   

Fuel Cell System and System Components

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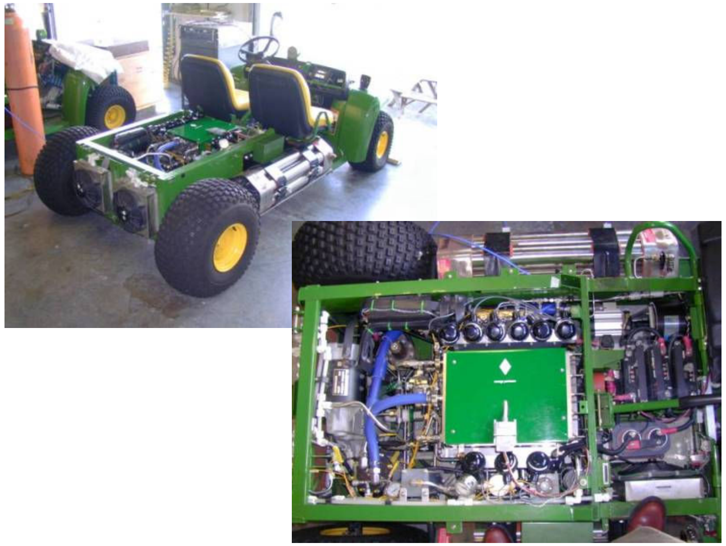
FESB = Faculty (School) of electrical engineering, mechanical engineering and naval architecture

Joint European Summer School for Fuel Cell and Hydrogen Technology

energy partners

10 kW FC System for a utility vehicle



Automotive 50 kW FC System concept

Stationary/residential 3.5 kW FC System

Passive fuel cell

Definition of system

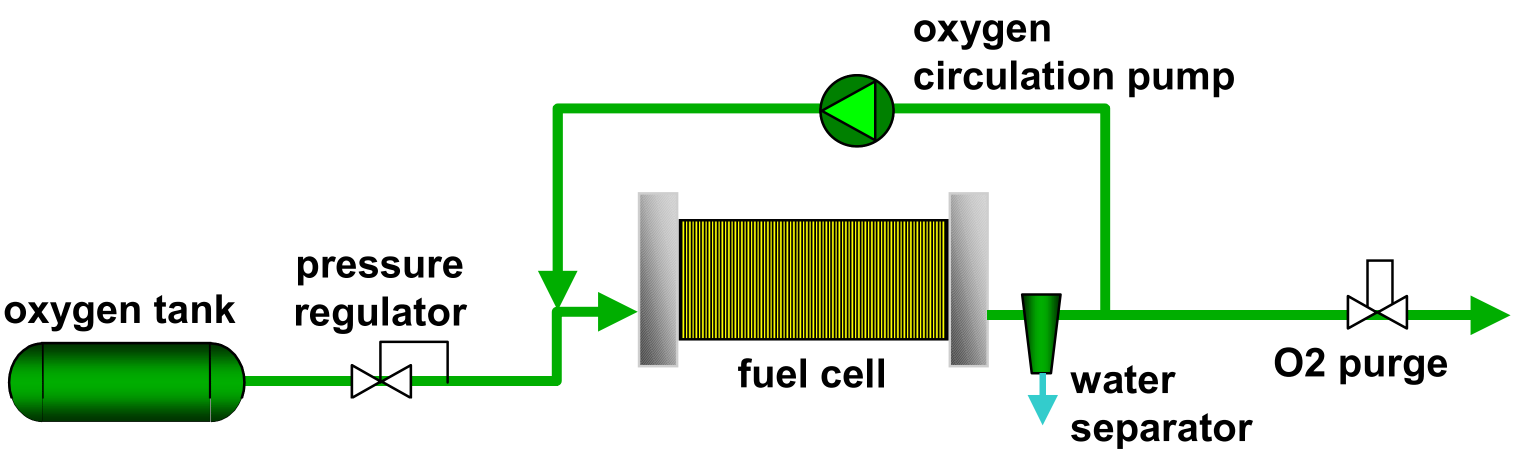
System – a group of units so combined as to form a whole and to operate in unison

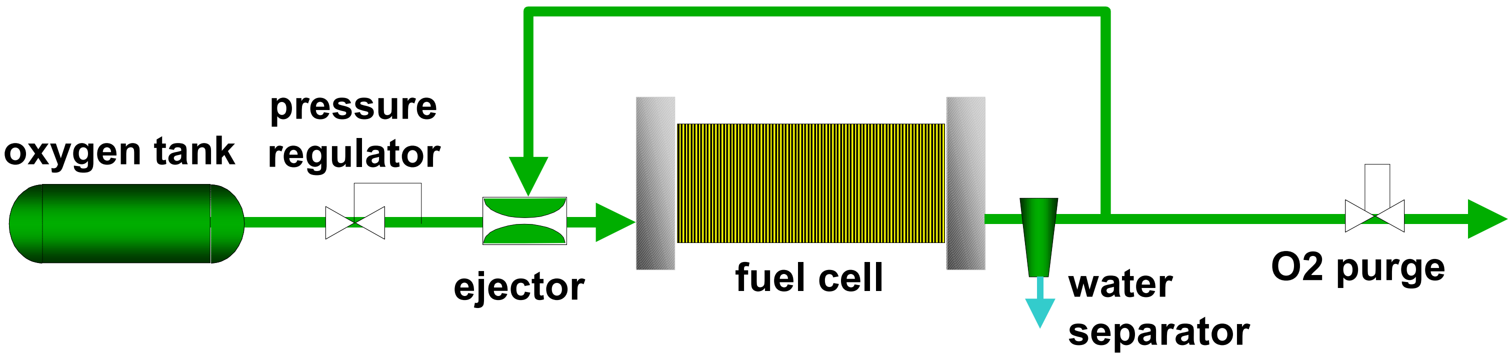
Webster Dictionary

Fuel cell system components

- Fuel cell stack
- Oxygen/air supply
- Hydrogen supply
- Water and heat management
- Fuel processing and integration of fuel processor
- Power conditioning and controls

Pure oxygen can be recirculated





Water balance

$$\dot{m}_{H2O,in} + \dot{m}_{H2O,gen} = \dot{m}_{H2O,out}$$

Water at exhaust may be present in vapor and liquid form

$$\dot{m}_{H2O,in} + \dot{m}_{H2O,gen} = \dot{m}_{H2O,out(v)} + \dot{m}_{H2O,out(l)}$$

For a closed loop system

$$\dot{m}_{H2O,gen} = \dot{m}_{H2O,out(l)}$$

Therefore:

$$\dot{m}_{H2O,in} = \dot{m}_{H2O,out(v)}$$

Water at inlet may be present in vapor and liquid form (depending on pressure, temperature and flow rate)

$$\dot{m}_{H2O,in(v)} + \dot{m}_{H2O,in(l)} = \dot{m}_{H2O,out(v)}$$

$$\dot{m}_{H2O,in(v)} = min\left[\frac{IN_{cell}}{4F} M_{H2O} S_{O2} \frac{P_{sat}(t_{in})}{P_{in} - P_{sat}(t_{in})}, \dot{m}_{H2O,out(v)}\right]$$

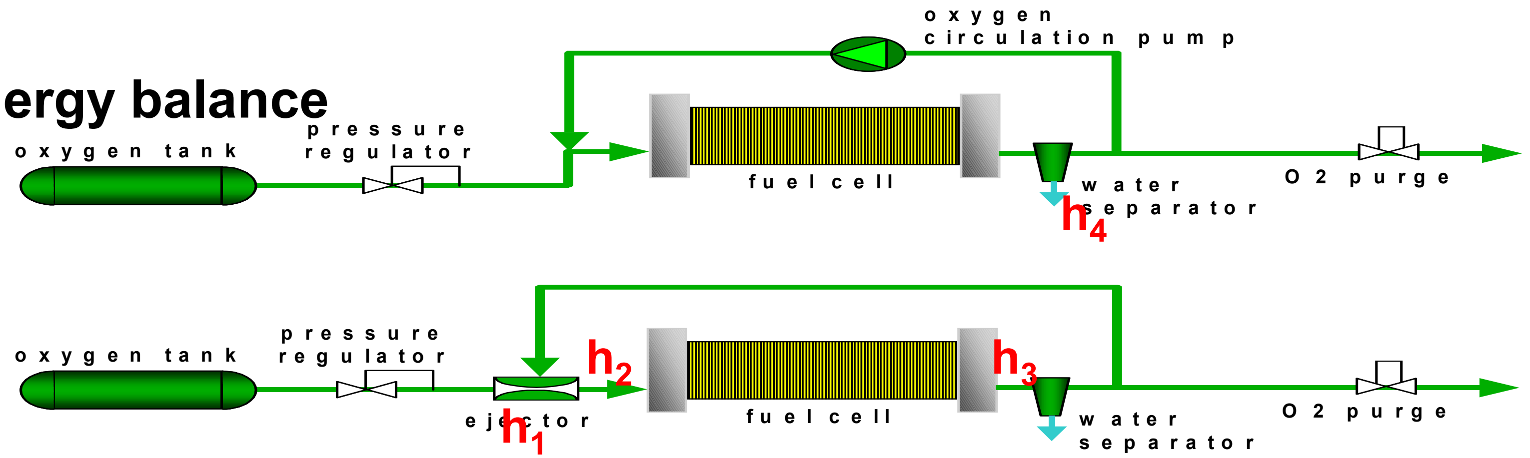
$$\dot{m}_{H2O,out(v)} = \frac{IN_{cell}}{4F} M_{H2O} (S_{O2} - 1) \frac{P_{sat}(t_{out})}{P_{out} - P_{sat}(t_{out})}$$

$$\dot{m}_{H2O,in(l)} = \dot{m}_{H2O,out(v)} - \dot{m}_{H2O,in(v)}$$

t_{in} is unknown but may be found out from energy balance

O2 supply

Energy balance



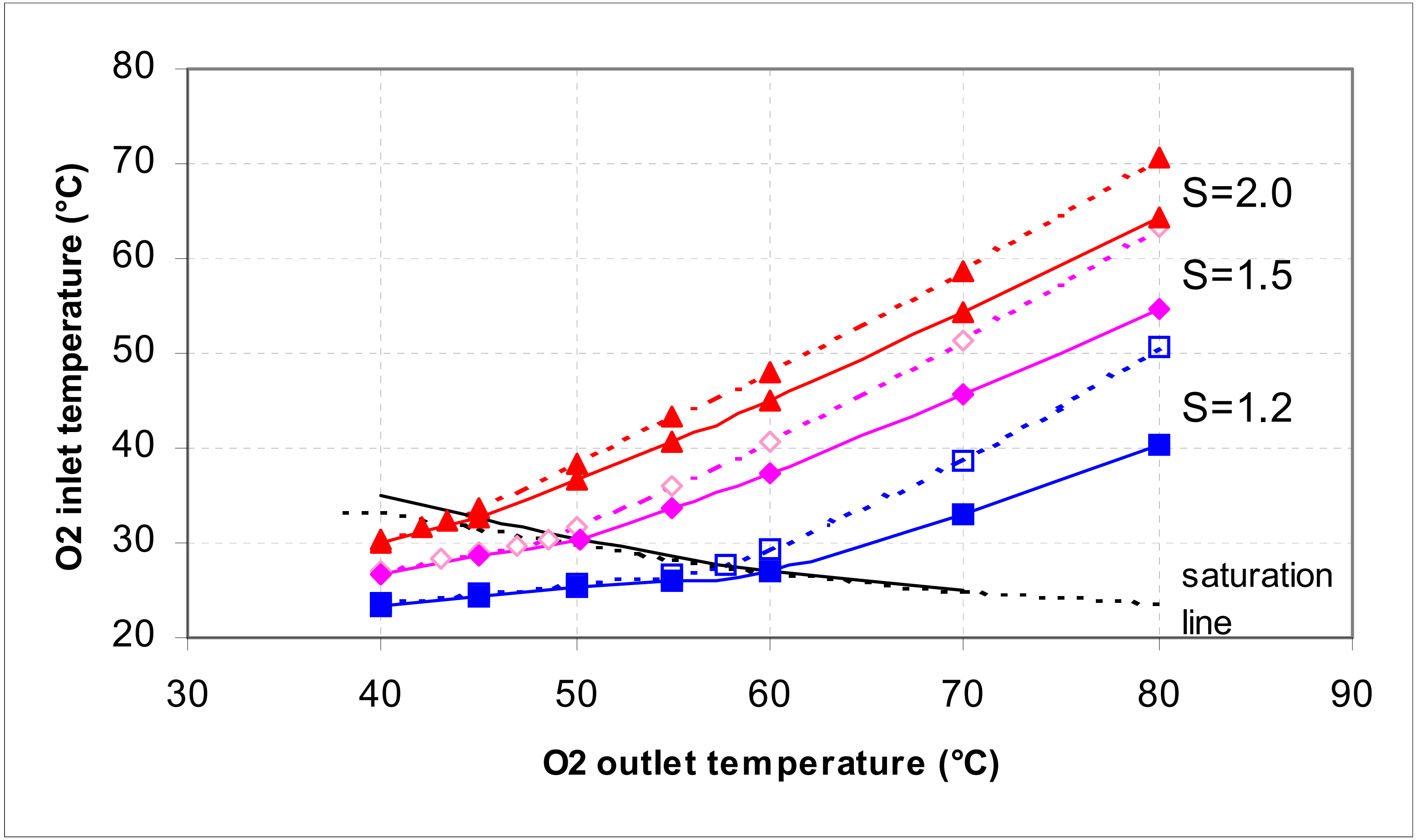
$$h_1 + h_4 = h_2$$

$$h_1 = \frac{IN_{cell}}{4F} M_{O2} c_{p,O2} t_{tank}$$

$$h_4 = \frac{IN_{cell}}{4F}\left(S_{O2} - 1\right)\left[M_{O2} c_{p,O2} t_{out} + M_{H2O} \frac{P_{sat}(t_{out})}{P_{out} - P_{sat}(t_{out})}\left(c_{p,H2O(v)} t_{out} + h_{fg}^{0}\right)\right]$$

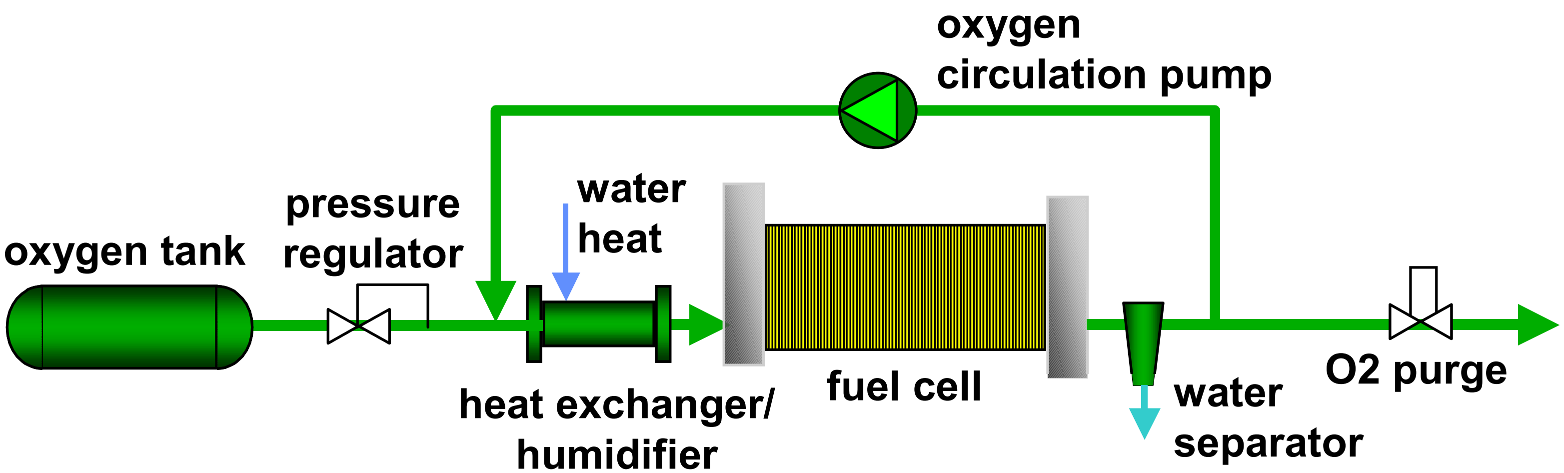
$$h_2 = \frac{IN_{cell}}{4F} S_{O2} M_{O2} c_{p,O2} t_{in} + \dot{m}_{H2O,in(v)}\left(c_{p,H2O(v)} t_{in} + h_{fg}^{0}\right) + \dot{m}_{H2O,in(l)} c_{p,H2O(l)} t_{in}$$

Achievable oxygen temperature at the stack inlet when the oxygen exhaust is recirculated back to the inlet



Dashed lines – atmospheric pressure
Solid lines – 300 kPa

Oxygen supply with humidification

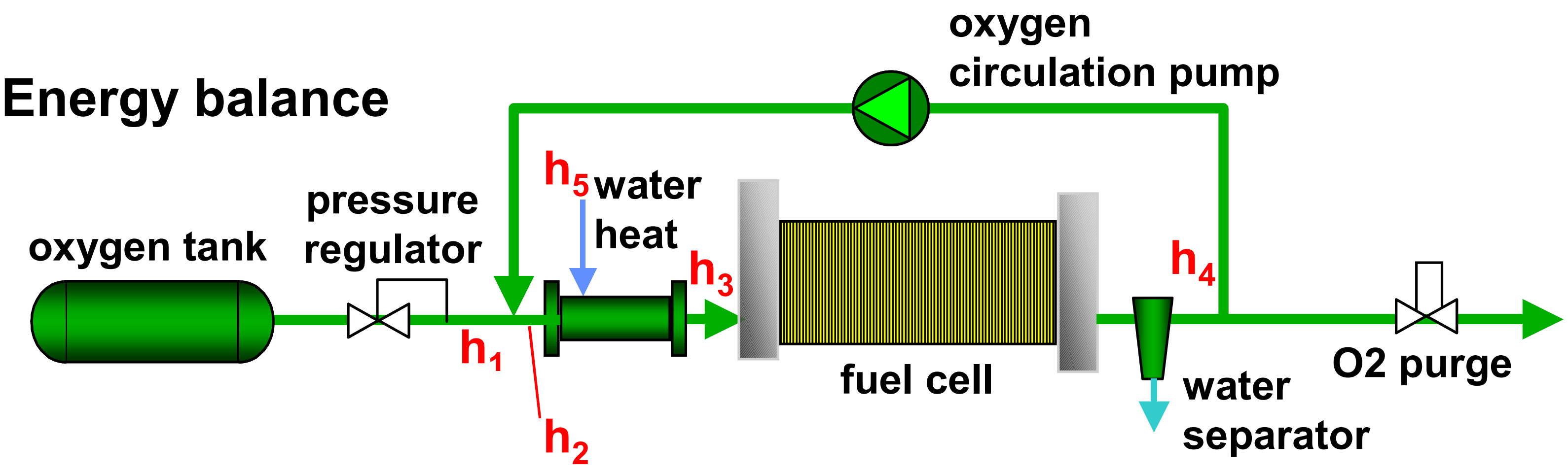


Amount of water needed for humidification:

$$\dot{m}_{H2O,in} = \frac{IN_{cell}}{4F} M_{H2O} \left[S_{O2} \frac{\varphi P_{sat}(T_{in})}{P_{in} - \varphi P_{sat}(T_{in})} - (S_{O2} - 1) \frac{P_{sat}(T_{out})}{P_{out} - P_{sat}(T_{out})} \right]$$

Heat needed for humidification can be calculated from energy balance:

Energy balance



Heat needed for humidification:

$$Q_{in} = h_3 - h_1 - h_4 - h_5$$

$$h_3 = \frac{IN_{cell}}{4F} S_{O2} \left[M_{O2} c_{p,O2} t_{st,in} + M_{H2O} \frac{\varphi P_{sat}(t_{st,in})}{P_{in} - \varphi P_{sat}(t_{st,in})} \left(c_{p,H2O(v)} t_{st,in} + h_{fg}^0 \right) \right]$$

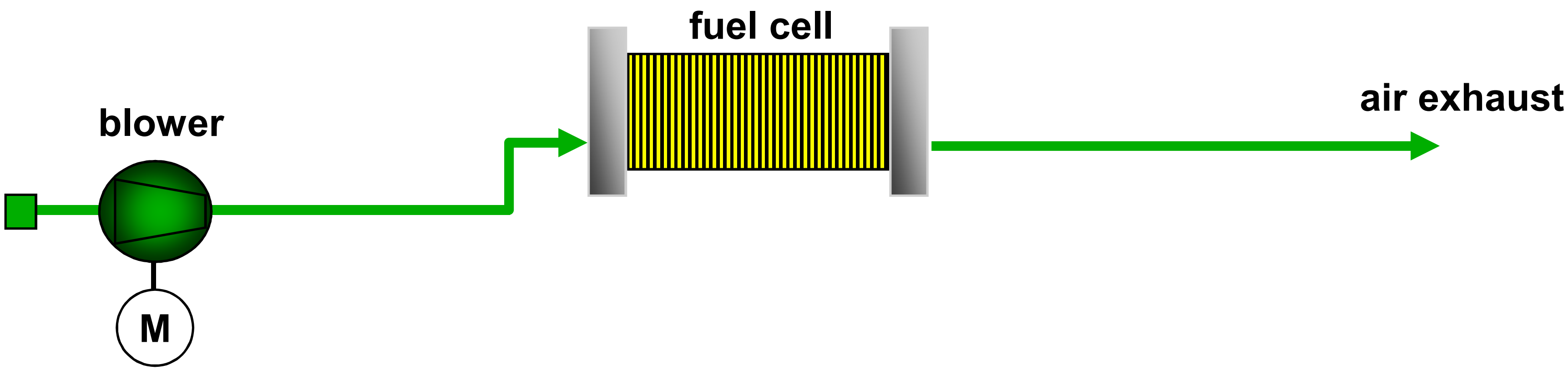
$$h_1 = \frac{IN_{cell}}{4F} M_{O2} c_{p,O2} t_{tank}$$

$$h_4 = \frac{IN_{cell}}{4F} (S_{O2} - 1) \left[M_{O2} c_{p,O2} t_{out} + M_{H2O} \frac{P_{sat}(t_{out})}{P_{out} - P_{sat}(t_{out})} \left(c_{p,H2O(v)} t_{out} + h_{fg}^0 \right) \right]$$

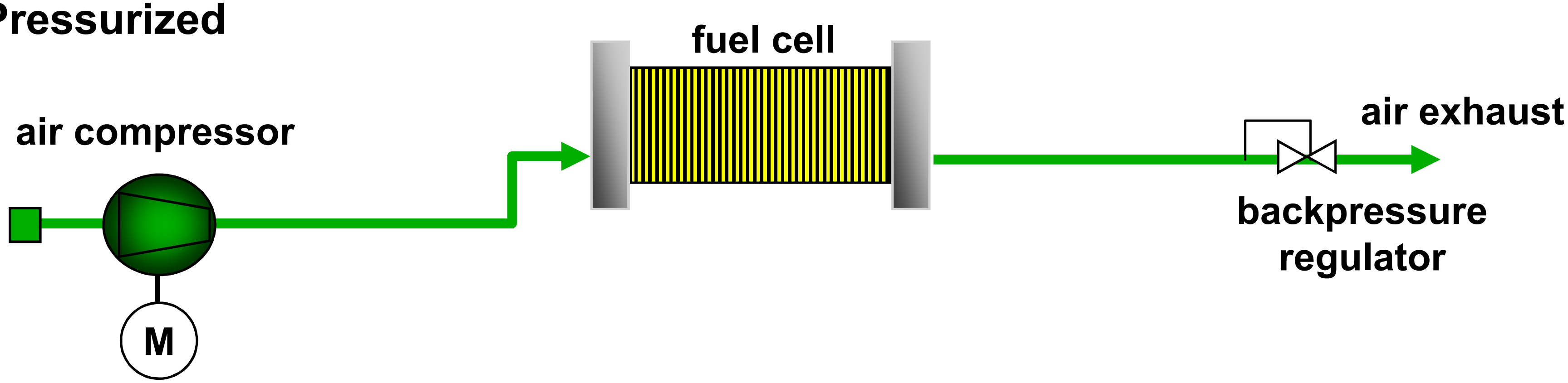
$$h_5 = \dot{m}_{H2O,in} c_{p,H2O(l)} t_w$$

Air supply for fuel cell system

Atmospheric pressure



Pressurized



Compression power

Ideal (adiabatic):

$$W_{comp} = \frac{\dot{m}_{Airin} \cdot c_p \cdot T_1}{\eta_{comp}} \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right]$$

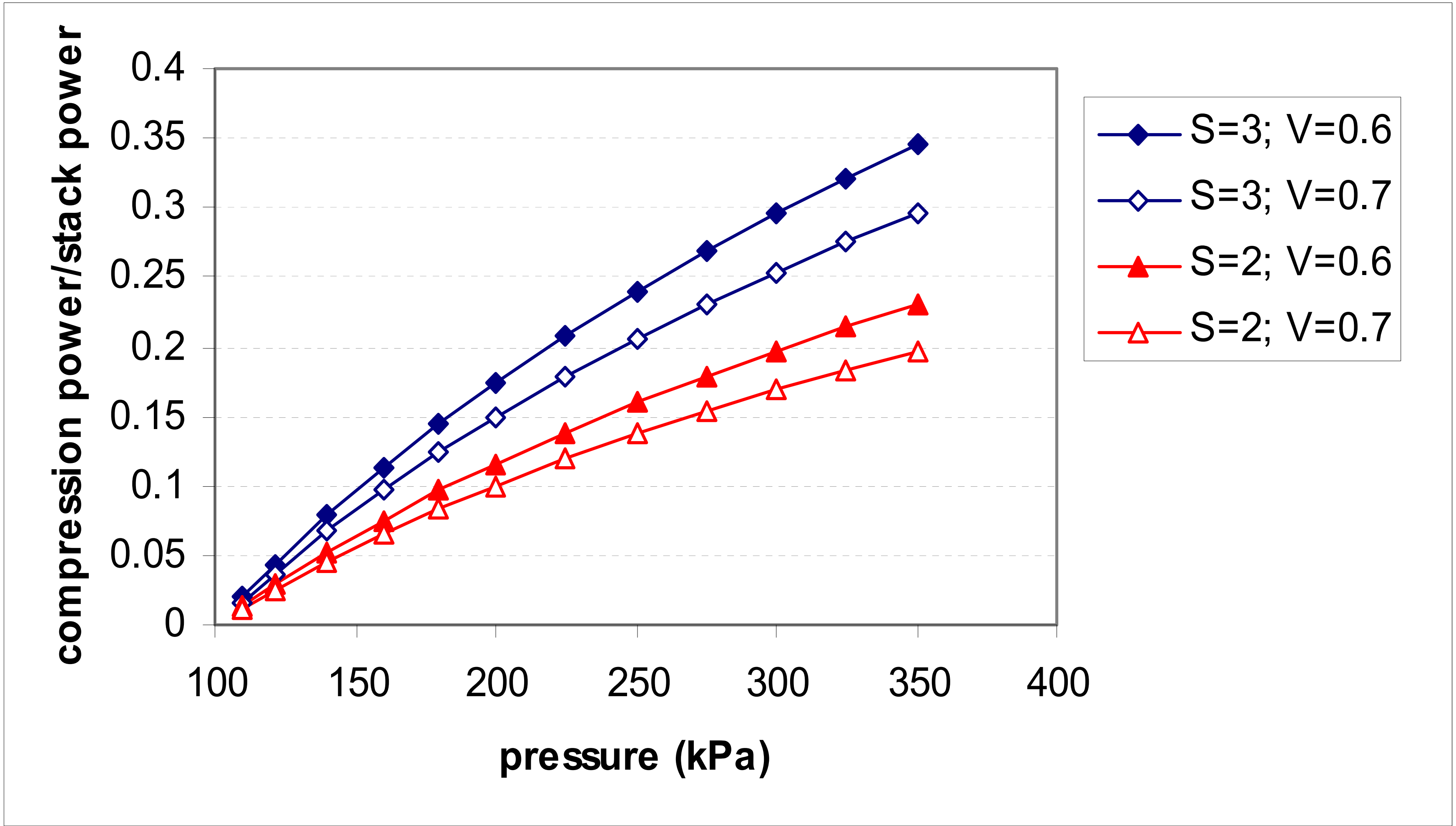
Total power needed:

$$W_{EM} = \frac{W_{comp}}{\eta_{mech} \cdot \eta_{EM}}$$

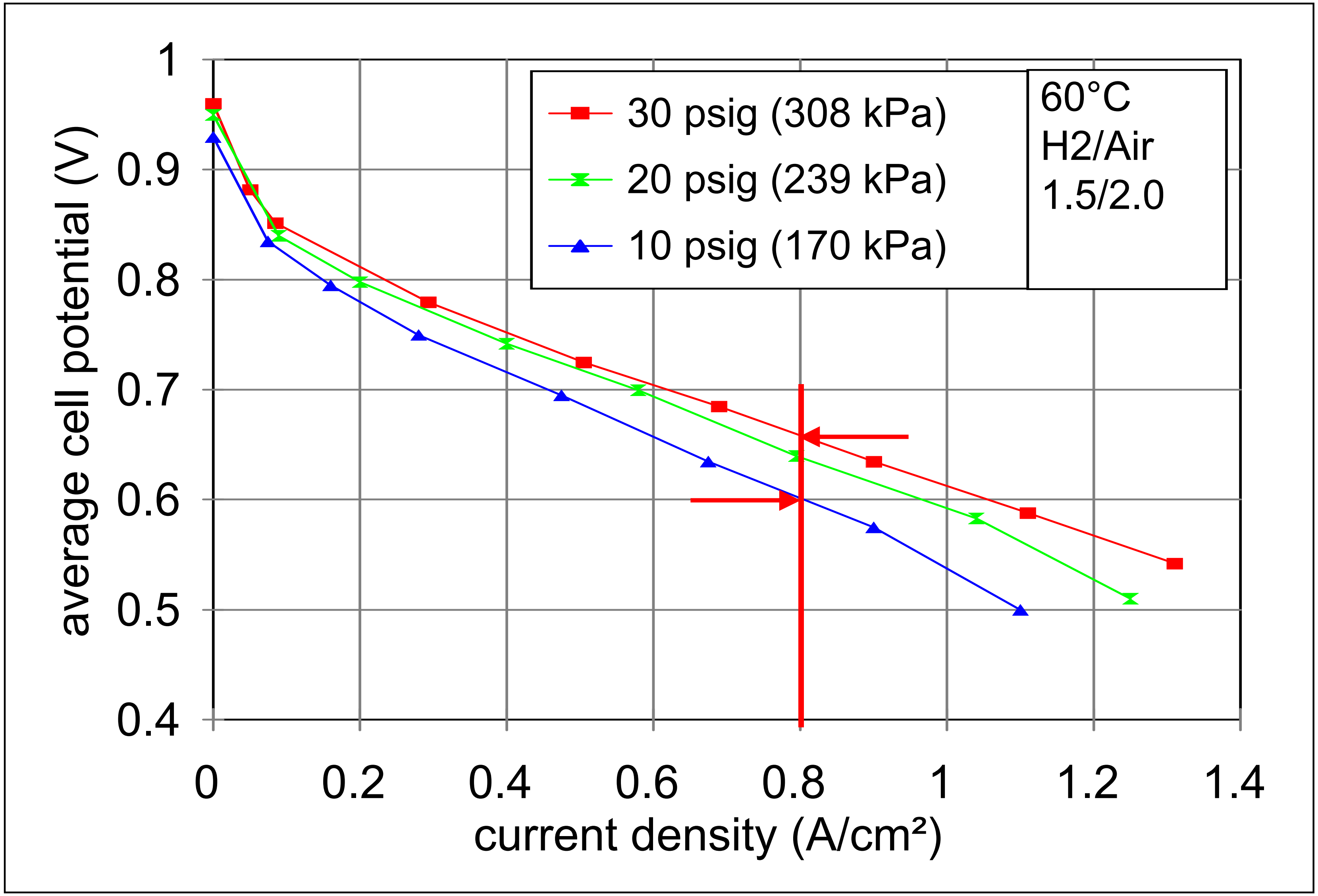
Temperature at the end of compression:

$$T_2 = T_1 + \frac{T_1}{\eta_{comp}} \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right]$$

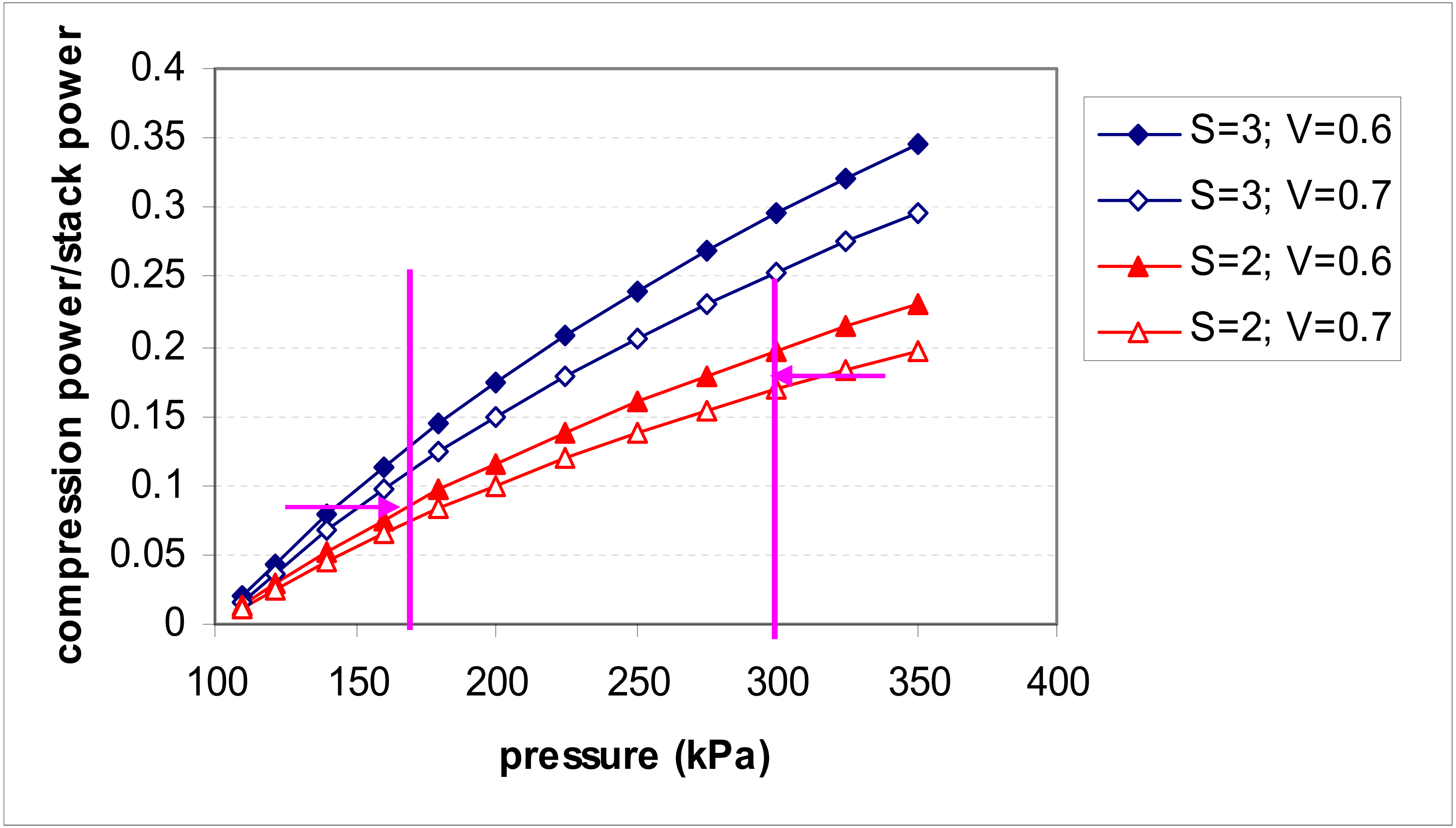
Compression power

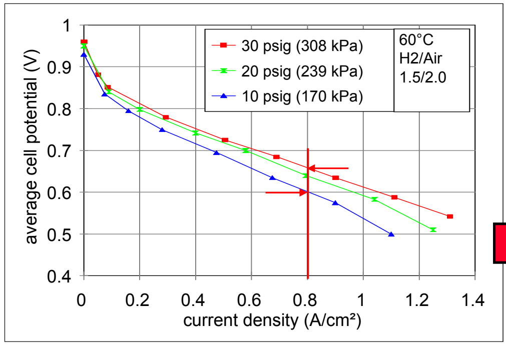


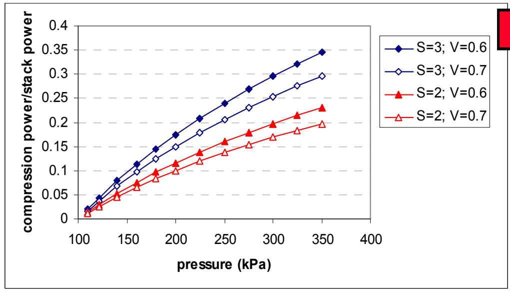
Stack operation at different pressures



Compression power





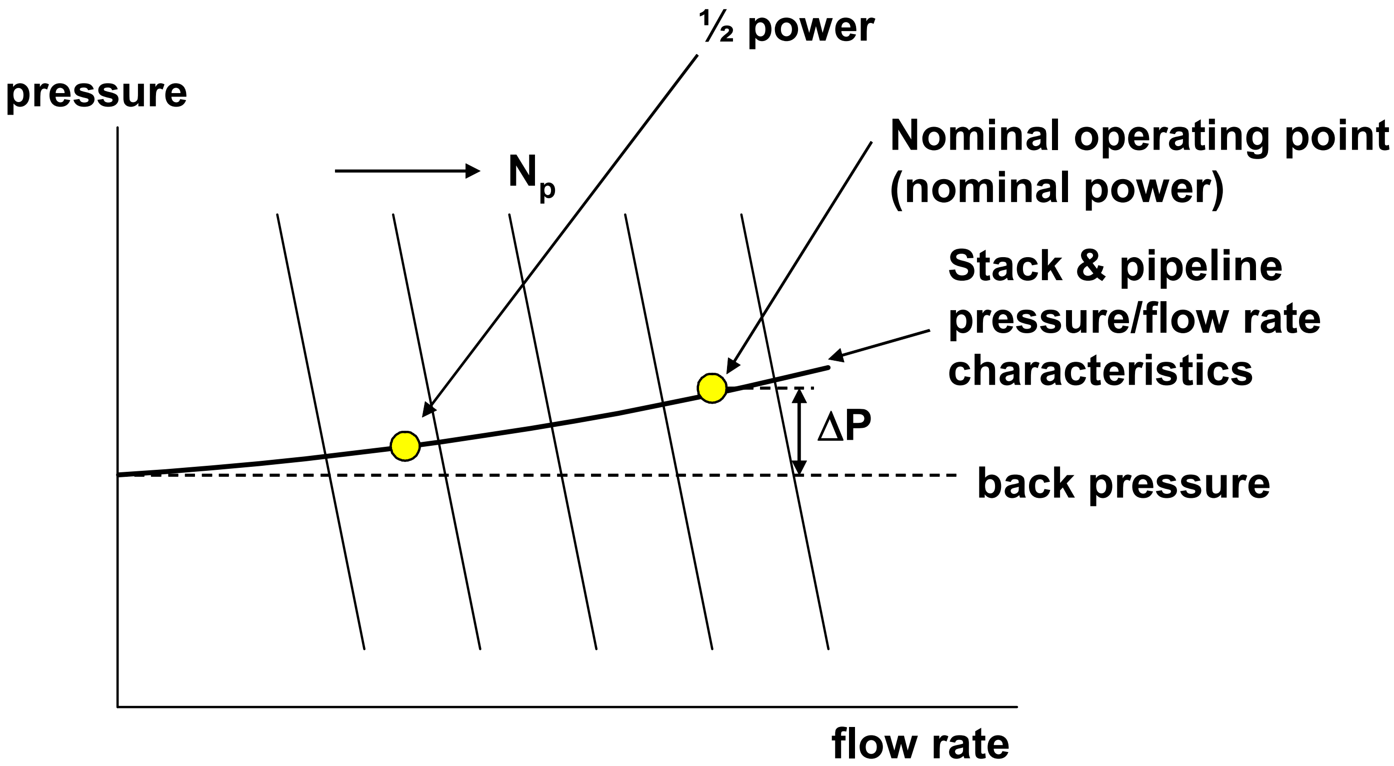


	300 kPa	170 kPa	
Current density:	0.8	0.8	A/cm^2
Cell voltage:	0.66	0.60	V
Power density:	0.528	0.48	W/cm^2
W_{comp}/W_{stack} :	0.17	0.083	
Compression power	0.088	0.040	W/cm^2
Net power:	0.44	0.44	W/cm^2
Efficiency:	0.37	0.37	

$$\eta_{sys} = \eta_{FC} \frac{W_{net}}{W_{FC}} = \frac{V_{cell}}{1.482} \frac{W_{net}}{W_{FC}}$$

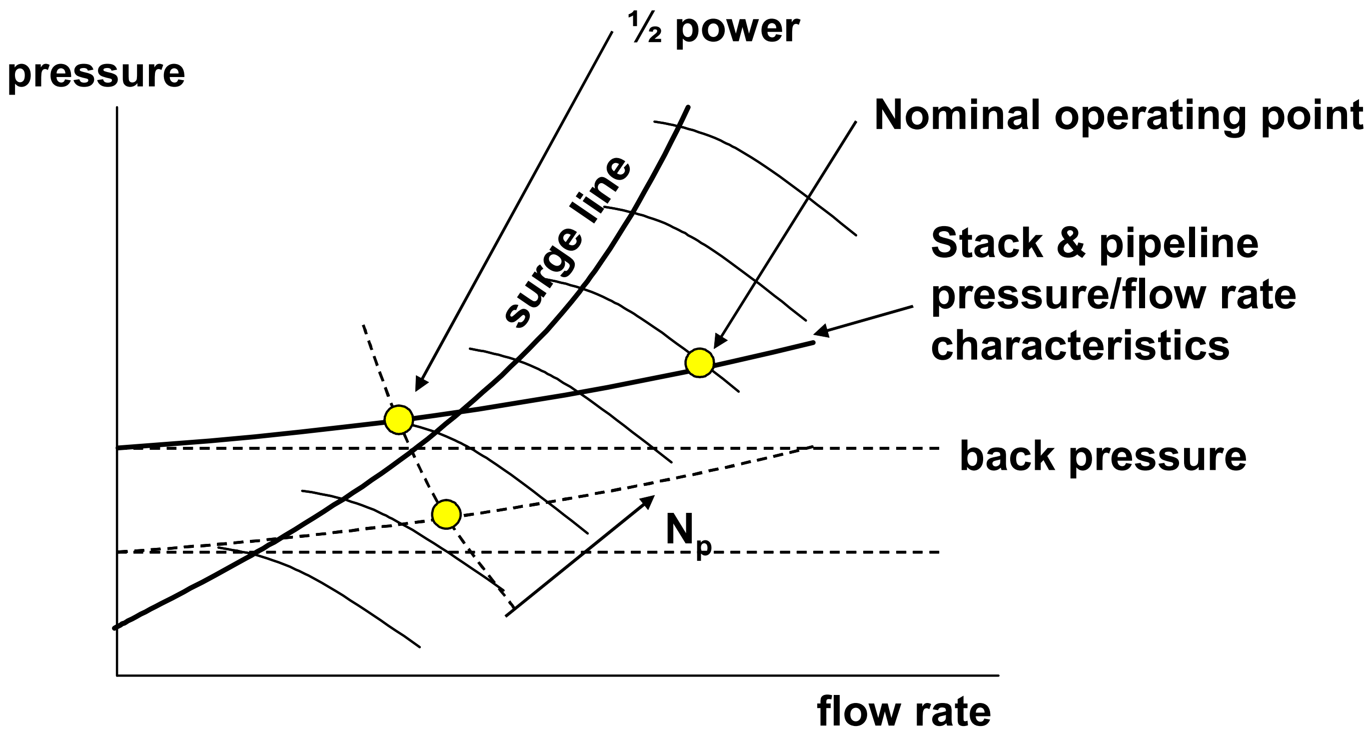
- **Each stack has different polarization curves**
- **Selection of operating pressure also depends on other factors (temperature, humidity …)**

Characteristic of positive displacement compressor



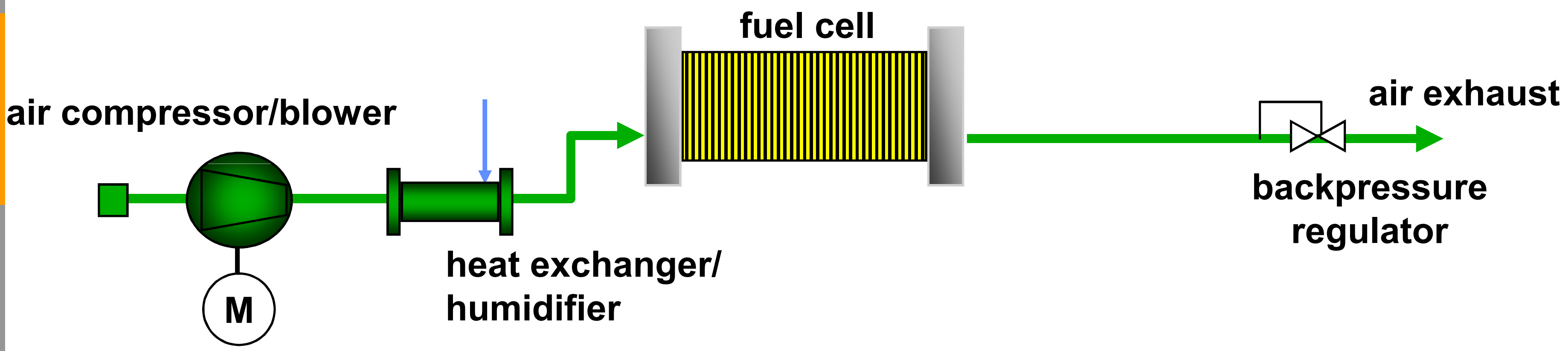
Reduction of flow rate does not need a change in back-pressure for positive displacement compressors

Characteristic of centrifugal compressor



Reduction of flow rate requires reduction of pressure for centrifugal compressors

Often, humidification is required

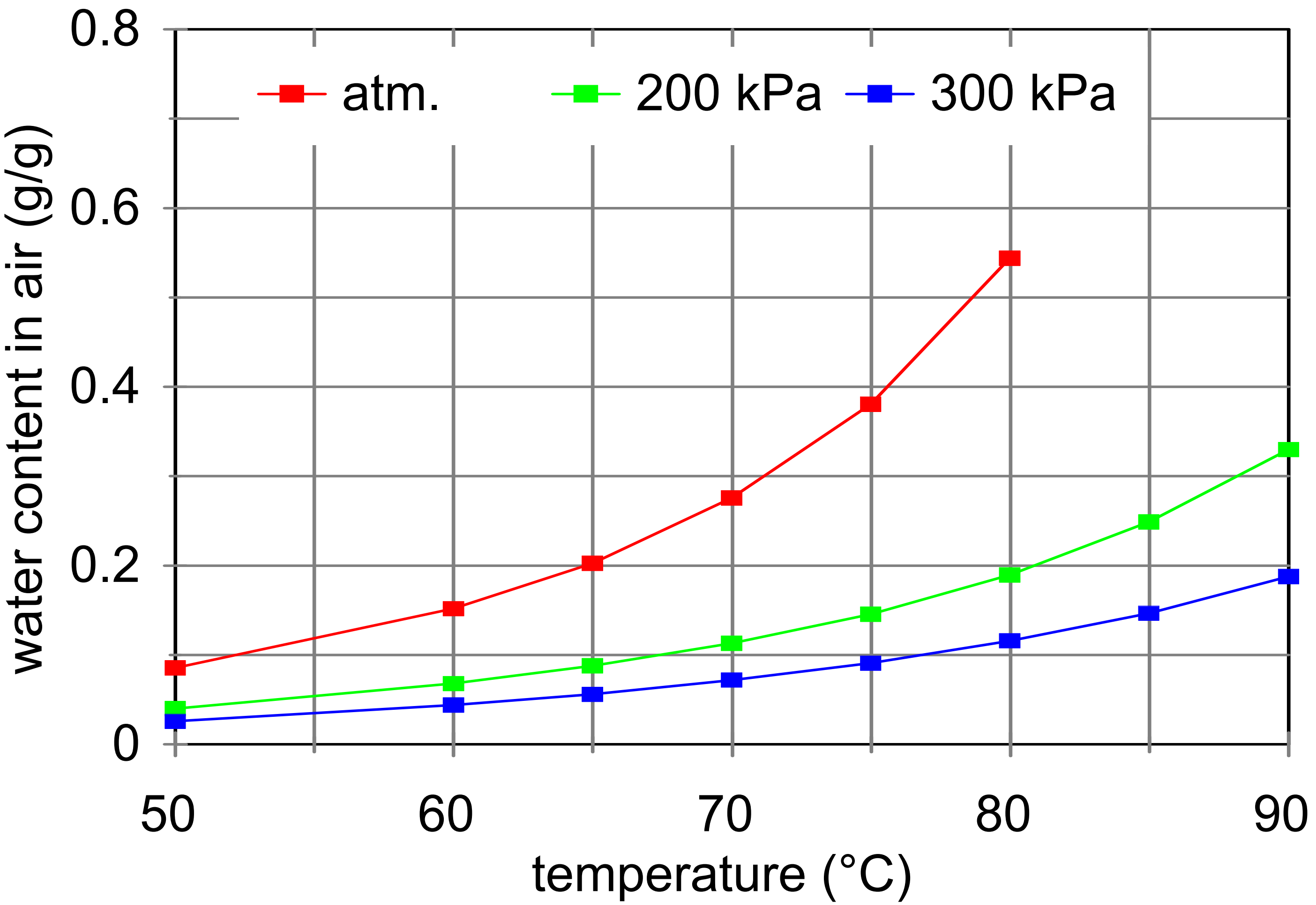


Air supply

Water & Heat

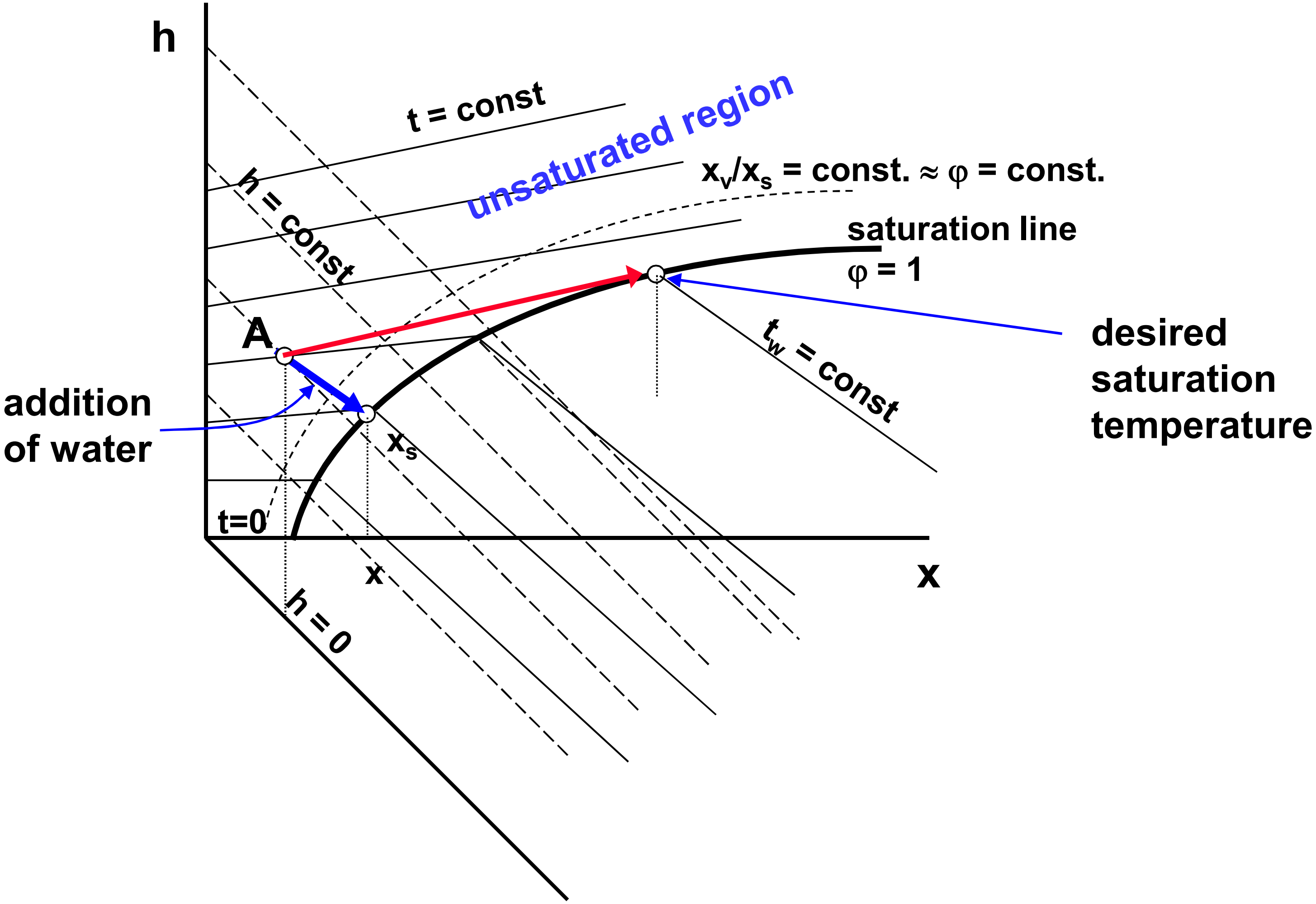
Water content in air

at various temperatures and pressures
100% relative humidity

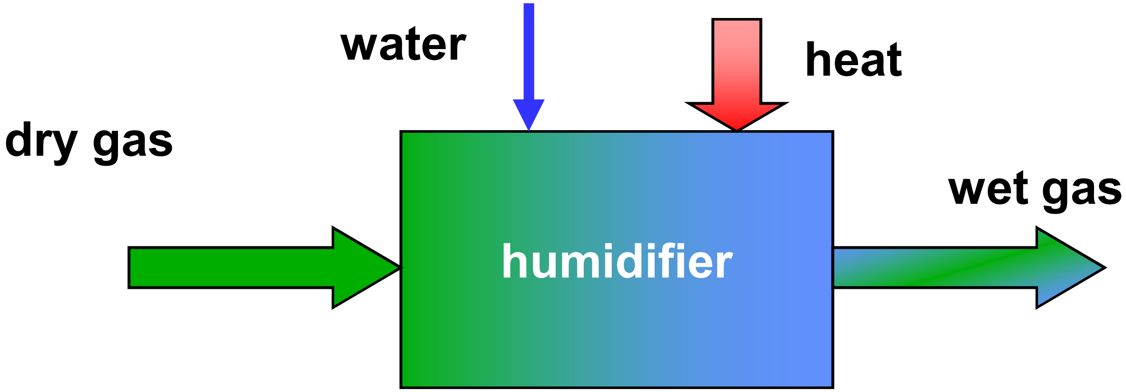


Air must be humidified (often saturated)

Humidification of air requires both water and heat



Humidification of air requires both water and heat

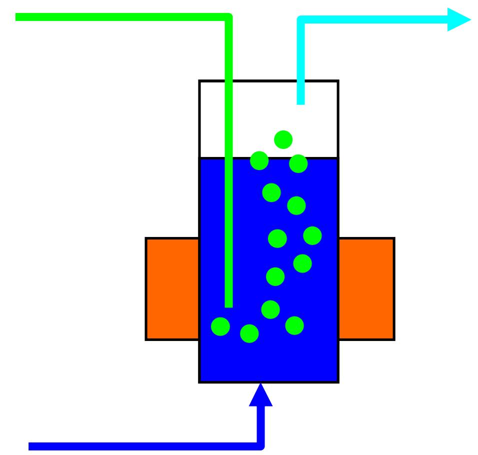


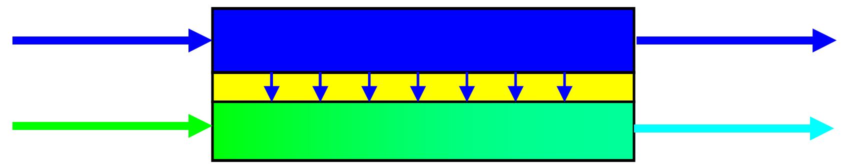
Source of water in fuel cell system: condensed water from the exhaust

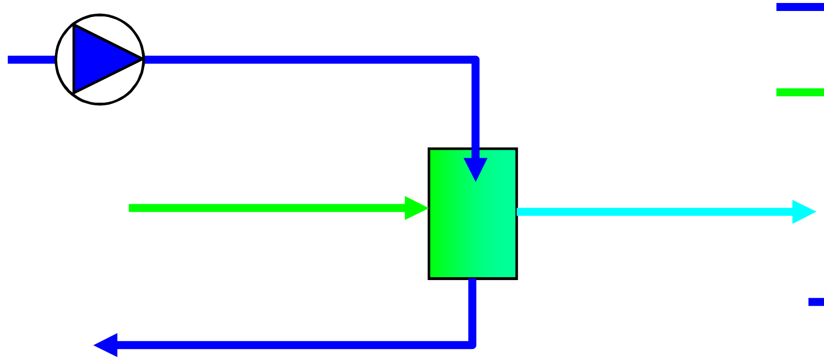
Source of heat in fuel cell system: fuel cell, compressor, fuel processor

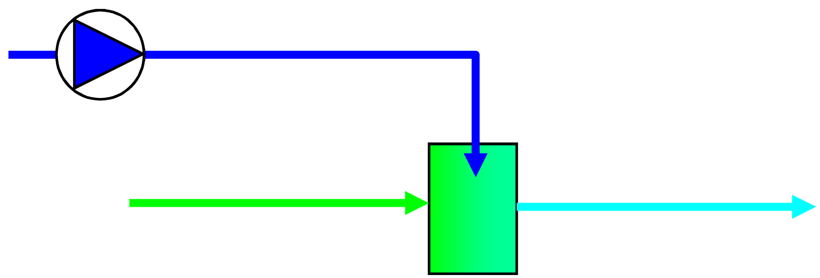
Methods of gas humidification

- Bubbling
- Membrane
- Water injection
- Steam injection





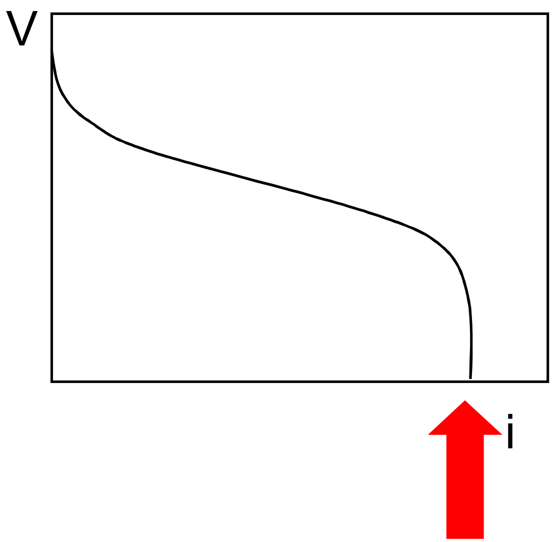


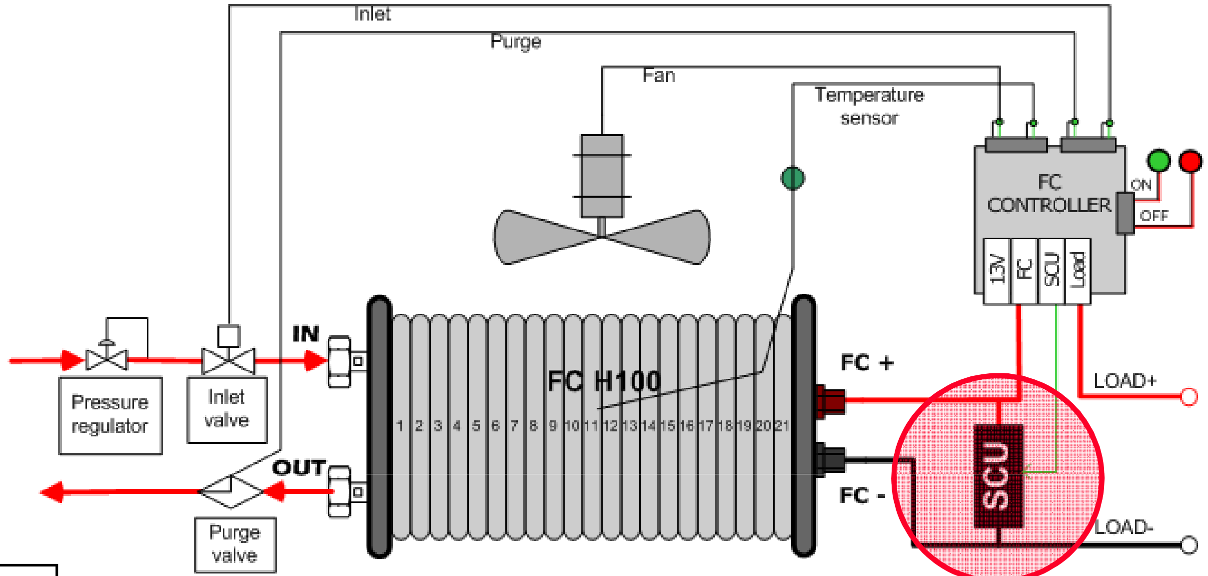


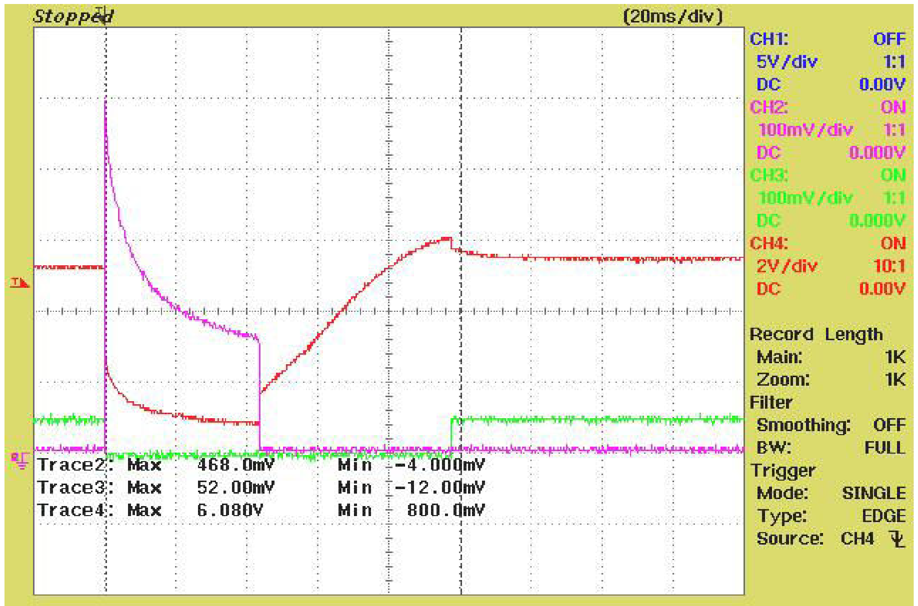
Humidification by Short Circuit

$$H_2 + \tfrac{1}{2}\, O_2 \rightarrow H_2O$$

$$N_{H2O} = \frac{I}{2F}$$

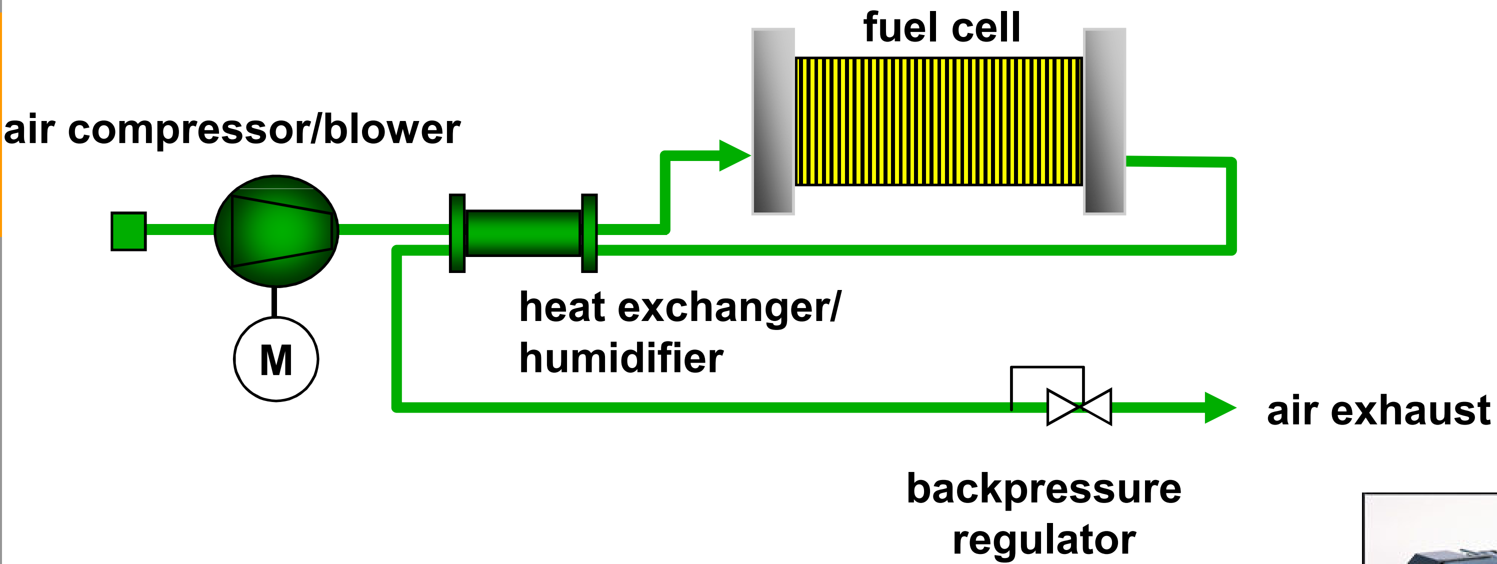


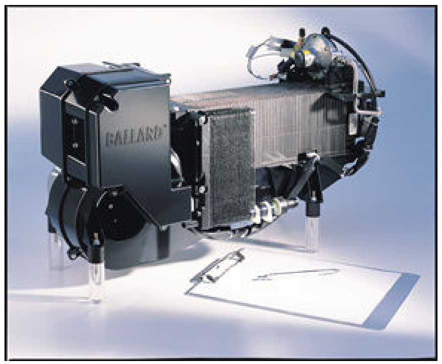




Air supply for fuel cell system

Using fuel cell water and heat at the cathode exhaust for Inlet air humidification

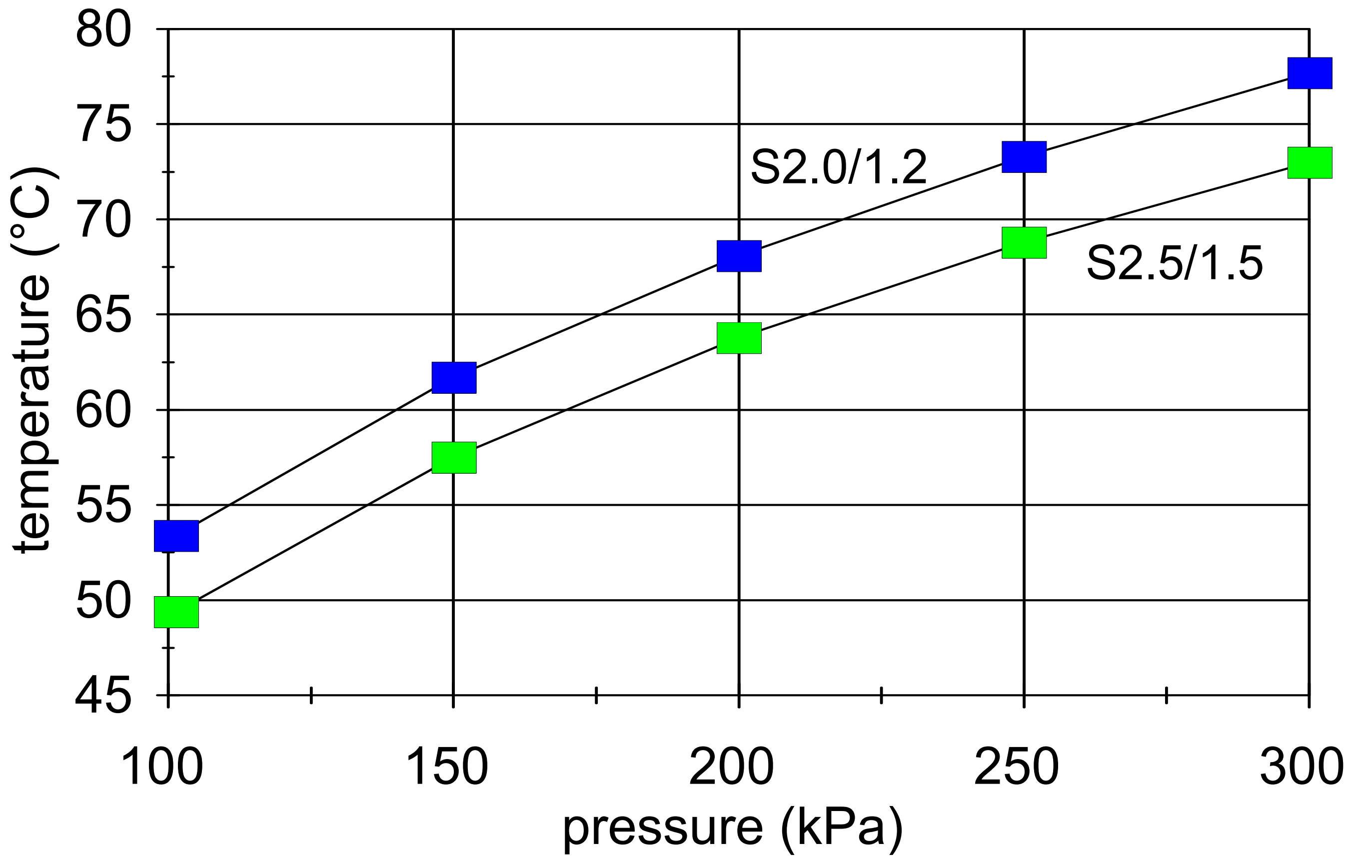




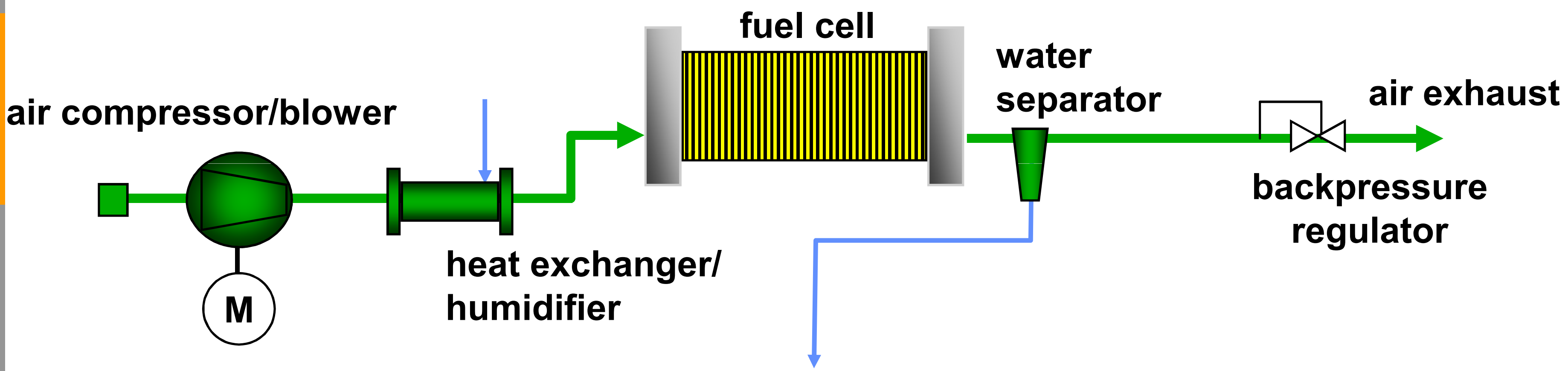
Air supply

Water & Heat

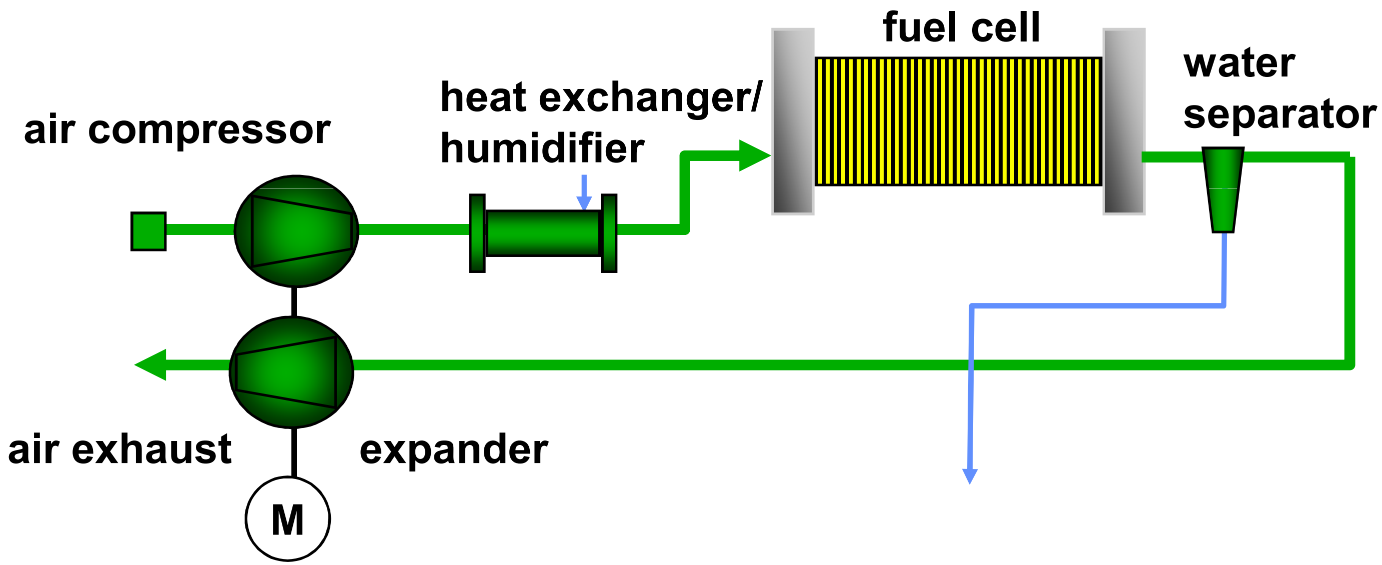
Temperatures and pressures where water generated is sufficient to humidify reactant gases (hydrogen/air)



Air supply with humidification and liquid water collection



Air supply for fuel cell system with compressor/expander



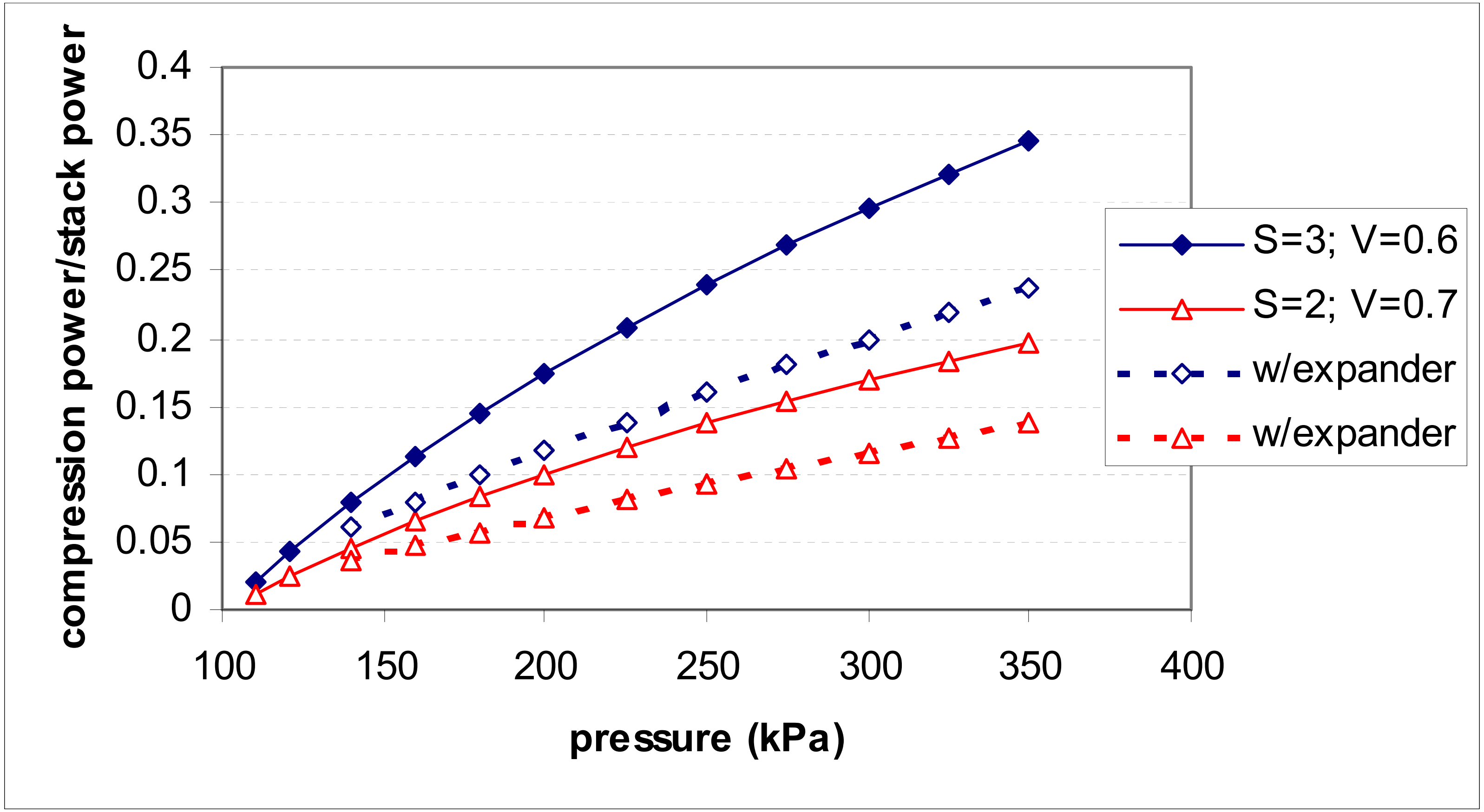
Expander power

$$W_{exp} = \dot{m}_{Airout} \cdot c_p \cdot T_{out} \left[1 - \left(\frac{P_0}{P_{out}} \right)^{\frac{k-1}{k}} \right] \eta_{exp}$$

Temperature at the end of expansion

$$T_{end} = T_{out} - T_{out} \left[1 - \left(\frac{P_0}{P_{out}} \right)^{\frac{k-1}{k}} \right] \eta_{exp}$$

Compression power w/compressor/expander

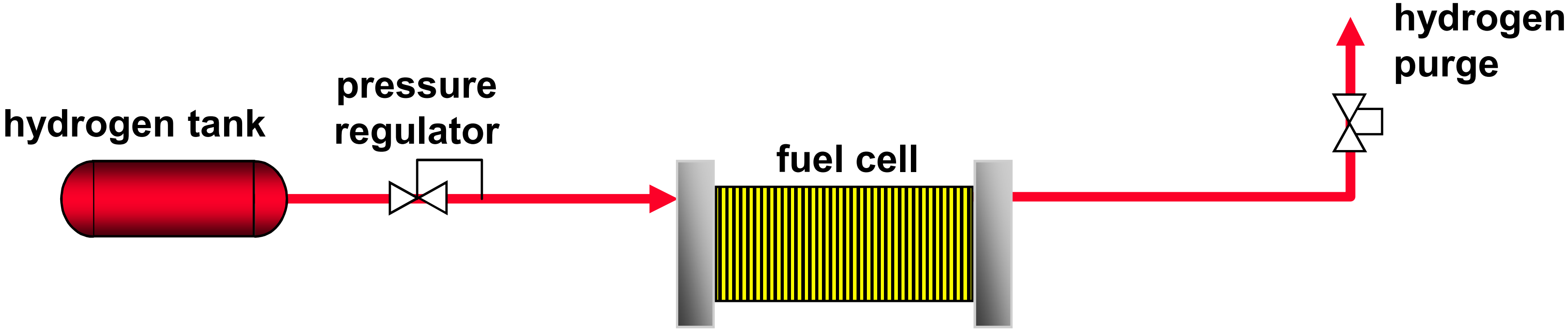


Pressure at the fuel cell inlet
Pressure drop: 20 kPa
Fuel cell temperature: 80°C

Fuel cell system components

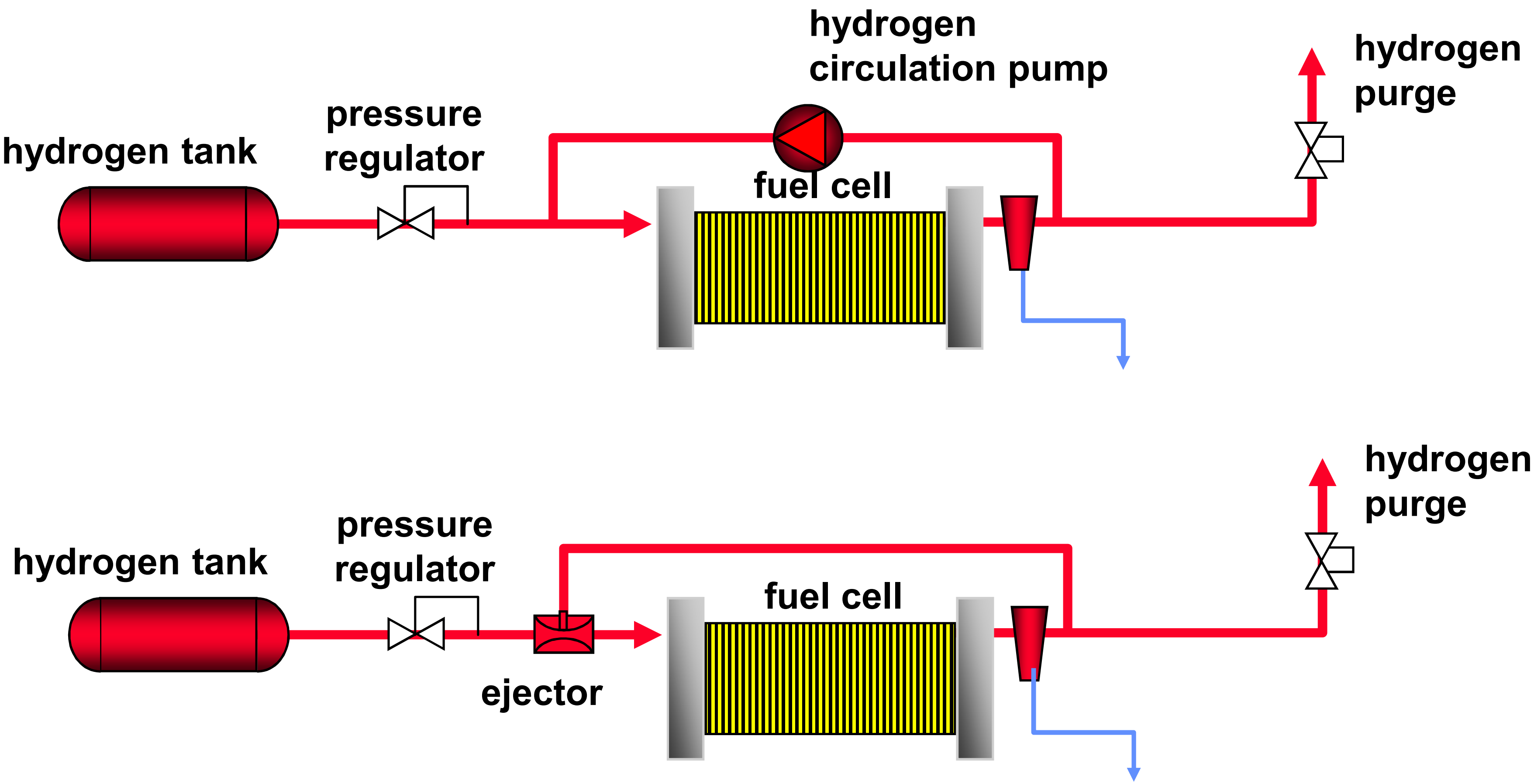
- Fuel cell stack
- Air supply
- Hydrogen supply
- Water and heat management
- Fuel processing and integration of fuel processor
- Power conditioning and controls

Hydrogen supply for fuel cell system in dead-end mode with intermittent purging

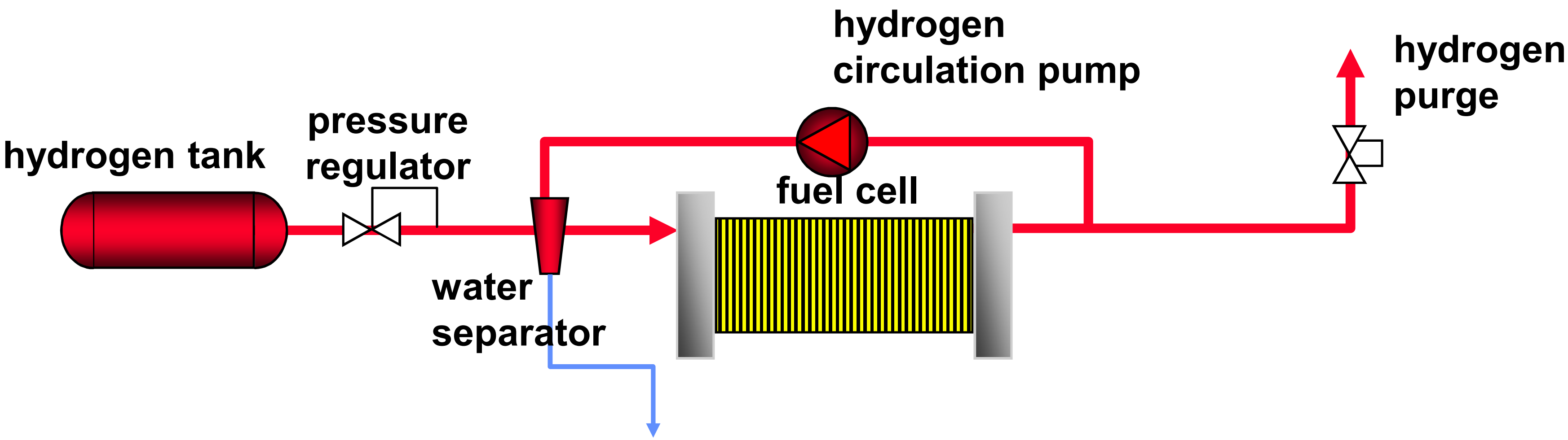


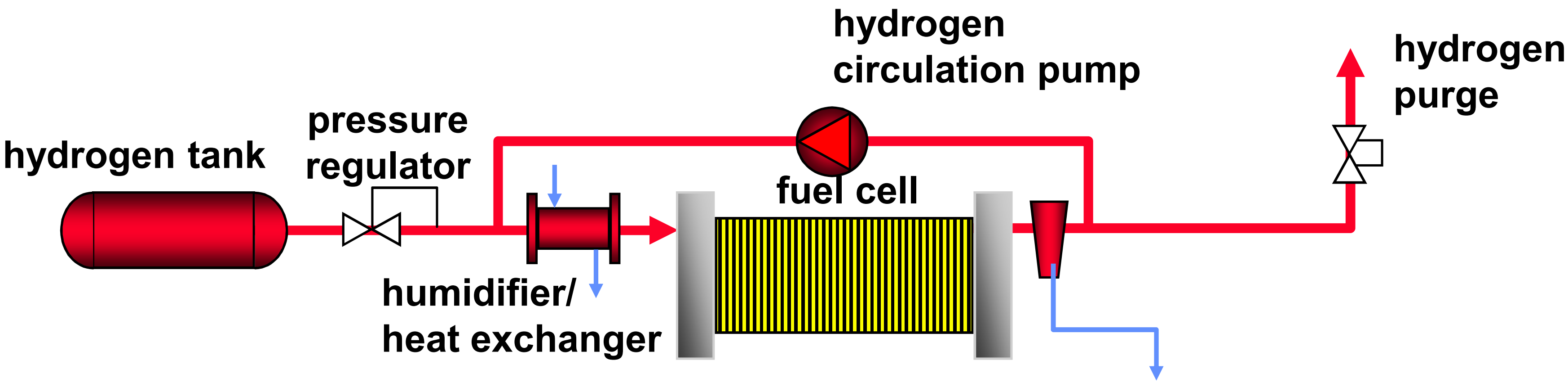
H2 supply

Hydrogen supply for fuel cell system with recirculation

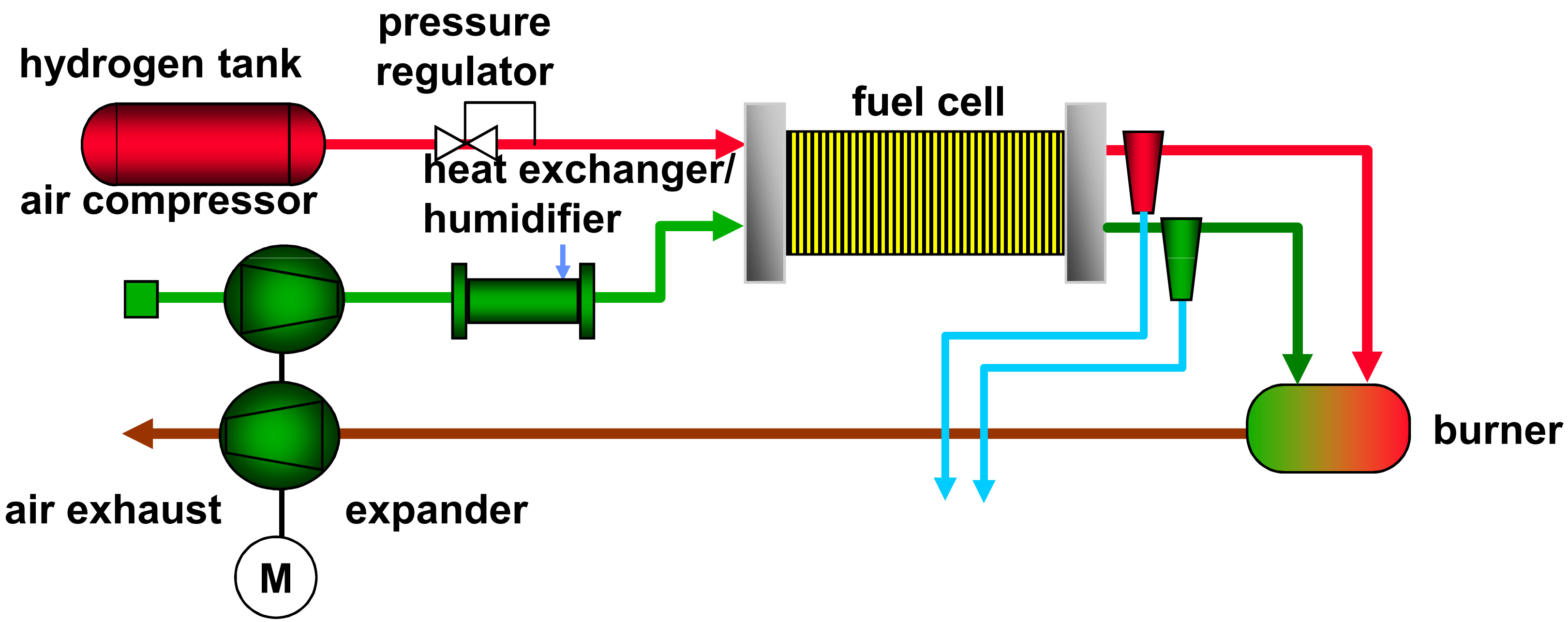


Hydrogen supply for fuel cell system with humidification





Hydrogen supply for fuel cell system with hydrogen flow through and afterburner w/expander

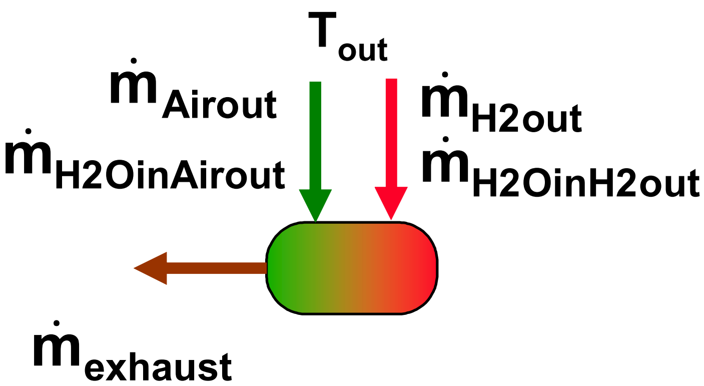


H2 supply

Expander power:

$$W_{exp} = \dot{m}_{exh} \cdot c_{pexh} \cdot T_B \left[1 - \left(\frac{P_0}{P_{out}} \right)^{\frac{k-1}{k}} \right] \eta_{exp}$$

Energy balance for the afterburner:



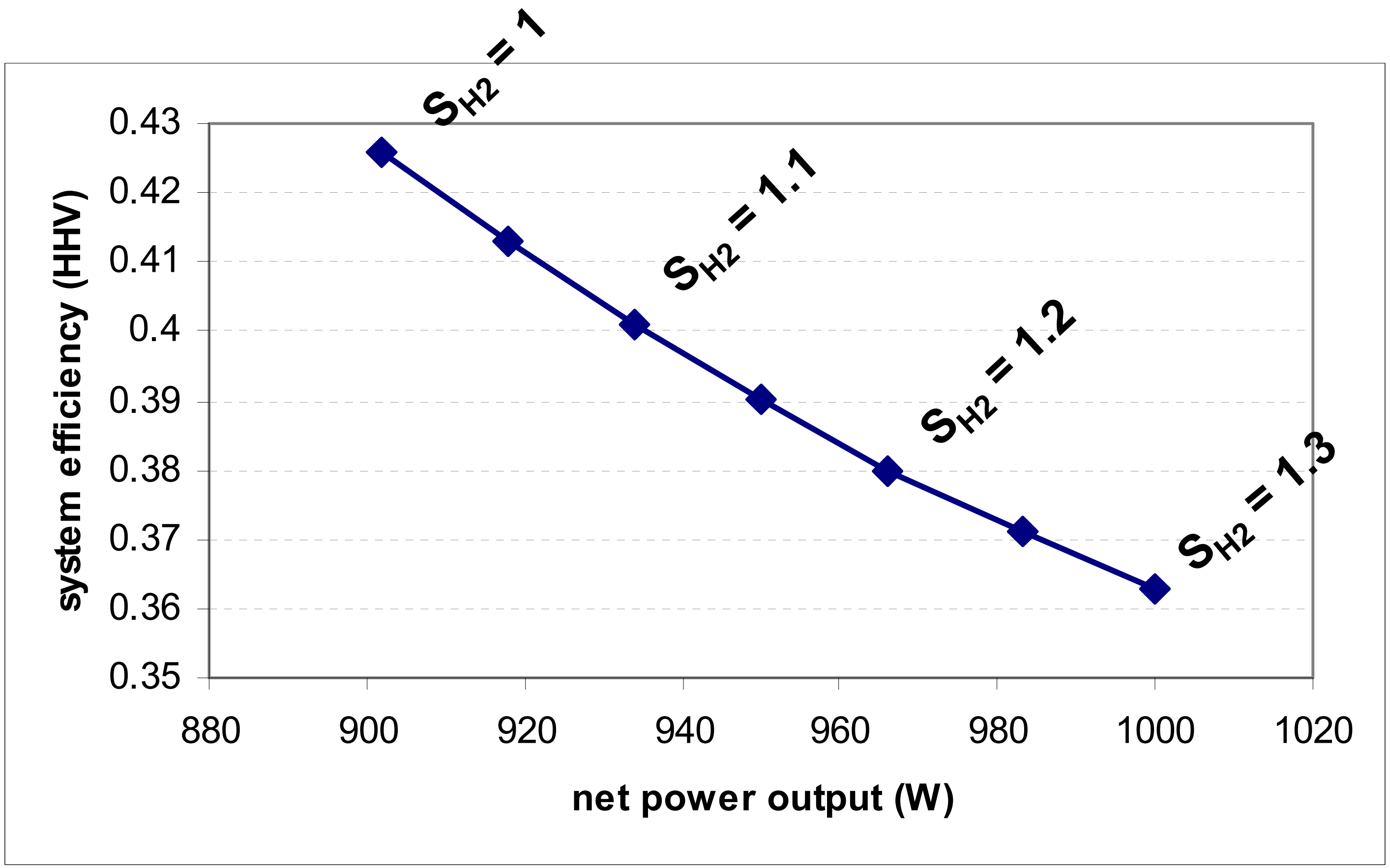
The more hydrogen is burned the more power is generated in expander

H2 supply

Does it make sense to waste hydrogen on combustion?

$$\eta_{sys} = \eta_{FC}\frac{W_{net}}{W_{FC}} = \frac{V_{cell}}{1.482}\frac{1}{S_{H2}}\frac{W_{FC}-W_{aux}}{W_{FC}}$$

$$W_{aux} = W_{other} + W_{comp} - W_{exp}$$



Fuel cell system components

- Fuel cell stack
- Air supply
- Hydrogen supply
- Water and heat management
- Fuel processing and integration of fuel processor
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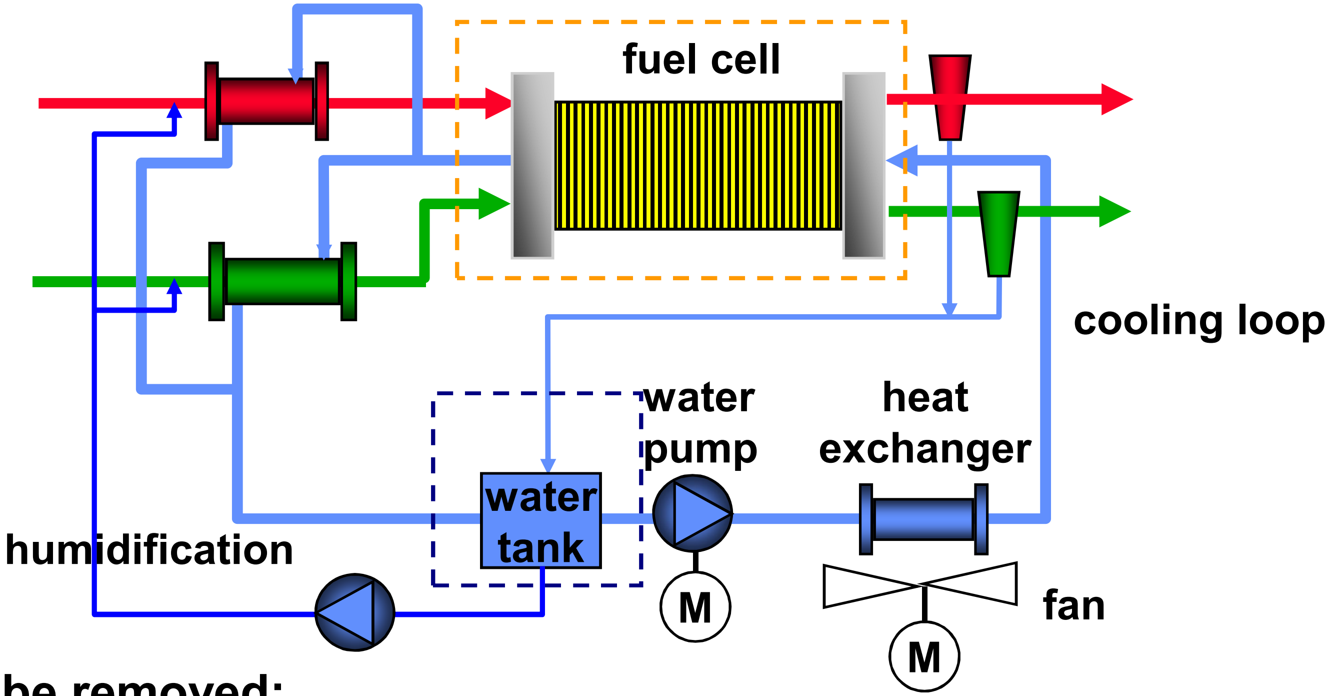
Water and heat management for fuel cell system



Heat to be removed:

Heat from the fuel cell – heat to the humidifiers

$Q = m_{cw}C_{p,w}\Delta t$ Δt = 5-10 °C → m_{cw}

Water balance:

Stack:

$m_{H20inAirin} + m_{H2OinH2in} + m_{H2Ogen} = m_{H20inAirout} + m_{H2OinH2out}$

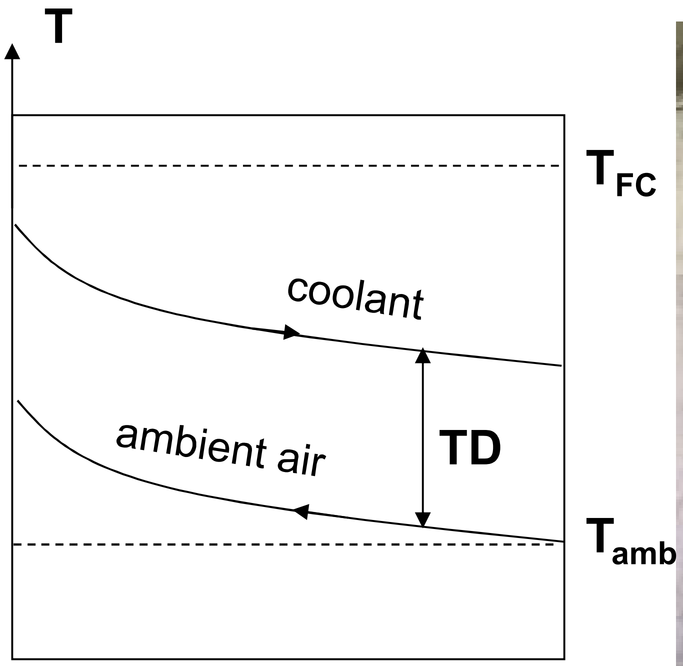
Tank:

$m_{H20inAirout,L} + m_{H2OinH2out,L} = (m_{H20inAirin} - m_{H2OinAmbAir}) + m_{H2OinH2in}$

External heat exchanger: $Q_{HX,rem} = hA\ LMTD$

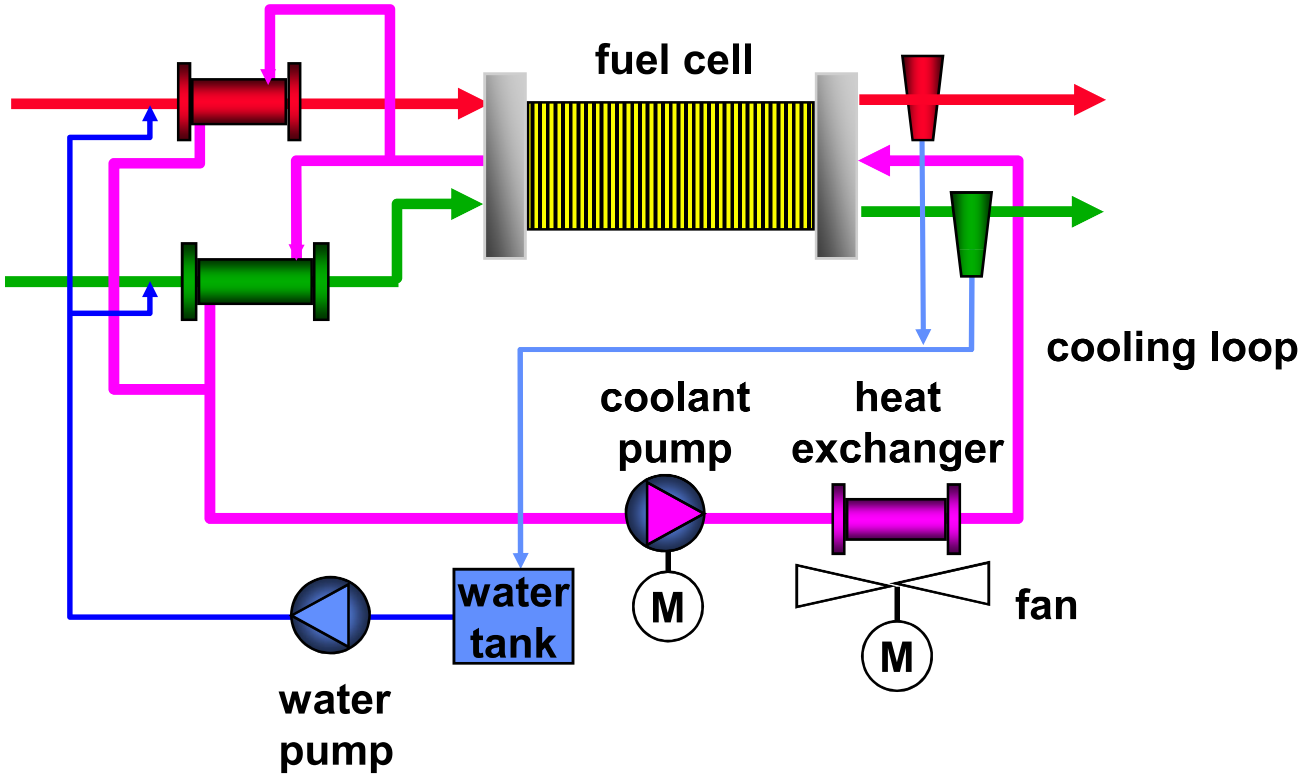
LMTD = logarithmic mean temperature difference

$$A = \frac{Q_{HX,rem}}{h\ LMTD}$$

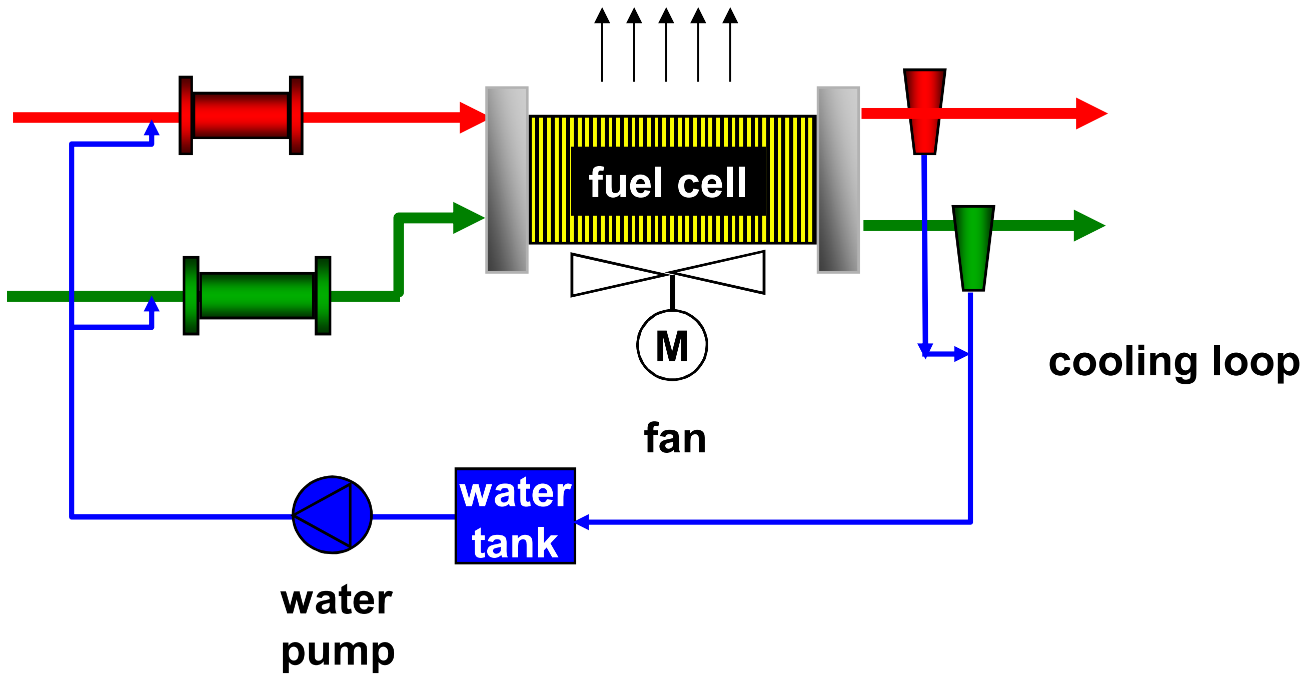


T_{FC} = 60-80 °C
T_{amb} = -30/+40 °C
LMTD < 40 °C

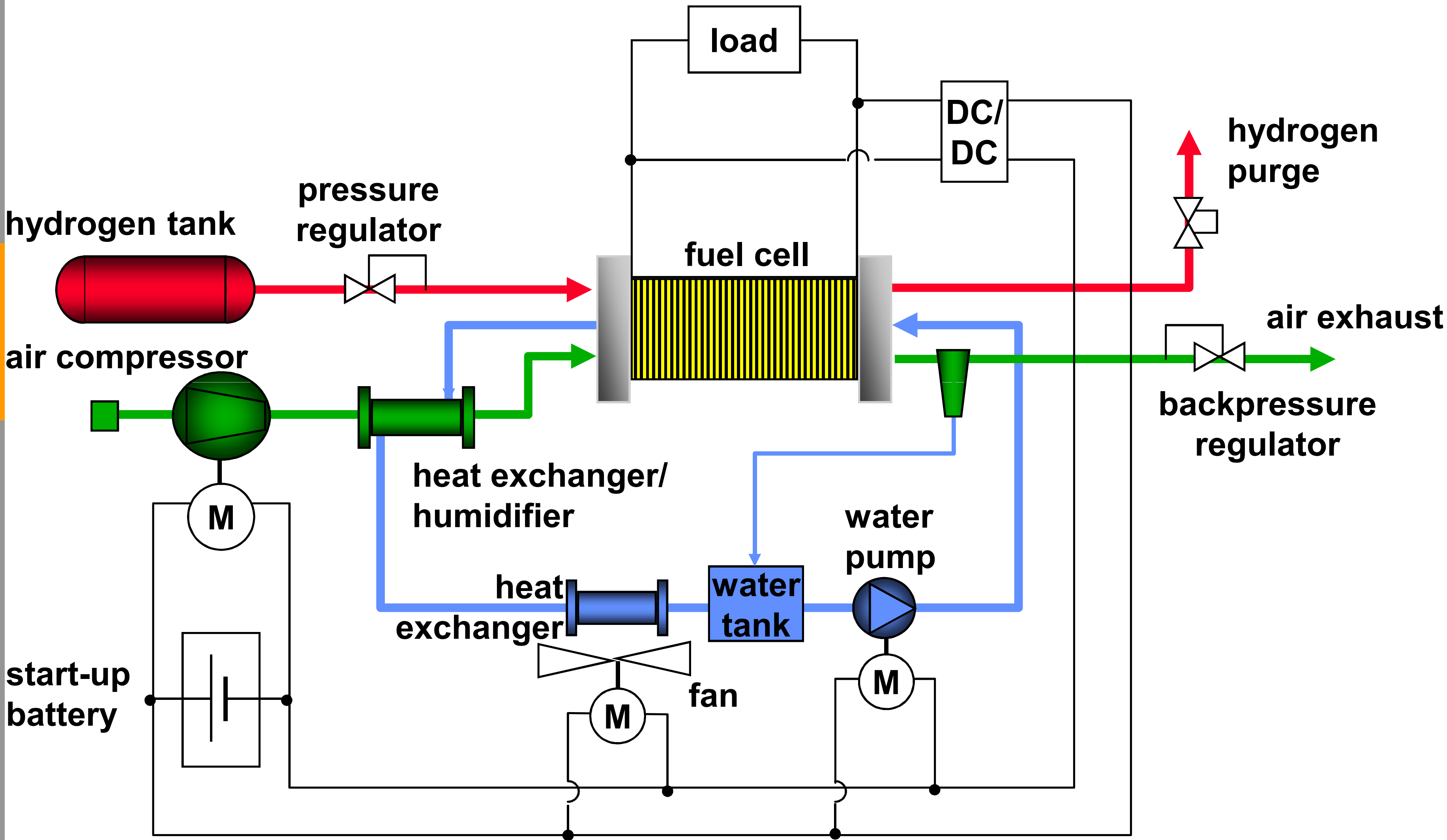
Water and heat management for fuel cell system with separate water and coolant loops



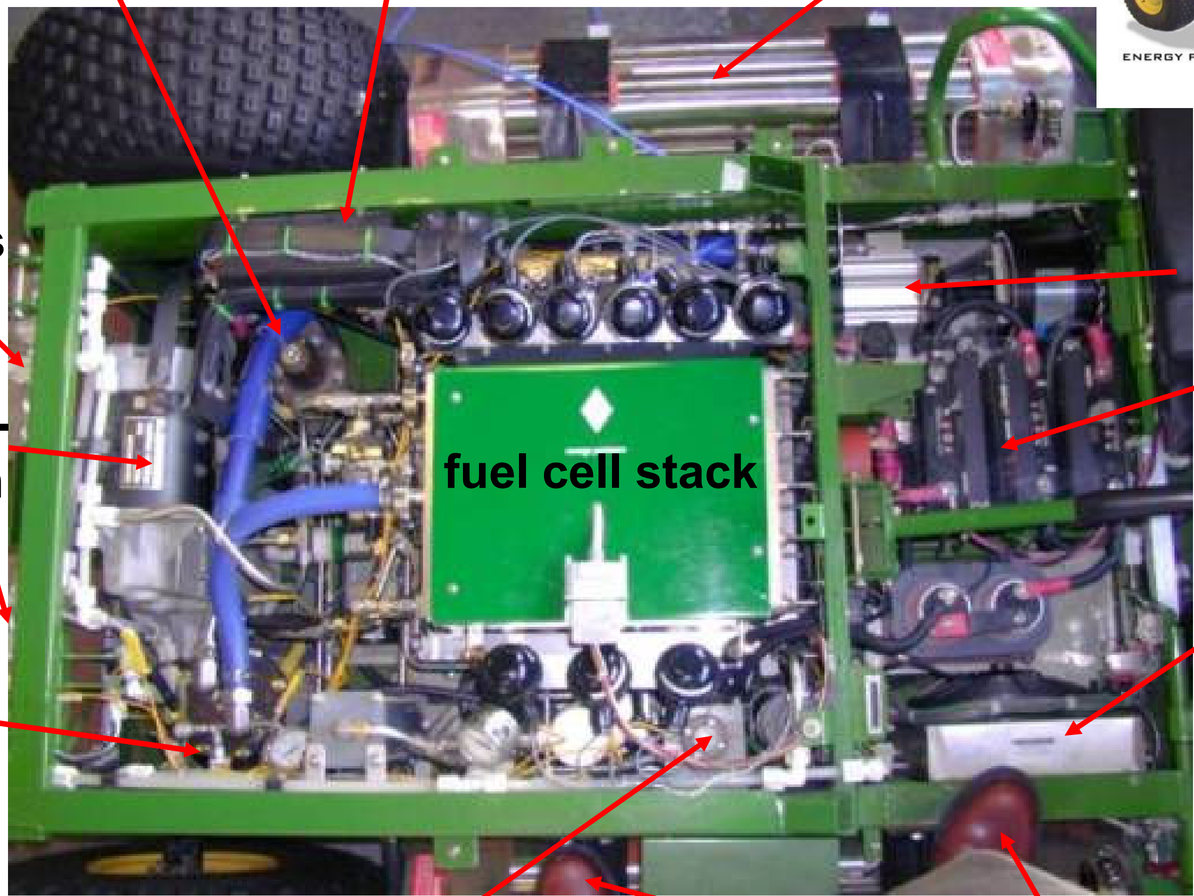
Fuel Cell System with Air Cooling



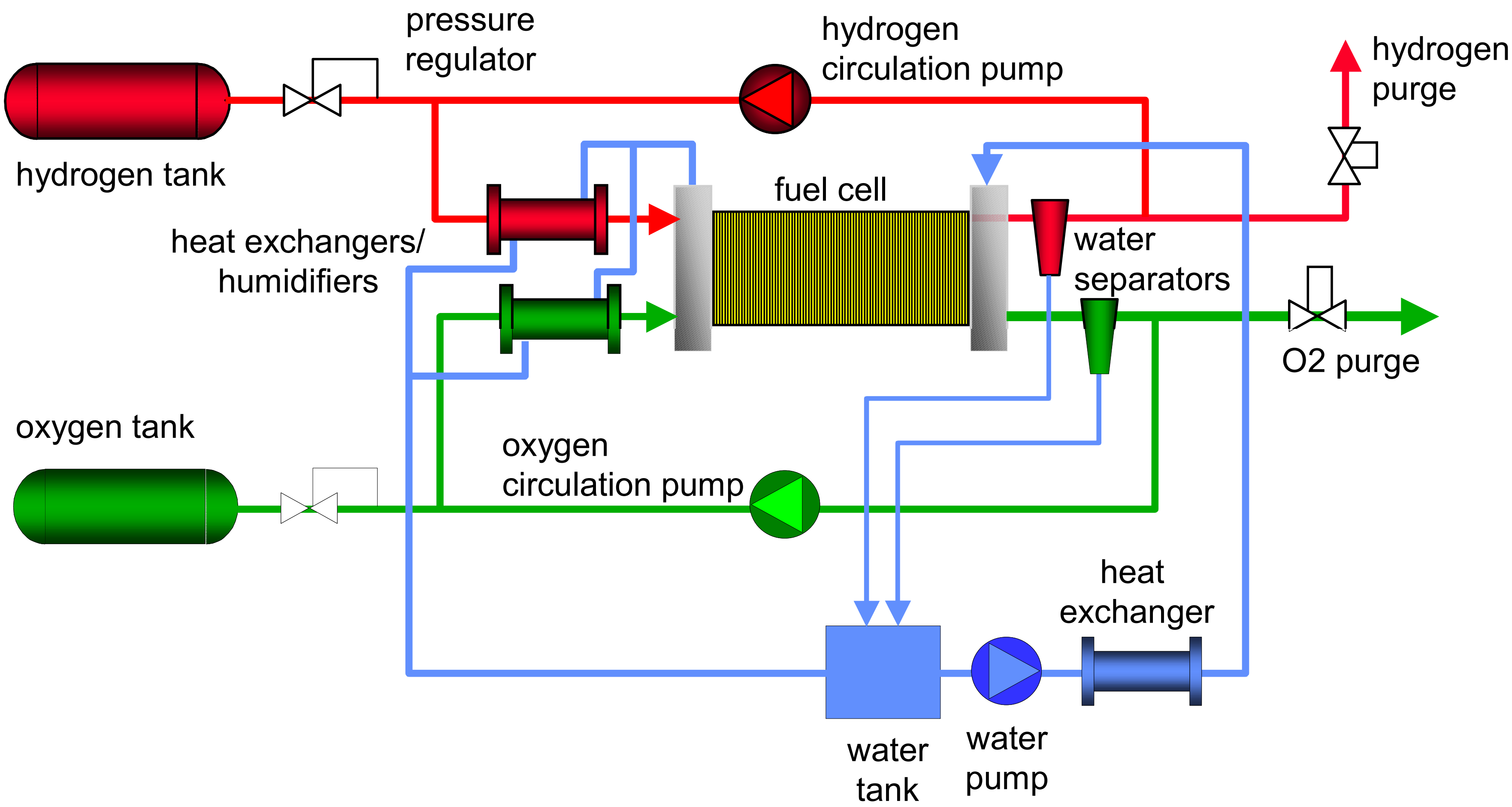
Example of a hydrogen/air fuel cell system



Actual fuel cell system



Example of a hydrogen/oxygen closed-loop fuel cell system



US005192627A

United States Patent [19]

Perry, Jr. et al.

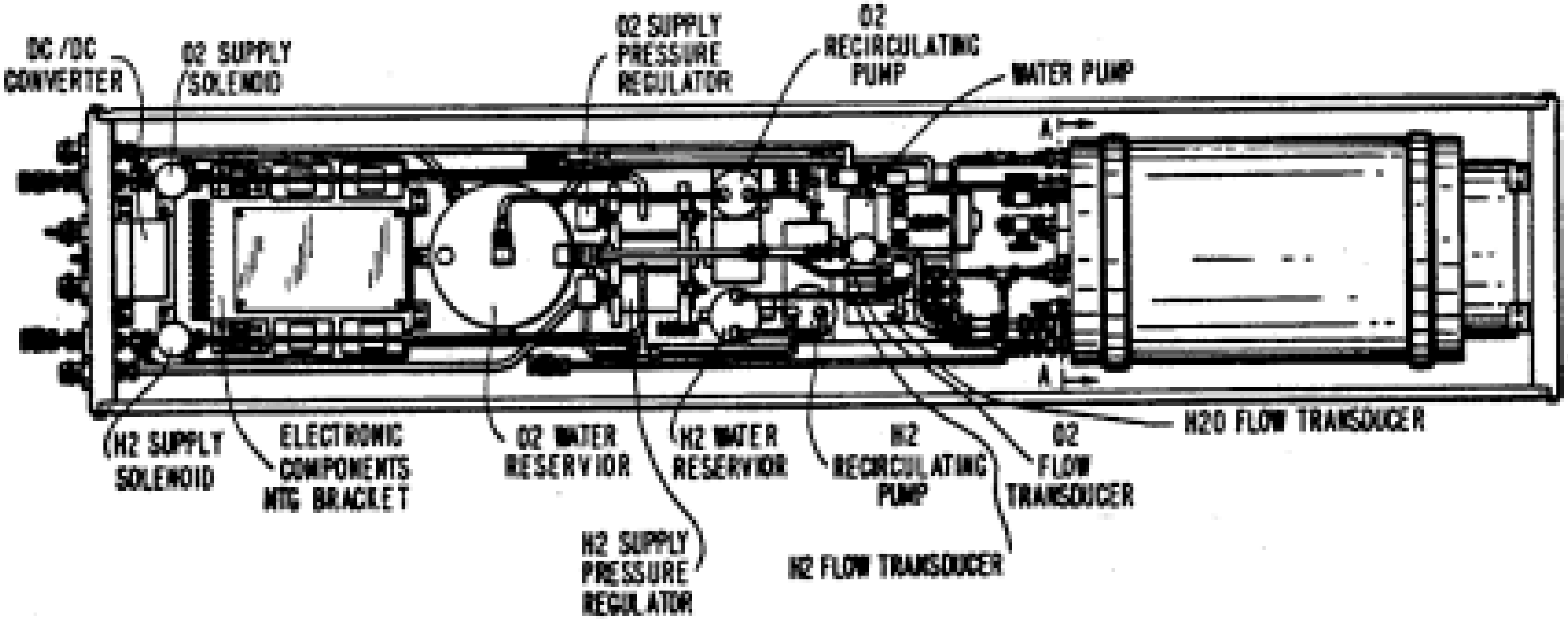
[11] Patent Number: 5,192,627

[45] Date of Patent: * Mar. 9, 1993

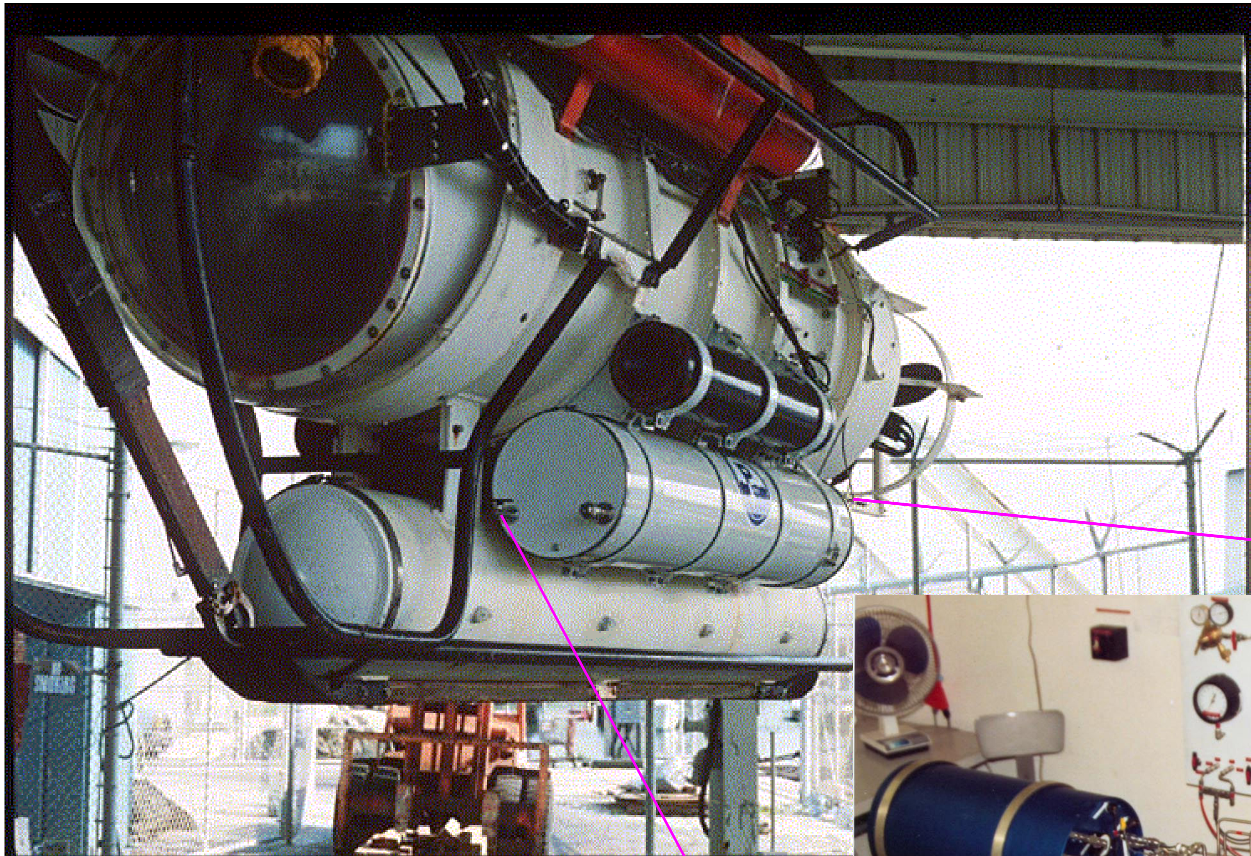
[54] CLOSED LOOP REACTANT/PRODUCT MANAGEMENT SYSTEM FOR ELECTROCHEMICAL GALVANIC ENERGY DEVICE

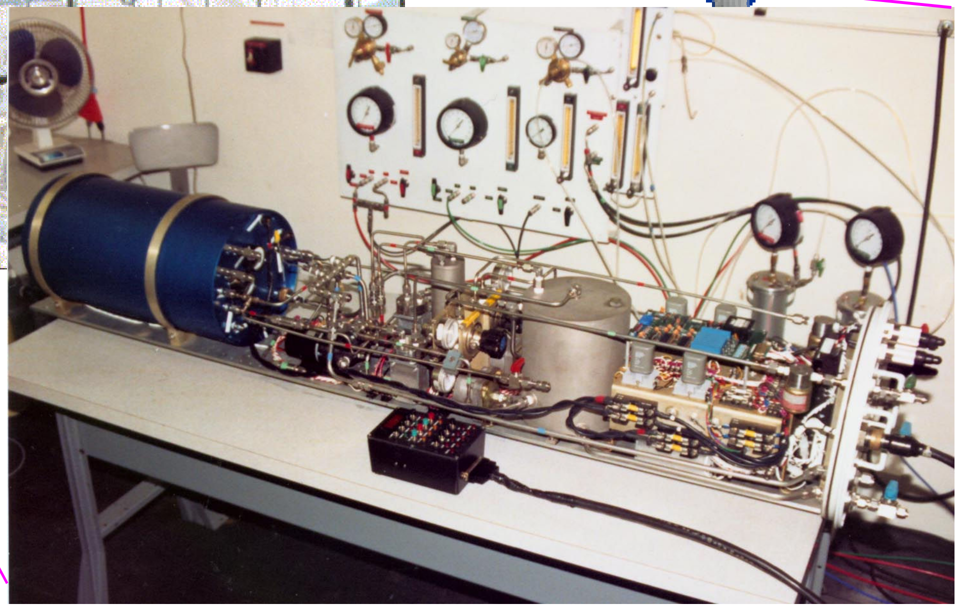
[52] U.S. Cl. 429/17; 429/19; 429/26; 429/34

[58] Field of Search 429/12, 17, 19, 26, 429/34, 20, 38, 39, 24, 25



First PEM Fuel Cell Powered Submarine (1989)



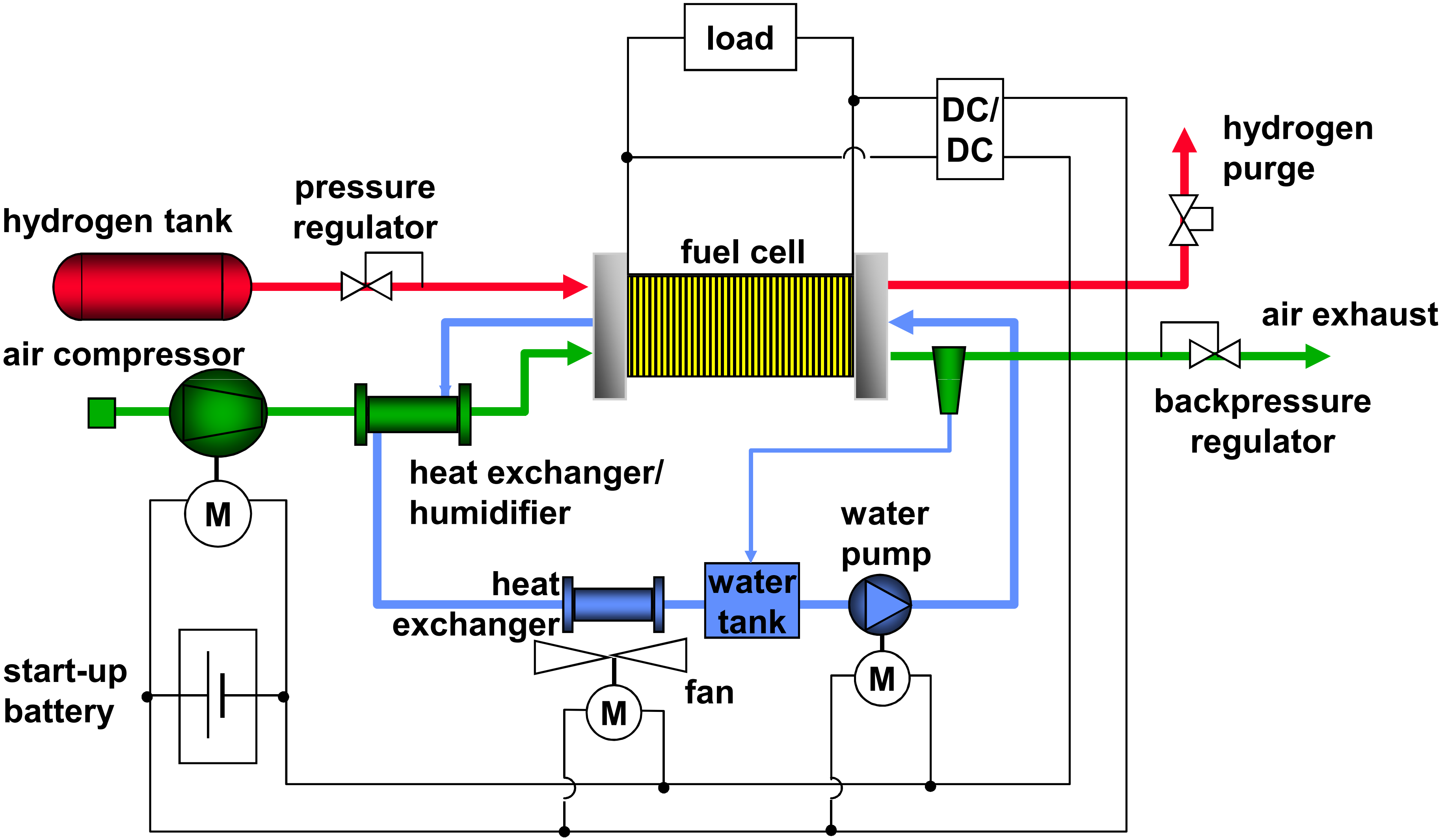


PC1401 by Perry Group

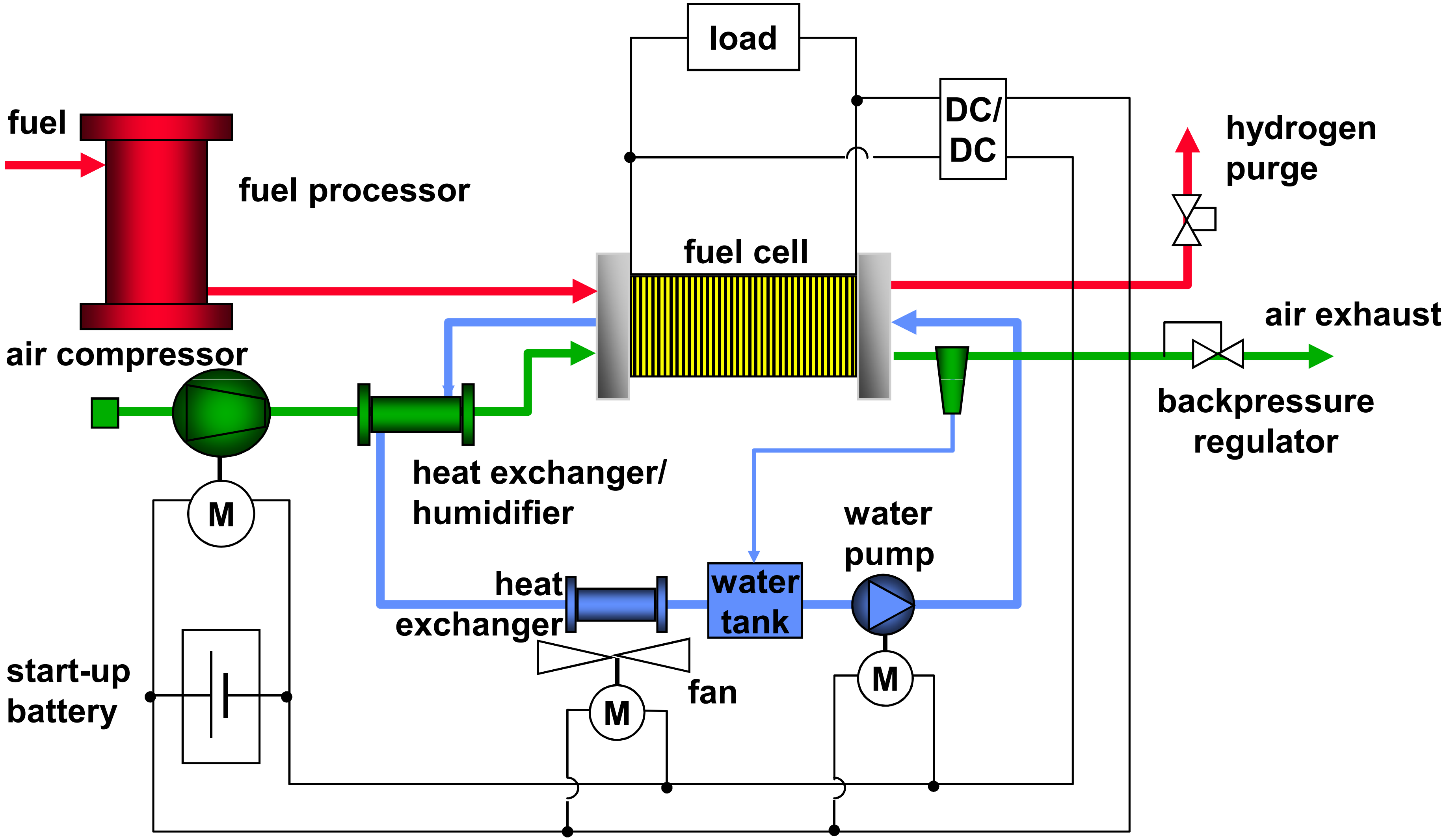
Fuel cell system components

- Fuel cell stack
- Air supply
- Hydrogen supply
- Water and heat management
- Fuel processing and integration of fuel processor
- Power conditioning and controls

Example of hydrogen/air fuel cell system



Fuel cell system with fuel processor



Fuels being considered (other than hydrogen)

- Natural gas
- Propane
- Methanol
- Gasoline
- Other liquid hydrocarbons
  - desulfurized gasoline
  - hydrocrackate
  - alkylate/isomerate
  - gas-to-liquid light paraffin
  - hydrotreated condensate

Fuel processing processes being considered

- Steam reforming
- Partial oxidation
- Autothermal

Basic Equations

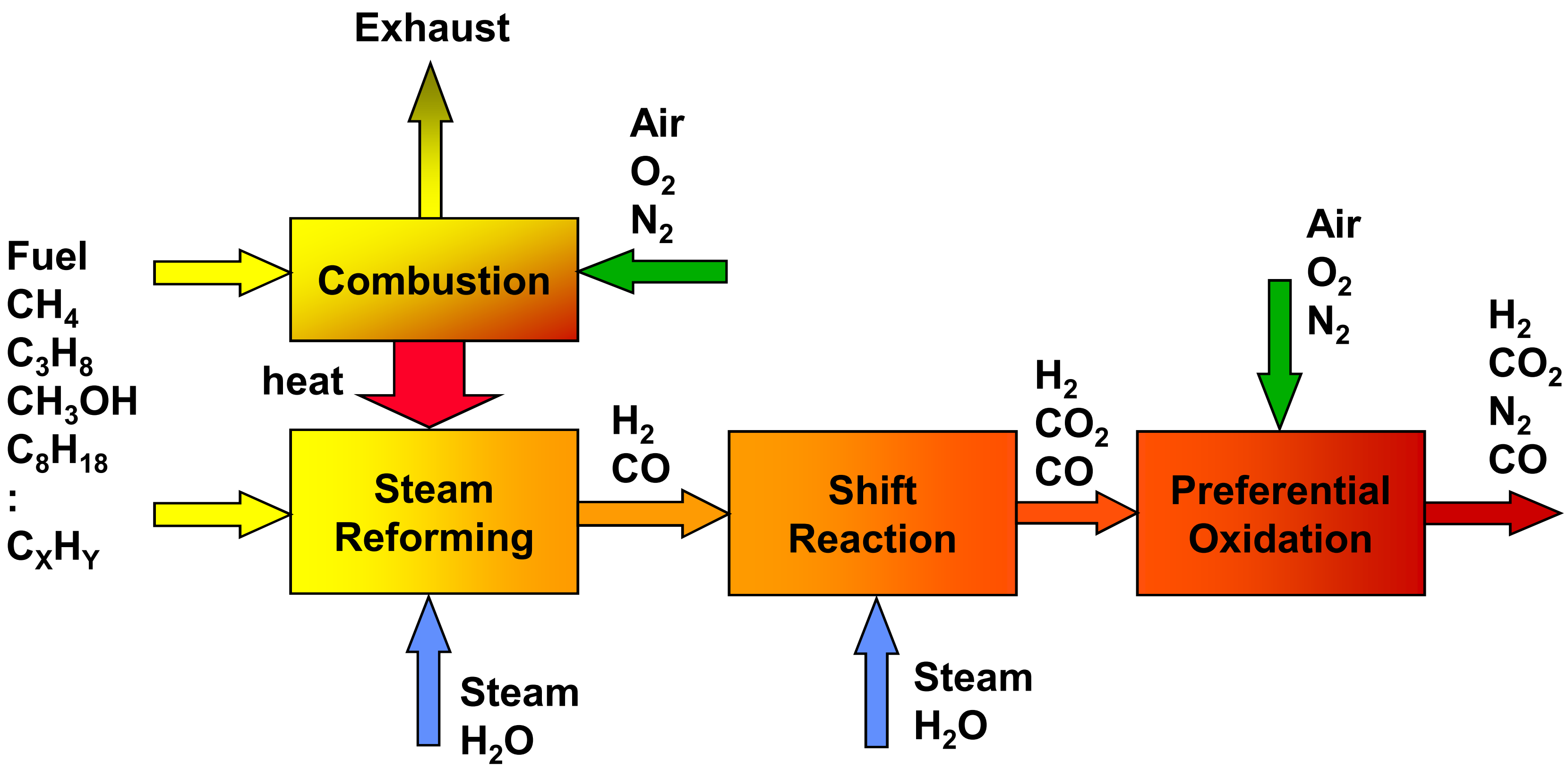
Combustion:	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O(g) + 802.5\ kJ$
	$C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O(g) + 5{,}063.8\ kJ$
	$CH_3OH + 1.5O_2 \rightarrow CO_2 + 2H_2O(g) + 638.5\ kJ$
Partial Oxidation:	$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 + 39.0\ kJ$
	$C_8H_{18} + 4O_2 \rightarrow 8CO + 9H_2 + 649.8\ kJ$
	$CH_3OH + \frac{1}{2}O_2 \rightarrow CO_2 + 2H_2 + 154.6\ kJ$
Steam Reforming:	$CH_4 + H_2O(g) + 203.0\ kJ \rightarrow CO + 3H_2$
	$C_8H_{18} + 8H_2O(g) + 1{,}286.1\ kJ \rightarrow 8CO + 17H_2$
	$CH_3OH + H_2O(g) + 87.4\ kJ \rightarrow CO_2 + 3H_2$
Gas Shift:	$CO + H_2O(g) \rightarrow CO_2 + H_2 + 37.5\ kJ$
Preferential oxidation:	$CO + 0.5\ O_2 \rightarrow CO_2 + 279.5\ kJ$
Water evaporation:	$H_2O(l) + 44.0\ kJ \rightarrow H_2O(g)$

HEAT OF FORMATION

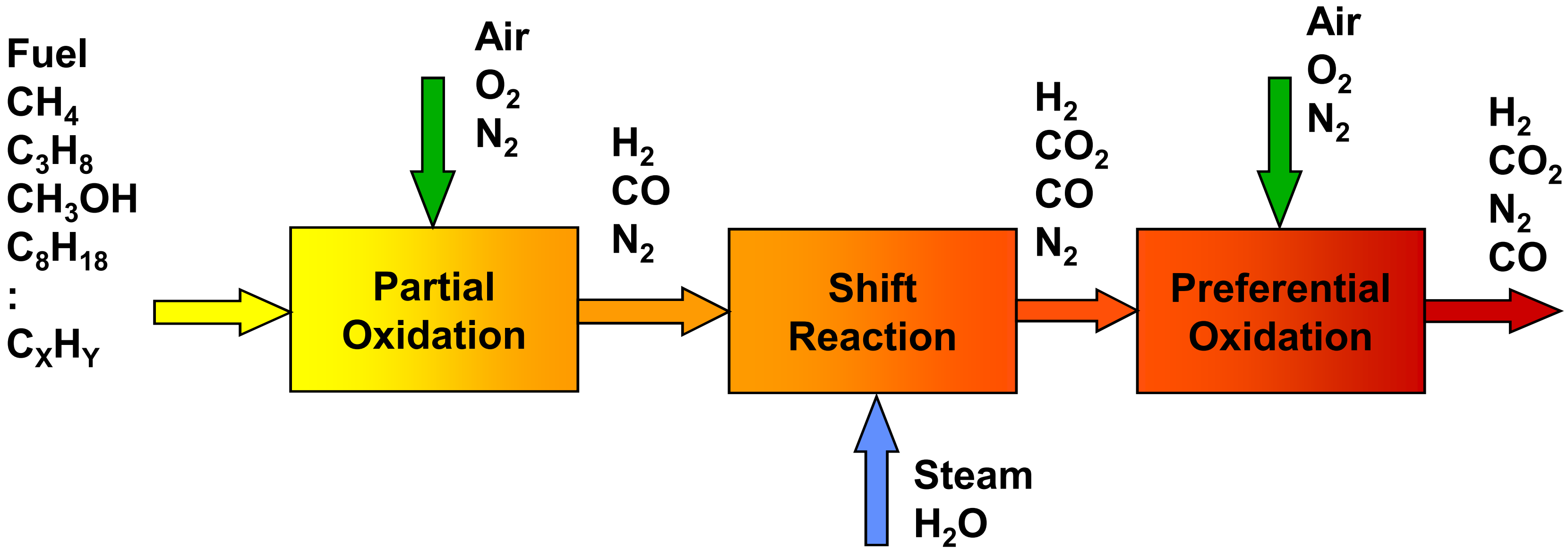
	MW	HF
		kJ/mol
H2	2.016	0
O2	31.9988	0
N2	14.0067	0
CO	28.0106	-113.8768
CO2	44.01	-393.4043
H2O(g)	18.0153	-241.9803
H2O(l)	18.0153	-286.0212
CH4	16.043	-74.85998
CH3OH	32.0424	-238.8151
C8H18	114.23	-261.2312

Source: R.C. Weast, Handbook of Chemistry and Physics, CRC Press, 1988

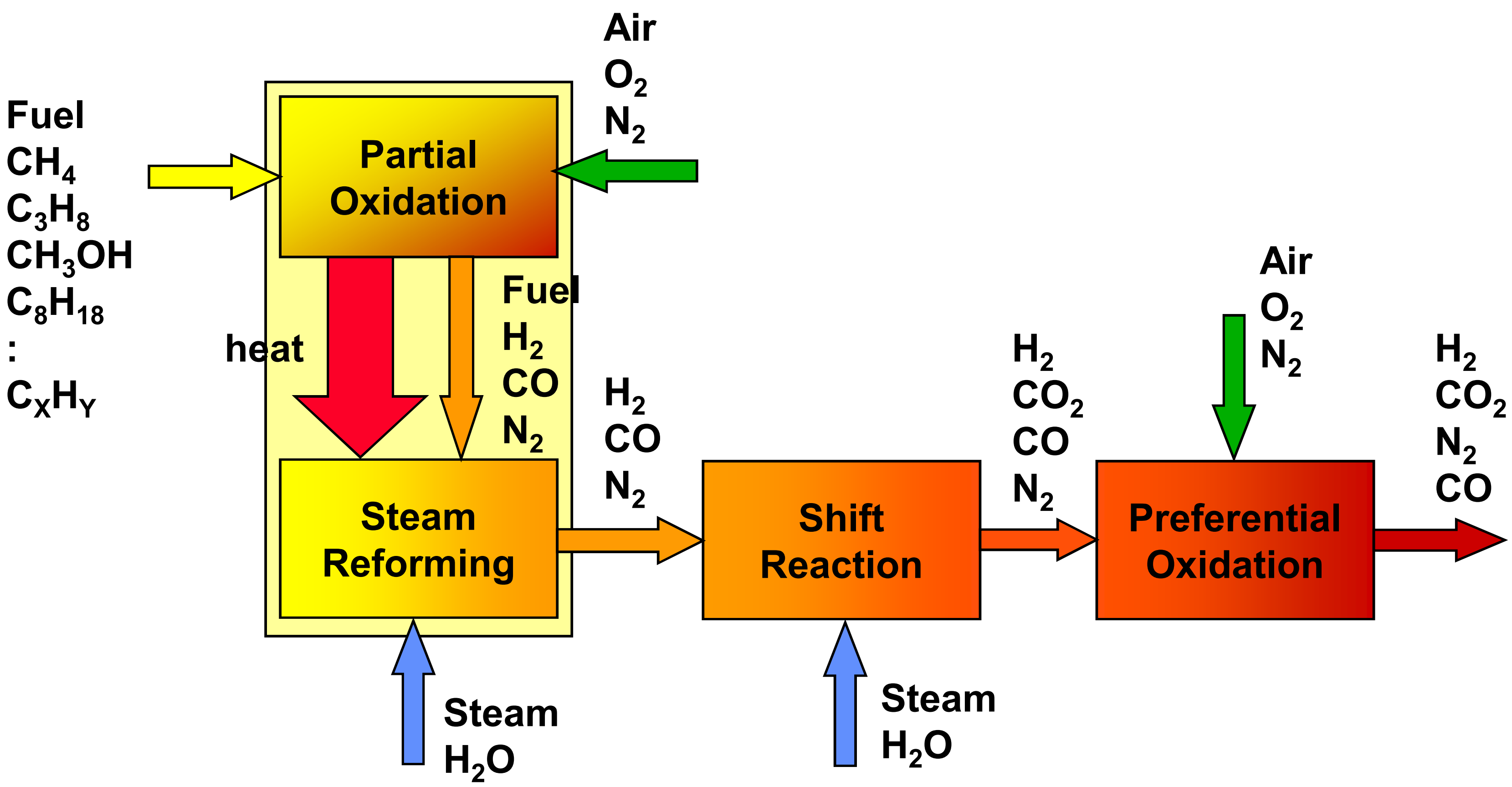
STEAM REFORMING



PARTIAL OXIDATION



AUTOTHERMAL



Overall equations for CH_4 C_8H_{18} and CH_3OH

$$C_nH_mO_p + xO_2 + (2n - 2x - p)H_2O \rightarrow nCO_2 + (2n - 2x - p + m/2)H_2$$

$$CH_4 + xO_2 + (2 - 2x)H_2O \rightarrow CO_2 + (4 - 2x)H_2$$
$$C_8H_{18} + xO_2 + (16 - 2x)H_2O \rightarrow 8CO_2 + (25 - 2x)H_2$$
$$CH_3OH + xO_2 + (1 - 2x)H_2O \rightarrow CO_2 + (3 - 2x)H_2$$

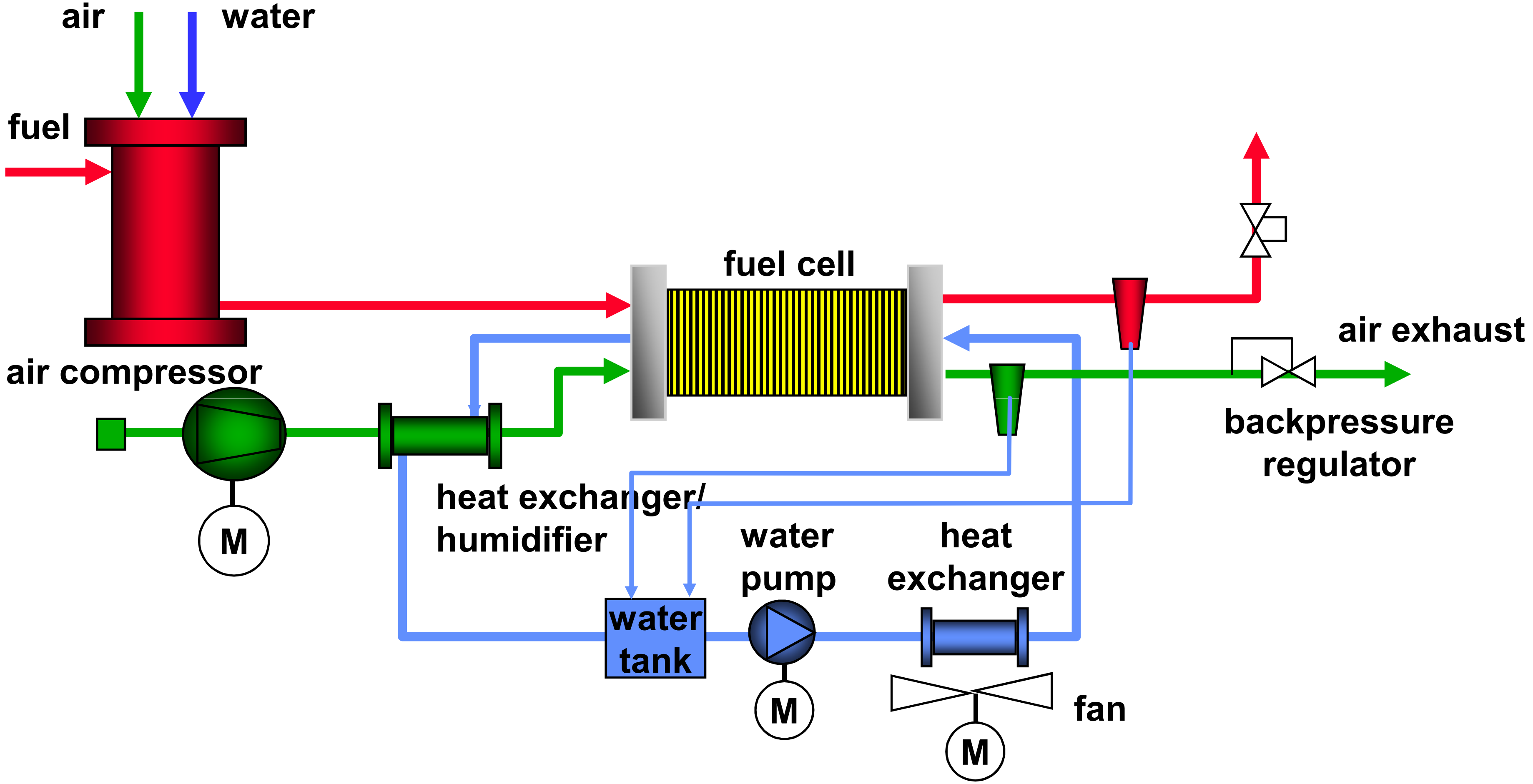
$$\text{Efficiency} = \frac{\text{Hydrogen out}}{\text{Fuel in}} = \frac{\text{mol } H_2 \text{ x } H_2 \text{ heating value}}{\text{mol fuel x fuel heating value}}$$

For CH_4:

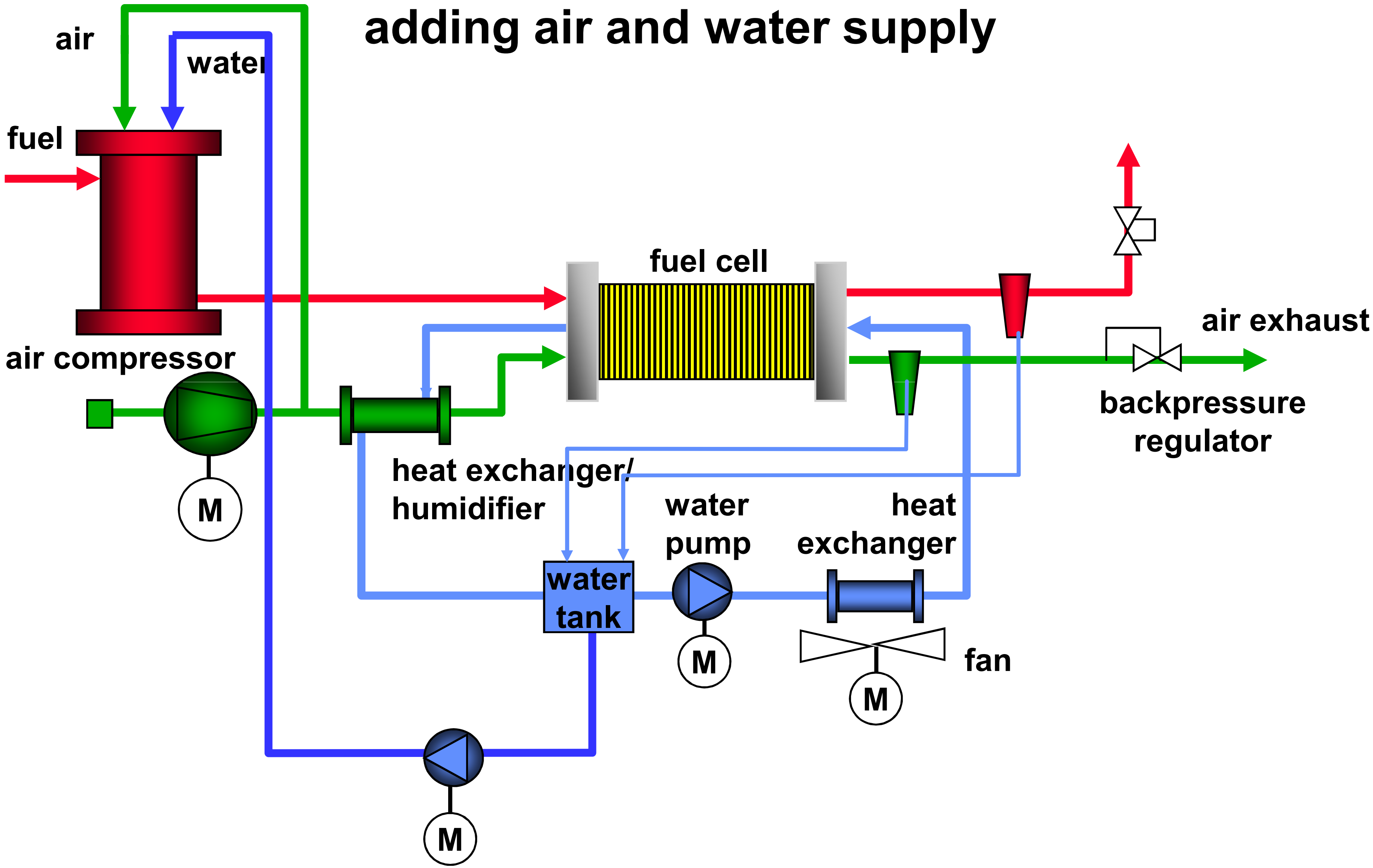
$$\text{Efficiency (LHV)} = (4 - 2x)\frac{242.0}{802.5} = 0.3 \cdot (4 - 2x)$$

$$\text{Efficiency (HHV)} = (4 - 2x)\frac{286.0}{890.6} = 0.321 \cdot (4 - 2x)$$

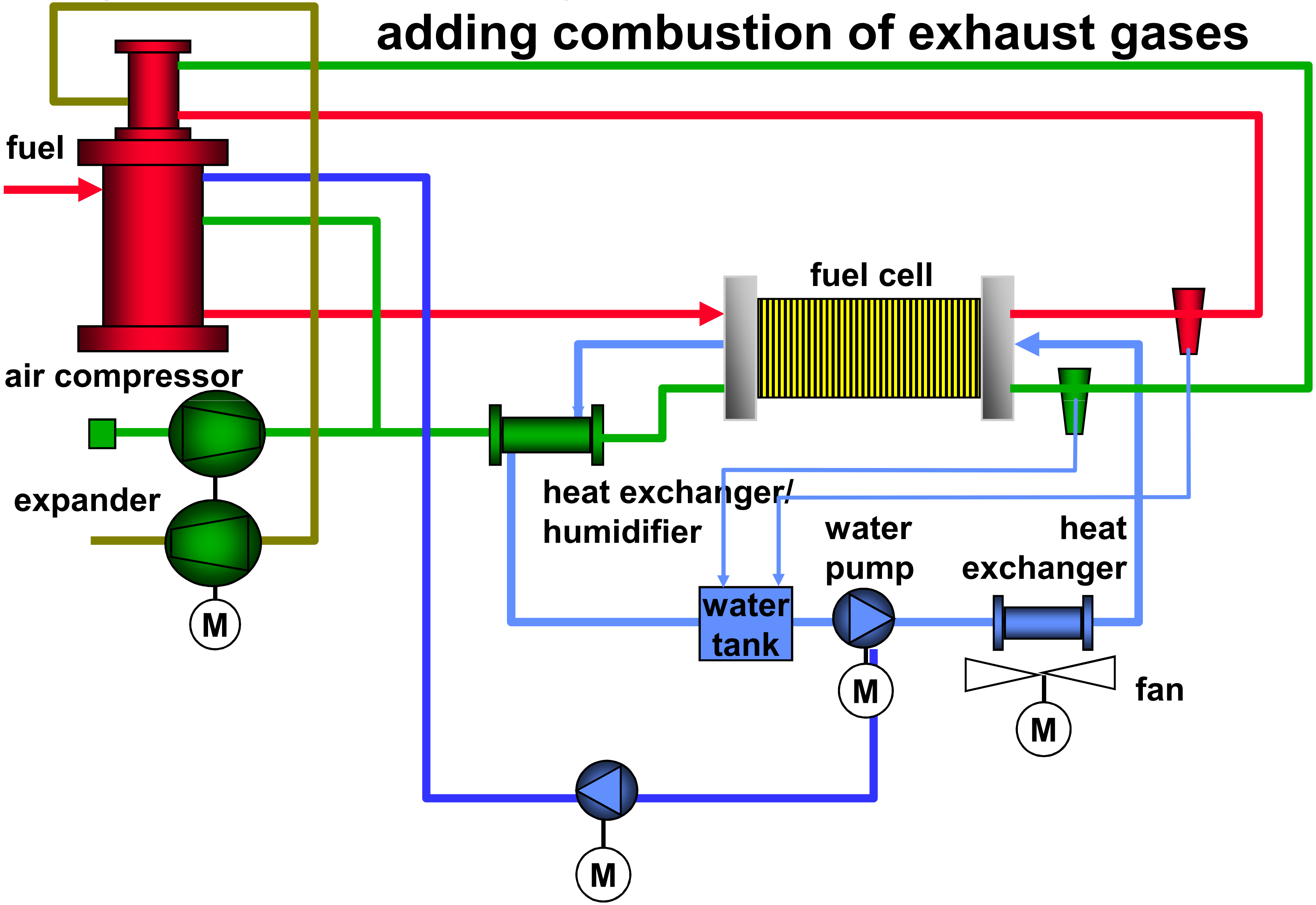
Fuel cell system with fuel processor



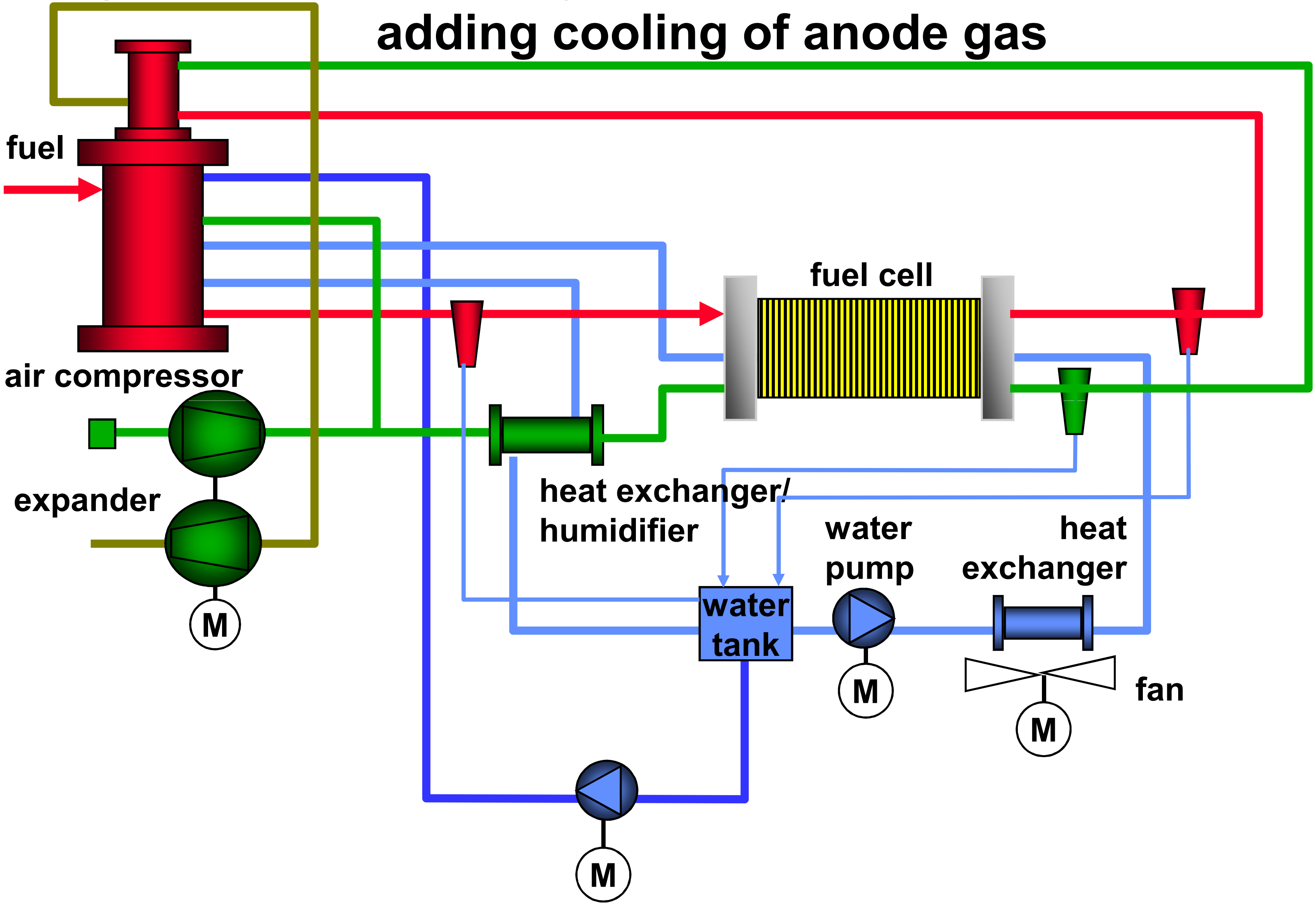
Integration of fuel cell system with fuel processor adding air and water supply



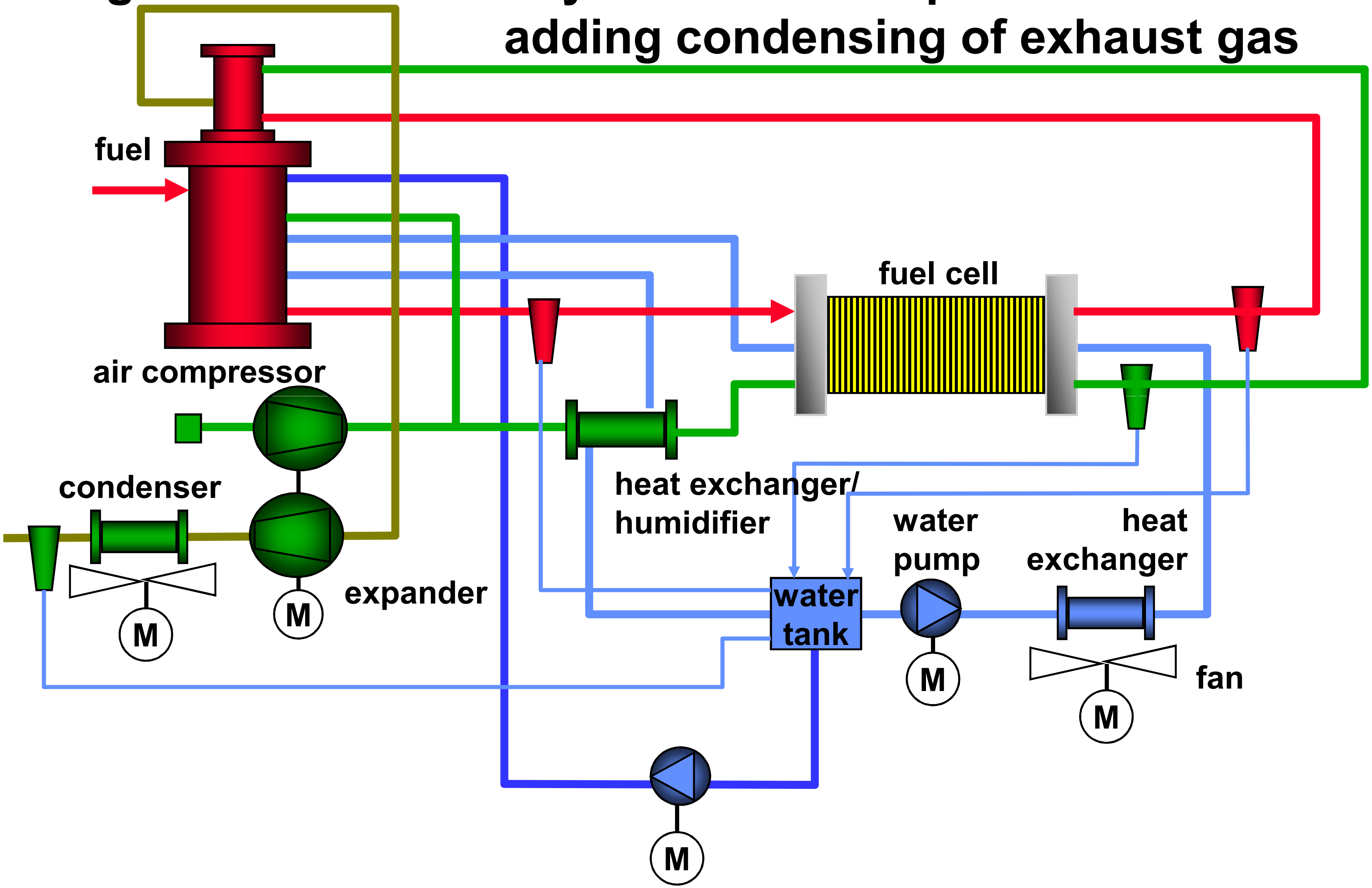
Integration of fuel cell system with fuel processor adding combustion of exhaust gases



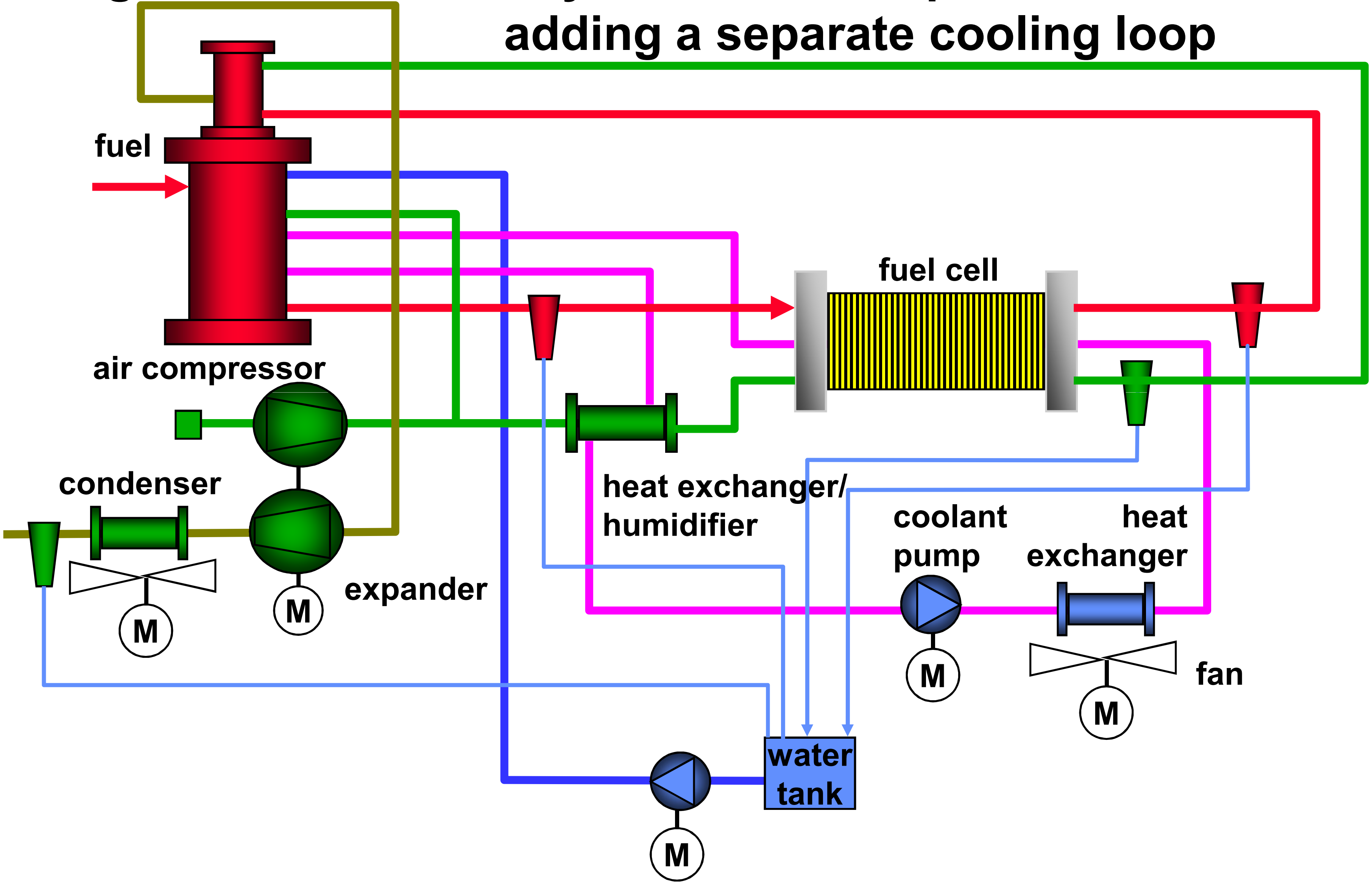
Integration of fuel cell system with fuel processor adding cooling of anode gas



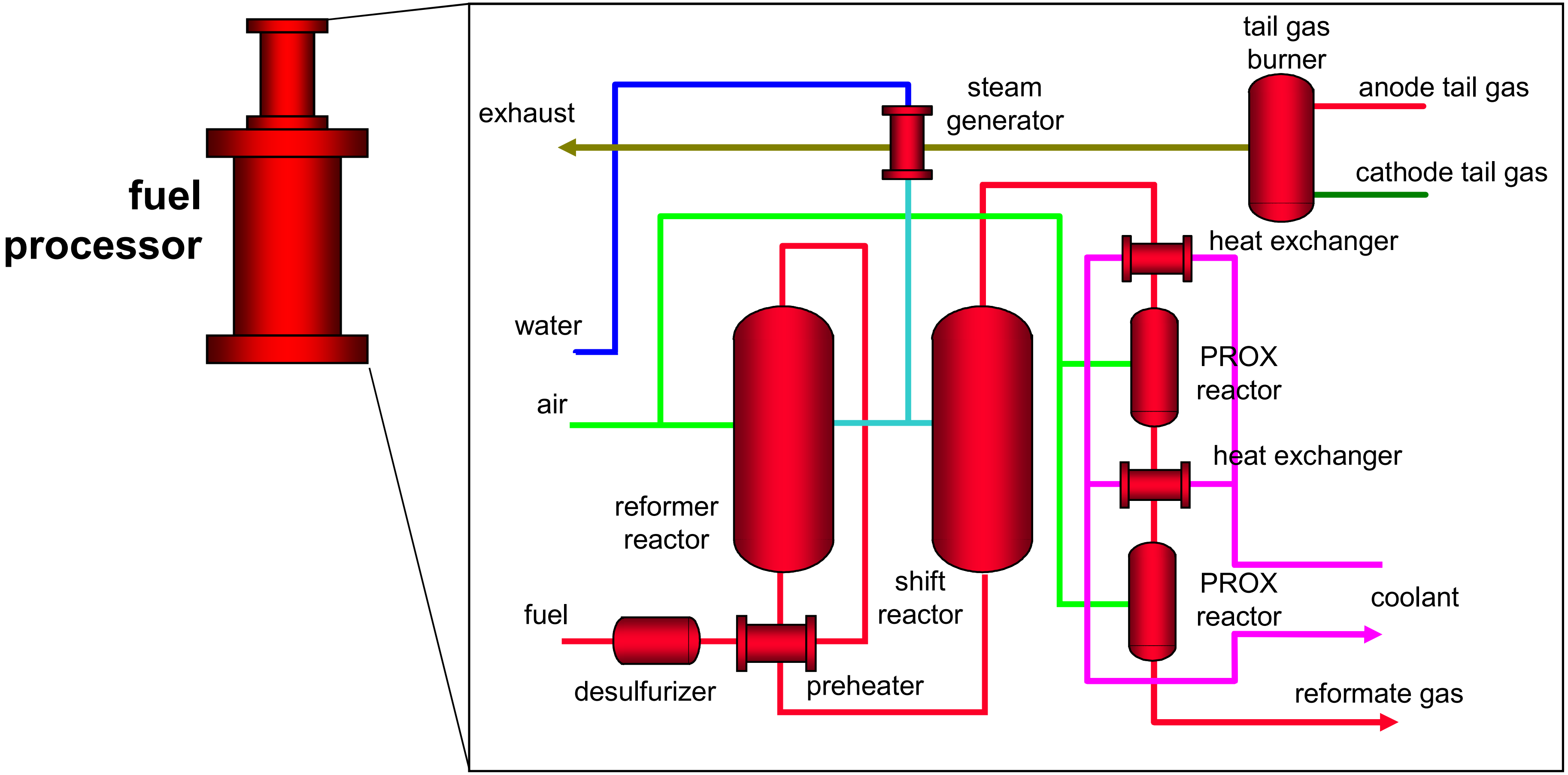
Integration of fuel cell system with fuel processor adding condensing of exhaust gas



Integration of fuel cell system with fuel processor adding a separate cooling loop



Fuel processor is more than a box!



Issues on fuel processor integration with fuel cell

- start-up fuel
- quality of gas product during start-up
- start-up time
- controls
- supply pressure (fuel, water, air)
- efficiency (heating value of hydrogen/fuel)
- heat loss
- possibility of using heat from combustion of fuel cell exhaust gases
- reformate composition
    - hydrogen content
    - water content
    - CO content
- reformate temperature
- pressure drop
- water consumption
- quality of water downlet
- emissions
- turn-down ratio
- transient behavior

Fuel cell system components

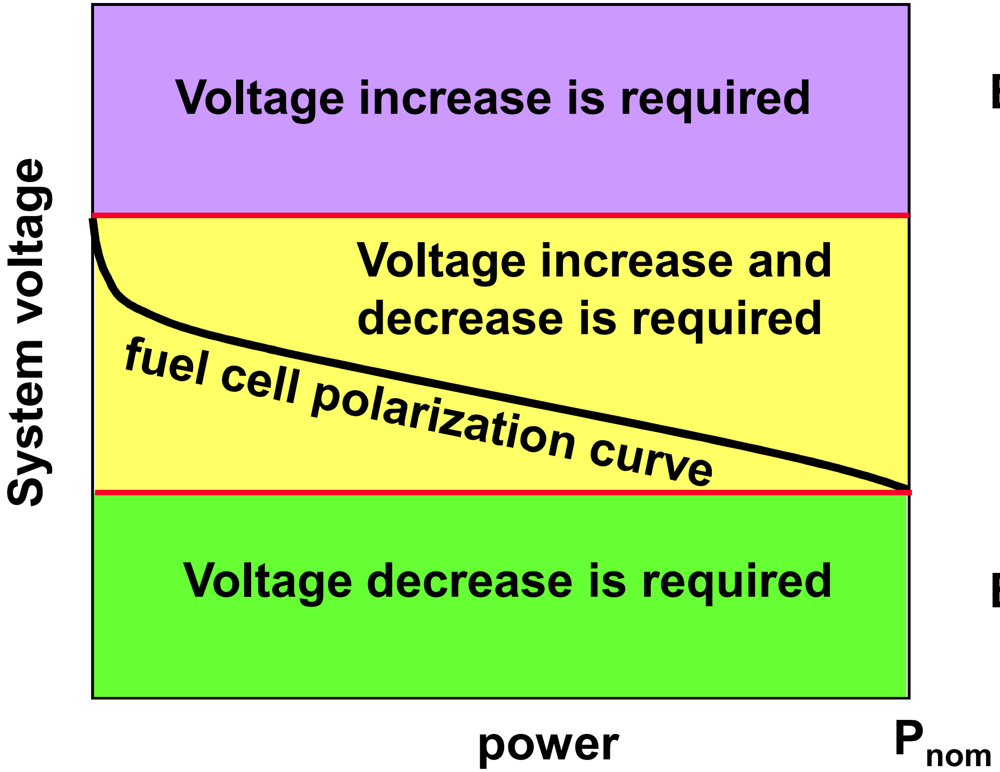
- Fuel cell stack
- Air supply
- Hydrogen supply
- Water and heat management
- Fuel processing and integration of fuel processor
- Power conditioning and controls

Fuel cell system design
from electrical engineering point of view

- Voltage match
- Power conditioning
- Battery requirements
- Controls

Power&Control

Fuel cell generates power at variable voltage!
Most loads cannot tolerate big voltage swings!
Voltage correction is required!



Boost converter DC/DC

Buck-boost converter DC/DC

Buck converter DC/DC

In addition for AC load DC/AC conversion is required **Inverter DC/AC**

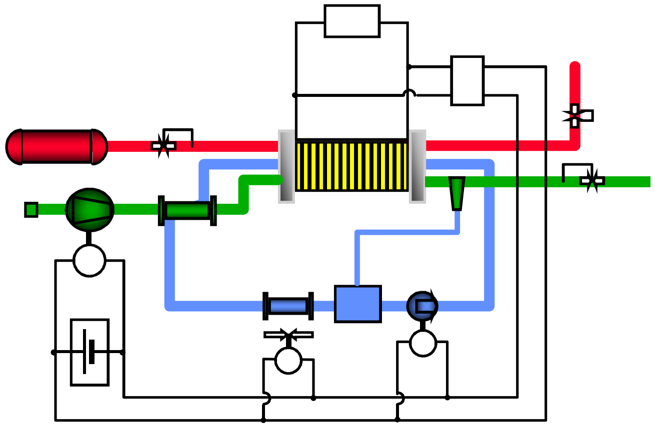
If ancillary equipment runs of voltage different than the load more than one converter/inverter may be needed in the system!

Fuel cell control

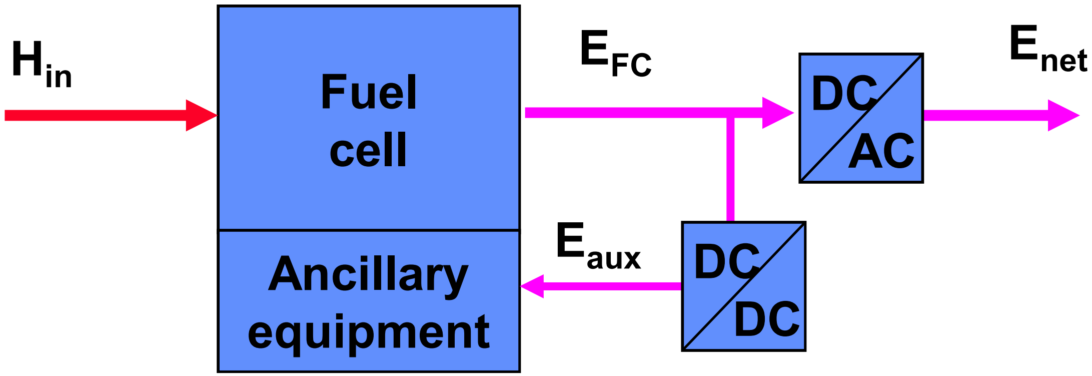
- ♦ Start-up procedure
- ♦ Monitoring of operating parameters
- ♦ Control of operating parameters
  - current
  - air supply
  - hydrogen supply
  - temperature
- ♦ Shut-down procedure
  - normal
  - fail-safe

Parasitic loads

- ➔ air supply (blower or compressor/expander)
- ➔ coolant pump
- ➔ water pump(s)
- ➔ heat exchanger fan(s)
- ➔ solenoid valves
- ➔ relays
- ➔ controller



Fuel Cell System Efficiency (Hydrogen as Fuel)



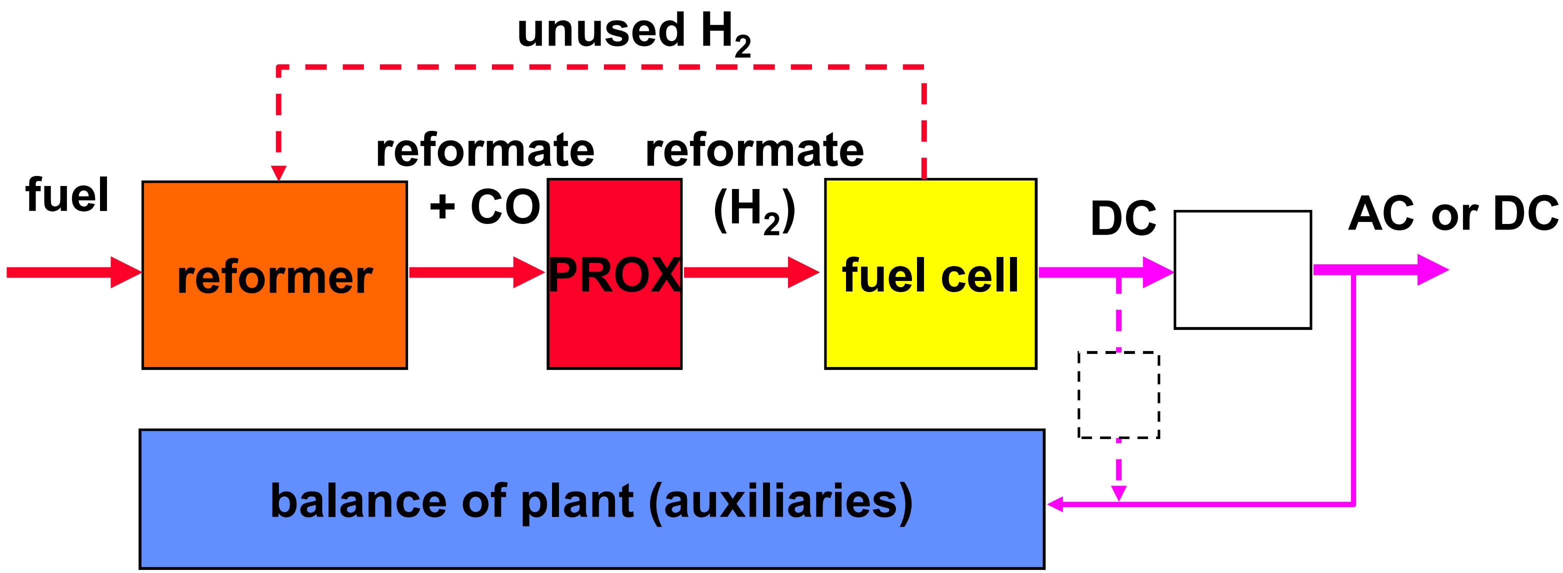
$$\eta_{sys} = \frac{E_{net}}{H_{in}} = \frac{E_{FC}}{H_{in}} \frac{E_{net}}{E_{FC}}$$

$$\frac{E_{FC}}{H_{in}} = \eta_{FC} \qquad \frac{E_{net}}{E_{FC} - \frac{E_{aux}}{\eta_{DC}}} = \eta_{AC} \qquad \frac{E_{aux}}{E_{FC}} = \xi$$

$$\boxed{\eta_{sys} = \eta_{FC}\eta_{AC}\left(1 - \frac{\xi}{\eta_{DC}}\right)}$$

Fuel Cell System Efficiency (with reformer)

$$\text{system efficiency} = \frac{\text{net electricity out}}{\text{LHV fuel in}} \qquad \eta_{system} = \eta_{ref}\eta_{PROX}\eta_{fu}\eta_{FC}\eta_{aux}$$

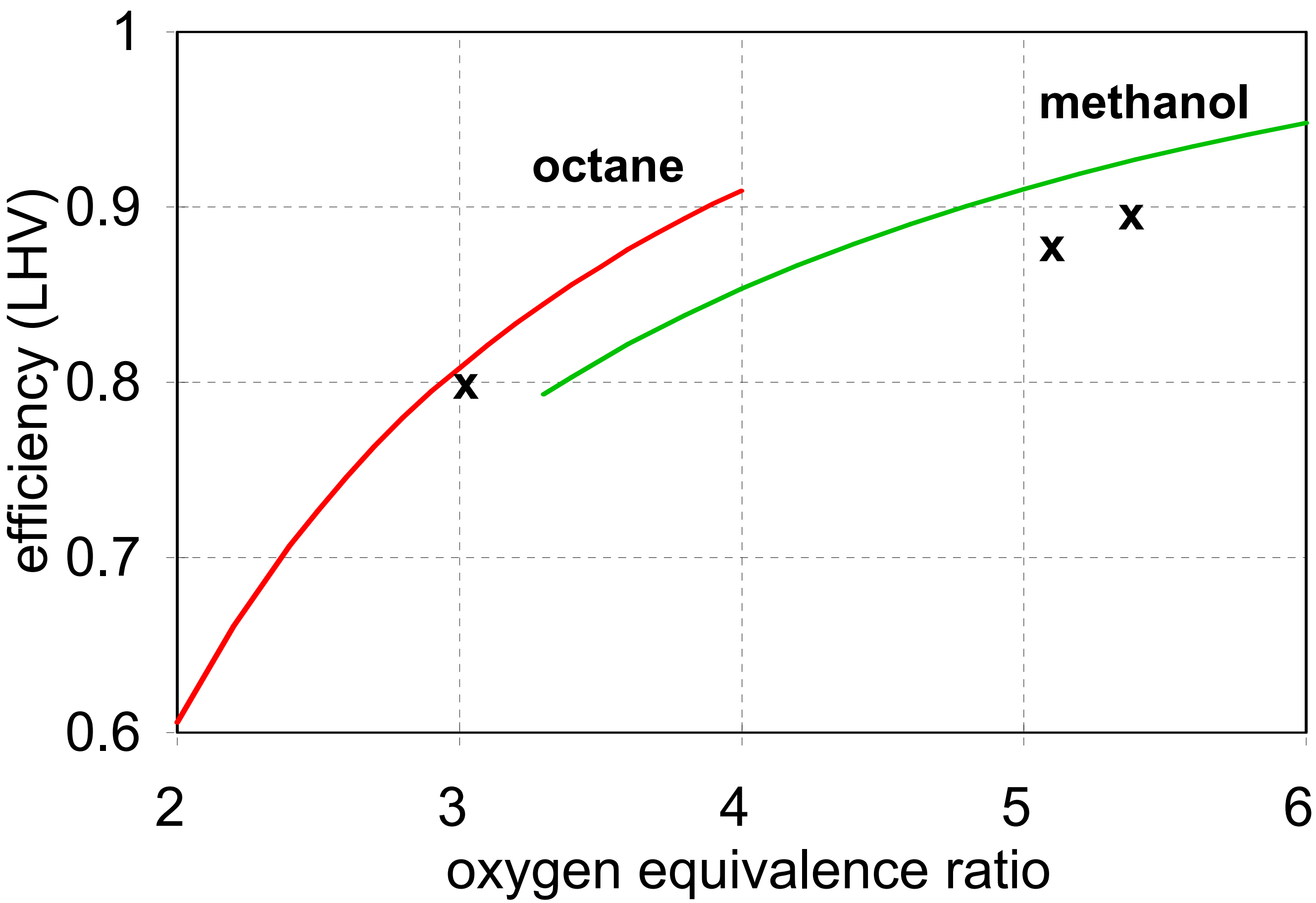


Definition of system efficiency

$$\text{system efficiency} = \frac{\text{net electricity out}}{\text{LHV fuel in}} \qquad \eta_{system} = \eta_{ref}\eta_{PROX}\eta_{fu}\eta_{FC}\eta_{aux}$$

$$\text{reformer efficiency} = \frac{\text{LHV hydrogen out}}{\text{LHV fuel in}}$$

Reformer efficiency
(POX/Autothermal)



oxygen equivalence ratio = (fuel/air actual)/(fuel/air theoretical for combustion)

Definition of system efficiency

$$\text{system efficiency} = \frac{\text{net electricity out}}{\text{LHV fuel in}} \qquad \eta_{system} = \eta_{ref}\eta_{PROX}\eta_{fu}\eta_{FC}\eta_{aux}$$

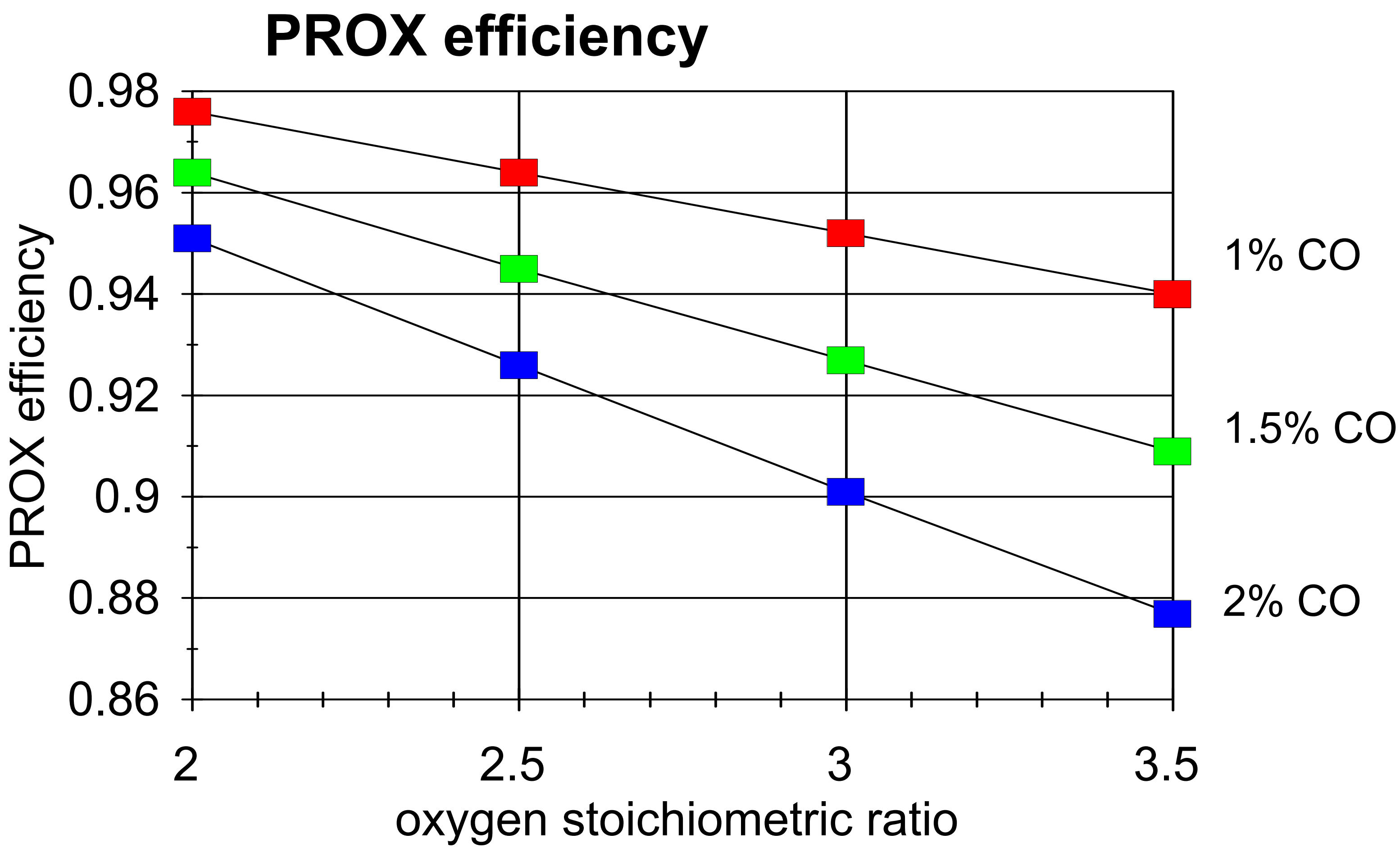
$$\text{reformer efficiency} = \frac{\text{LHV hydrogen out}}{\text{LHV fuel in}}$$

$$\text{PROX efficiency} = \frac{\text{LHV hydrogen out}}{\text{LHV hydrogen in}}$$

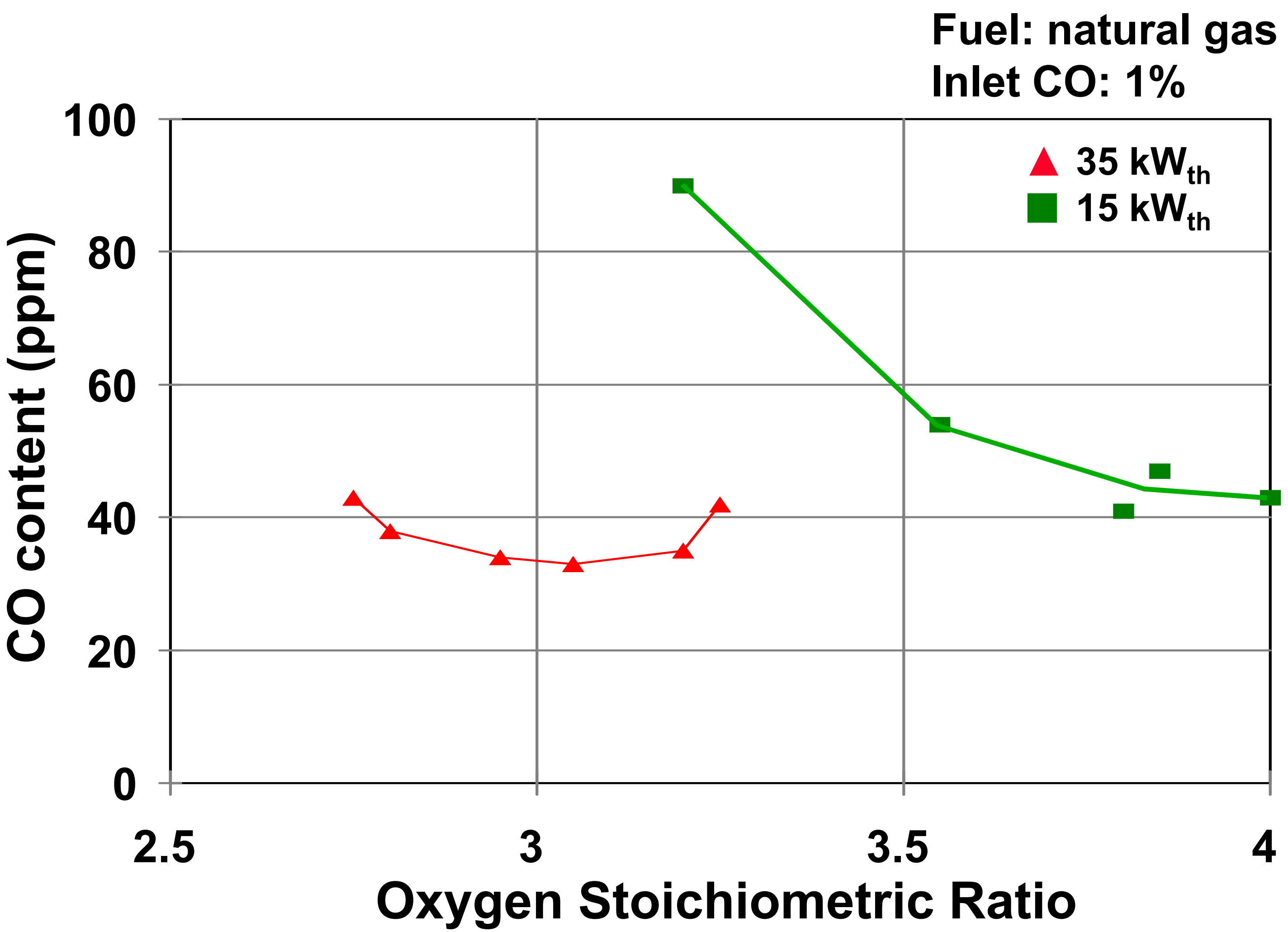
PROX reaction: $CO + ½ O_2 \rightarrow CO_2$

Oxygen stoichiometric ratio = actual oxygen/theoretical oxygen

Unwanted (but unavoidable) reaction: $H_2 + ½ O_2 \rightarrow H_2O$



CO level at PROX Outlet



Definition of system efficiency

$$\text{system efficiency} = \frac{\text{net electricity out}}{\text{LHV fuel in}}$$

$$\eta_{system} = \eta_{ref}\eta_{PROX}\eta_{fu}\eta_{FC}\eta_{aux}$$

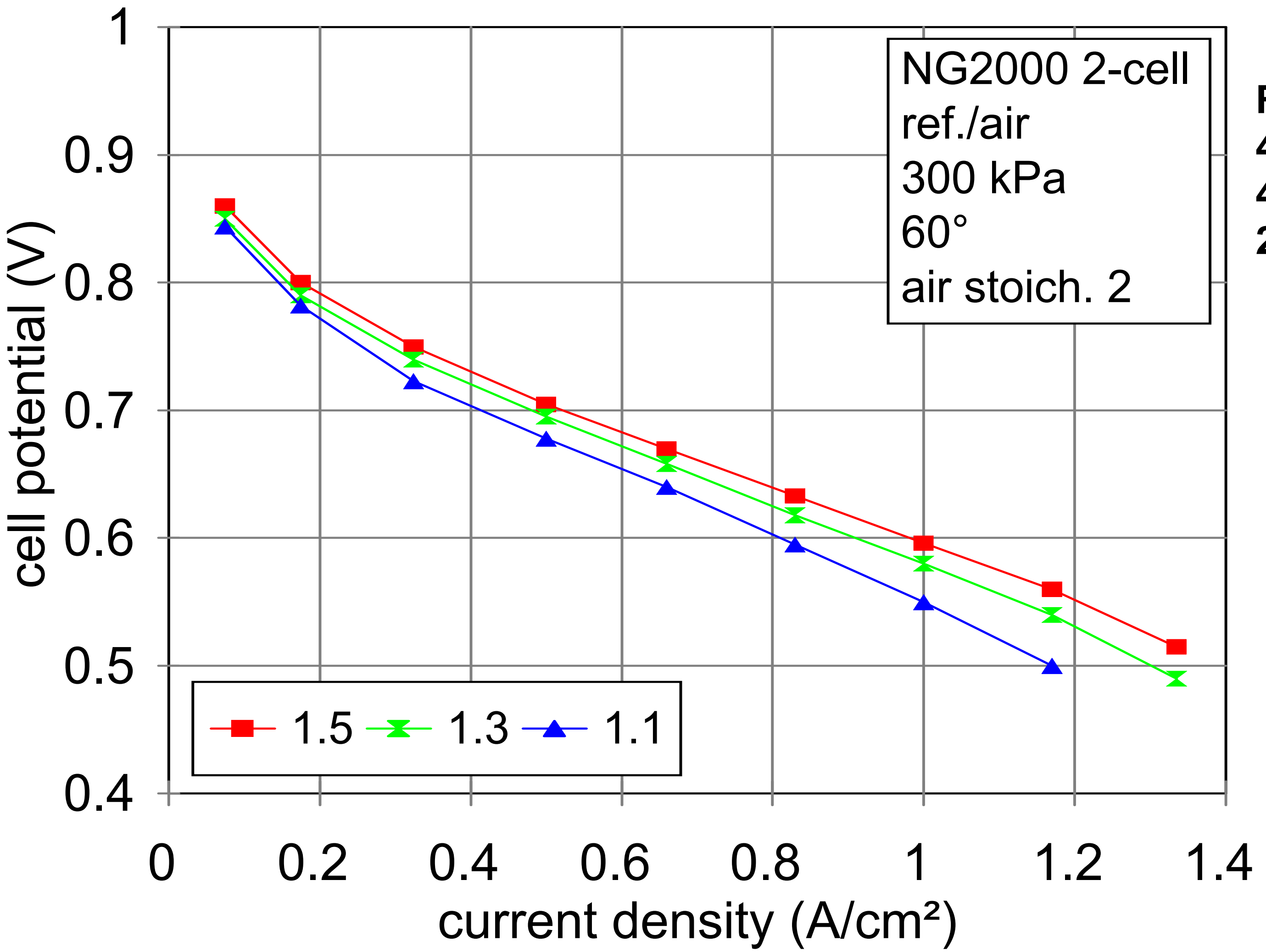
$$\text{reformer efficiency} = \frac{\text{LHV hydrogen out}}{\text{LHV fuel in}}$$

$$\text{PROX efficiency} = \frac{\text{LHV hydrogen out}}{\text{LHV hydrogen in}}$$

$$\text{fuel utilization} = \frac{\text{LHV hydrogen consumed}}{\text{LHV hydrogen in fuel cell}}$$

$$\eta_{fu} = 1/S_{H2}$$

Effect of fuel flow rate



Reformate:
40% H2
40% N2
20% CO2

Definition of system efficiency

$$\text{system efficiency} = \frac{\text{net electricity out}}{\text{LHV fuel in}} \qquad \eta_{system} = \eta_{ref}\eta_{PROX}\eta_{fu}\eta_{FC}\eta_{aux}$$

$$\text{reformer efficiency} = \frac{\text{LHV hydrogen out}}{\text{LHV fuel in}}$$

$$\text{PROX efficiency} = \frac{\text{LHV hydrogen out}}{\text{LHV hydrogen in}}$$

$$\text{fuel utilization} = \frac{\text{LHV hydrogen consumed}}{\text{LHV hydrogen in fuel cell}} \qquad \eta_{fu} = 1/S_{H2}$$

$$\text{fuel cell efficiency} = \frac{\text{gross electricity out}}{\text{LHV hydrogen consumed}} \qquad \eta_{FC} = \frac{V_{cell}}{1.254}$$

Fuel cell efficiency

current (A)

voltage (V)

$$\eta_{fc} = \frac{\text{electricity out}}{\text{hydrogen in}} = \frac{I \cdot V}{\dot{m}_{H2} \cdot \Delta H}$$

hydrogen heating value
141,900 J/g (HHV)
120,000 J/g (LHV)

hydrogen mass flow rate (g/s)

$$\dot{m}_{H2} = \frac{I \cdot M_{H2}}{n \cdot F}$$

hydrogen molecular weight
2.016 g/mol

number of electrons involved (2)

Faraday’s constant
96,485 C

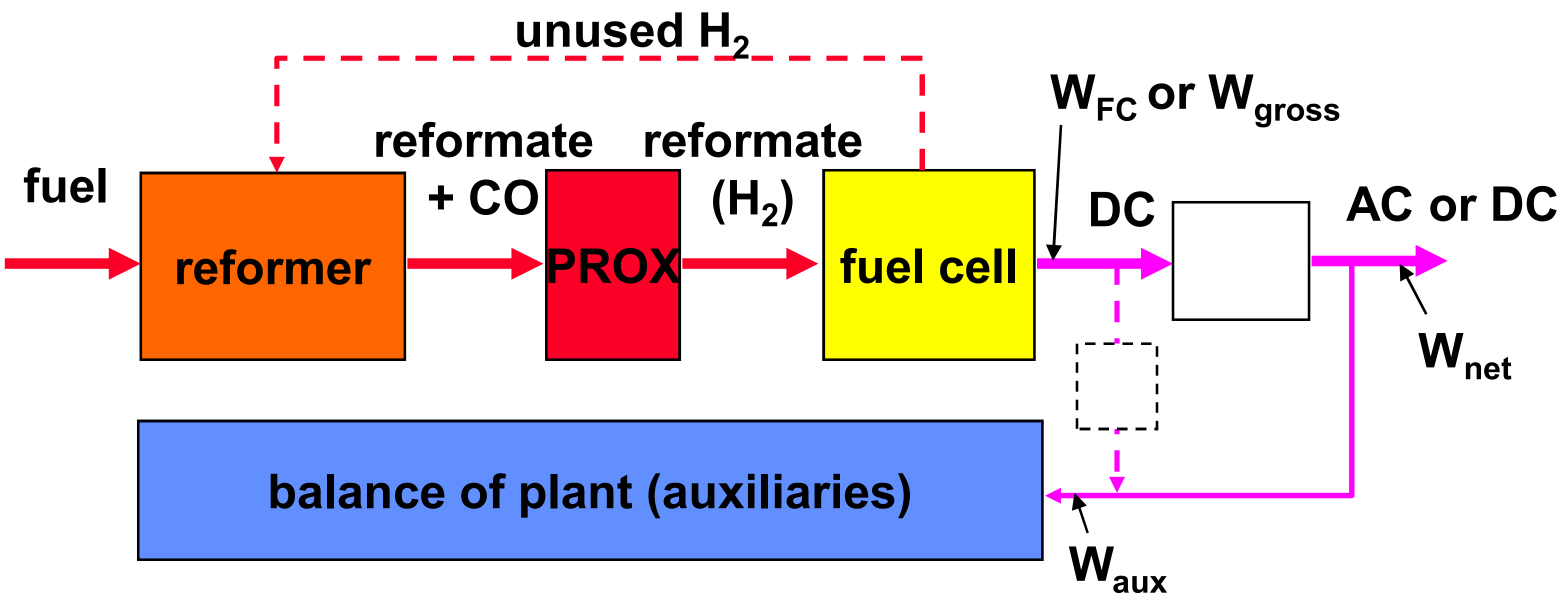
$$\eta_{fc} = V/1.482 \quad \text{(HHV)}$$

$$\eta_{fc} = V/1.254 \quad \text{(LHV)}$$

Definition of system efficiency

system efficiency $= \dfrac{\text{net electricity out}}{\text{LHV fuel in}}$	$\eta_{system} = \eta_{ref}\eta_{PROX}\eta_{fu}\eta_{FC}\eta_{aux}$
reformer efficiency $= \dfrac{\text{LHV hydrogen out}}{\text{LHV fuel in}}$	
PROX efficiency $= \dfrac{\text{LHV hydrogen out}}{\text{LHV hydrogen in}}$	
fuel utilization $= \dfrac{\text{LHV hydrogen consumed}}{\text{LHV hydrogen in fuel cell}}$	$\eta_{fu} = 1/S_{H2}$
fuel cell efficiency $= \dfrac{\text{gross electricity out}}{\text{LHV hydrogen consumed}}$	$\eta_{FC} = \dfrac{V_{cell}}{1.254}$
aux load eff. $= \dfrac{\text{net electricity out}}{\text{gross electricity out}}$	$\eta_{aux} = \left(\dfrac{W_{net}}{W_{net} + W_{aux}}\right)$

aux load eff. = $\dfrac{\text{net electricity out}}{\text{gross electricity out}}$ $\qquad \eta_{aux} = \left[\dfrac{W_{net}}{W_{net} + W_{aux}}\right]$



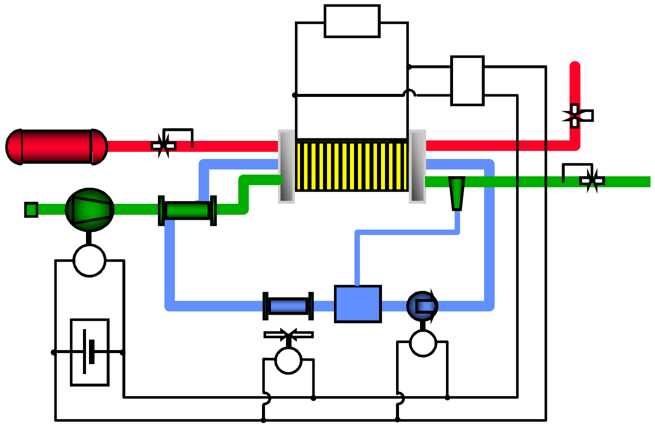
$$\xi = \frac{W_{aux}}{W_{FC}}$$

W_{aux} same current and voltage as W_{net} $\qquad \eta_{aux} = (\eta_{DC} - \xi)$

W_{aux} different current and voltage than W_{net} $\qquad \eta_{aux} = \eta_{DC}\left(1 - \dfrac{\xi}{\eta_{AC}}\right)$

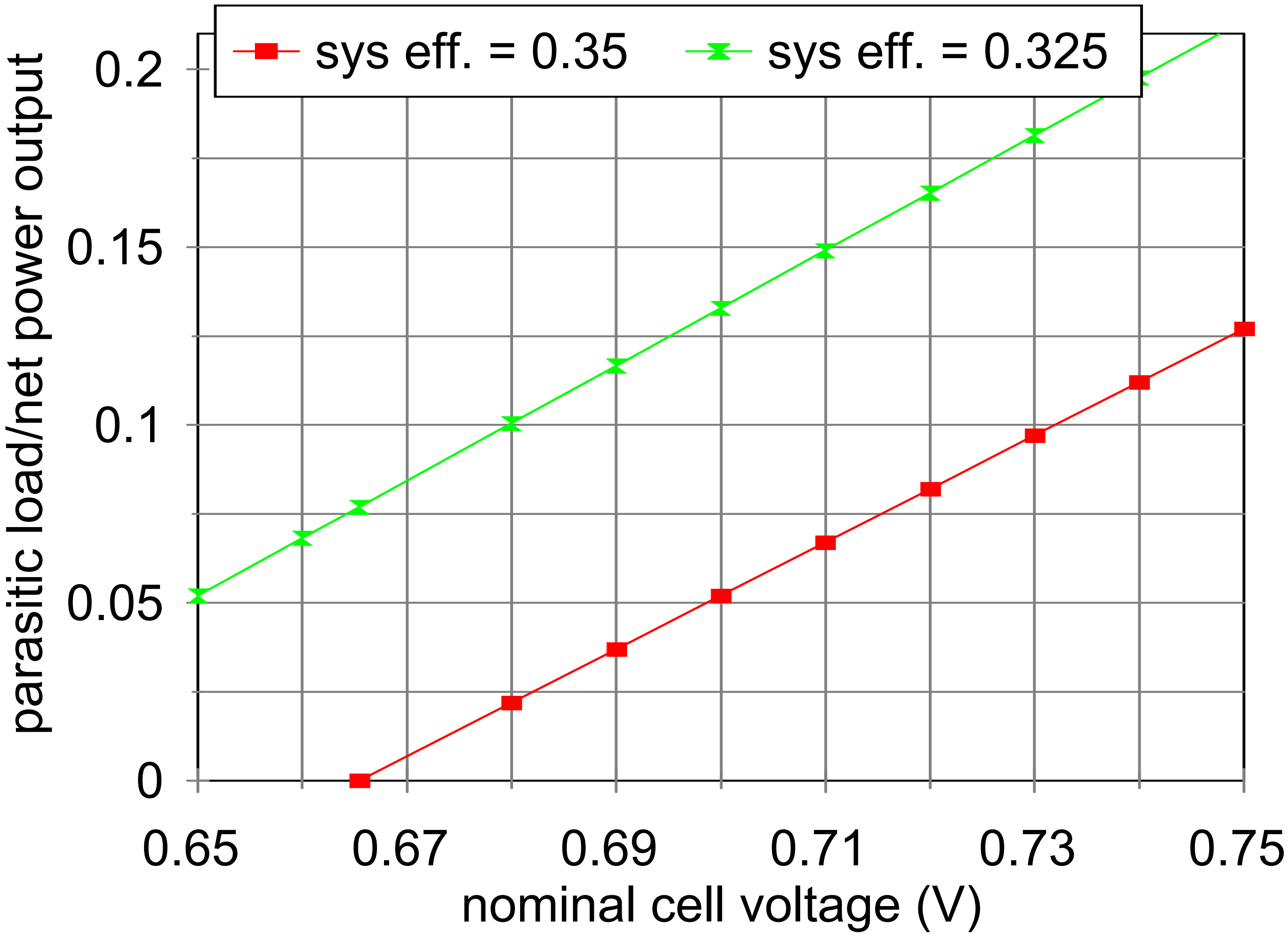
Parasitic load

- air supply (blower or compressor/expander)
- coolant pump
- water pump(s)
- heat exchanger fan(s)
- solenoid valves
- relays
- controller

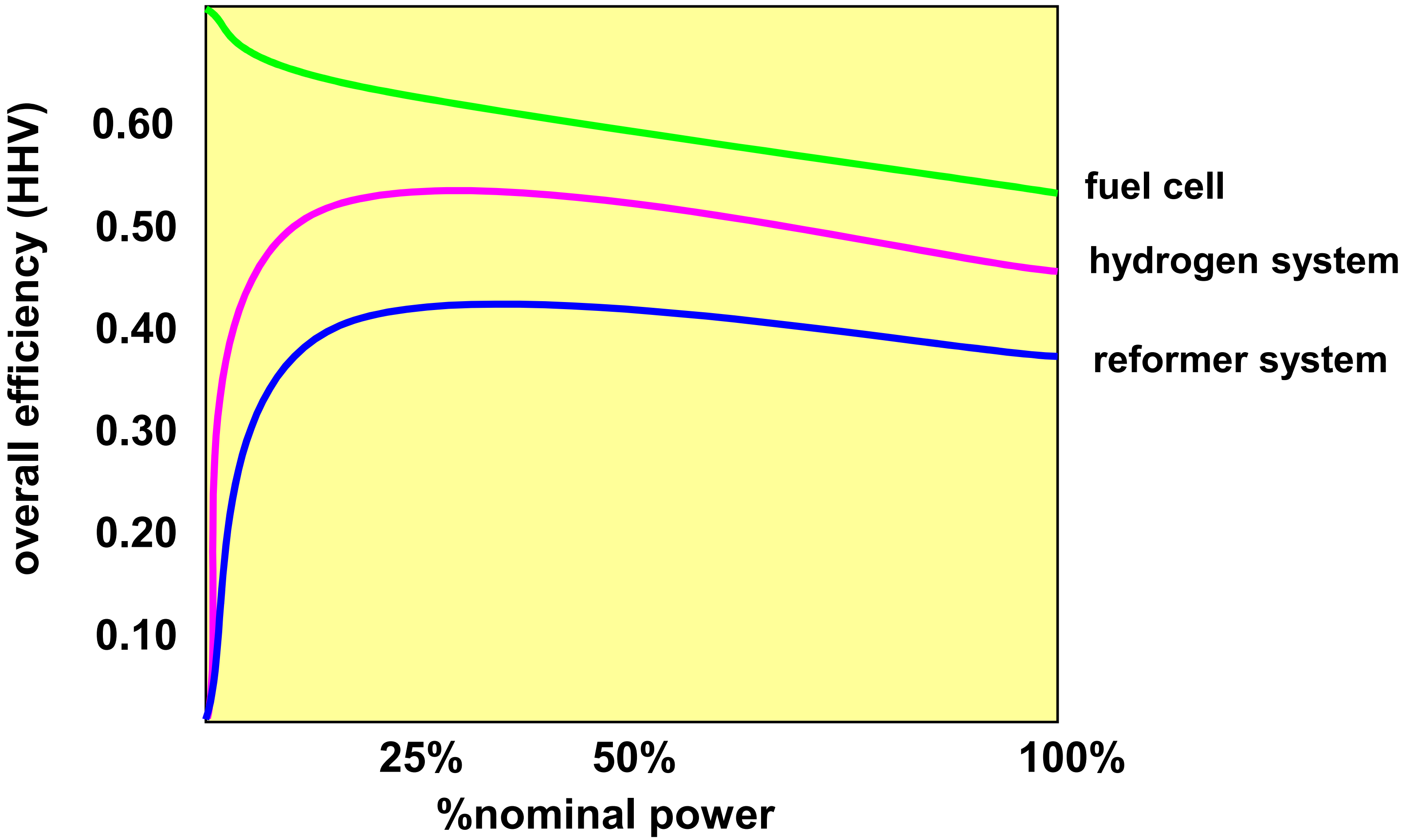


System efficiency

η_{ref} = 0.8
η_{PROX} = 0.97
η_{fu} = 0.85
η_{FC} = variable
η_{aux} = variable



Fuel cell system efficiency

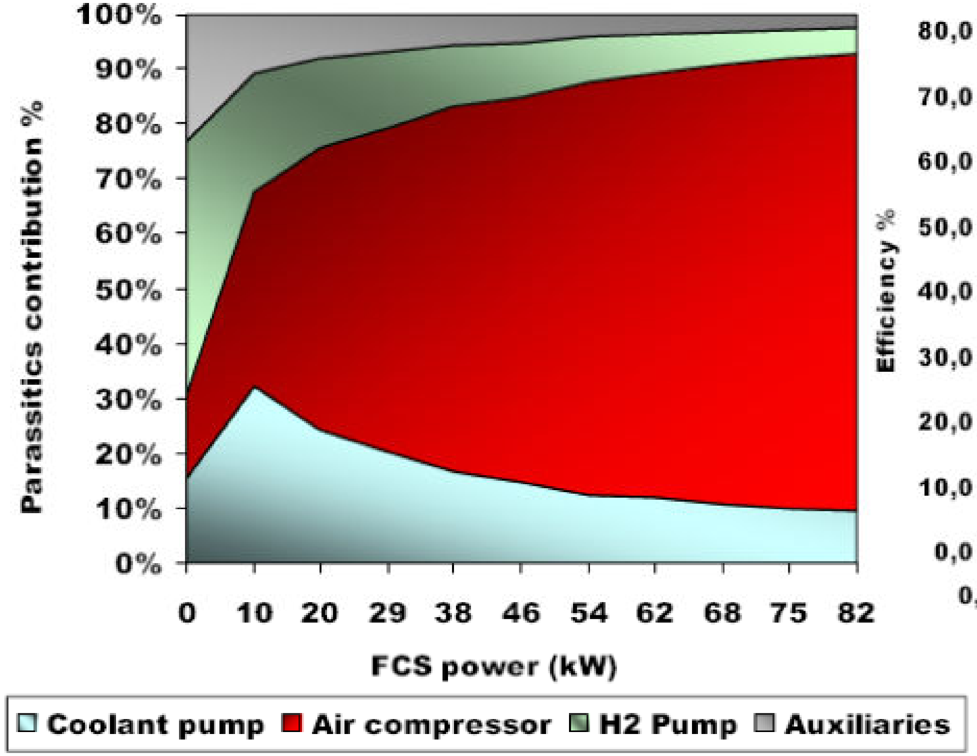


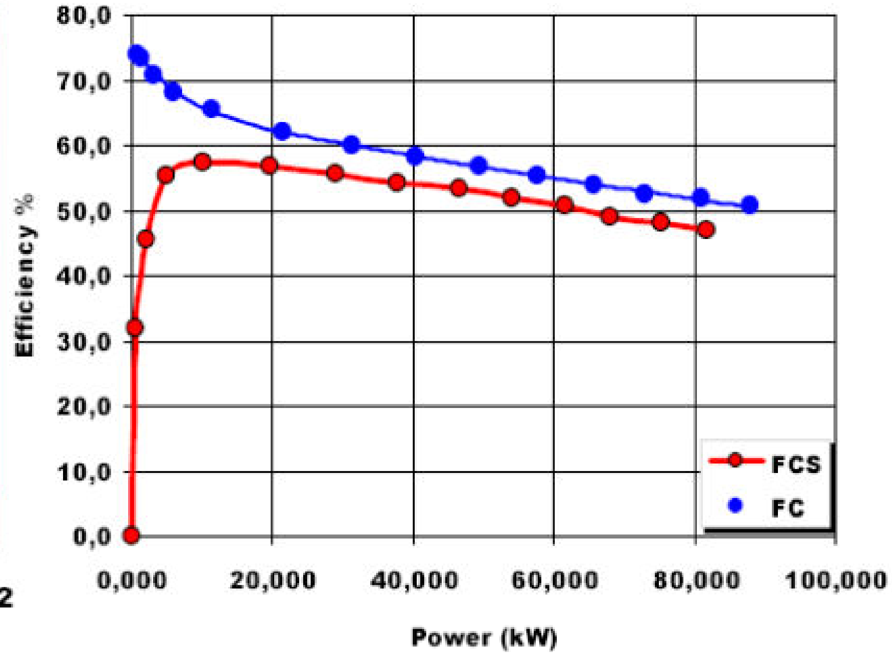
$$\text{Overall efficiency} = \frac{\text{electricity produced}}{\text{lower heating value of fuel consumed}}$$

Fuel:
- natural gas
- gasoline

Efficiency

HDL 82 FCPM Efficiency Diagram

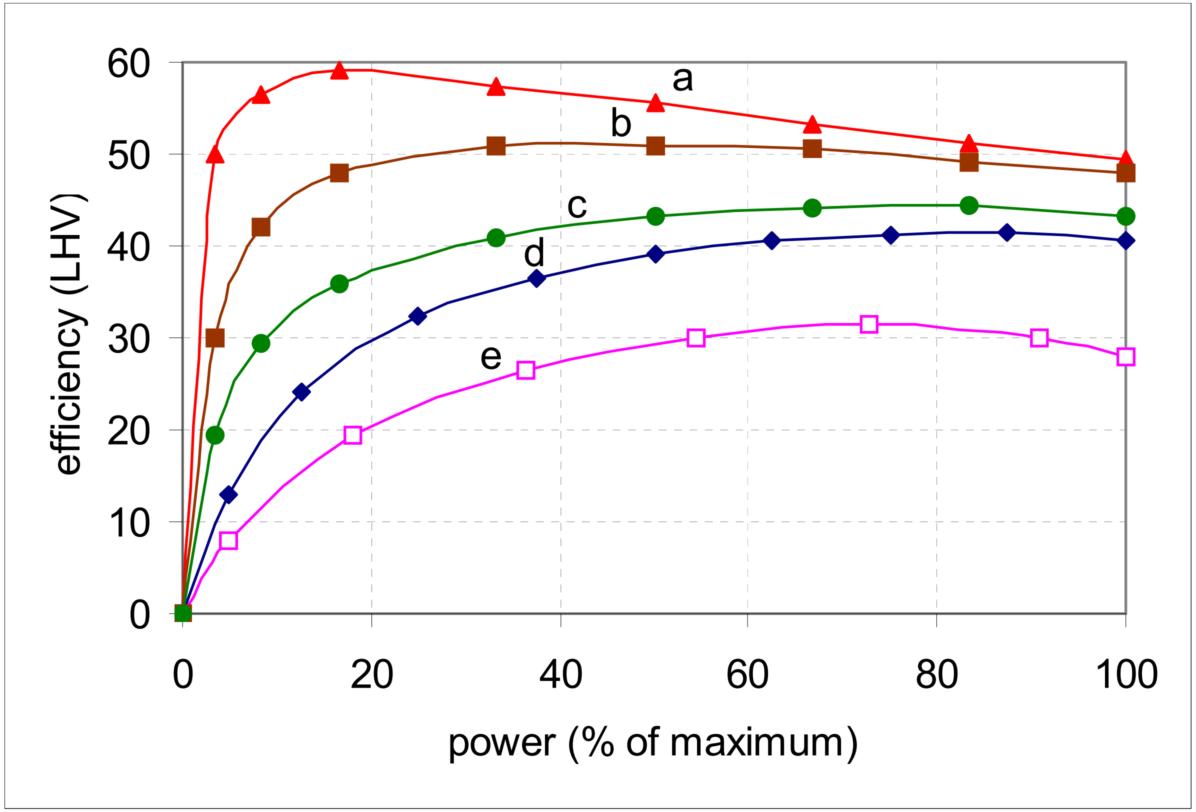




- 750 W of parasitic losses in IDLE MODE
- 6350 W of parasitic losses @ max power

NUVERA

Efficiency of fuel cell vs. ICE



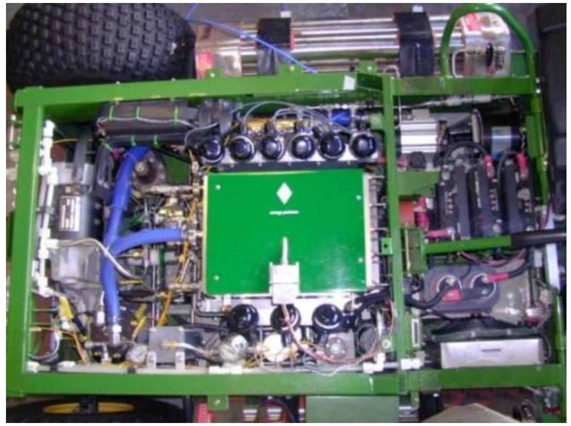
a) Low pressure, low temperature fuel cell system
b) High pressure, high temperature fuel cell system
c) Fuel cell system with an on-board reformer
d) Compression-ignition engine (diesel)
e) Spark-ignition engine

Efficiency

Fuel Cell Systems

The systems may be as simple as

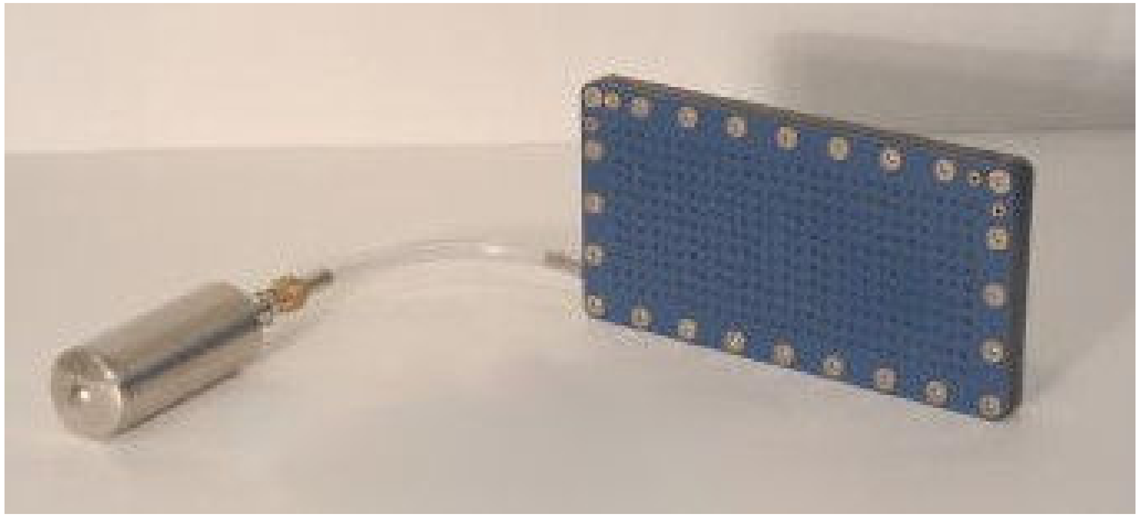
or as complicated as



or even more complicated

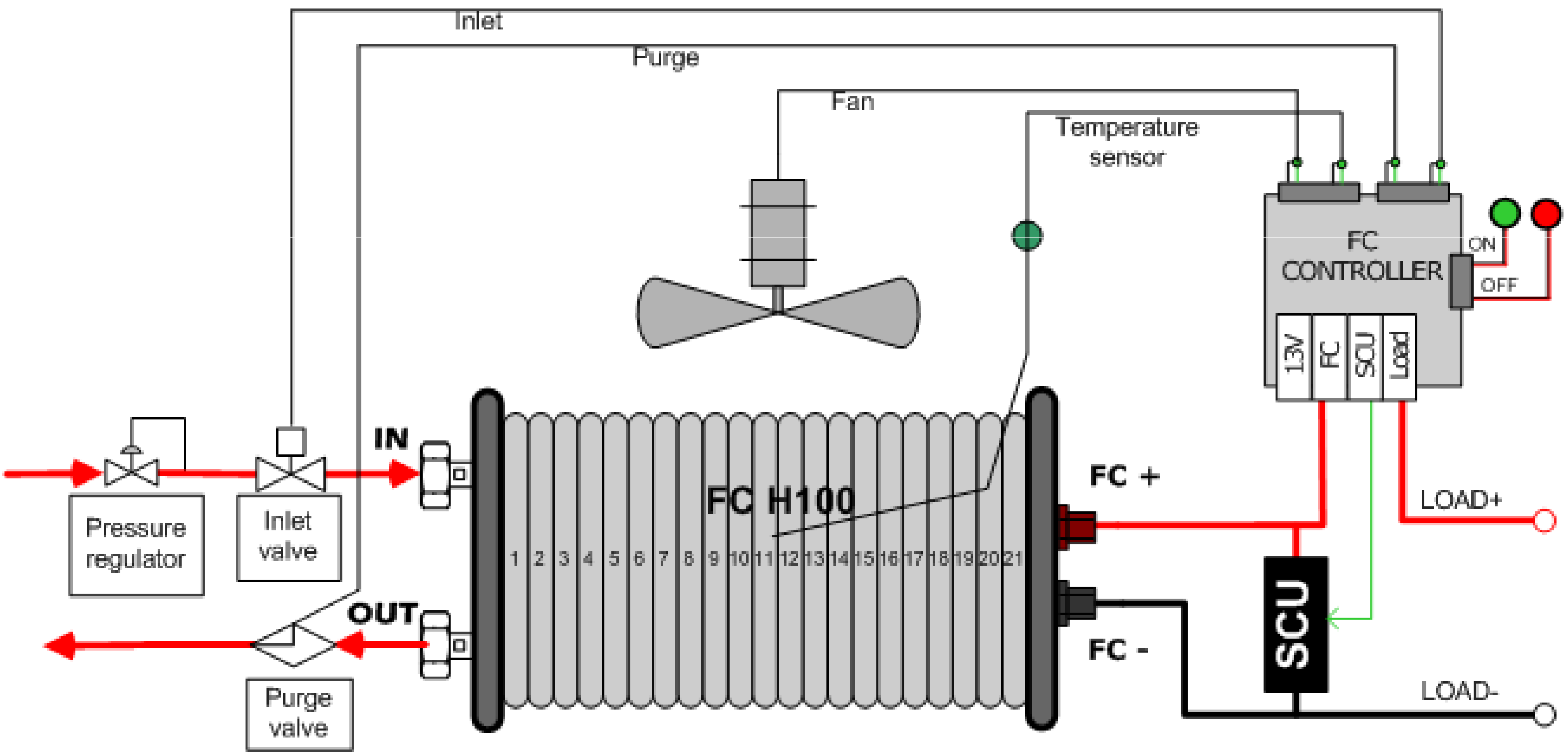
The simplest fuel cell system

Passive fuel cell with open cathode
Metal hydride bottle

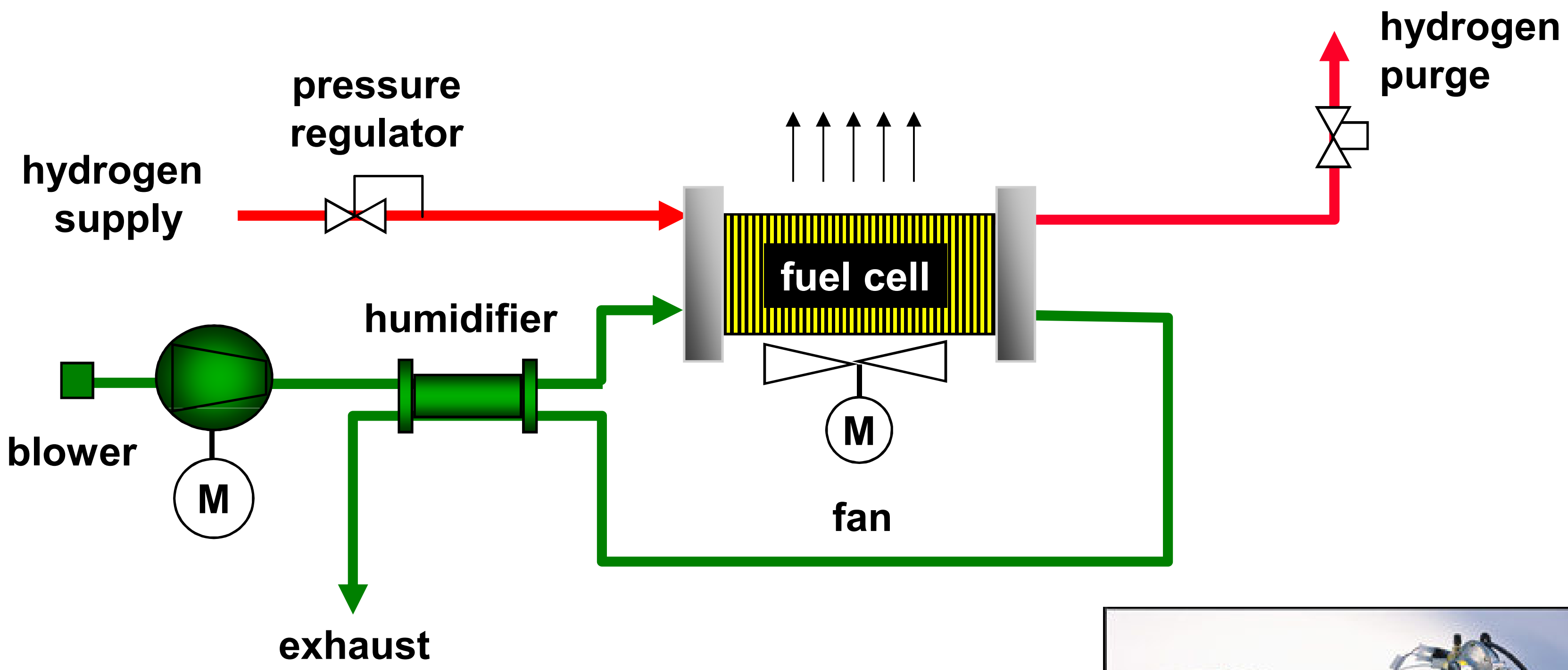


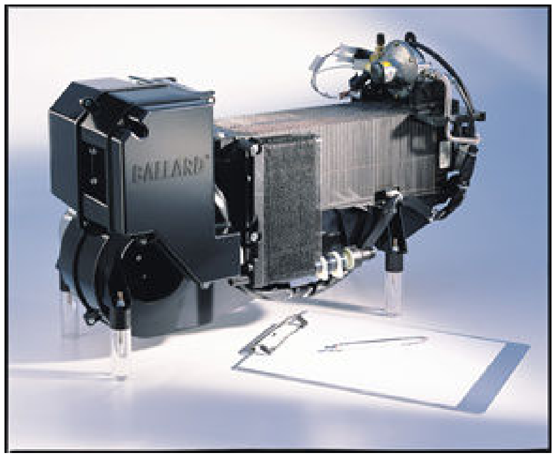
PaxiTech

A simple fuel cell system

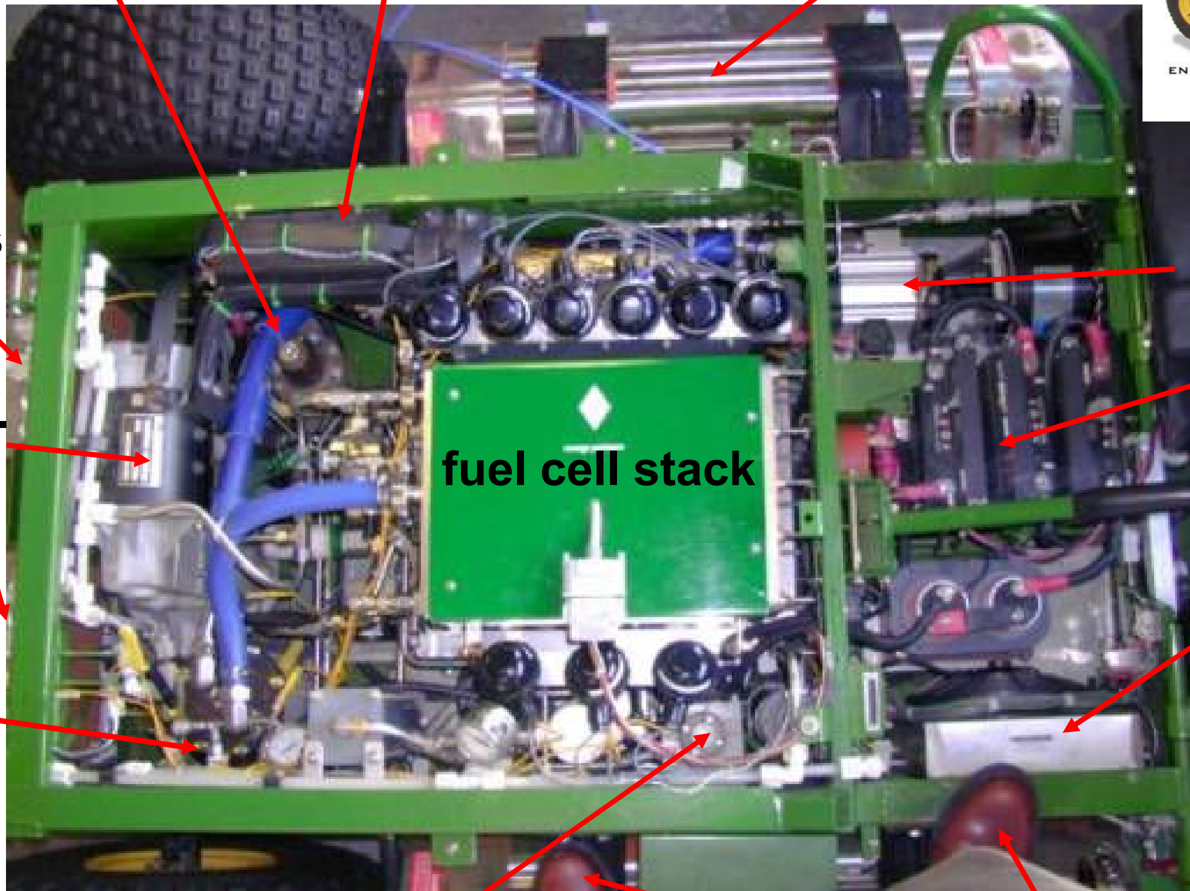


Nexa Fuel Cell System

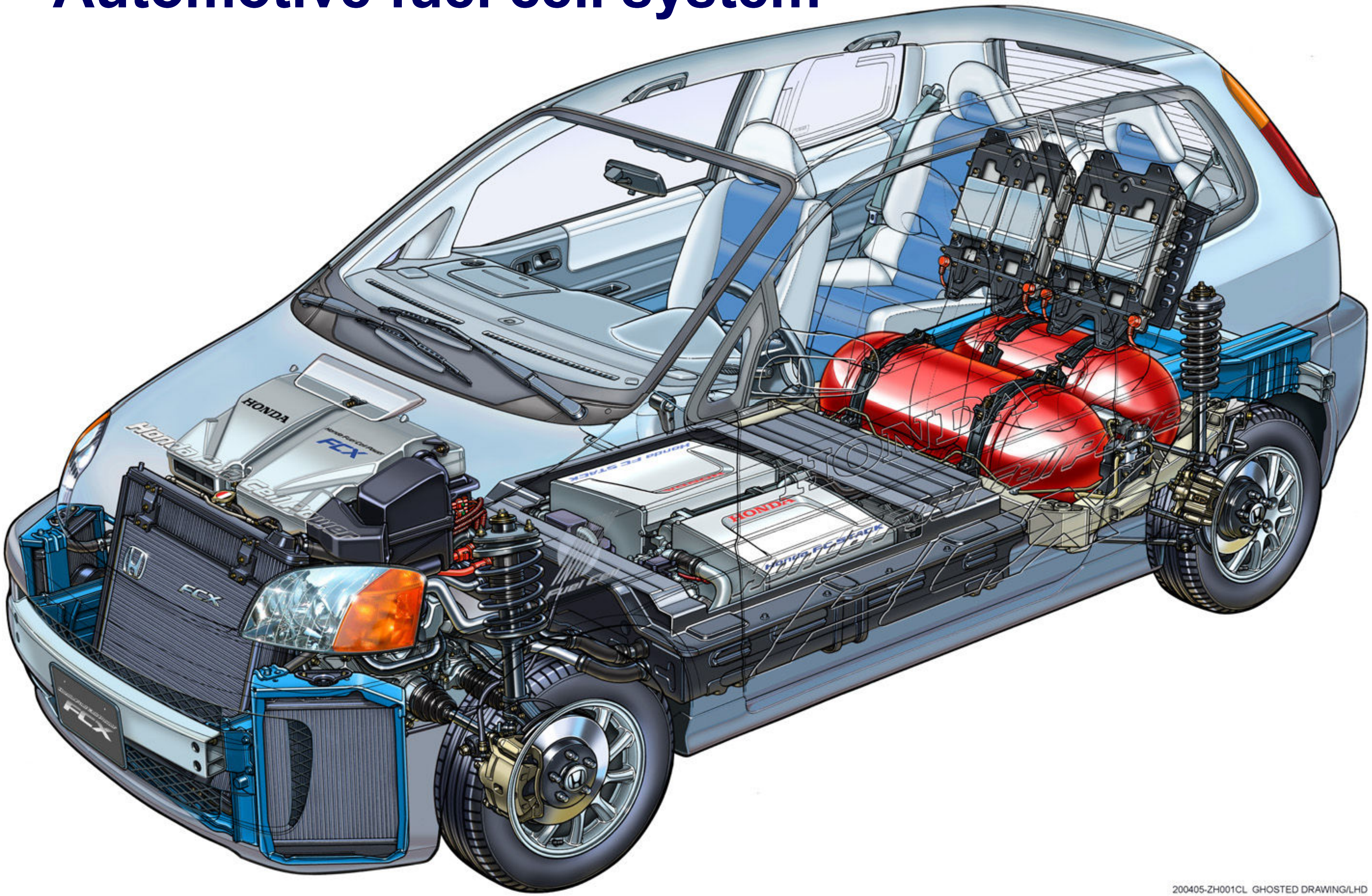




A bit complicated fuel cell system



Automotive fuel cell system



Combined Heat and Power
Fuel Cell System