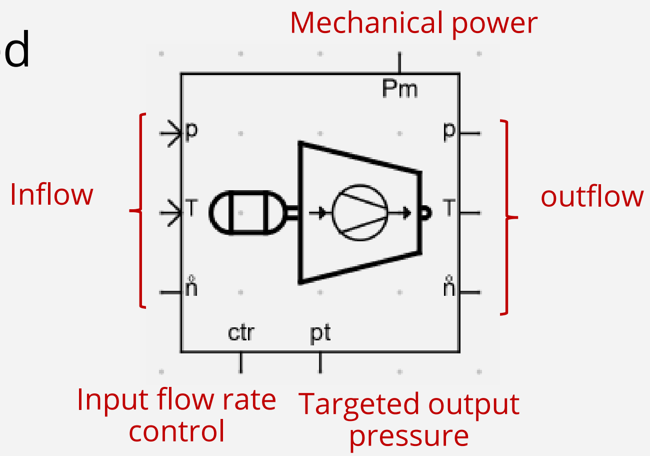


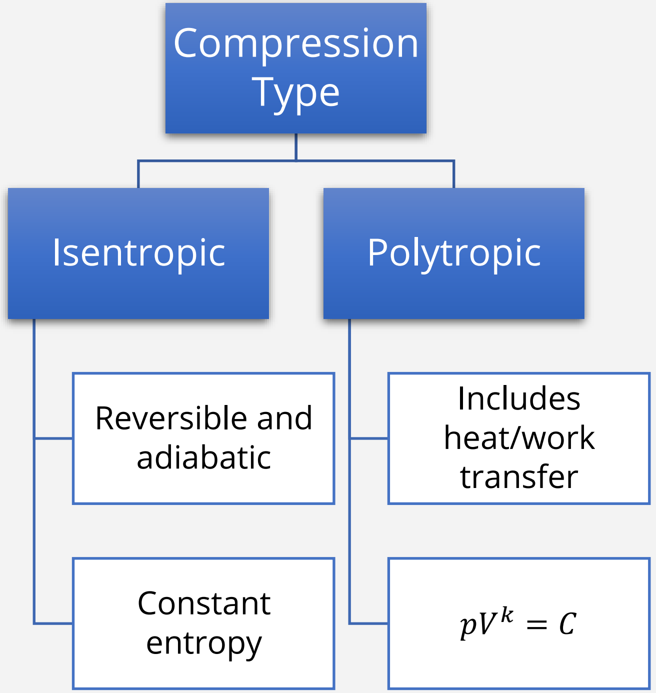


Gas Compressor

- Deliver gases at a desired rate and pressure by performing work on the input gases
- Requires a certain amount of mechanical energy
- Mass flow dynamics are characterised by a first-order transfer function
- Two compression types
- Iterative algorithm are used

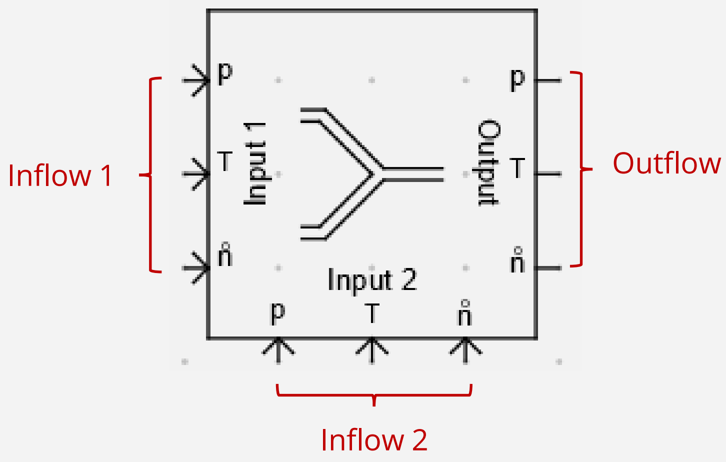






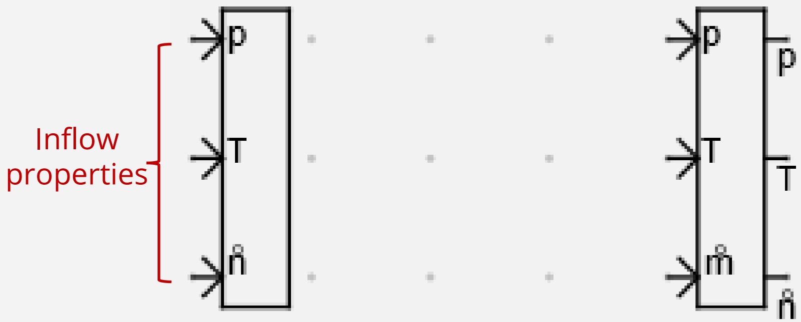
Flow Mixer

- Computes the state of the final fluid flow after mixing two input fluids
  - Flow rate
  - Temperature
  - Pressure
  - Molar fractions
- No chemical reaction takes place due to mixing
- Uses iterative algorithms
- Accepts two incoming fluids



Fluid Property Calculator

- Takes pressure, temperature, flow rate, and the molar fractions of a flow of H_2O, H_2, N_2, and O_2 mixture as inputs
- Used to monitor thermodynamic properties of the fluid
  - Enthalpy
  - Entropy
  - Heat capacity
  - Gibs energy
  - Mass flow rate
  - Water vapor fraction
- Used to convert mass flow rate to molar flow rate



Applications

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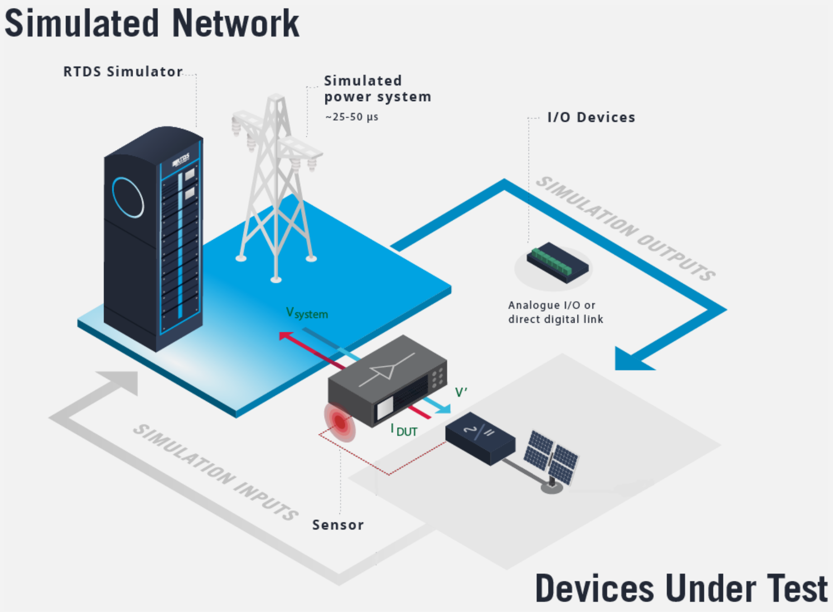

HIL Applications

- **Control Systems Testing:**
  - Fuel (H_2 and O_2/air) supply management
  - Water supply and H_2 production control
  - Membrane humidity control
  - Temperature and coolant flow control
- **Safety Features Testing:** Fault detection mechanisms and emergency shutdown protocols
  - Fuel starvation detection
  - Membrane's low humidity detection
  - High pressure and overheating detection
  - Pressure regulation systems for H_2 gas storage

Applications

Other Applications

- **Performance Optimization**: Determines optimal operating conditions across varying loads, temperatures, and environmental factors
- **System Integration**: Simulates the integration of hydrogen systems with existing energy infrastructure, including renewables and the power grid
- **Power-to-Hydrogen Systems**: Simulate hydrogen in energy storage and distribution for renewable energy applications
- **Bidirectional Energy Flow**: Models scenarios where hydrogen systems supply energy back to the grid
- **Dynamic Response**: Tests system performance under shifting grid demands and frequency variations
- **Design and Development**: Validates new system designs and configurations before implementation

Thank you!

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J. Rupasinghe, Y. Hu and Y. Zhang, "Real-Time Digital Simulation of Hydrogen Energy Systems with Multi-Energy Flow in Focus," *2024 IEEE Power & Energy Society General Meeting (PESGM)*, Seattle, USA, 2024.

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