


Cell and Stack Design

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Joint European Summer School for Fuel Cell and Hydrogen Technology

$P = V \times I$

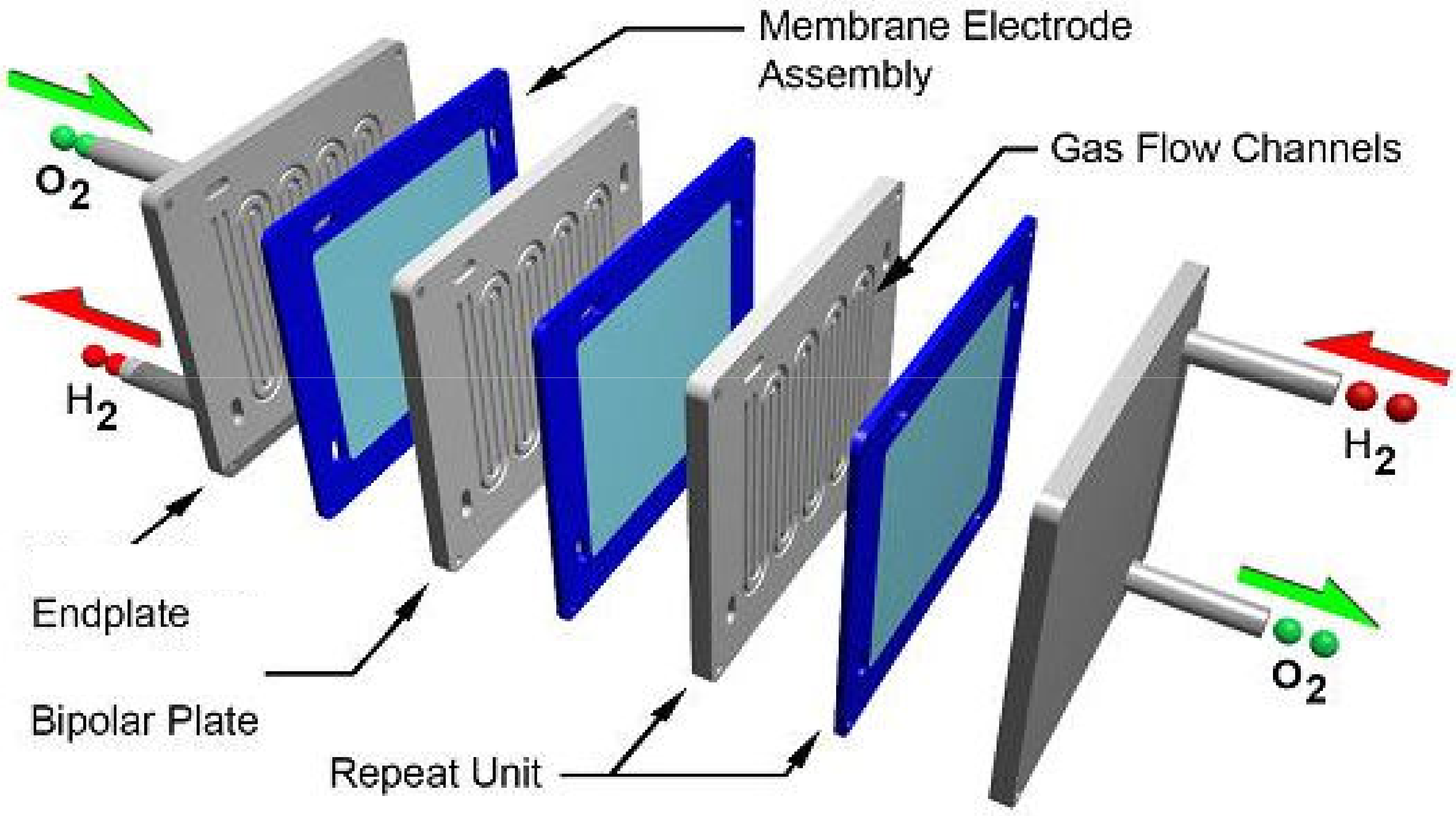
Fuel cell generates current at <1 V

- For 1 kW it would have to generate >1000 Ampers
- For 100 kW it would have to generate >100000 Ampers
- At 1 Amp/cm^2 it would need >10 m^2

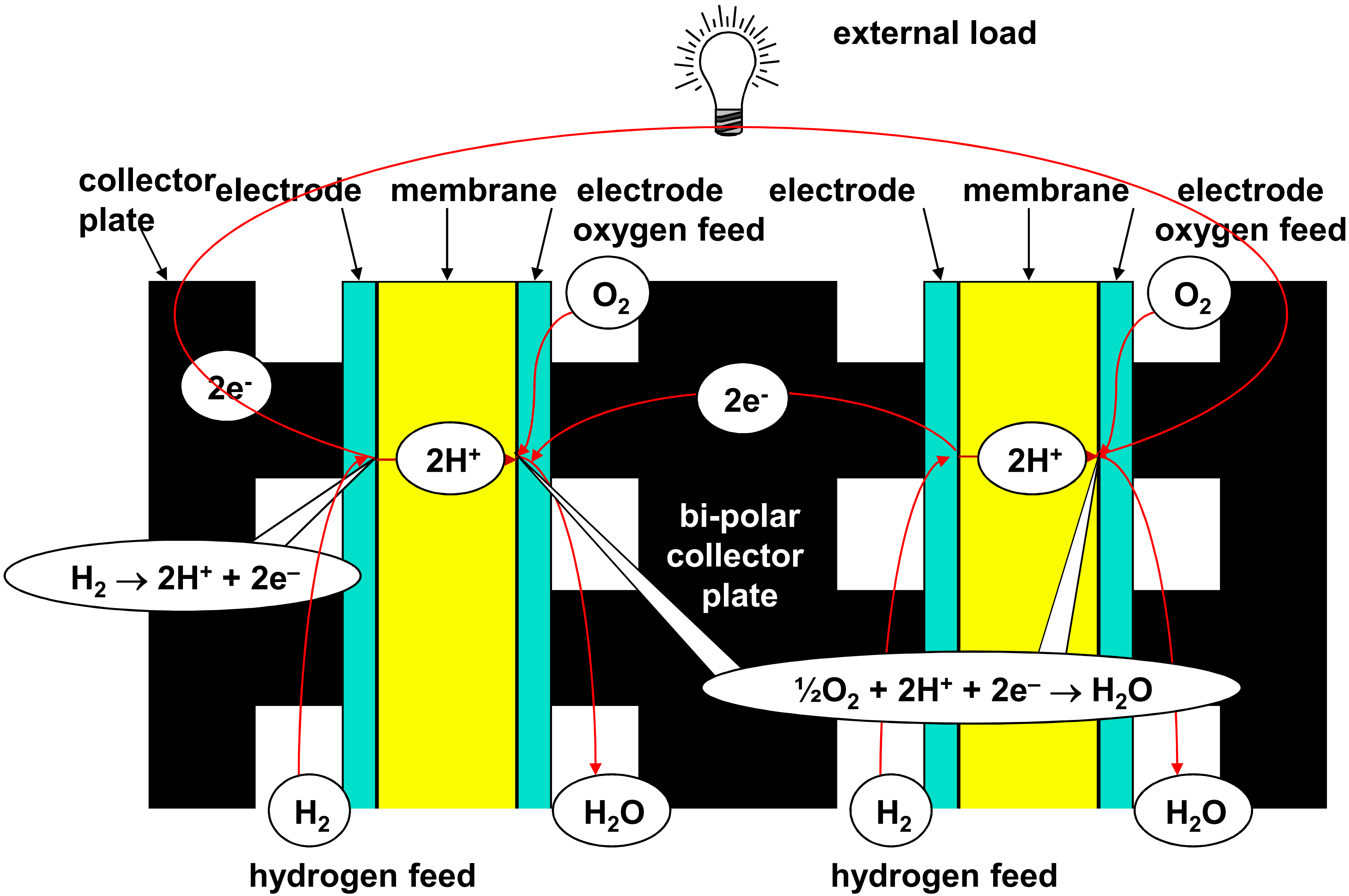
Fuel cells are connected/stacked in series – stack

- up to 200 cells in stack
- For 100 kW it would need to generate >500 A at <200 V
- Each cell in stack would need active area of >500 cm^2

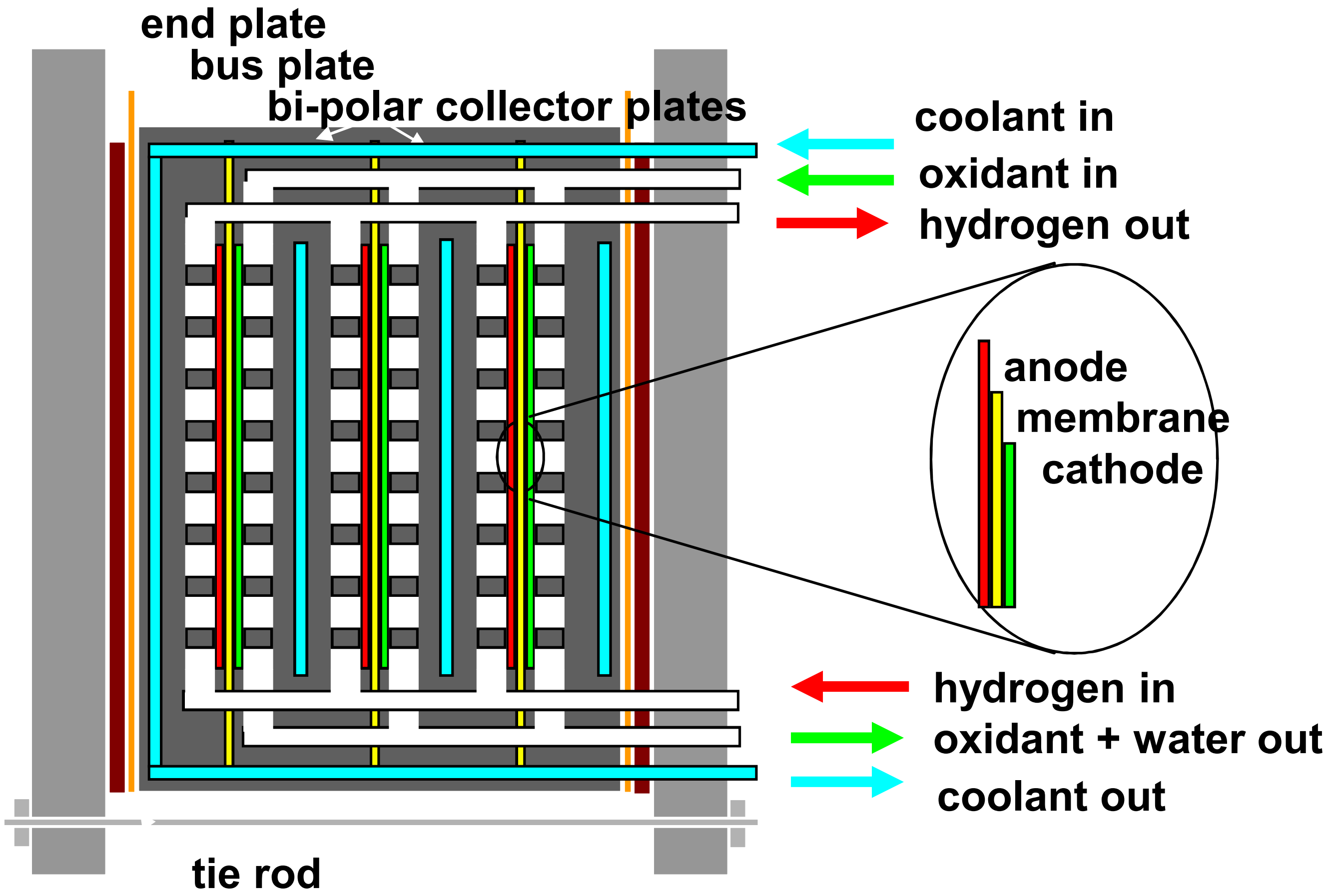
In order to get higher voltage fuel cells are stacked in a stack



Stack of PEM Fuel Cells - Basic Principle



In order to get higher voltage fuel cells are stacked in a stack



Stacks with more than 100 cells have been built

Individual stacks may be connected (in series or in parallel)

energy partners

PROTON

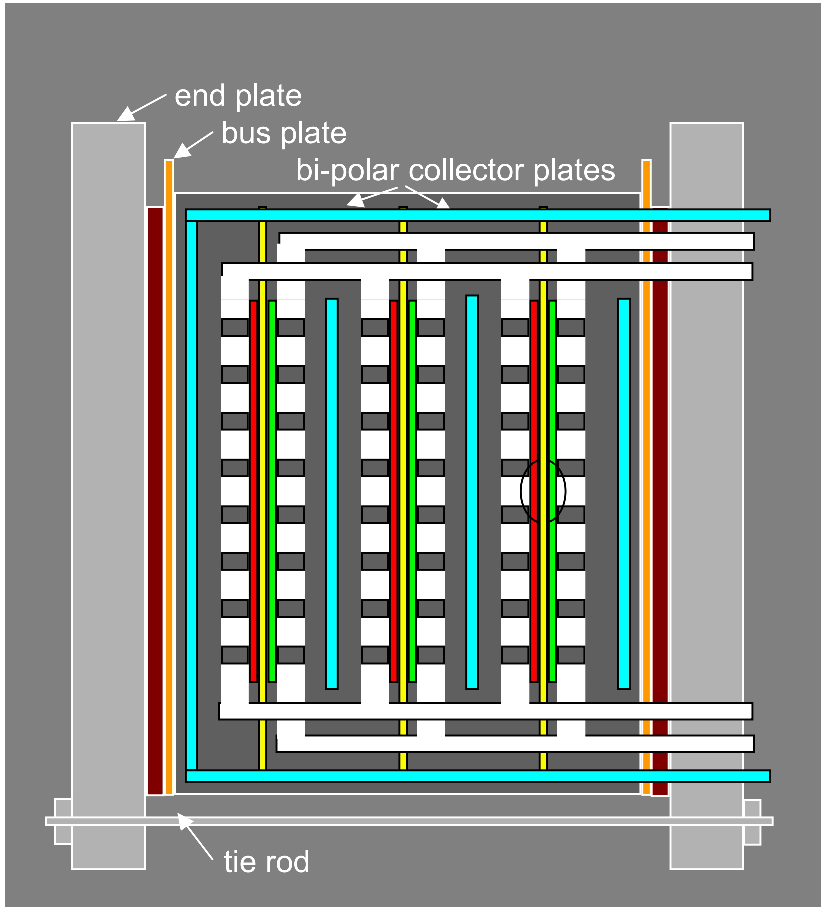
300 cm²	**65 cm²**
25-110 cells	**60 cells**
4.5-20 kW	**1 kW**
0.6 W/cm²	**0.25 W/cm²**
@0.6 V/cell	**@0.7 V/cell**
pressurized up to 3 bar	**ambient pressure**
liquid cooled	**air cooled**

Major stack components

MEA

Bi-polar plate

Membrane
Catalyst
Catalyst support
Catalyst layer
Gas diffusion layer
Gaskets/frames
Flow field
Separator/connector
Bus plates/terminals
End plates
Clamping mechanism
Fluid connections
Manifolds
Cooling plates/arrangements
Humidification section (optional)



Stack design goals

- **Performance**
  - **Power density**
  - **Stability**
  - **Durability**
- **Size and weight**
- **Manufacturability**

>1 W/cm^2	peak
0.6-0.7 W/cm^2	normal operation (nominal)
0.3-0.4 W/cm^2	high efficiency operation

< 1 kg/kW
< 1 l/kW

Constraints/inputs

- **Application requirements**
  - **Load variability**
  - **Environmental conditions**
- **Operating conditions**
  - **Pressure, temperature, flow rates, humidity**

Stack sizing

$W = V_{st} \cdot I$

$$V_{st} = \sum_{i=1}^{N_{cell}} V_i = \overline{V}_{cell} \cdot n_{cell}$$

$I = i \cdot A_{cell}$

$V_{cell} = f(i)$

$w = i\,V = W/(n_{cell}\,A_{cell})$

$\eta = V_{cell}/1.482$

W = stack power output
V_{st} = stack voltage
I = stack current
V_{cell} = cell voltage
n_{cell} = number of cells
i = current density
A_{cell} = cell active area
w = power density
η= stack efficiency

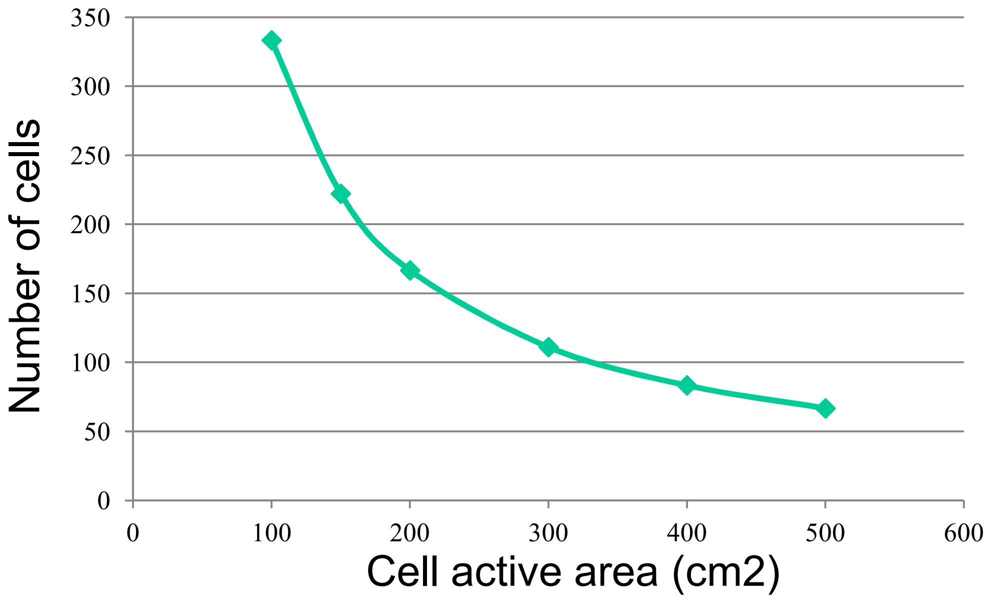
Stack volume
Stack weight

example

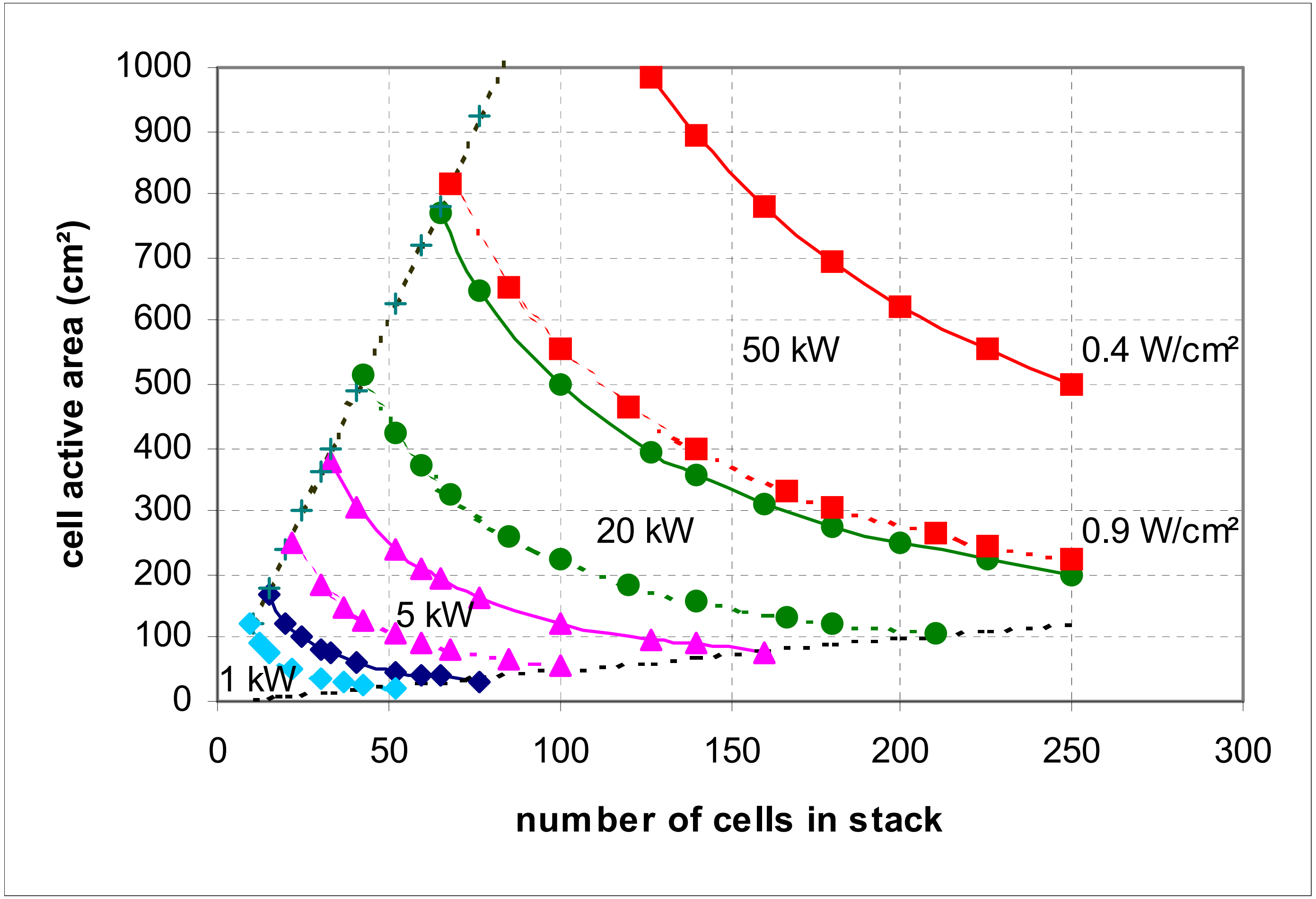
Given:
Power output: 20 kW
Vcell = 0.6 V

Find:
Active area
Number of cells

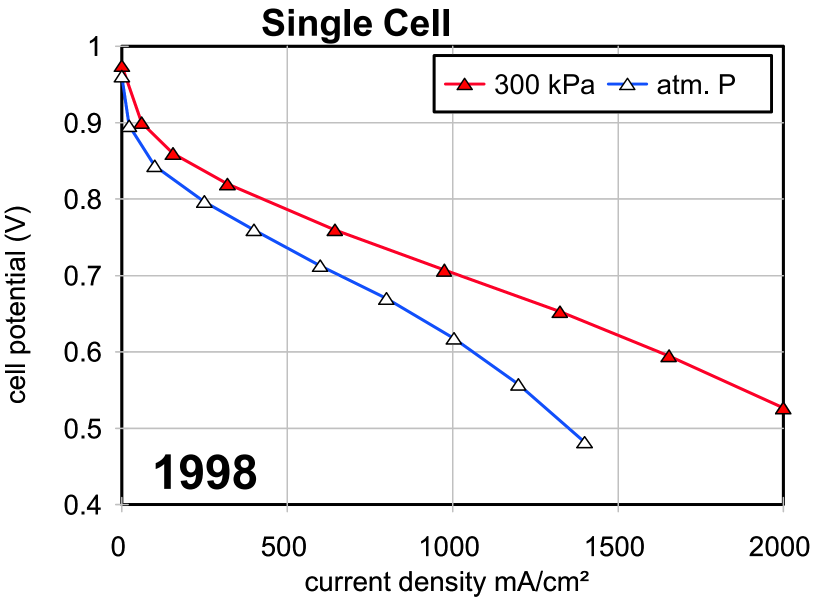
W	20	20	20	20	20	20
Vcell	0,6	0,6	0,6	0,6	0,6	0,6
i	1	1	1	1	1	1
A	100	150	200	300	400	500
I	100	150	200	300	400	500
w	0,6	0,6	0,6	0,6	0,6	0,6
Ancell	33333,33	33333,33	33333,33	33333,33	33333,33	33333,33
Ncell	333,33	222,22	166,67	111,11	83,33	66,67
Vstack	200	133,3333	100	66,66667	50	40

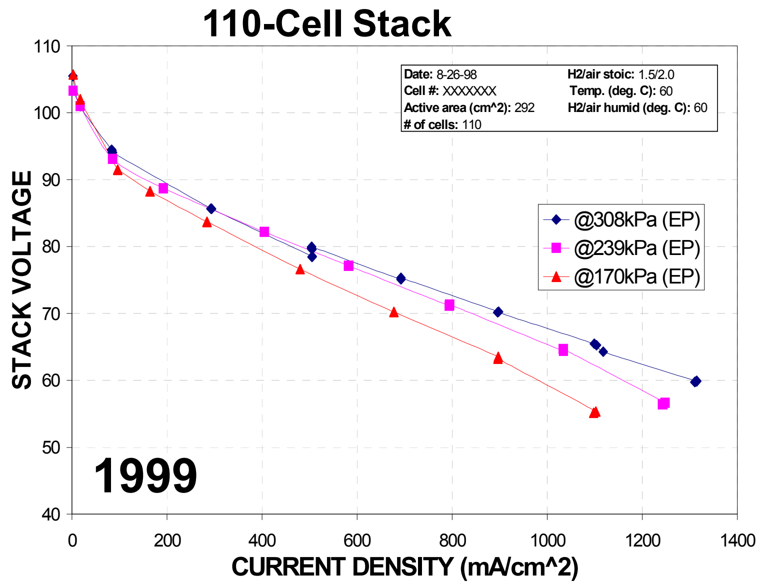


Stack sizing

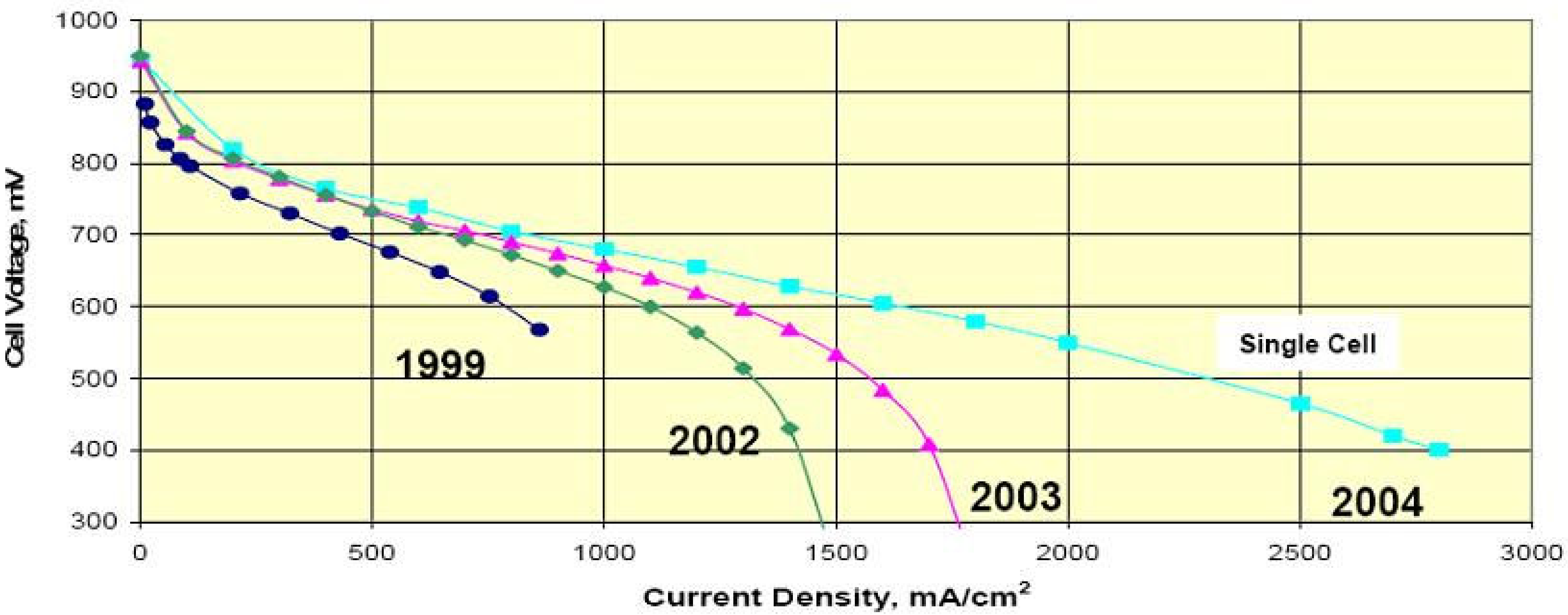


energy partners

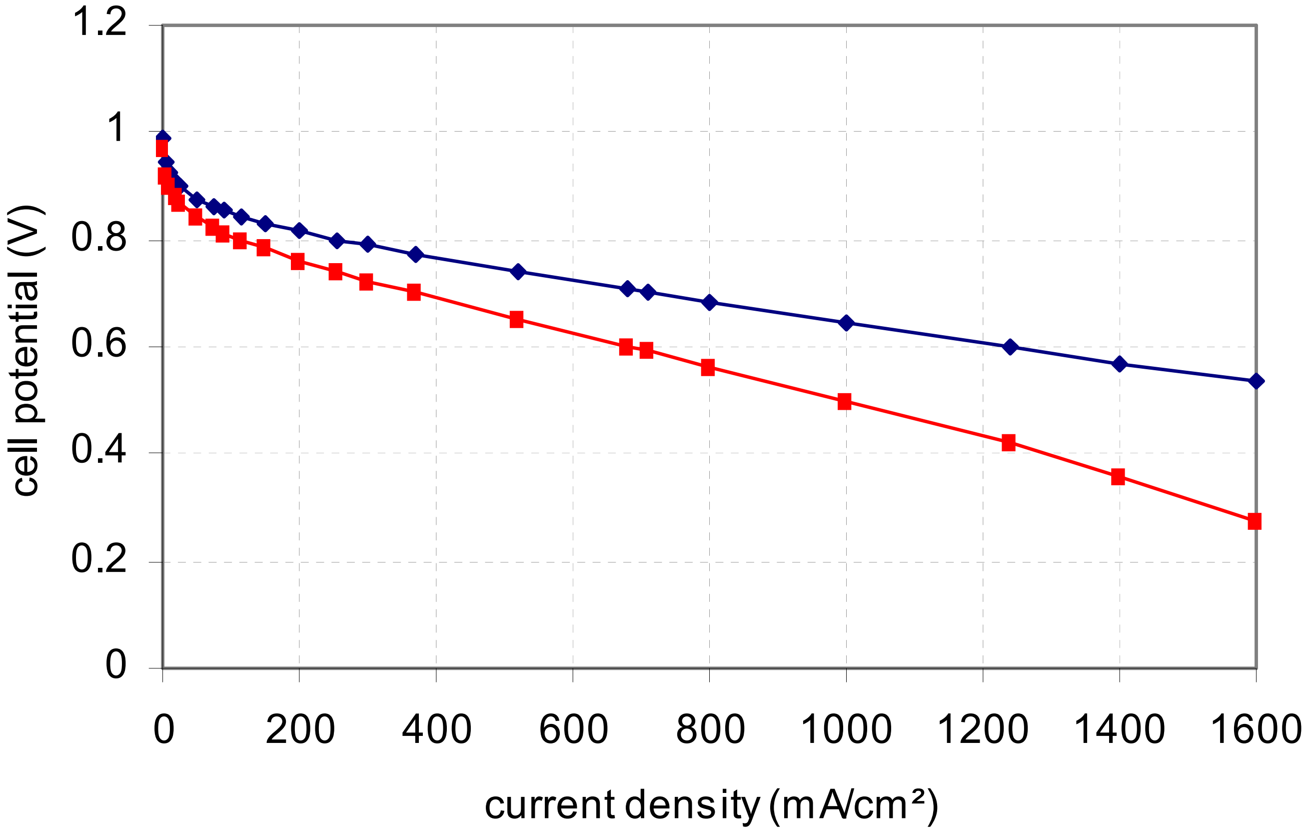




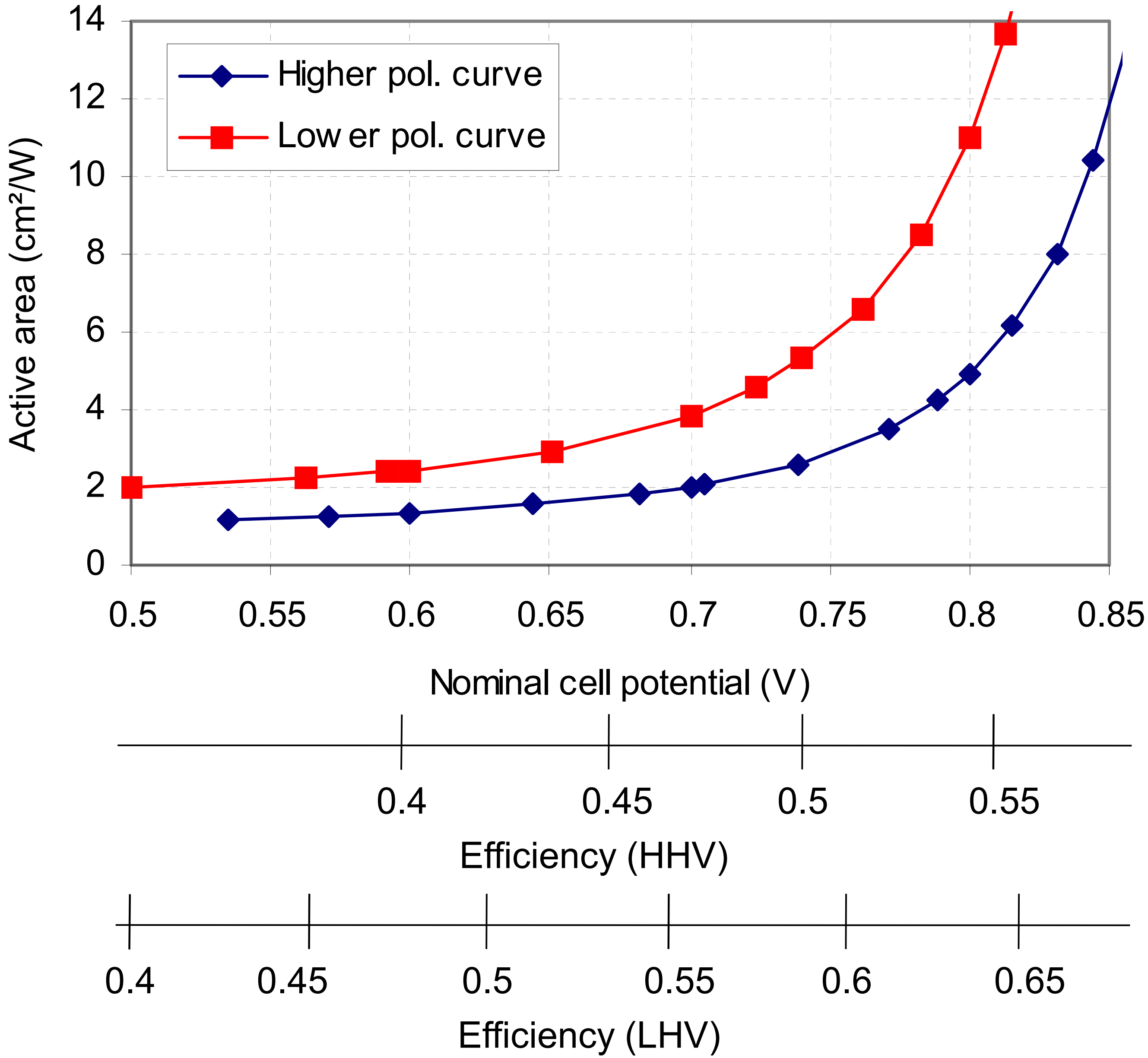
UTC Fuel Cells
A United Technologies Company



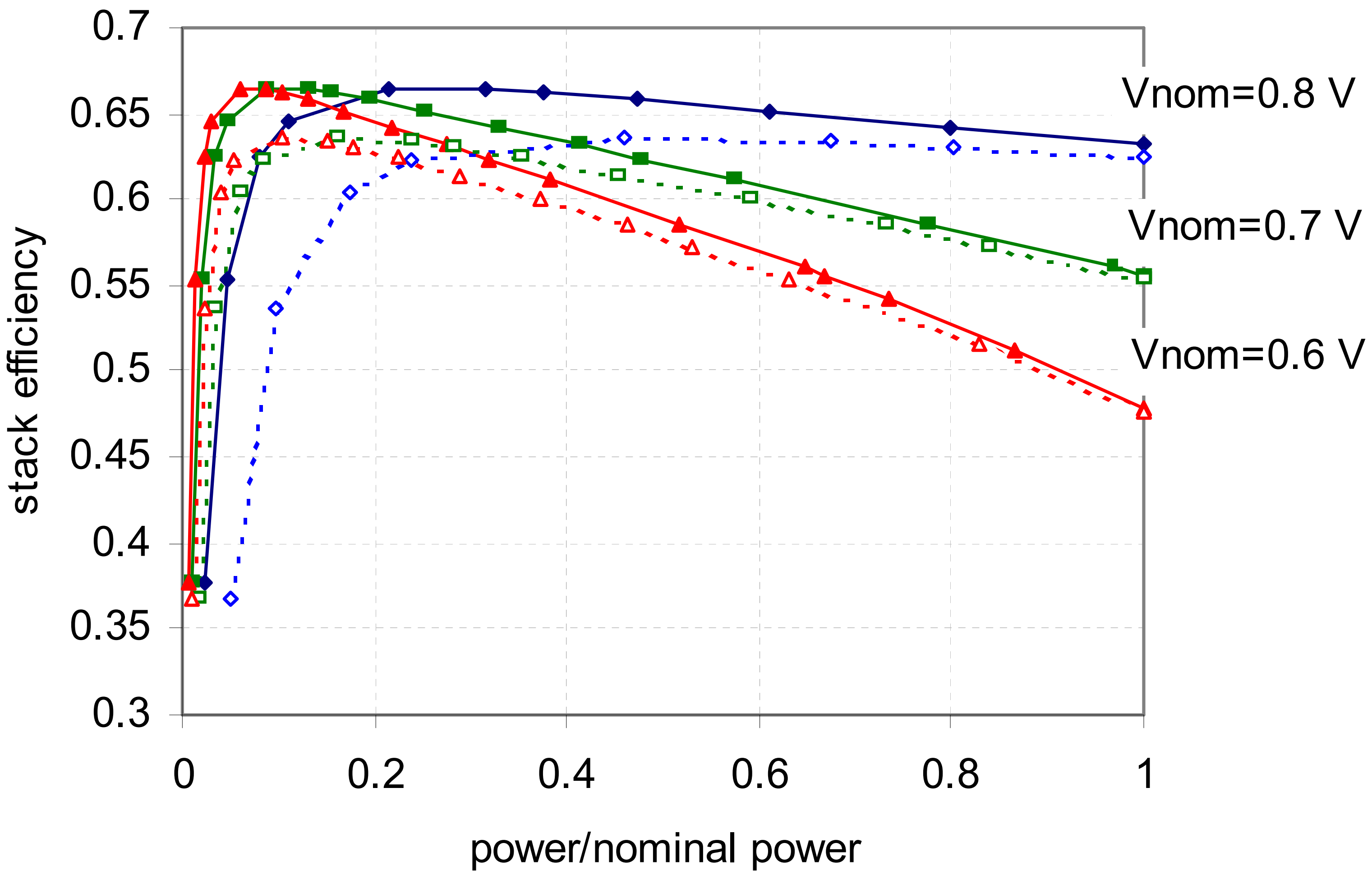
Typical polarization curves



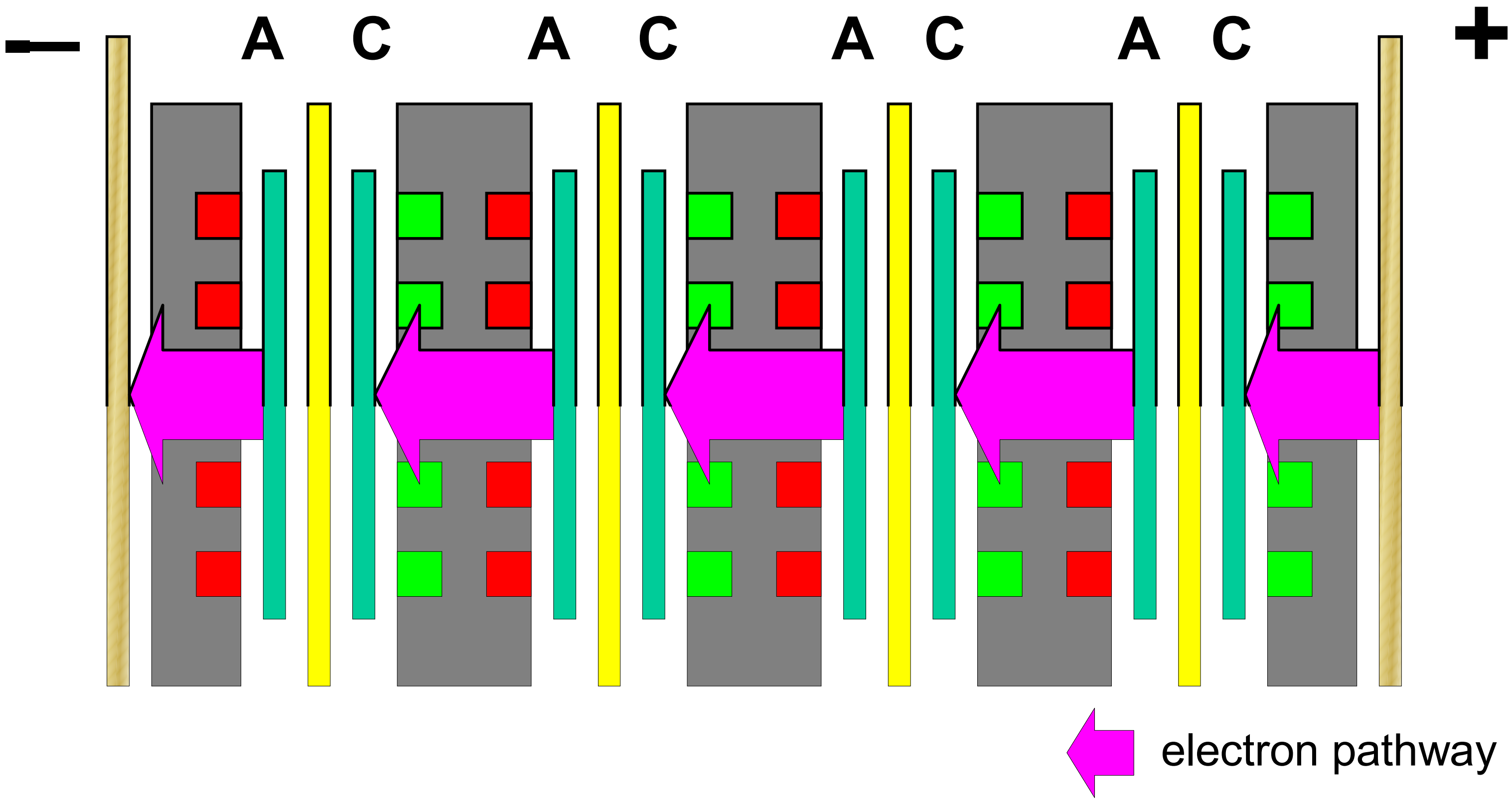
Stack size vs. efficiency



Stack efficiency vs. nominal (selected) cell voltage

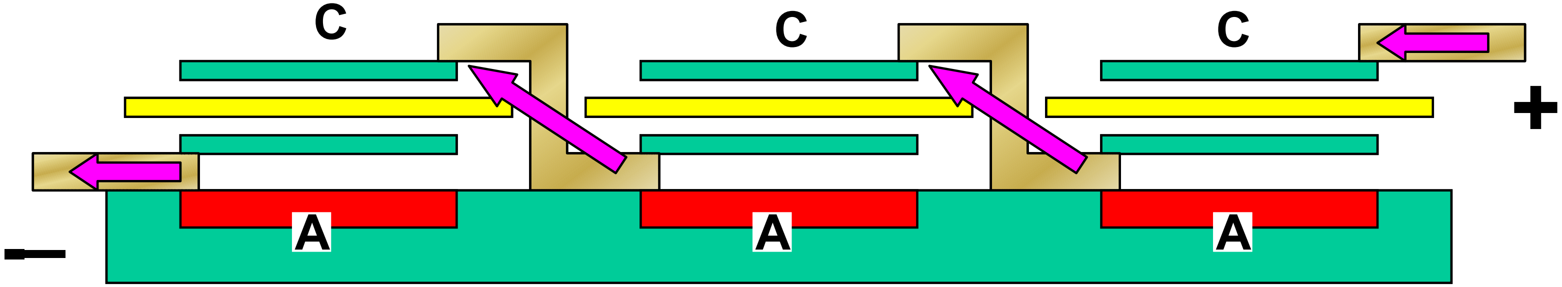


Bipolar Stack Configuration

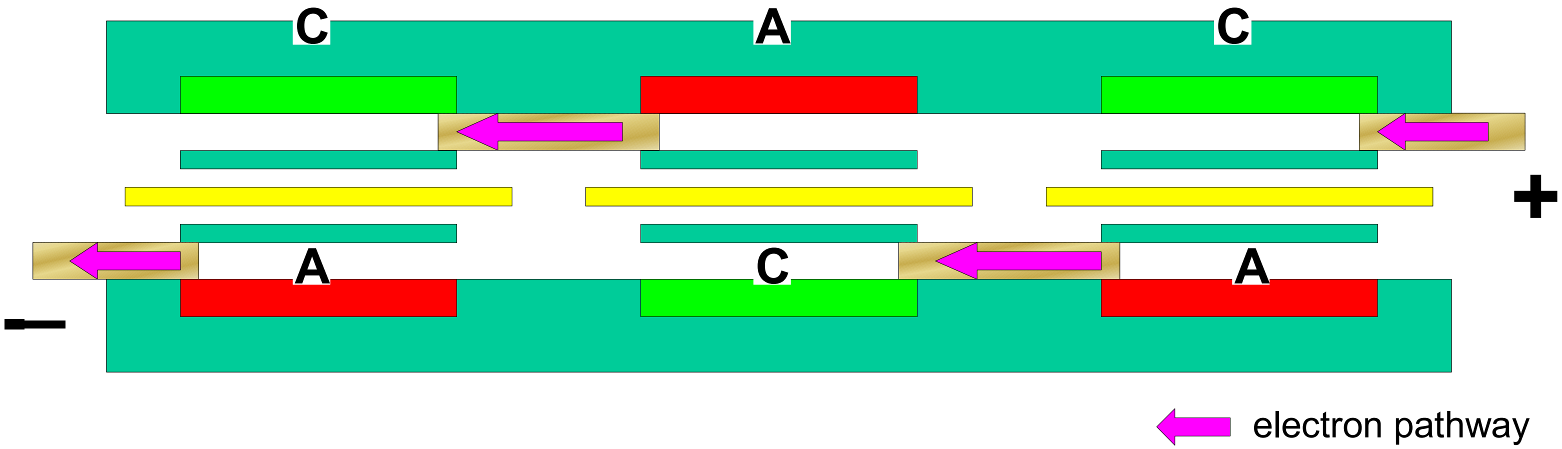


Monopolar Stack Configurations

zig-zag configuration



flip-flop configuration



Stack design/engineering issues

- Uniform distribution of reactants to each cell
- Uniform distribution of reactants inside each cell
- Uniform or desired temperature distribution in each cell
- Minimal resistive losses
  - good electrical contacts
  - selection of materials
- Account for thermal expansion
- No crossover or overboard leaks
- Minimum pressure drop (reactant gases and coolant)
- No water accumulation pockets
- Design for manufacture/design for assembly

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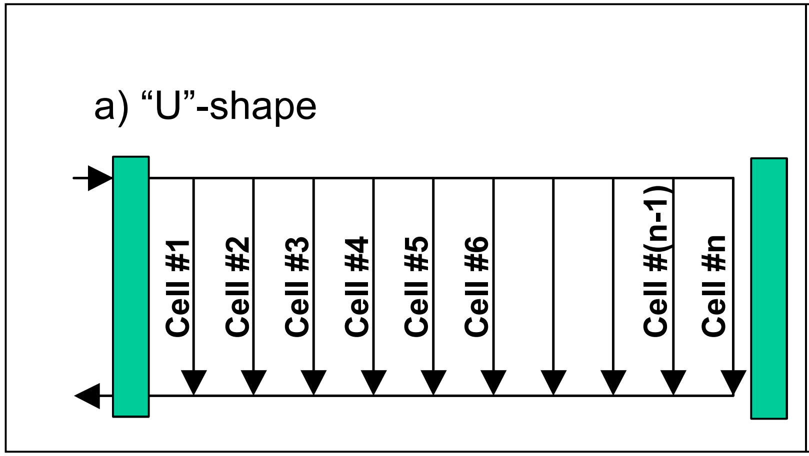
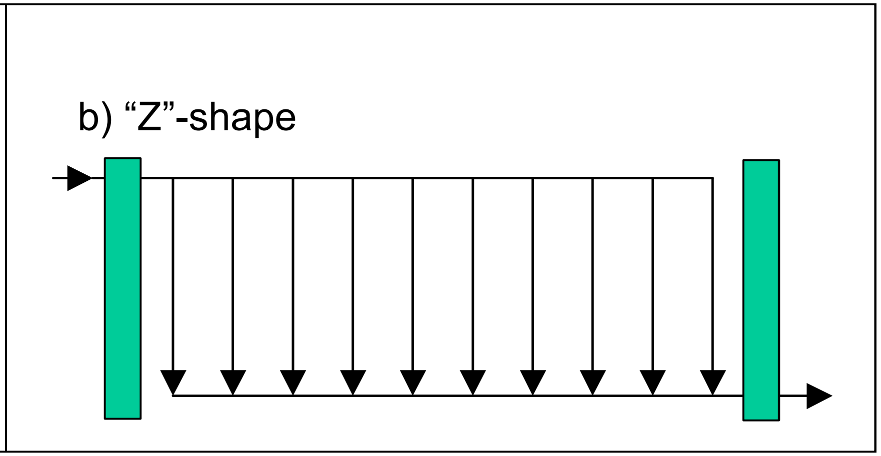
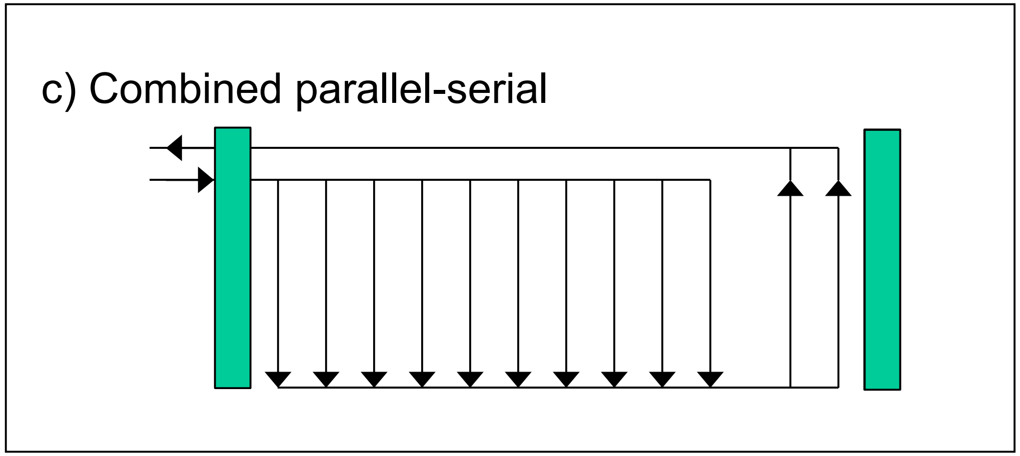
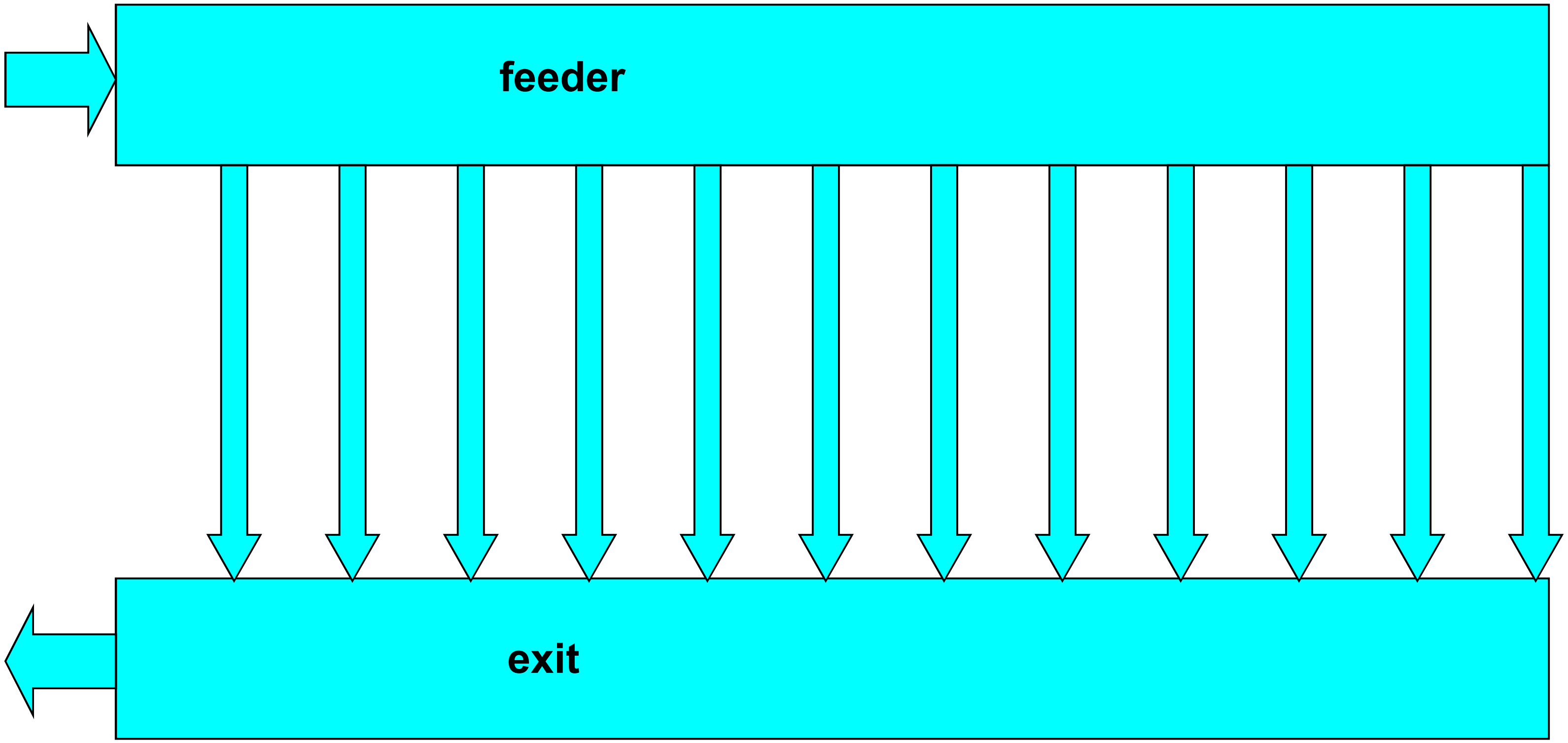






Pressure drop

$$\Delta P_{feeder} \ll \Delta P_{cell}$$



Pressure drop

$$\Delta P = f\rho \frac{L}{D}\frac{v^2}{2}$$

For non-compressible flow
also for compressible as long as $\Delta P<0.1P$

For laminar flow for $Re < 2000$ $f = \frac{64}{Re}$ $Re = \frac{Dv}{\nu}$

$$\Delta P = 32\mu \frac{L}{D^2} v$$

For non-circular conduits $D = 4R_h$ $R_h = \frac{A}{P_m}$

$$v = \frac{\dot{m}}{\rho A} \qquad \Delta P = 2\nu \frac{L P_m^2}{A^3}\dot{m}$$

For compressible flow $P_1^2 - P_2^2 = \dot{m}^2 \frac{RT}{A^2}\left(f\frac{L}{D} + 2\,ln\frac{P_1}{P_2} \right)$

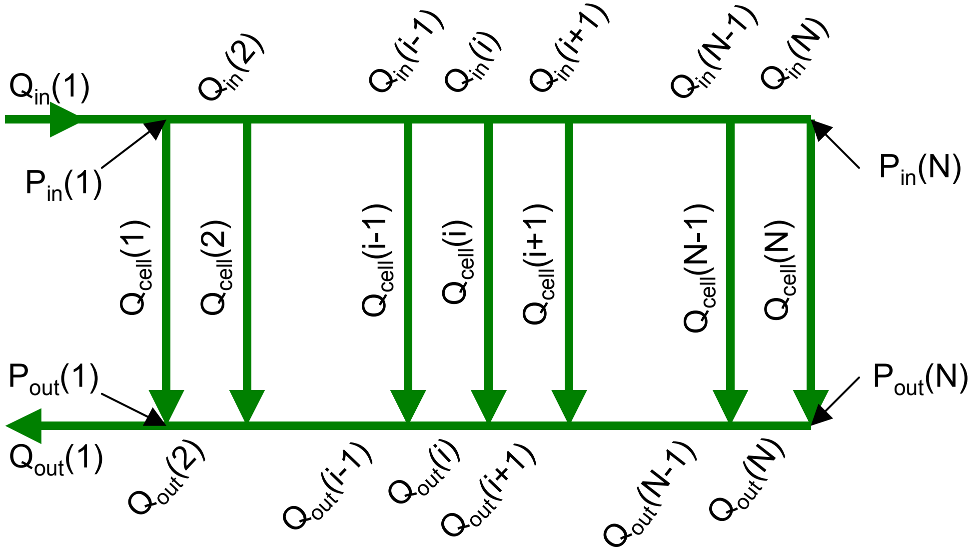
Piping Network Problem

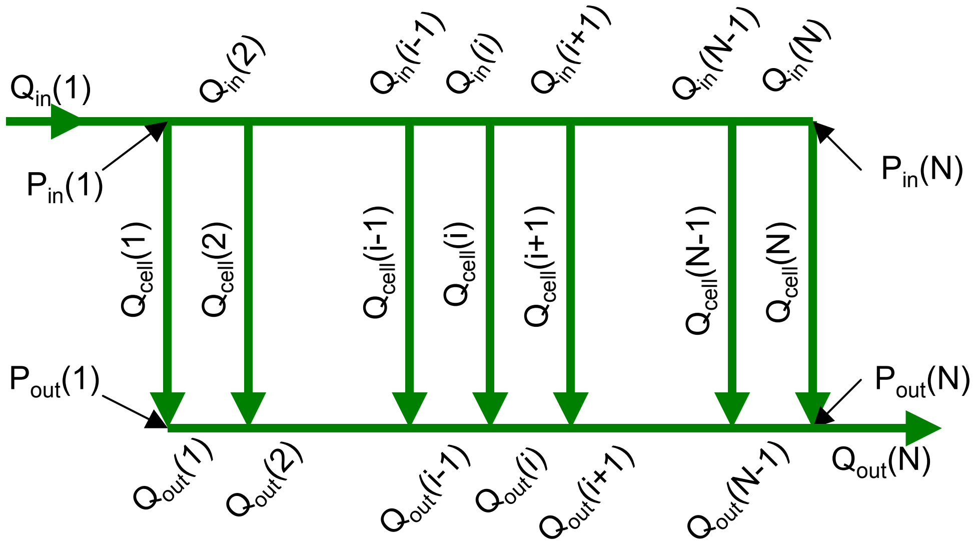
The flow in any network must satisfy the basic relations of continuity and energy conservation:

1) The flow into any junction must equal the flow out of it

2) The flow in each segment has a pressure drop that is a function of the flow rate through that segment

3) The algebraic sum of the pressure drops around any closed loop must be zero





1) The flow into any junction must equal the flow out of it

in inlet manifold:

Qin(i) = Qcell(i) + Qin(i+1)

in outlet manifold, “U” configuration

Qout(i) = Qcell(i) + Qout(i+1)

in outlet manifold, “Z” configuration

Qout(i) = Qcell(i) + Qout(i-1)

Qin(1) = Qstack

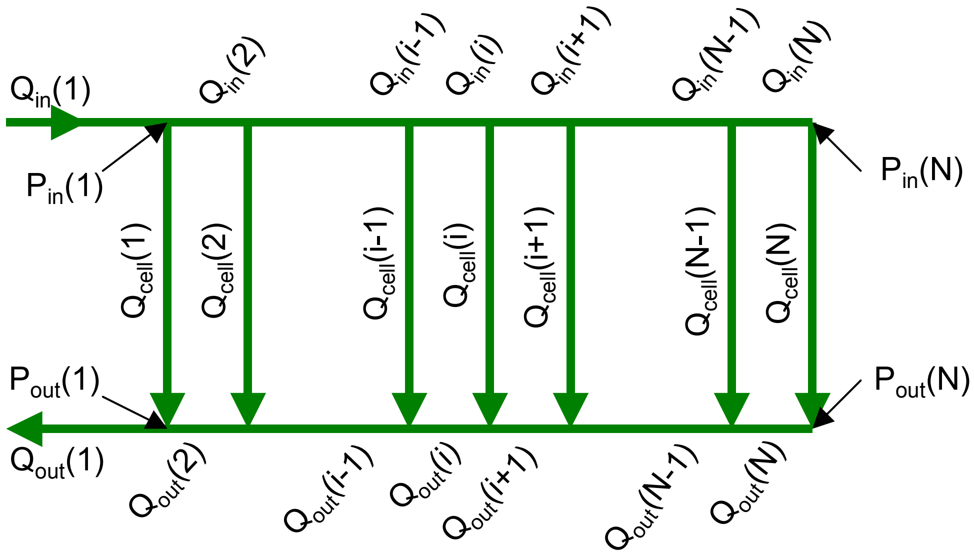
For a non-operating stack, i.e., no species consumption nor generation, the flow at the stack outlet is equal to the flow at inlet:

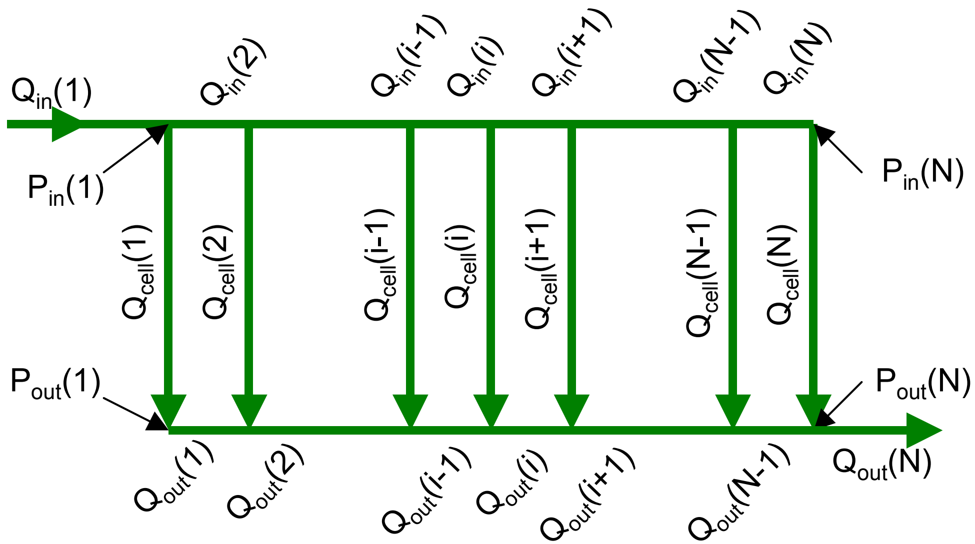
for “U” configuration

Qout(1) = Qin(1)

for “Z” configuration

Qout(N) = Qin(1)





2) The flow in each segment has a pressure drop that is a function of the flow rate through that segment

Bernoulli equation (without gravity forces):

$$\Delta P(i) = -\rho \frac{[u(i)]^2 - [u(i-1)]^2}{2} + f\,\rho \frac{L}{D_H} \frac{[u(i)]^2}{2} + K_f \rho \frac{[u(i-1)]^2}{2}$$

For laminar flow: $f = \dfrac{64}{Re}$

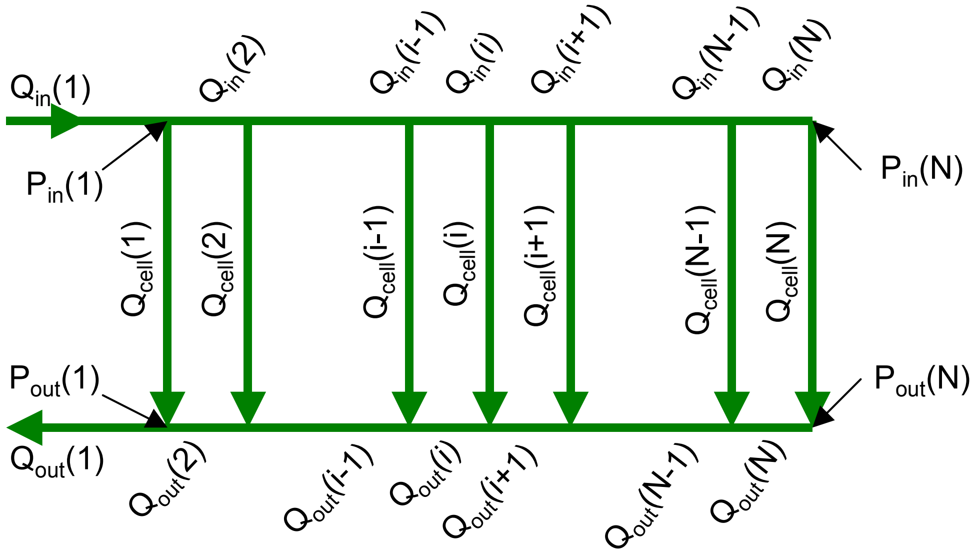
For turbulent flow: $f = \dfrac{1}{\left(1.14 - 2\,log\,\dfrac{\varepsilon}{D}\right)^2}$

3) The algebraic sum of the pressure drops around any closed loop must be zero

For i = 1 to (N – 1)

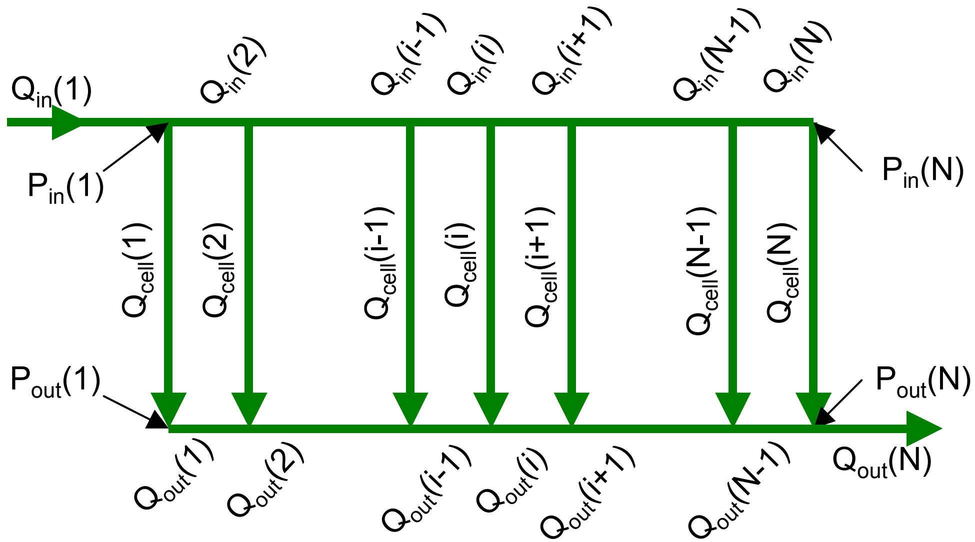
in “U” configuration

ΔPin(i+1) + ΔPcell(i+1) + ΔPout(i+1) – ΔPcell(i) = 0



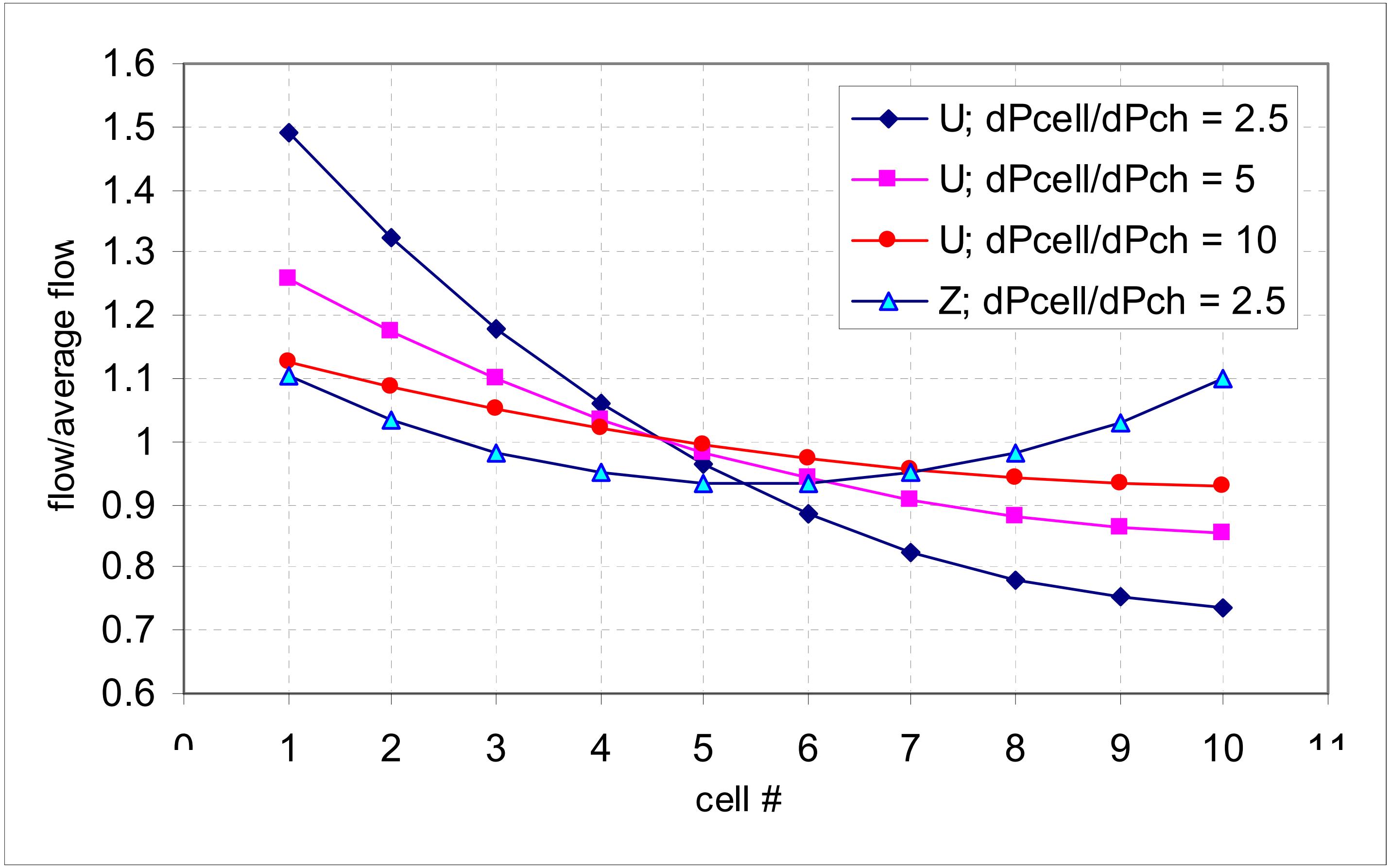
in “Z” configuration

ΔPin(i+1) + ΔPcell(i+1) – ΔPout(i) – ΔPcell(i) = 0



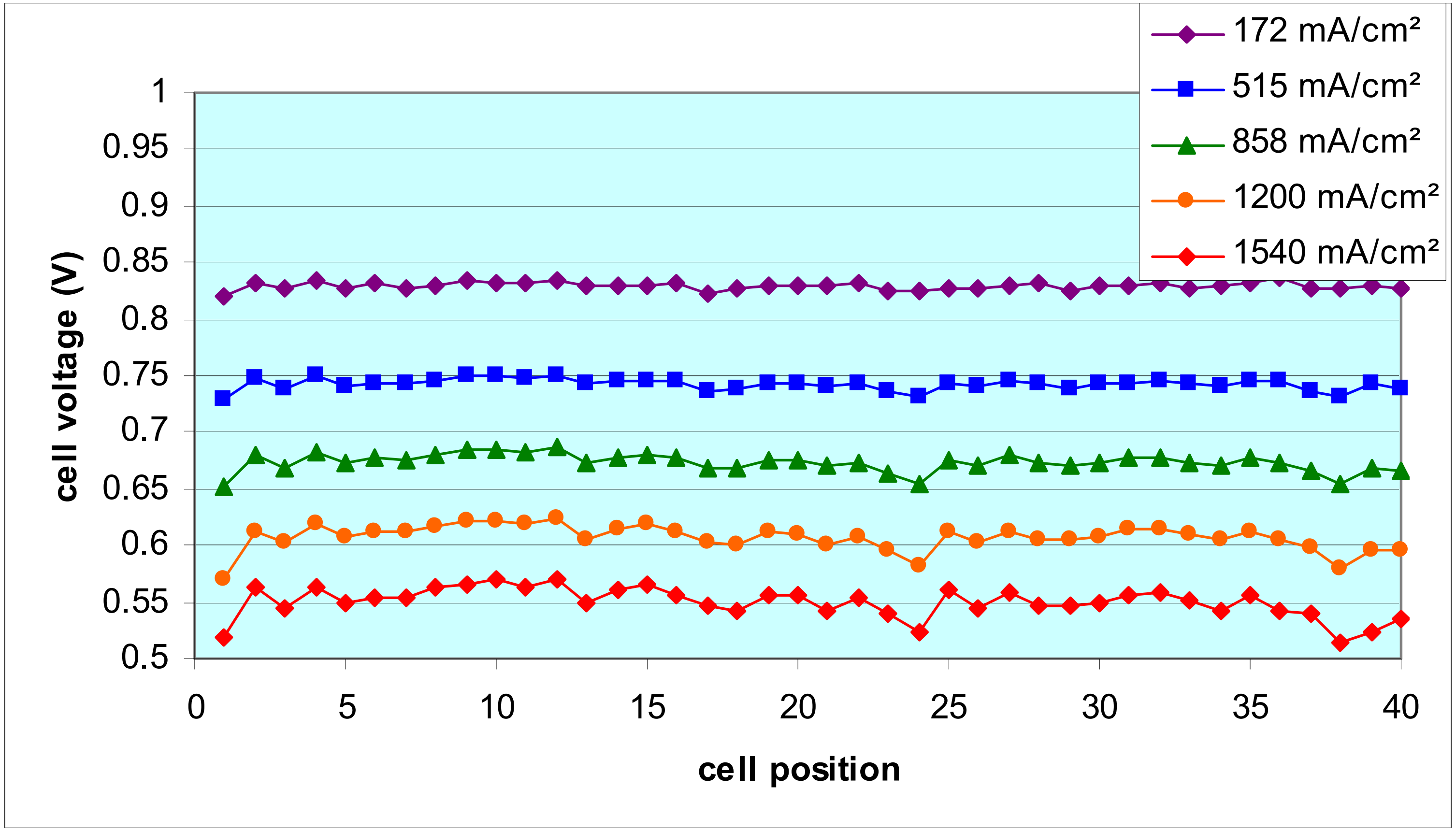
The problem must be solved by iteration a loop at a time

Flow Distribution through Individual Cells



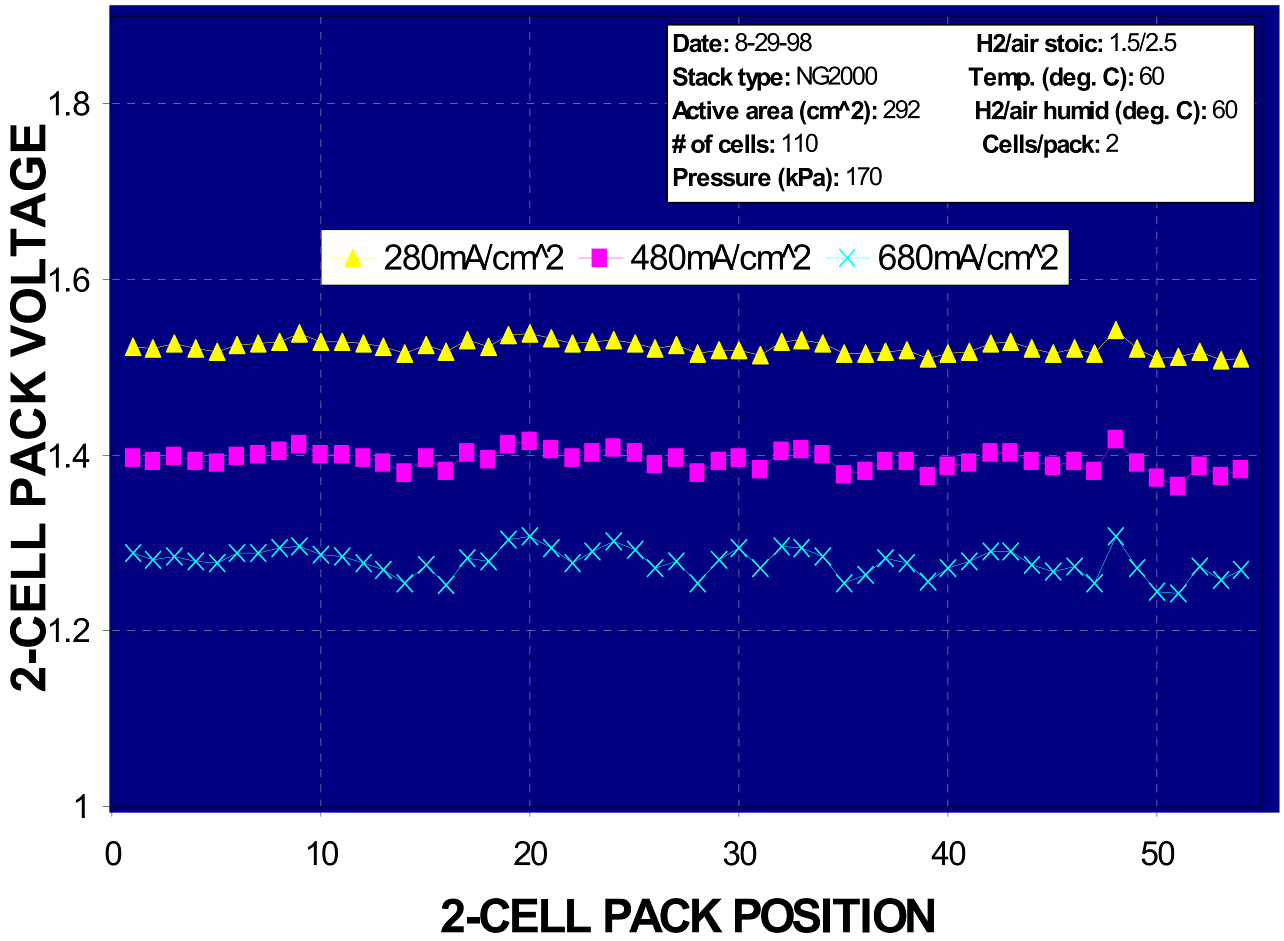
Uniform distribution

Example of cell voltages in a 40-cell stack



Example of cell voltages in a 110-cell stack

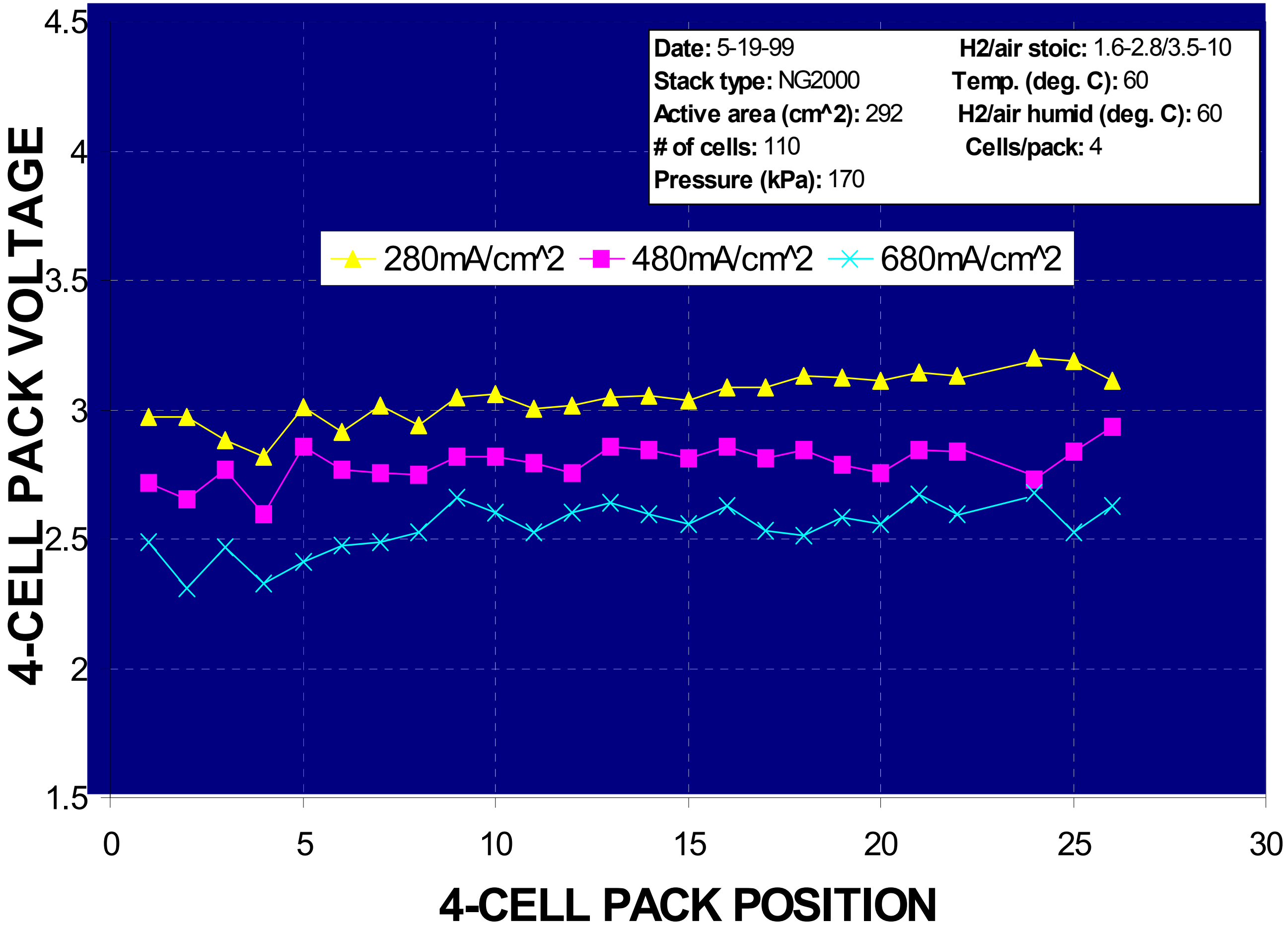
In the lab



Source: *Fuel Cell Power for Transportation*, SAE SP-1505, pp. 63-69, 2000

Example of cell voltages in a 110-cell stack

In the vehicle



Source: *Fuel Cell Power for Transportation*, SAE SP-1505, pp. 63-69, 2000

Flow field

Stack design/engineering issues

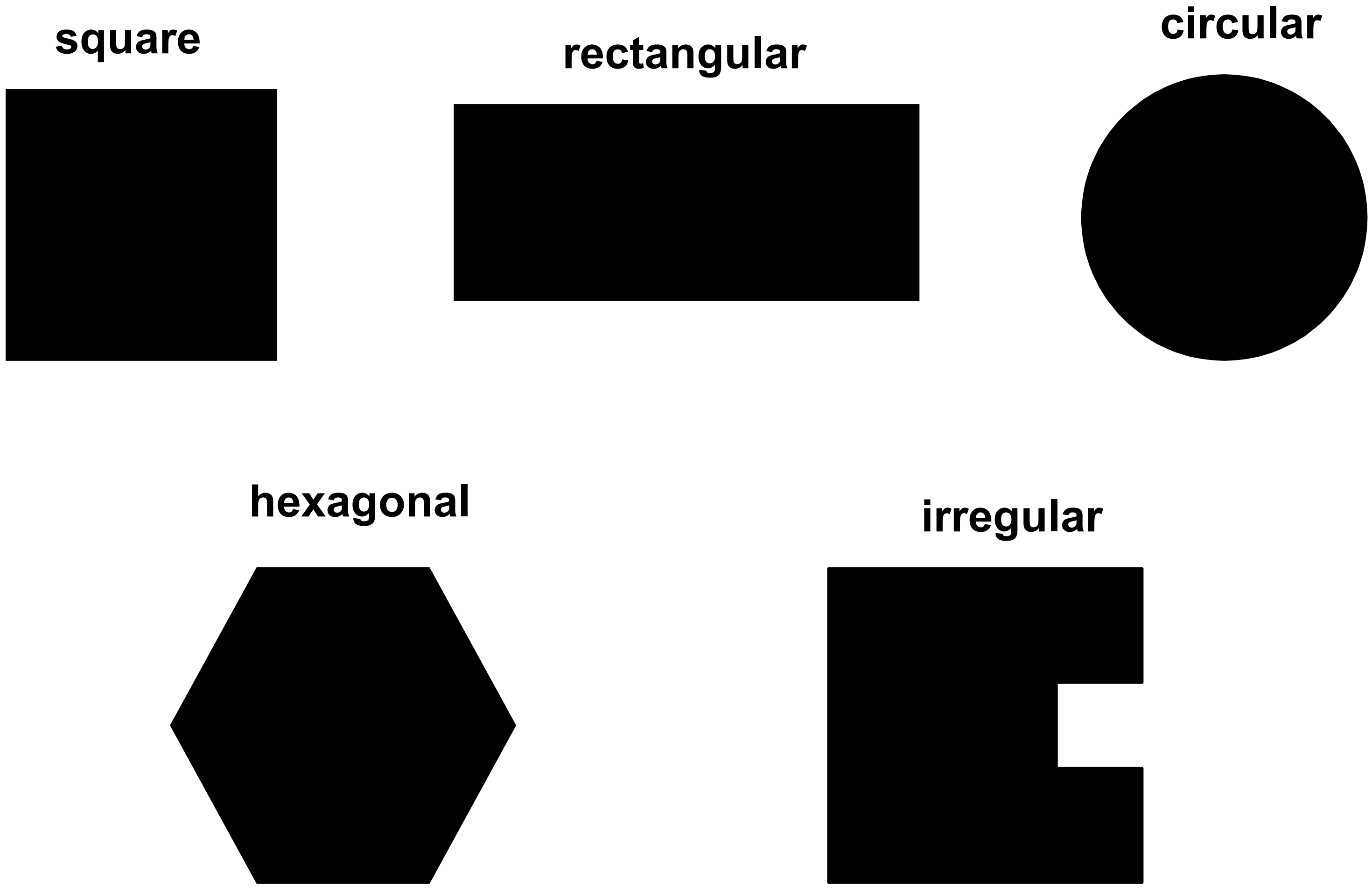
- Uniform distribution of reactants to each cell
- **Uniform distribution of reactants inside each cell**

Flow field needed to ensure uniform reactant distribution

Flow field design variables

- Shape
- Orientation (position of inlet and outlet manifolds)
- Orientation (horizontal or vertical)
- Configuration of channels
- Dimensions of channels and spacing
- Anode vs. cathode orientation
- Geometry of channels

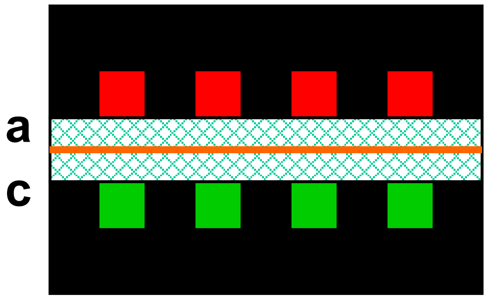
Flow field shape



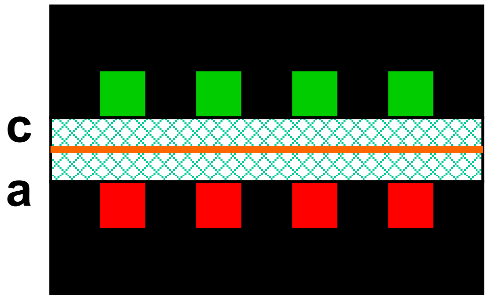
Flow field orientation

horizontal stack-up

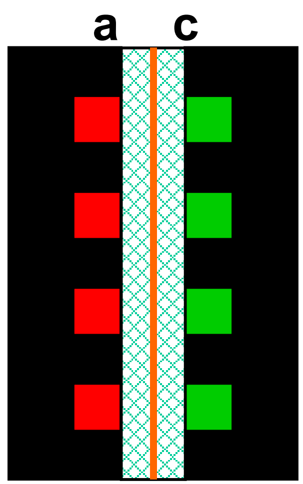
anode facing up



cathode facing up

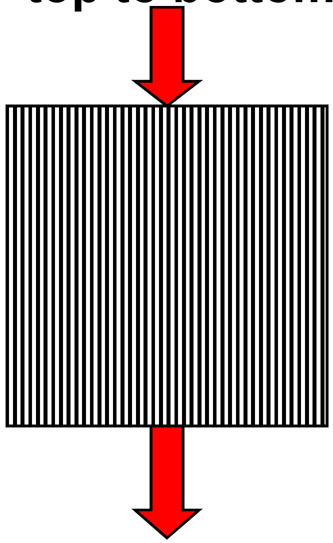


vertical stack-up

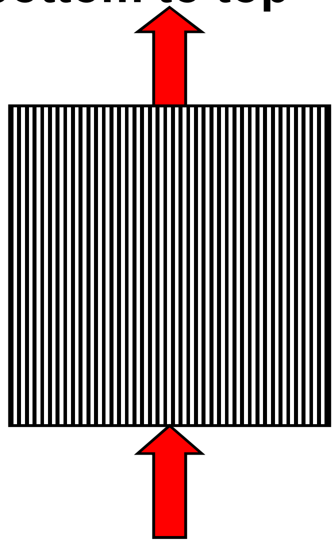


Flow field orientation

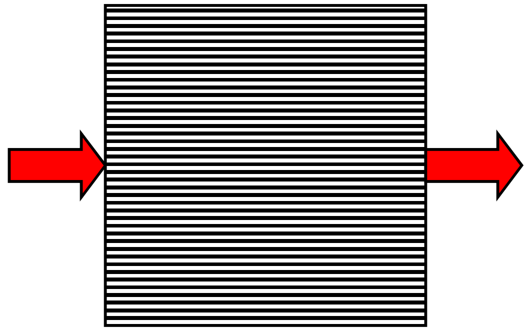
top to bottom



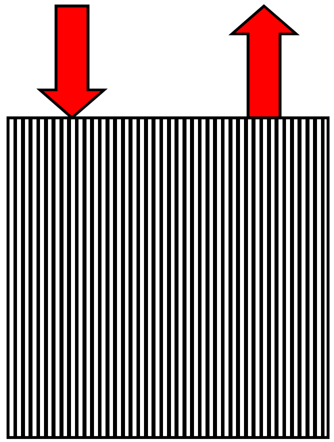
bottom to top



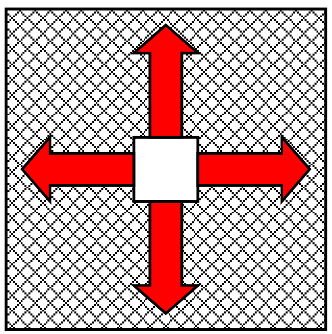
side to side



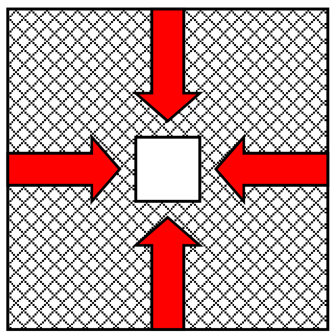
same side inlets and outlets



radial (outwards)

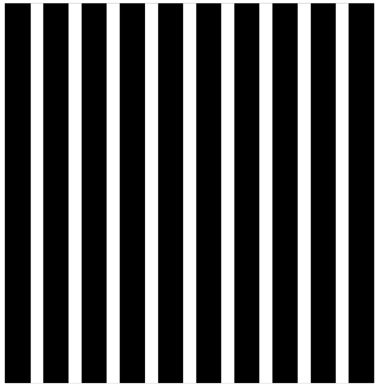


radial (inwards)

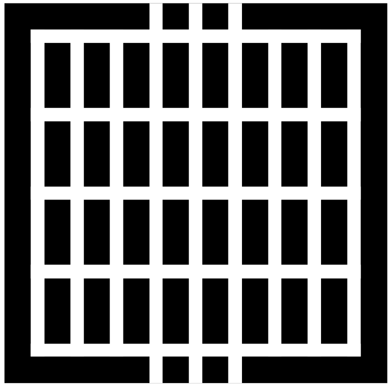


Flow field configurations

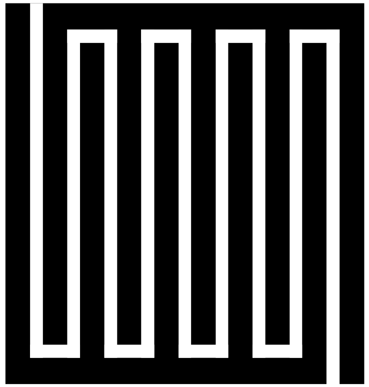
straight



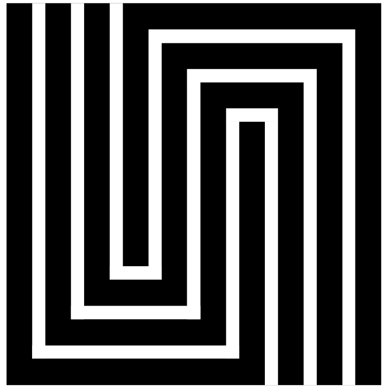
criss-cross



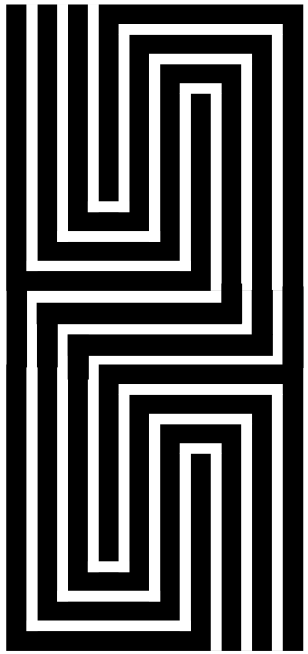
single channel serpentine



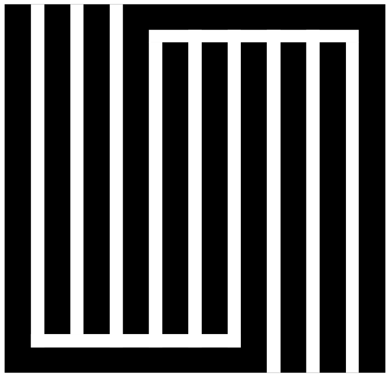
multi-channel serpentine



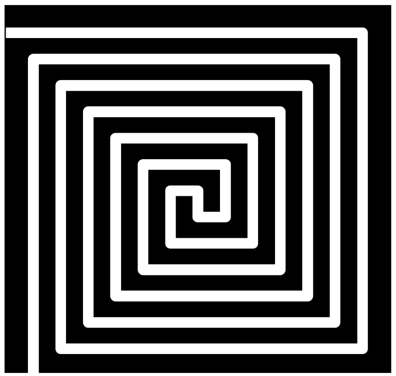
subsequent serpentine



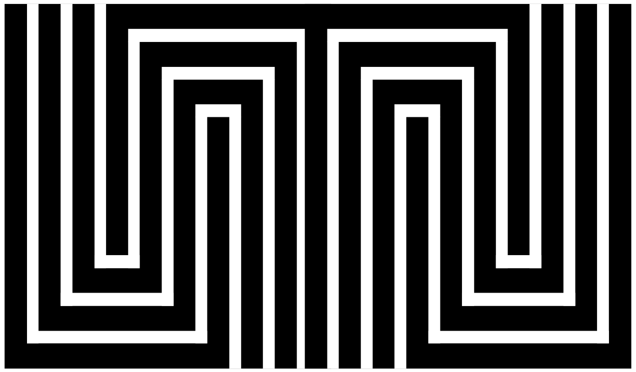
mixed serpentine



spiral

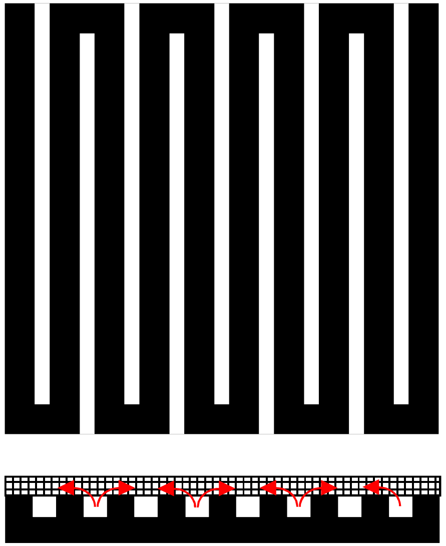


mirror serpentine

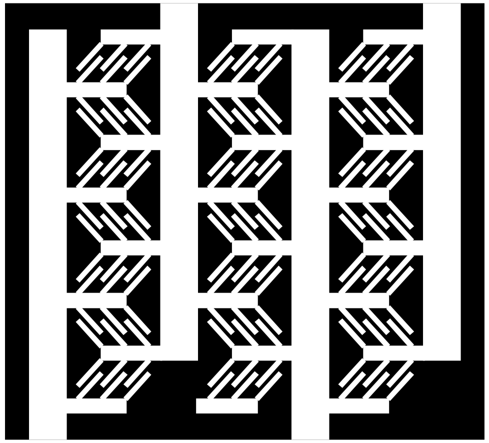


Flow field configurations (cont.)

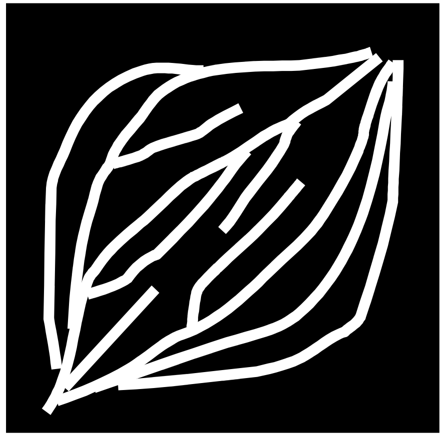
interdigitated



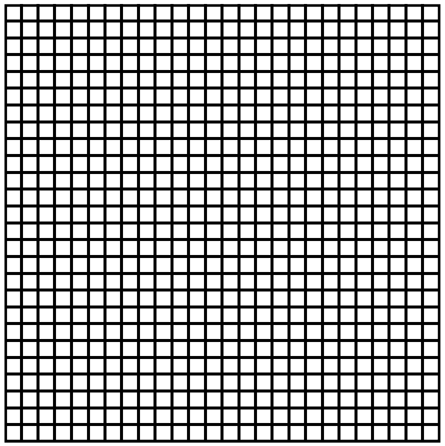
biomimetic



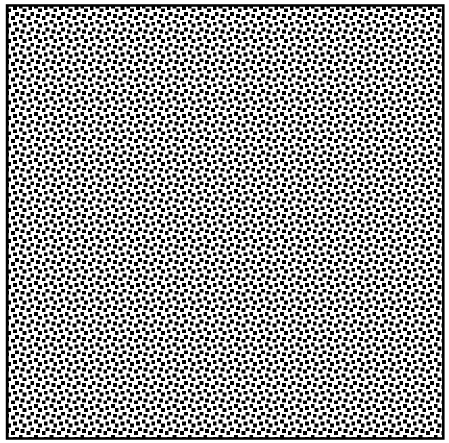
fractal



screen/mesh

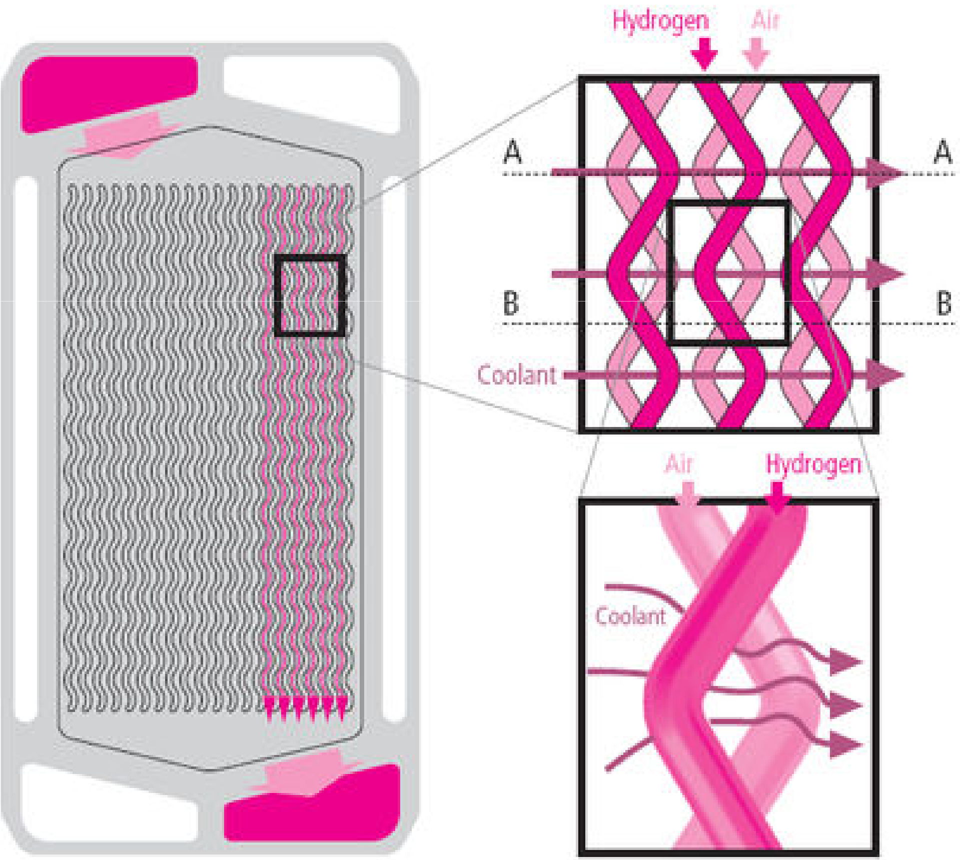


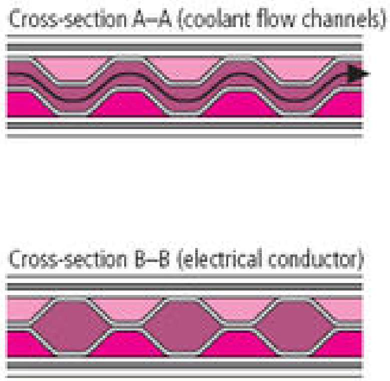
porous



HONDA FCX Clarity

unveils flow field design



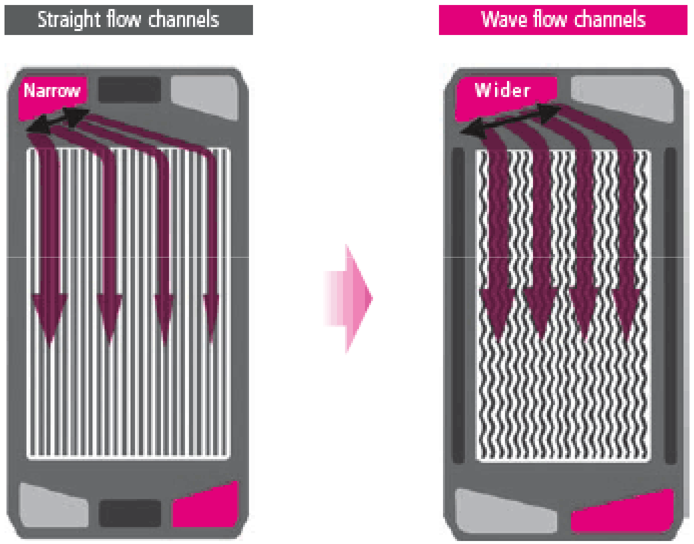


With wave flow-channels the hydrogen and air flow vertically while the coolant that cools the electrical generating layer flows horizontally. This results in a compact construction that allows hydrogen, air and coolant to be supplied to the electrical generating layer with maximum efficiency.

Improved flow field design

reactant gases distribution

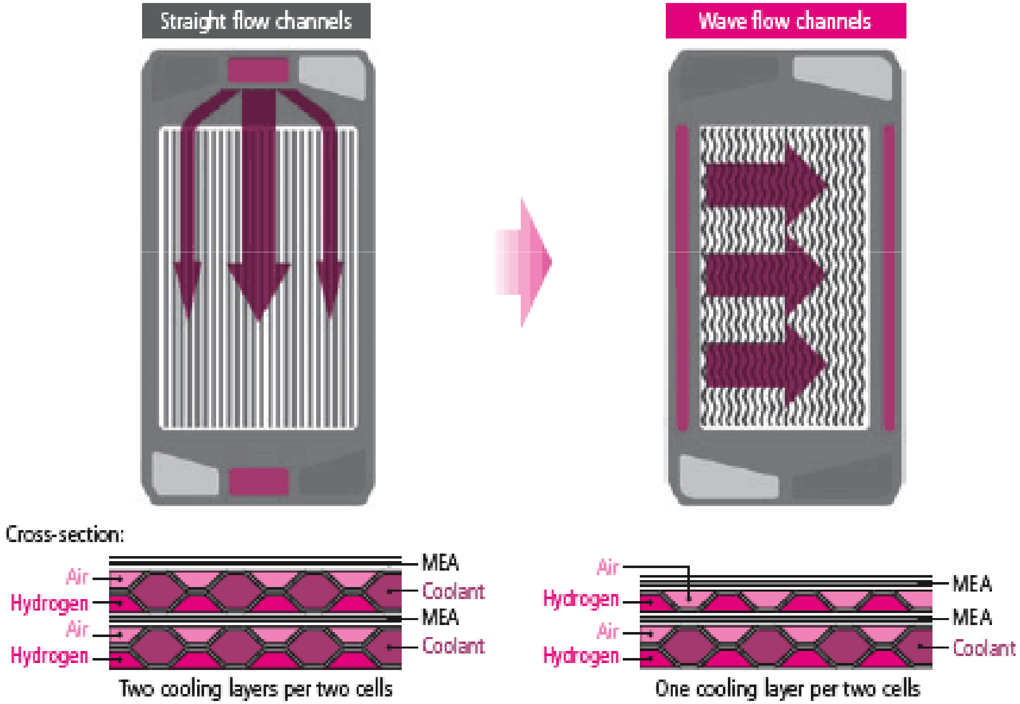
■ Improved hydrogen-air distribution



The wave shape and increased flow-channel length result in improved hydrogen and air diffusion. The coolant inlets and outlets are positioned horizontally, allowing the connecting ducts to be expanded for improved distribution. These innovations result in an approximate 10% improvement in generating performance.

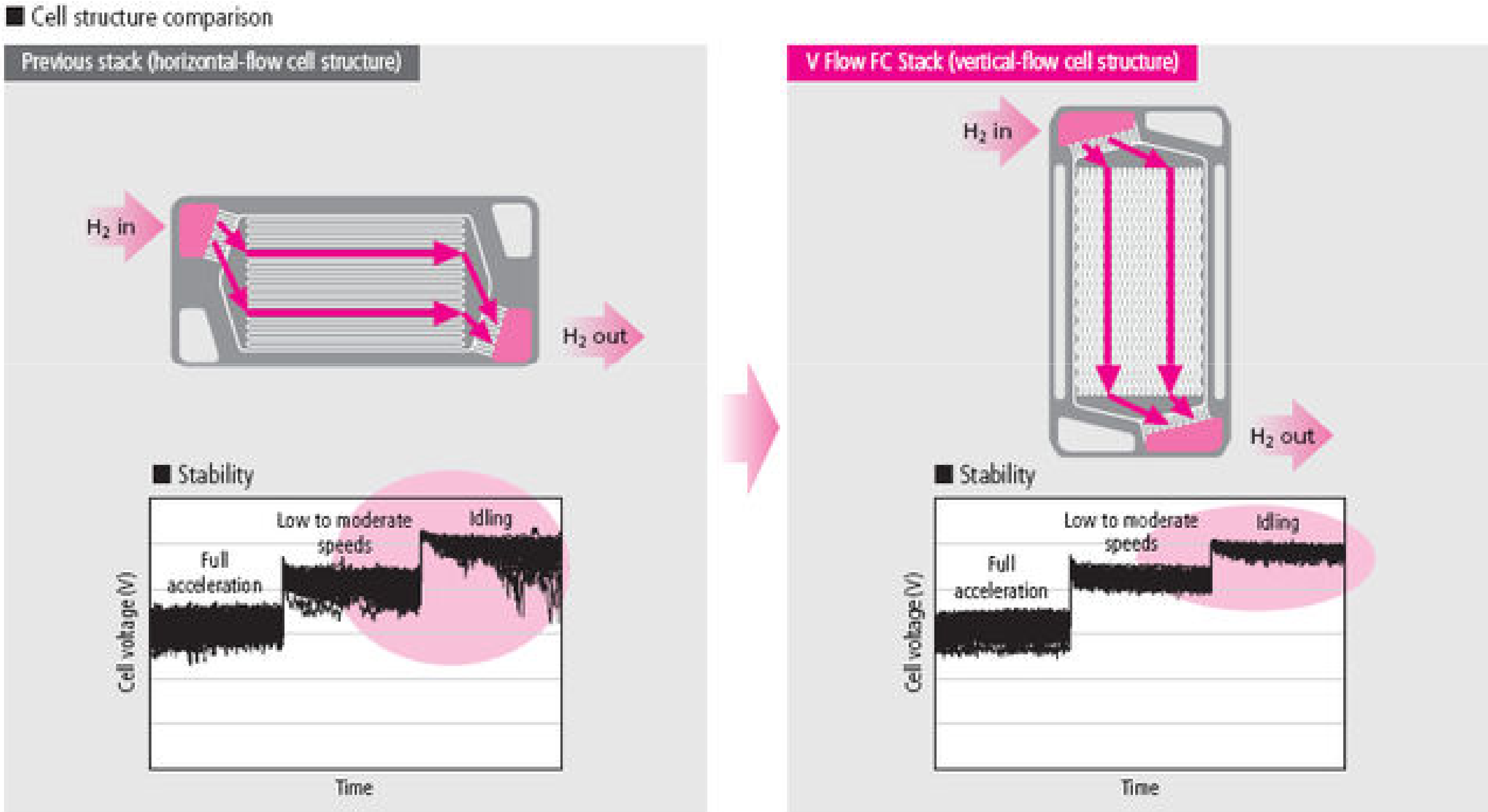
coolant distribution

■ Improved coolant distribution



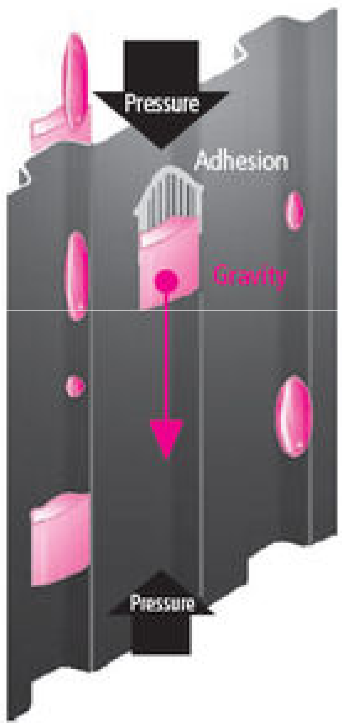
Horizontal coolant flow improves distribution, resulting in even cooling over the entire surface. The number of cooling layers can be decreased to 50%, reducing stack length by 20% and stack weight by 30%.

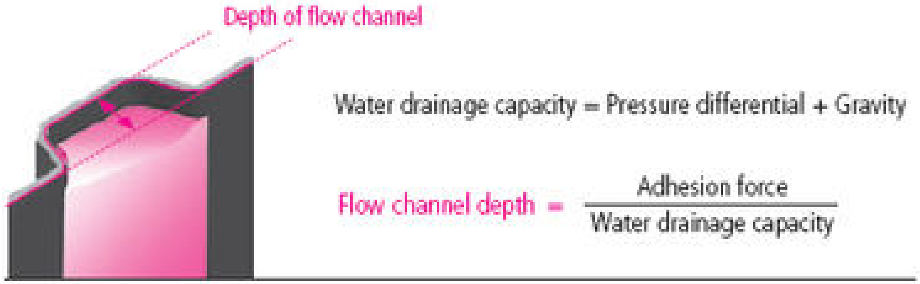
Improved flow field design – better performance



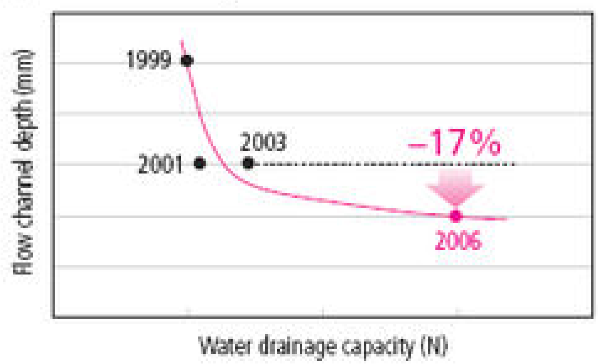
Improved water drainage

■ V Flow cell structure

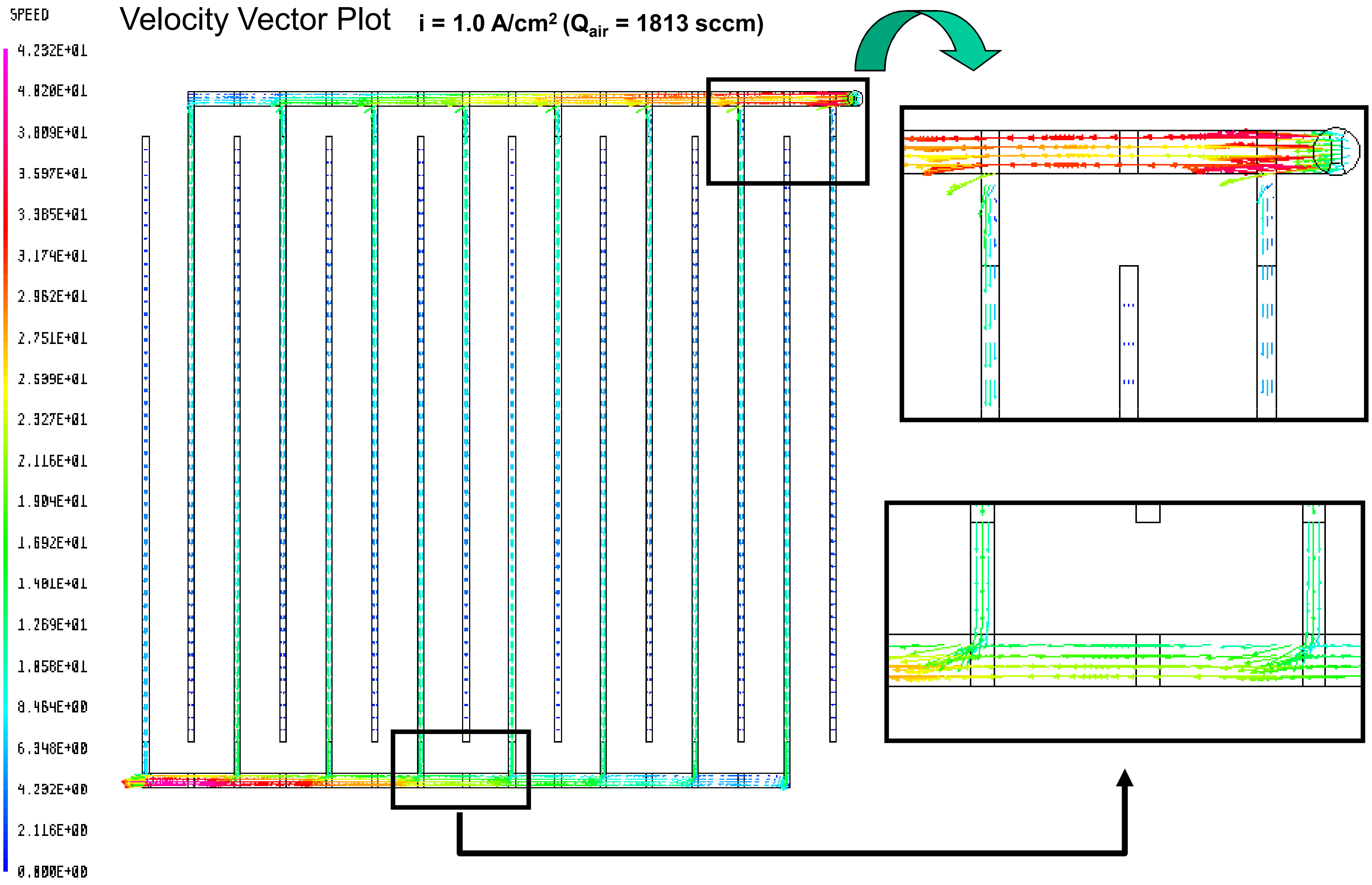




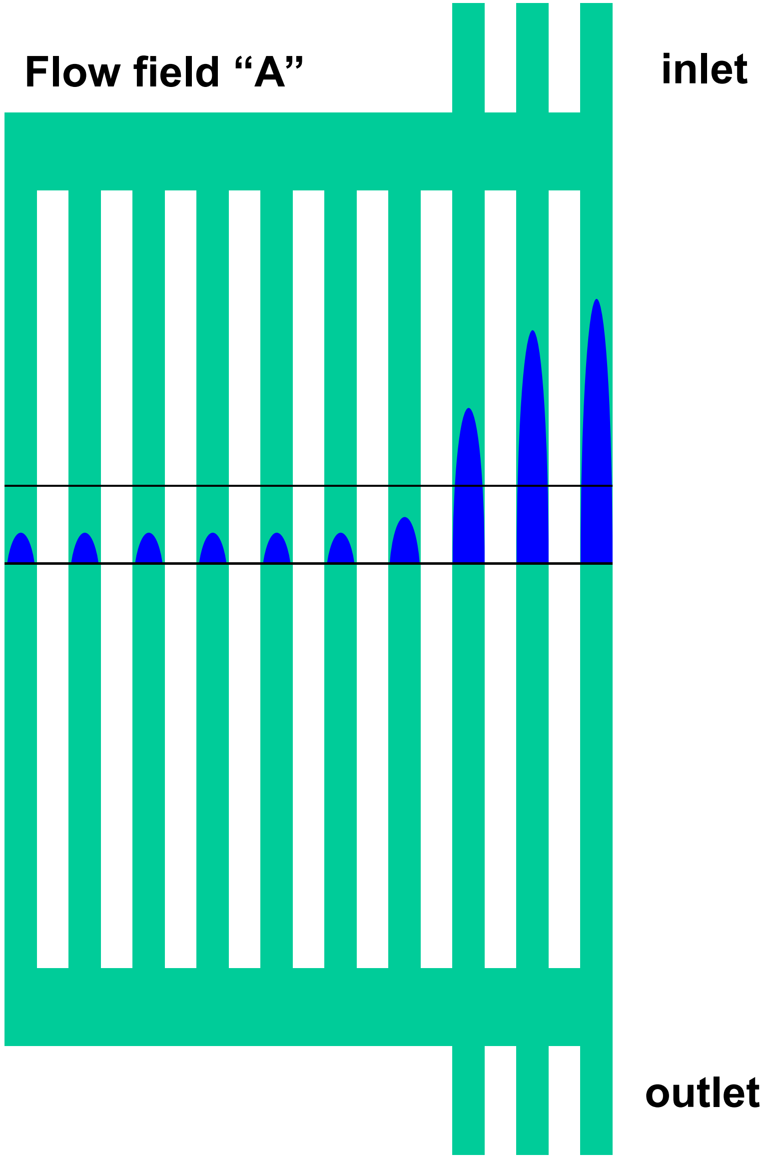
■ Improved water drainage

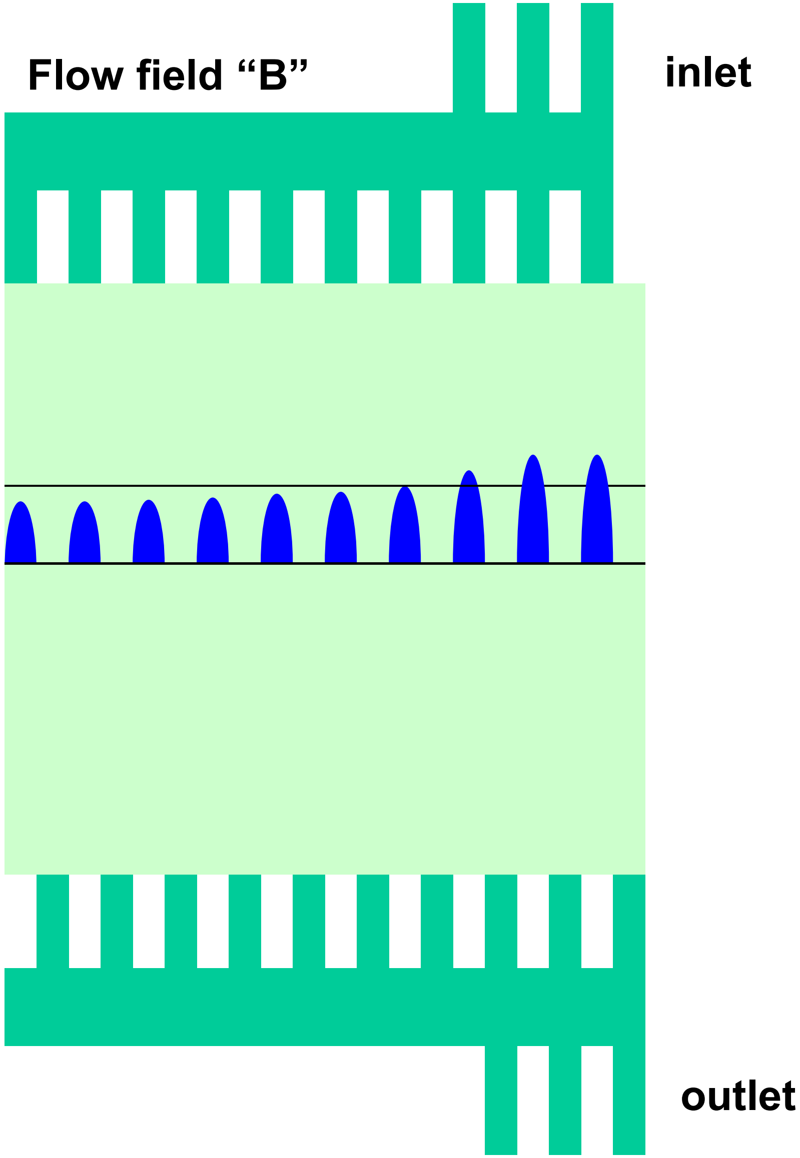


CFD can be a powerful tool for flow field design

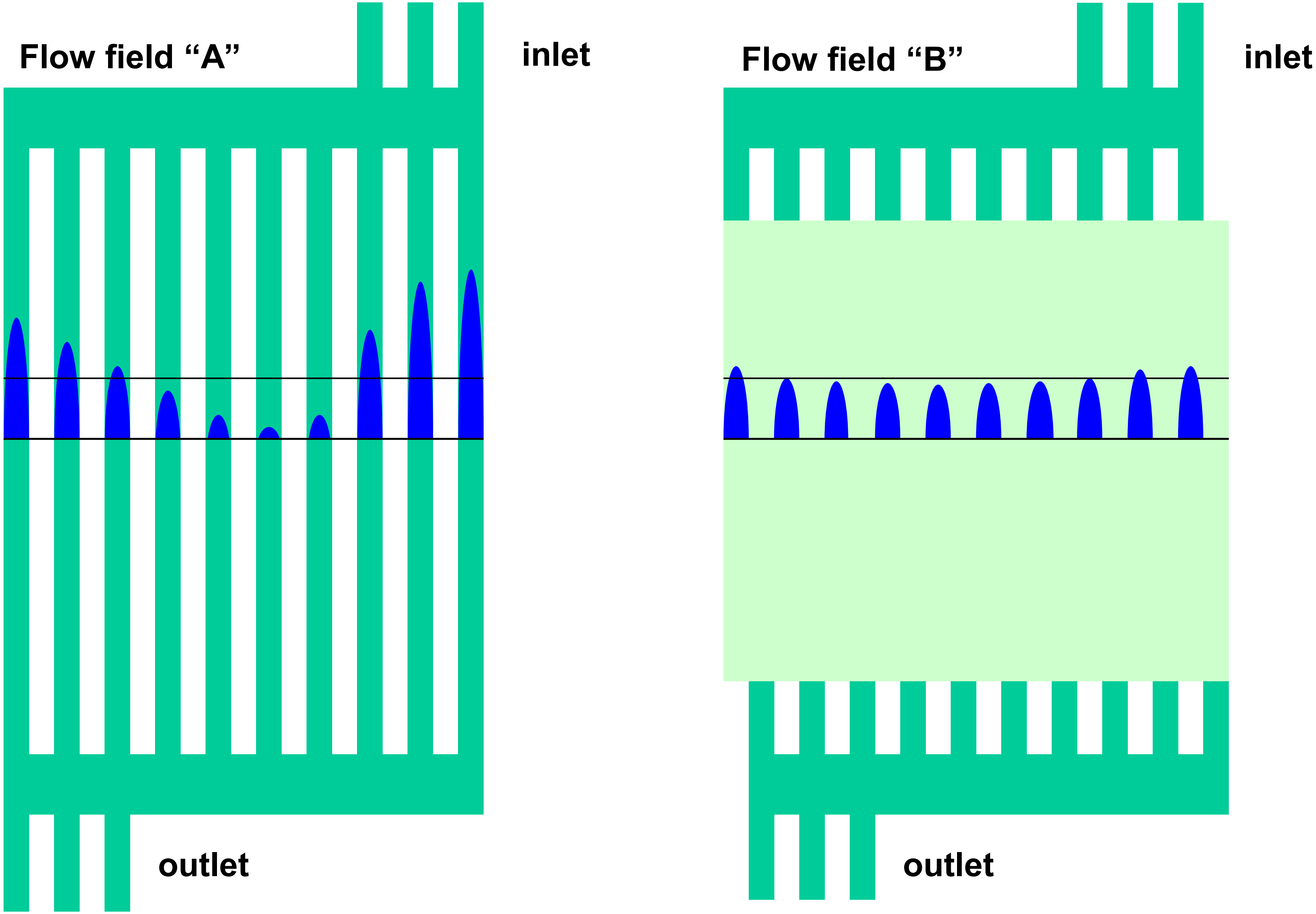


Velocity distribution in flow field channels



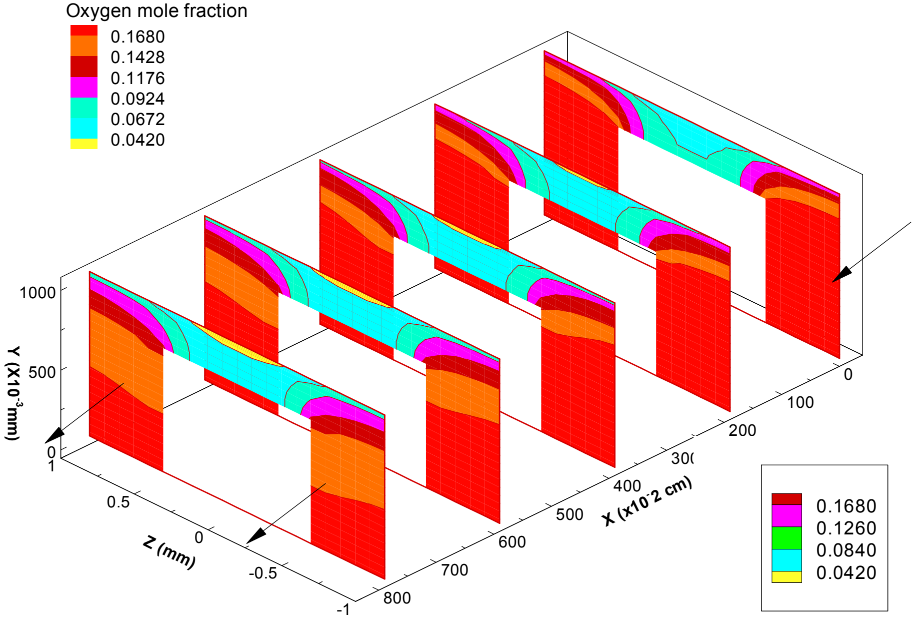


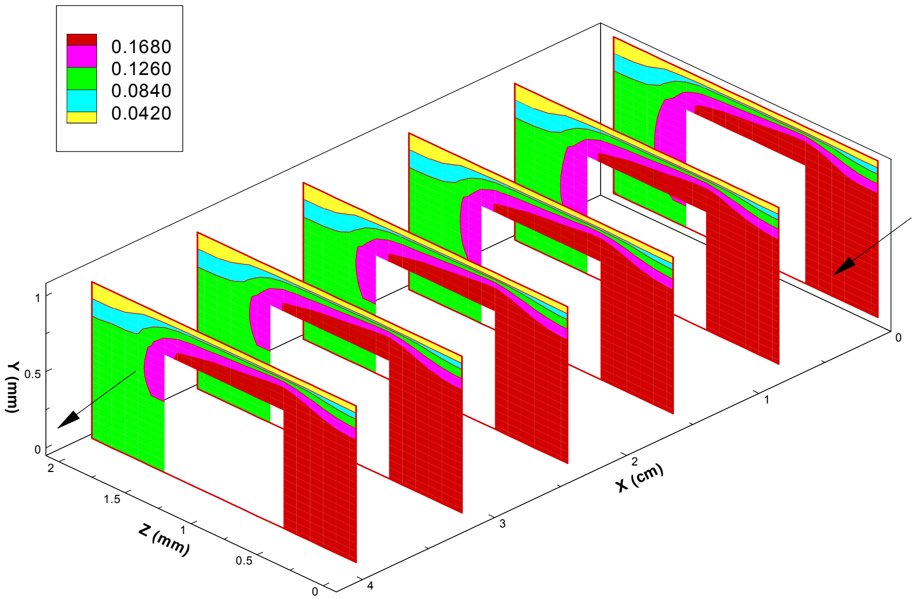
Velocity distribution in flow field channels



Oxygen molar fraction

conventional flow field vs. interdigitated flow field

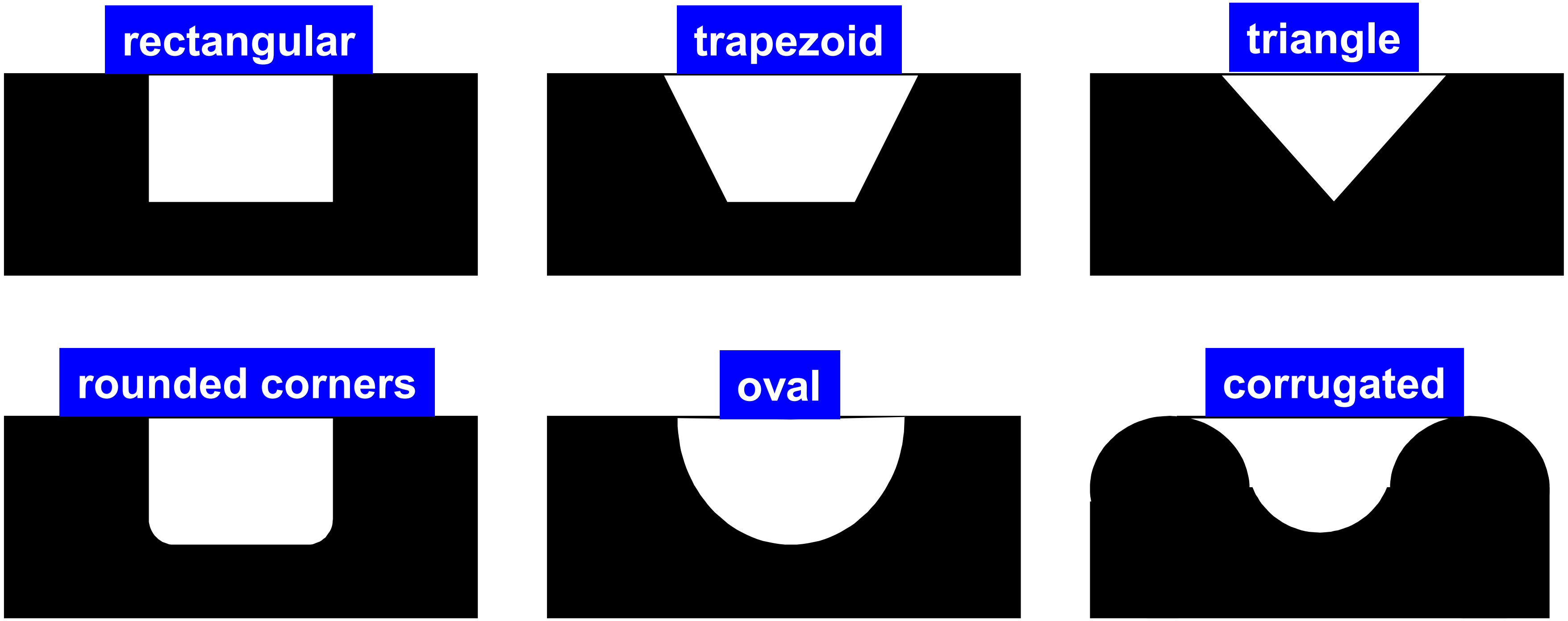




UNIVERSITY OF Miami

H. Liu, T. Zhou and L. You, NSF Workshop on Engineering Fundamentals of Low-Temperature PEM Fuel Cells, Arlington, VA, November 14-15, 2001

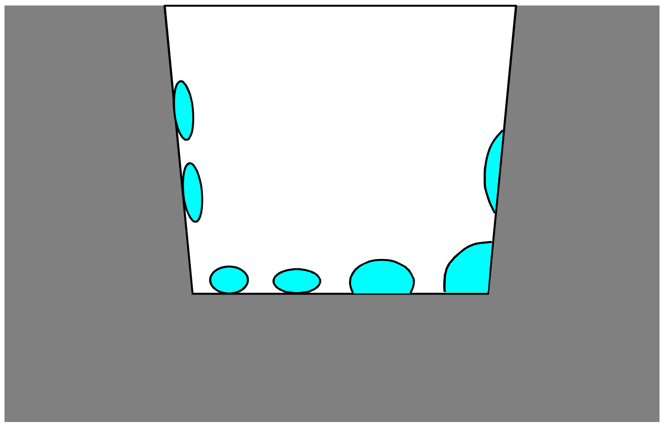
Channel shape



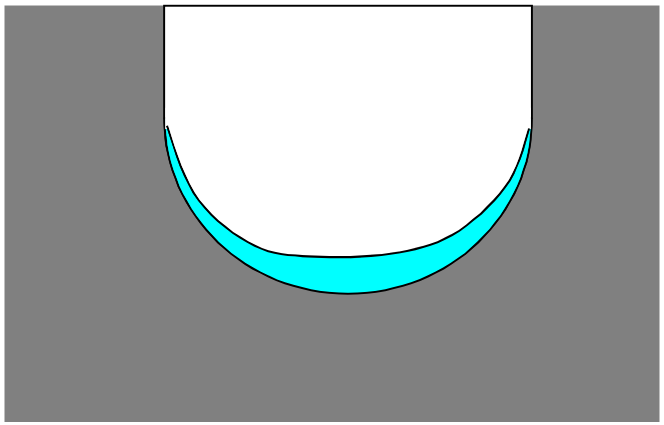
- Shape dictated not only by design, but also by
  the manufacturing process (machining, molding, stamping, …)

Flow field

Effect of Channel Shape on Water Form



droplets

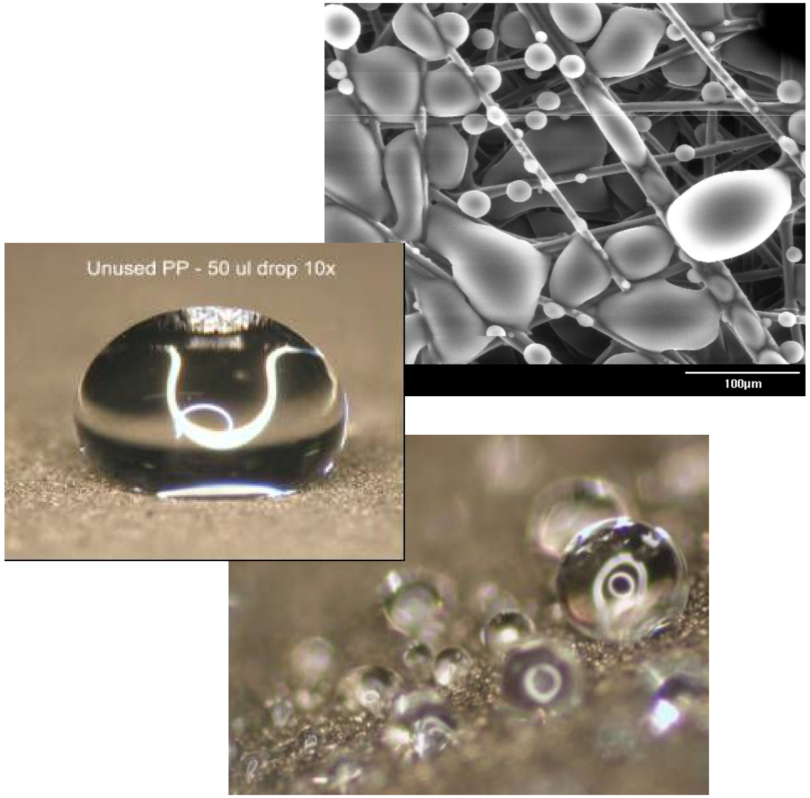


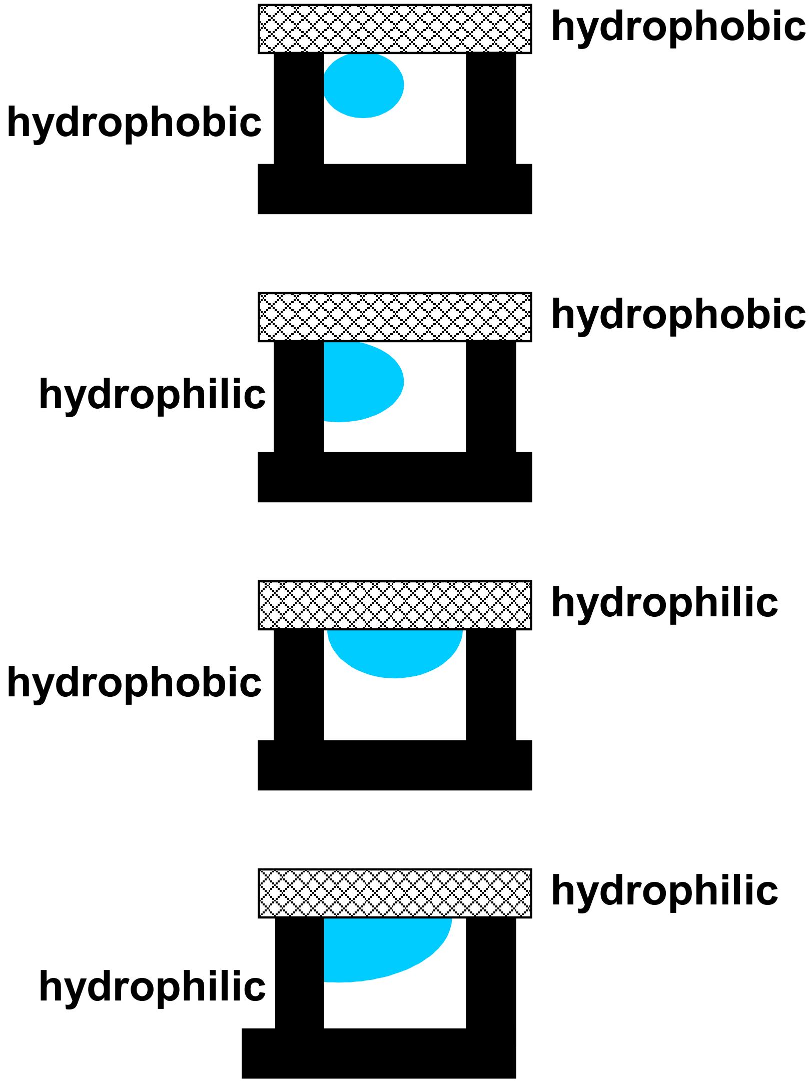
film

Interaction between flow field and GDL

Issues:

- Hydrophobicity/hydrophilicity
- Velocities required for water removal
- Droplet coalescing
- Droplet movement in bends and turns

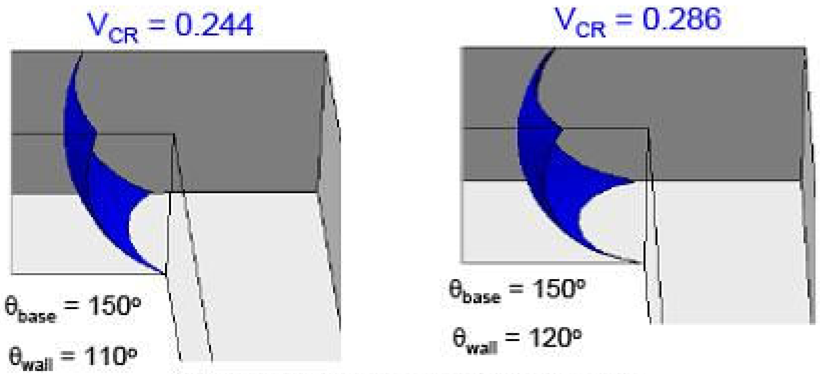




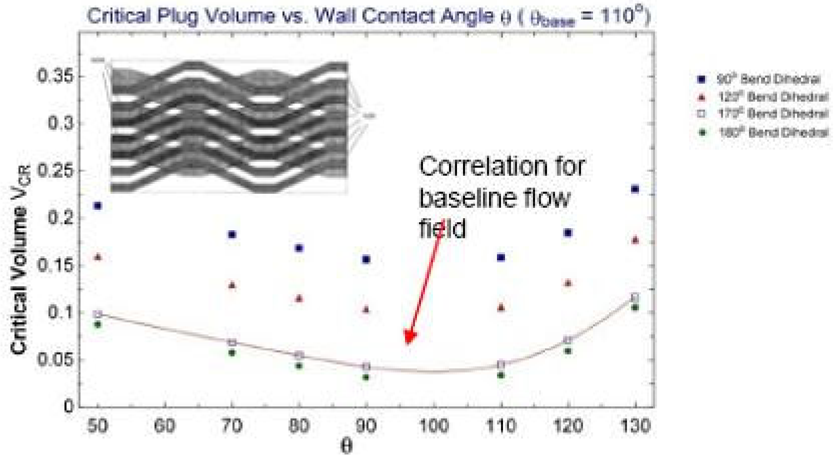
Channel Characterization

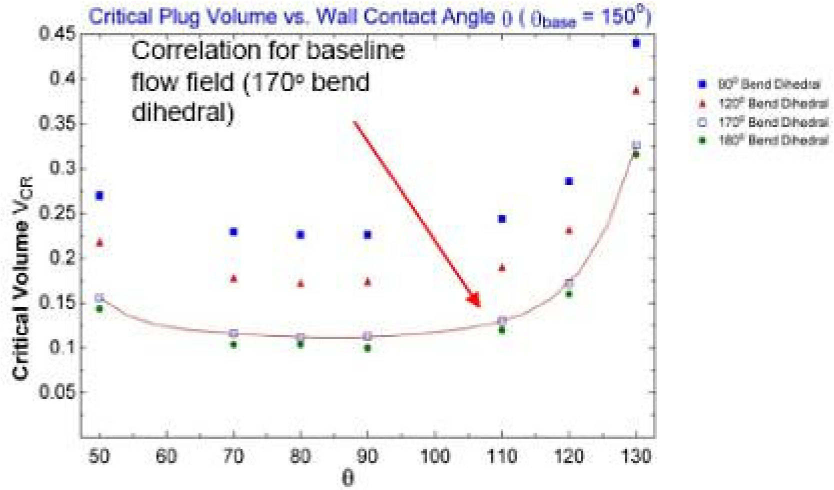
Single Channel Experiments

- effect of wettability on 2-phase flow transition presented.
- high speed microscopy shows extreme pressure spikes and density waves in channels at typical reactant purge velocities
- determined critical volume at which static liquid film or drop will spontaneously plug a channel:
  - ➢ function of channel and base (GDL) contact angles
  - ➢ solution generated via *Surface Evolver*
- use to predict location of channel plugging
- assist with developing channel purge strategies



symmetry plane on bend dihedral



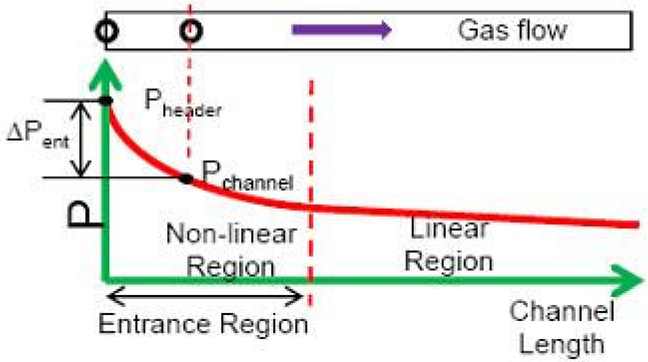


❑ Understanding critical volume for liquid plug formation can assist with flow field purge strategy.

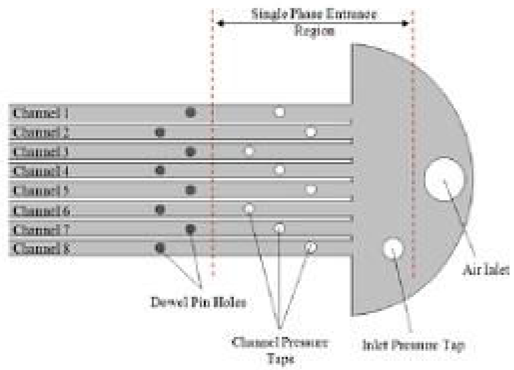
S. Kandlikar et al., (2009)

Water Transport in Channels - Flow Maldistribution

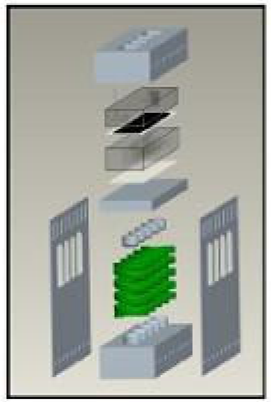
Entrance Region Pressure Drop Method:



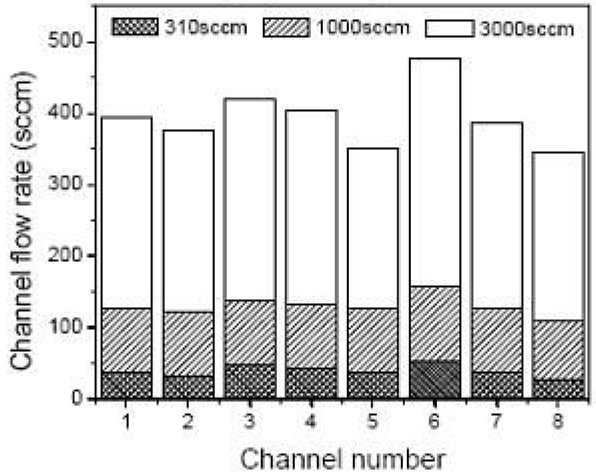
Individual pressure taps at the channel entrance



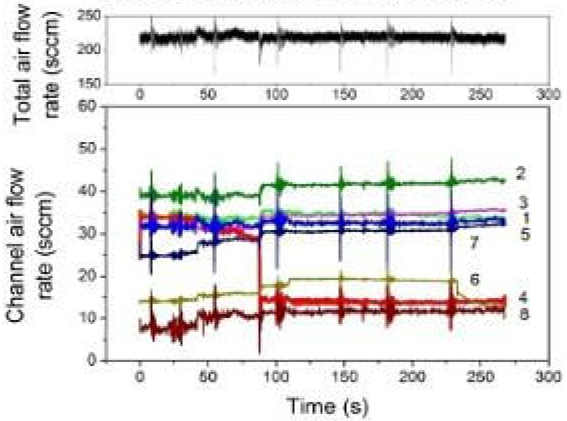
Test section with visual access



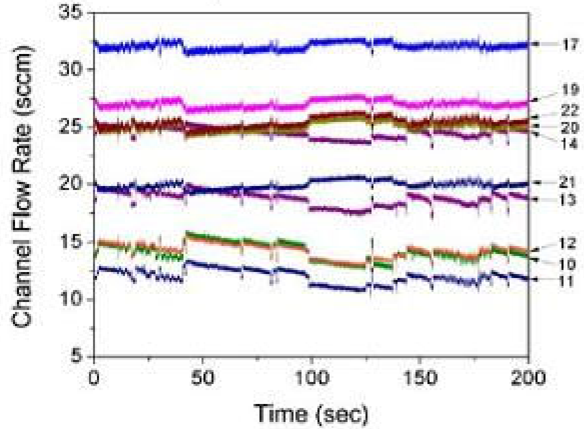
Channel maldistribution
Single-phase gas flow



EX-SITU *parallel channel flow*



IN-SITU *parallel channel flow*

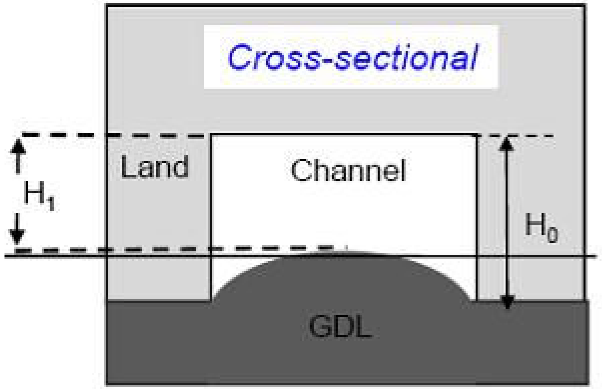


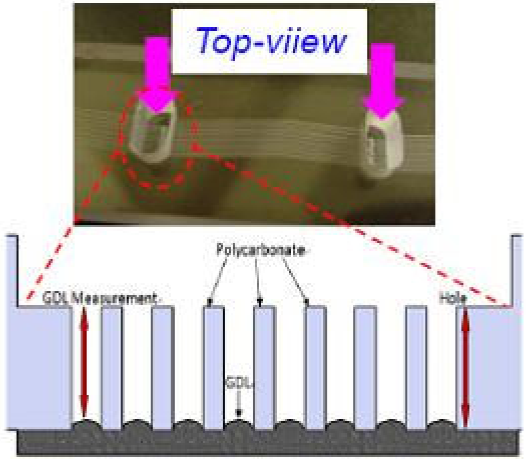
- Instantaneous flow distribution in individual channels measured.
- In-situ and ex-situ flow maldistribution and two-phase flow interactions in fuel cell gas channels characterized.

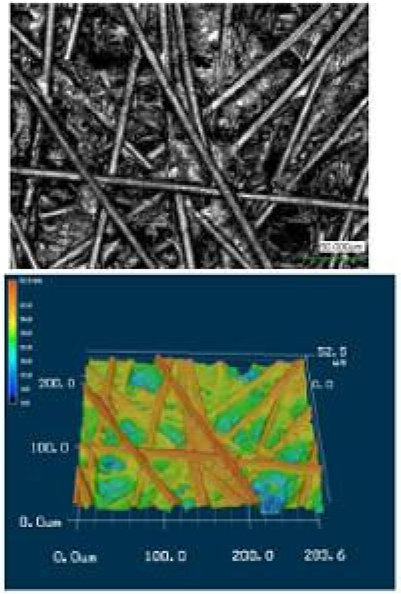
S. Kandlikar et al., (2009)

GDL Compression and Intrusion

Optical measurements:







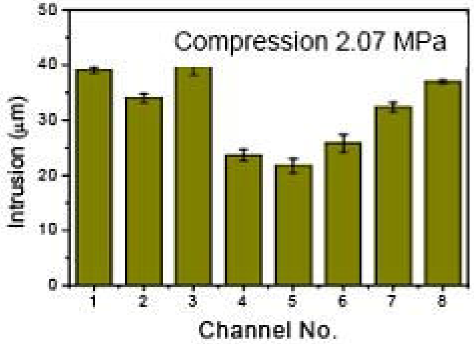
Entrance Region model:

$$\Delta p_{GDL,core} = \Delta p_{GDL,meas} - \Delta p_{minor}$$

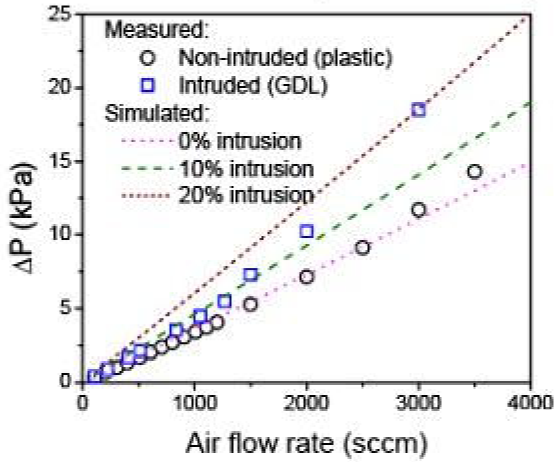
$$\Delta p_{core} = 2\frac{f_{app}\,\mathrm{Re}\,\mu x}{D_h^2}$$

$$H = \frac{W \cdot D_h}{2W - D_h}$$

Optical measurements of intrusion



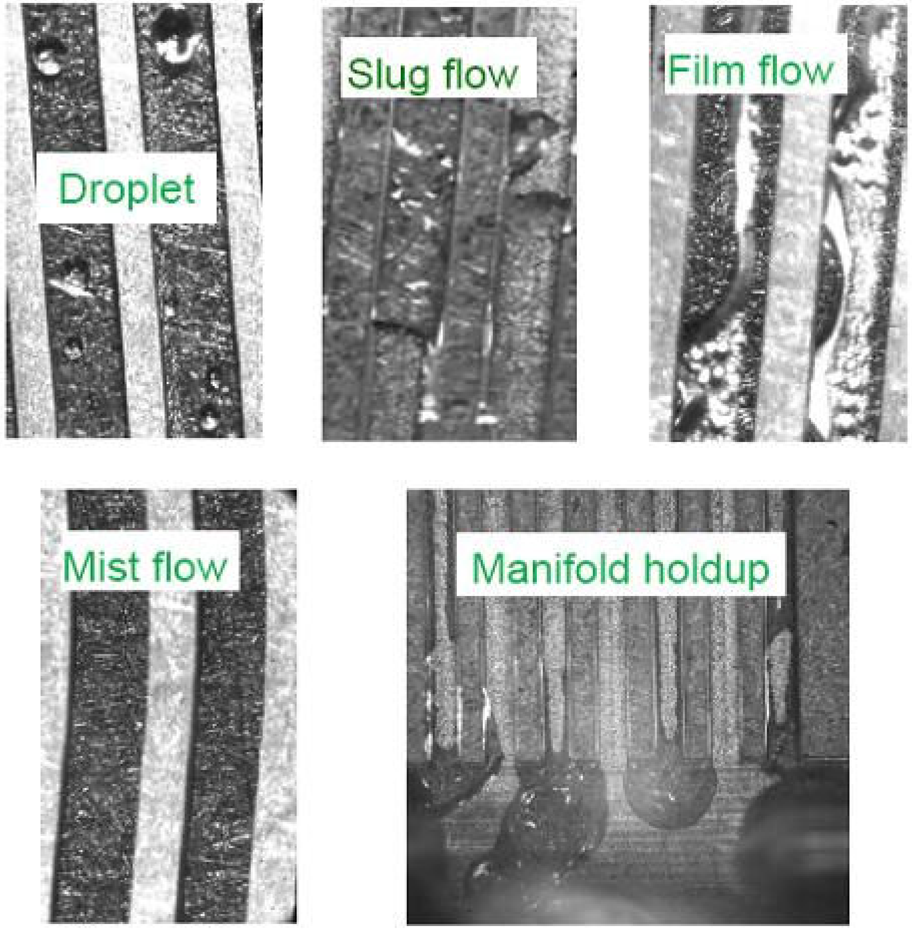
Intrusion effect on pressure drop



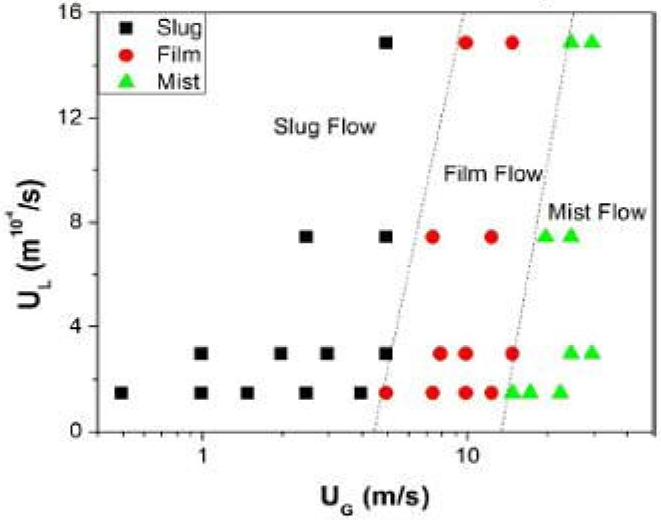
- Intrusion effects are seen as multiple orifices in series, rather than uniform reduction in channel flow area.
- Optical intrusion measurements correlate well with pressure drop predictions and experimental data.
- Instantaneous channel flow measurement in individual channels under in-situ and ex-situ conditions

S. Kandlikar et al., (2009)

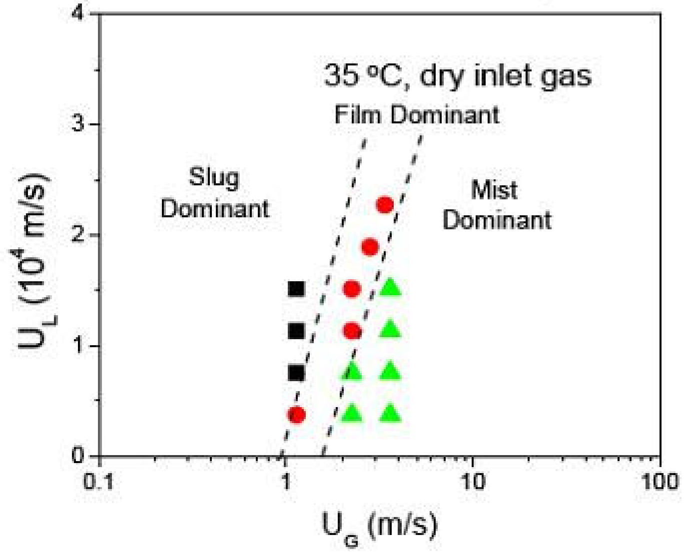
Two-Phase Flow Patterns



Ex-situ Flow Pattern Map

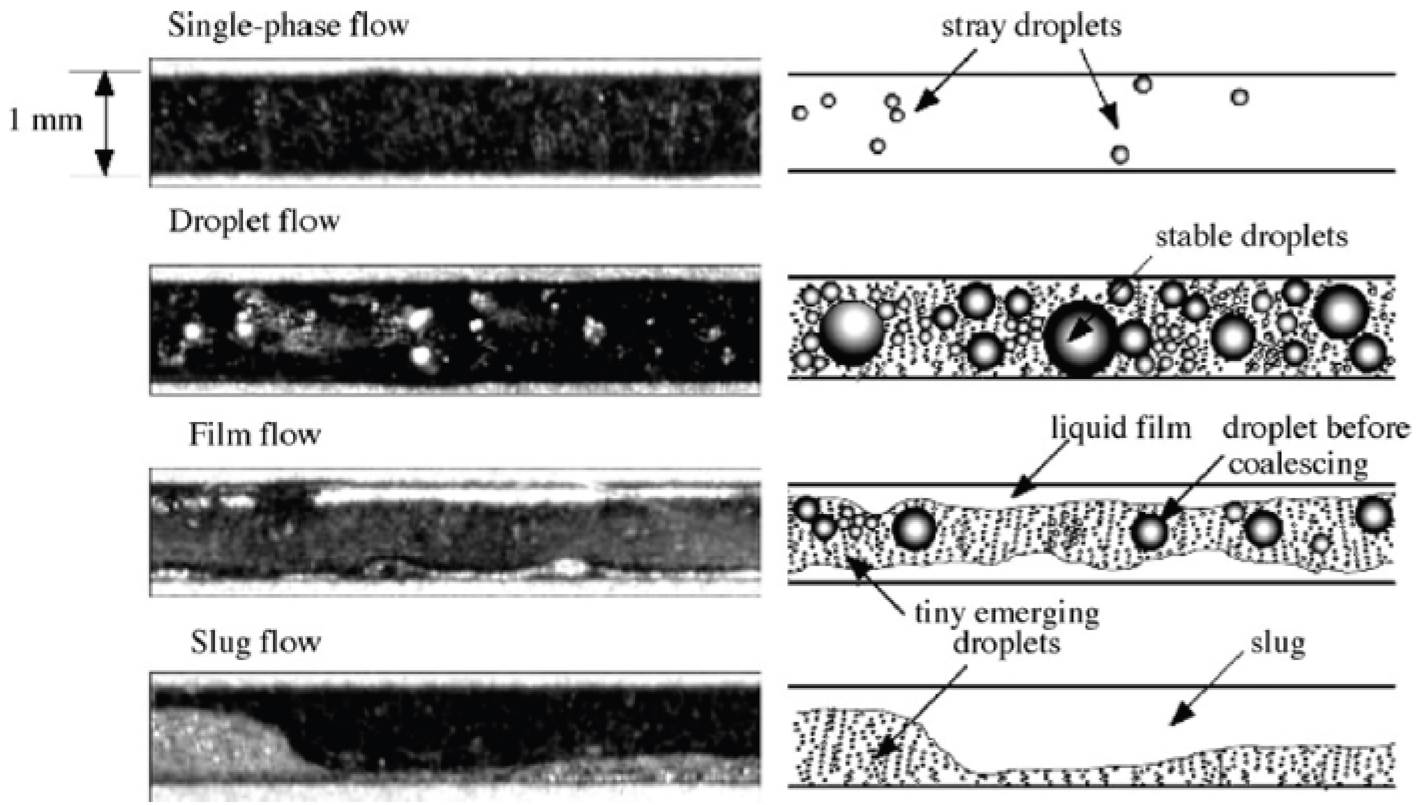


In-situ Flow Pattern Map



- Three basic flow patterns observed: Slug Flow, Film Flow and Mist Flow in both in-situ and ex-situ experiments.
- Slug flow is highly undesirable as it leads to severe flow maldistribution.
- Manifold water holdup adversely affects channel flow.

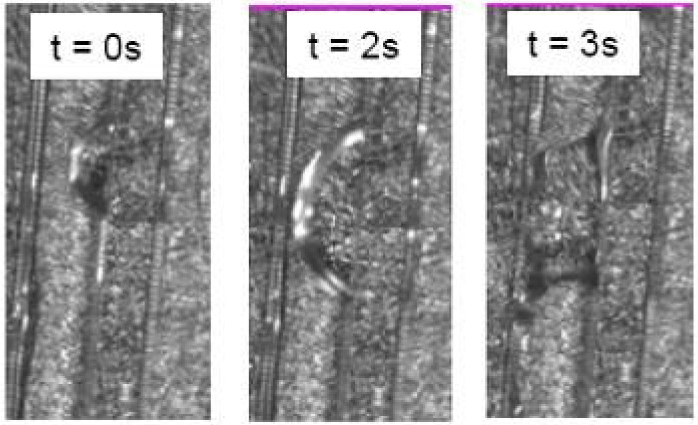
S. Kandlikar et al., (2009)

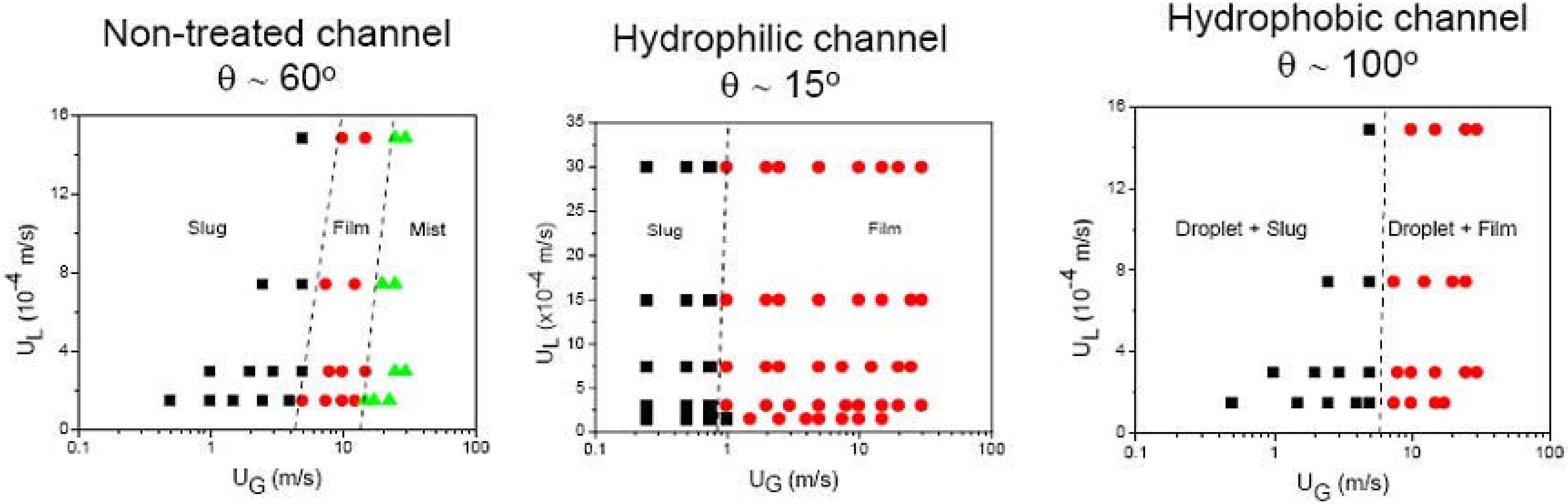


Single-phase flow
1 mm
stray droplets
Droplet flow
stable droplets
Film flow
liquid film
droplet before
coalescing
tiny emerging
droplets
Slug flow
slug

Slug Formation and Droplets on Channel

- ❑ An important trigger for the slug formation in channel is the large stationary droplets on the channel wall.
- ❑ The critical droplet size is a function of
  - ➢ channel contact angle
  - ➢ channel contact angle hysteresis.



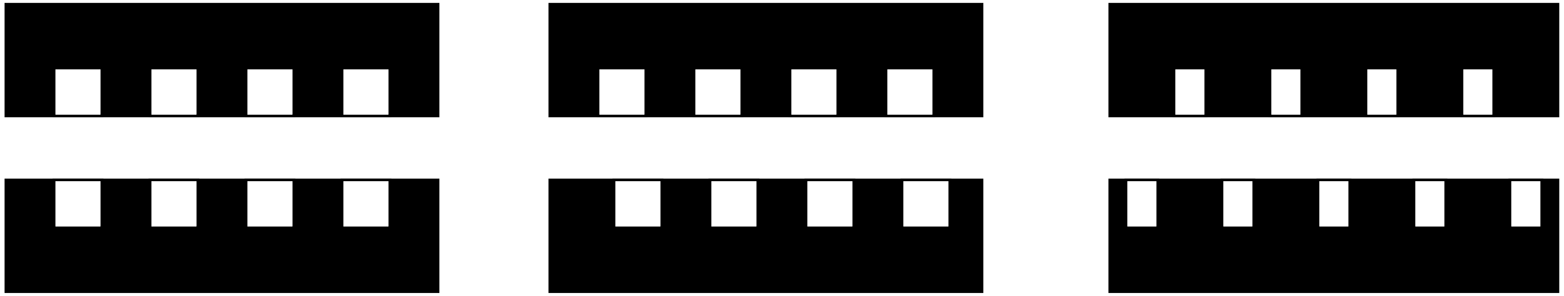


- ❑ Hydrophilic channels are preferred as they promote film flow rather than slug flow.
- ❑ Large contact angle hysteresis is not desirable as it promotes slug formation.

S. Kandlikar et al., (2009)

Anode vs. cathode orientation

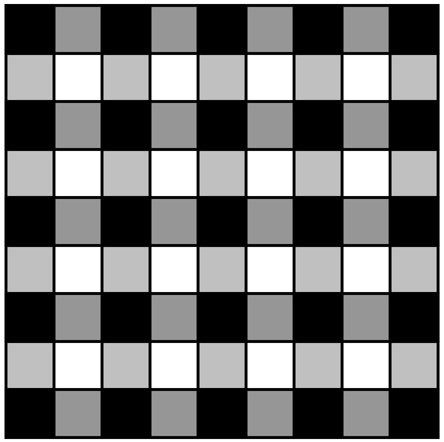
Parallel



$k = l/(l+c)$ $k = (l-o)/(l+c)$ $k = (l-c)/(l+c)$

Effect on electrical resistance

Cross



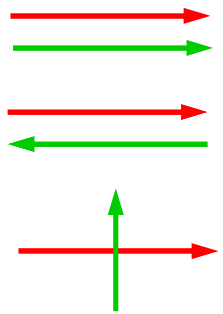
$k = [l/(l+c)]^2$

Anode vs. cathode flow direction

Co-flow

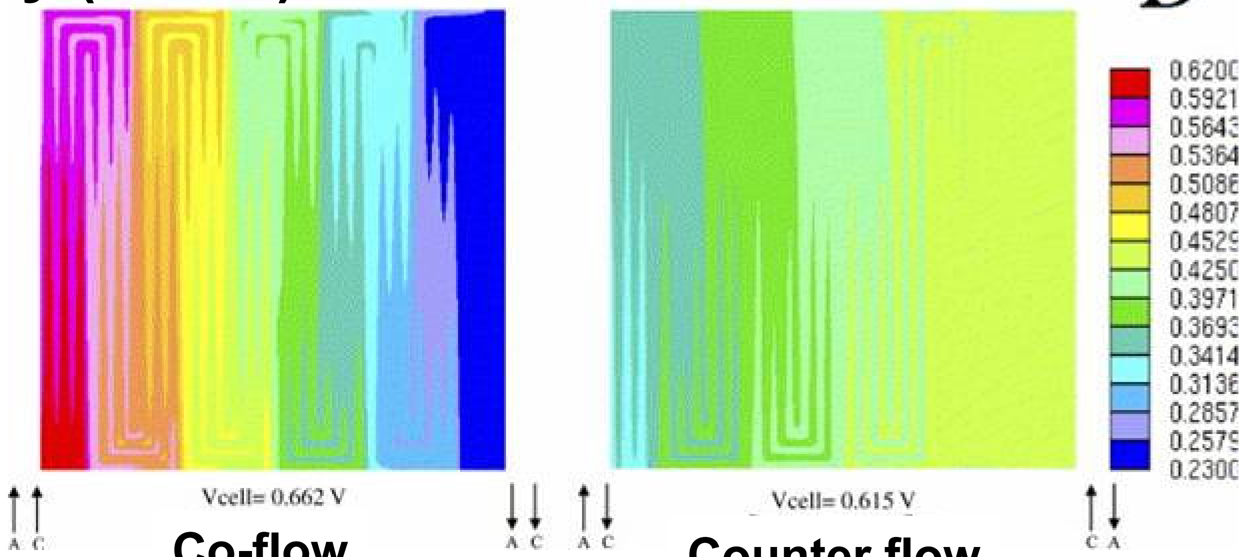
Counter-flow

Cross flow



Current density (A/cm^2) distributions

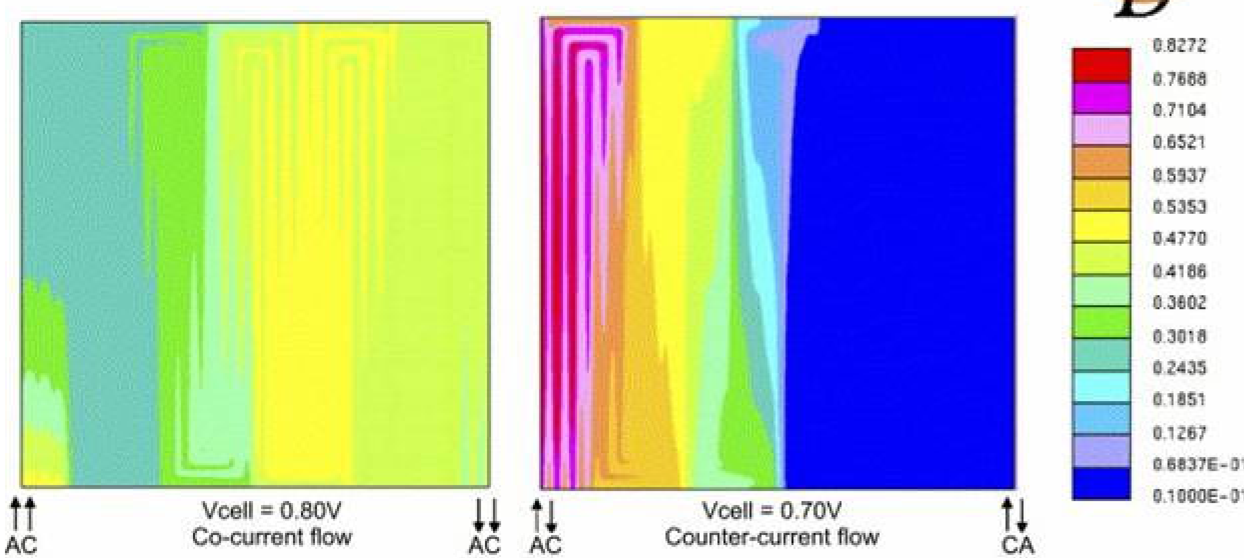
Stationary operating conditions:
H2 80 ◦C
Air 70 ◦C dew point at 40%
1.2/2.0 Stoich with 101 kPa pressure 70 ◦C cell temperature



Co-flow **Counter flow**

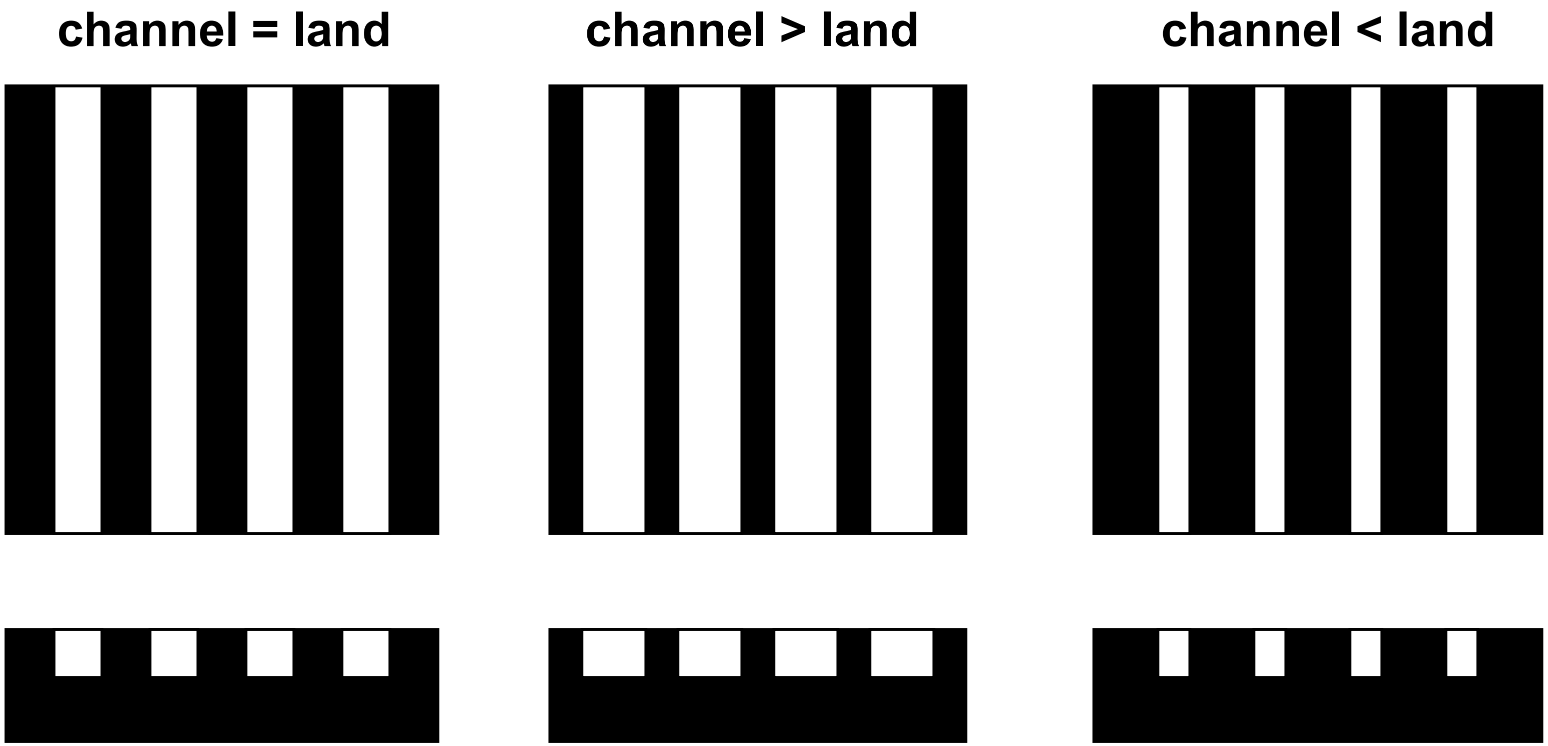
$$I_{avg} = 0.4\ A/cm^2$$

Automotive operating conditions:
H2 75% RH at 80 ◦C/
Air: DRY dew point at 100%
1.3/2.0 Stoich
274 kPa pressure
80 ◦C cell temperature



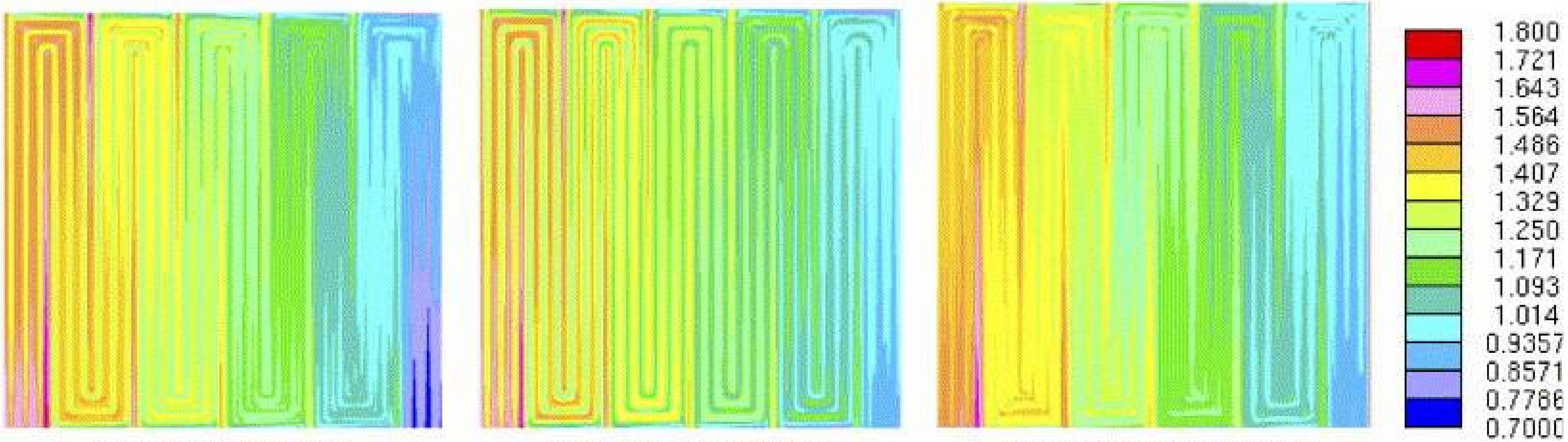
S. Shimpalee, J.W. Van Zee, Numerical studies on rib & channel dimension of flow-field on PEMFC performance, *Int. J. of Hydrogen Energy*, *Volume 32, Issue 7, 2007*, *Pages 842-856*

Channel dimensions and spacing



• Dimensions dictated by flow rates and desired velocities

Current density (A/cm^2) distributions at I_{avg} = 1.2 A/cm^2; stationary conditions

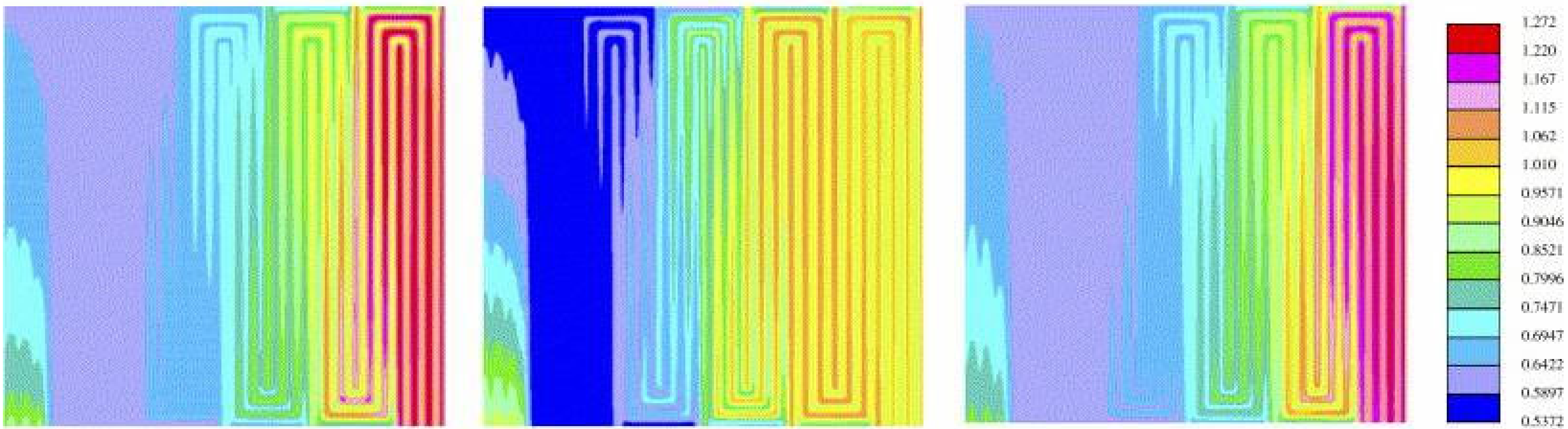


Base case 0.9 mm/0.9 mm
Vcell = 0.521 V

Channel wide 1.0 mm/0.7 mm
Vcell = 0.522 V

Channel narrow 0.7 mm/1.0 mm
Vcell= 0.5365 V

Current density (A/cm^2) distributions at I_{avg} = 0.8 A/cm^2; automotive conditions

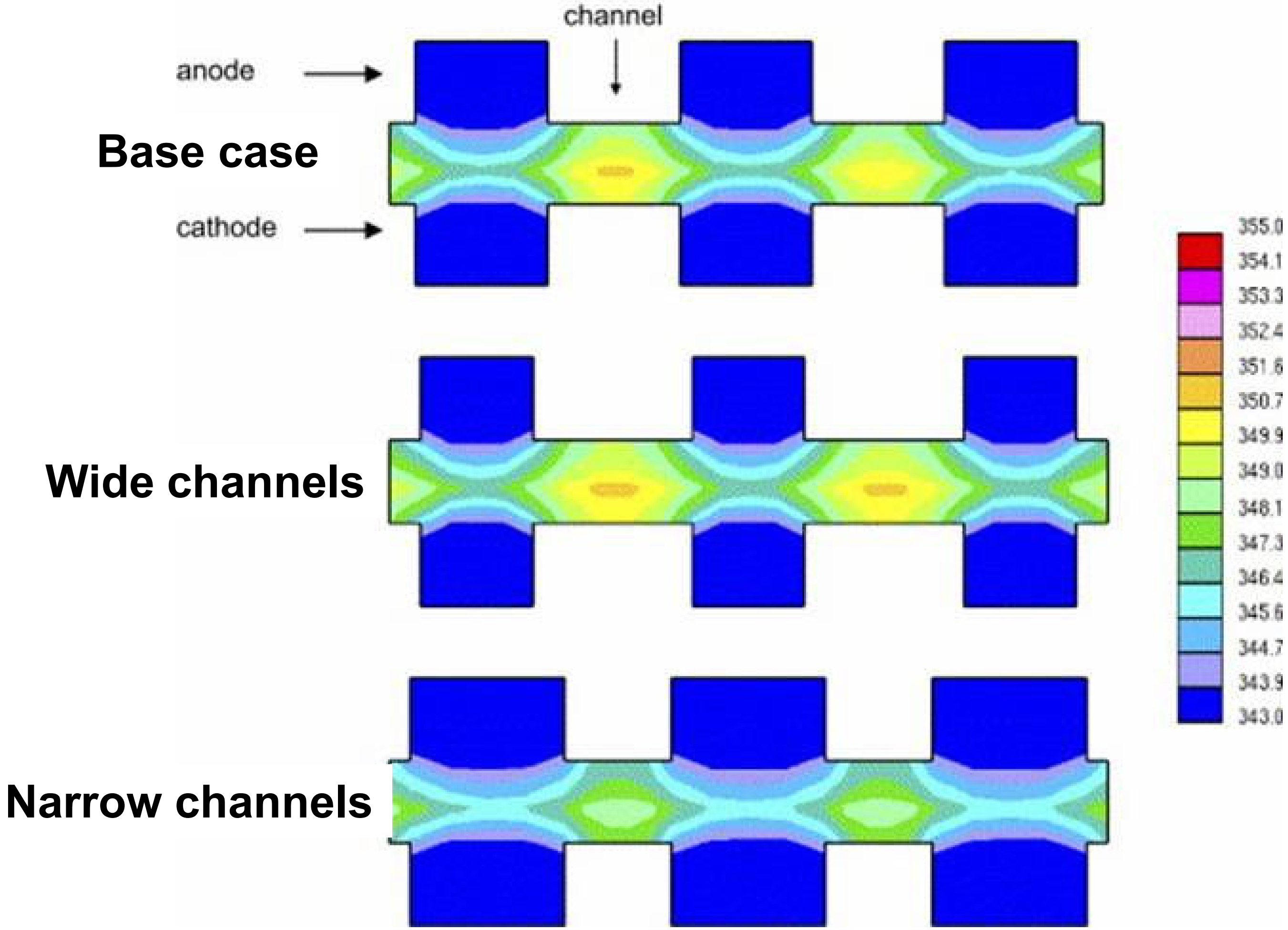


Base case 0.9 mm/0.9 mm
Vcell = 0.672 V

Channel wide 1.0 mm/0.7 mm
Vcell = 0.707 V

Channel narrow 0.7 mm/1.0 mm
Vcell = 0.677 V

Temperature (K) distributions at the cross flow plan (*x*–*y* plane) located in the middle of flow-field



S. Shimpalee, J.W. Van Zee, Numerical studies on rib & channel dimension of flow-field on PEMFC performance, *Int. J. of Hydrogen Energy*, *Volume 32, Issue 7*, *2007*, *Pages 842-856*

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Numerical studies on rib & channel dimension of flow-field on PEMFC performance

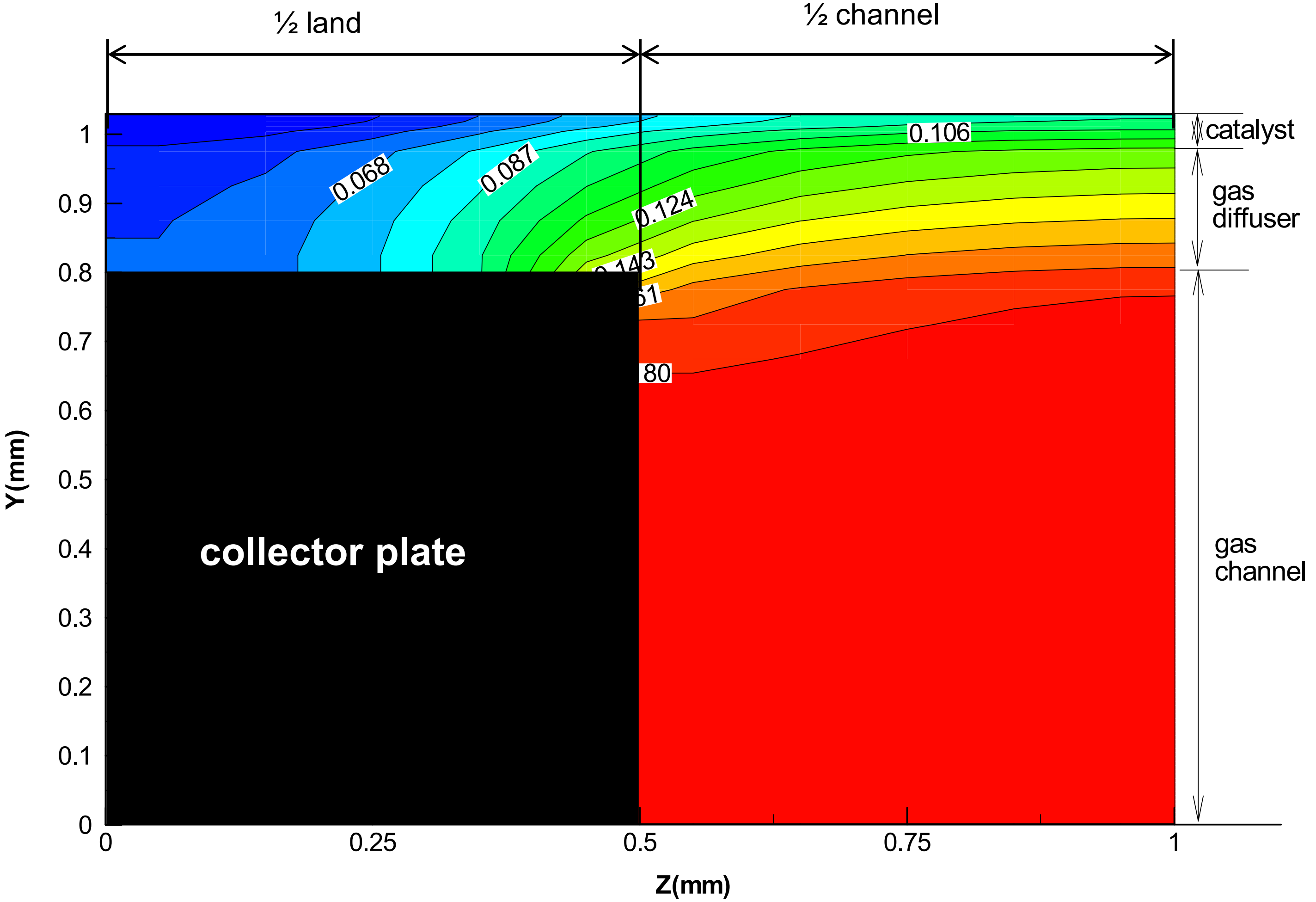
S. Shimpalee*, J.W. Van Zee

NSF I/UCRC for Fuel Cells, Department of Chemical Engineering, University of South Carolina, Columbia, SC 29208, USA

Conclusions: The effect of channel/rib width on PEMFC performance

- **The performance is slightly higher for the narrower channel with wider rib spacing for stationary condition.**
- **Larger rib area gives better heat transfer from MEA toward collector.**
- **The global uniformity of distributions is similar for all channel/rib width.**
- **Wider channel with narrower rib shows more local nonuniformity distributions between channel and rib.**
- **Pressure drop increases when the channel area is reduced.**

Effect on local current density



Source: University of Miami presentation at Annual National Laboratory R&D Meeting
DOE Fuel Cells for Transportation Program, Oak Ridge, June 6 - 8, 2001

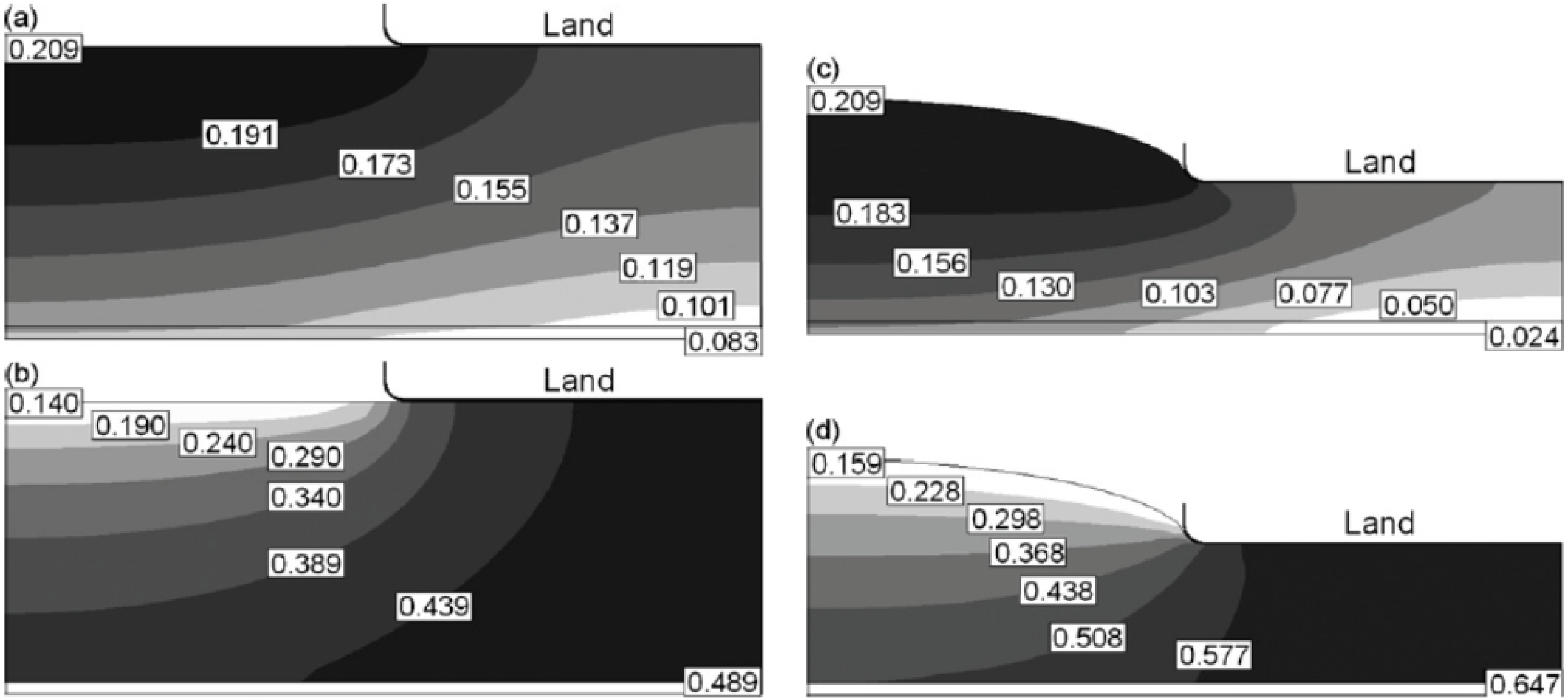


Fig. 6. Distributions of (a) oxygen mole fraction with 0% compression ratio, (b) liquid water saturation level with 0% compression ratio, (c) oxygen mole fraction with 50% compression ratio and (d) liquid water saturation level with 50% compression ratio (cell voltage: 0.3V; contact angle of the GDL: 89◦;contact resistance: neglected).Zhou, Wu reference

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Passive control of liquid water storage and distribution in a PEFC through flow-field design

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Fuel Cell Dynamics and Diagnostics Laboratory, Radiation Science and Engineering Center, Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, United States

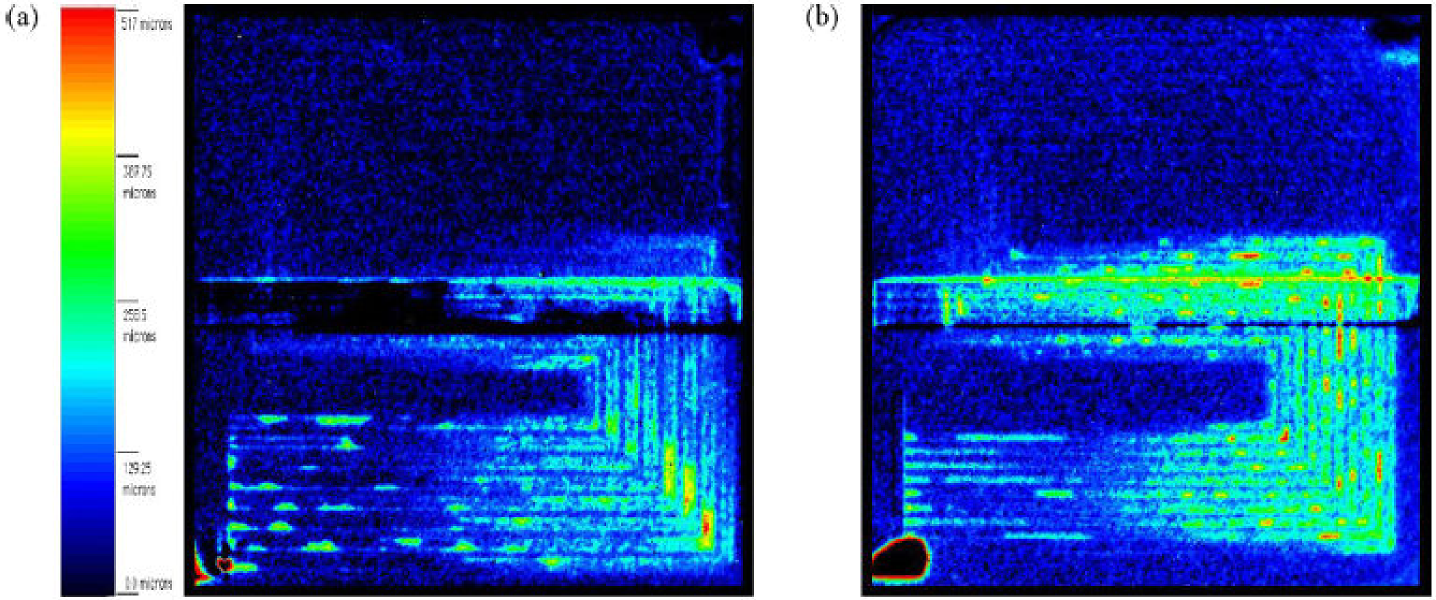
The motivation of this study was to understand the implication of L:C ratio and channel–DM interface on the liquid water content stored in the diffusion media and flow channels during steady-state operation

Neutron imaging at the Penn State Breazeale Nuclear Reactor Fuel Cell Imaging Laboratory was used to quantify liquid water content and distribution in 50 cm^2 fuel cells with L:C ratios from 1:3 to 2:1.

Table 1
Experimental test matrix

Cell configuration landing-channel	Current density ($A\,cm^{-2}$)	Inlet relative humidity (%)
0.5×0.5	$0 \rightarrow 1.5$	50/100
0.5×1.5	$0 \rightarrow 1.5$	50/100
1.0×0.75	$0 \rightarrow 1.5$	50/100
1.0×1.0	$0 \rightarrow 1.5$	50/100
1.0×1.5	$0 \rightarrow 1.5$	50/100
2.0×1.0	$0 \rightarrow 1.5$	50/100
2.0×2.0	$0 \rightarrow 1.5$	50/100

All tests were performed at 80 °C, 150 kPa, anode/cathode stoichiometry of 2/2.

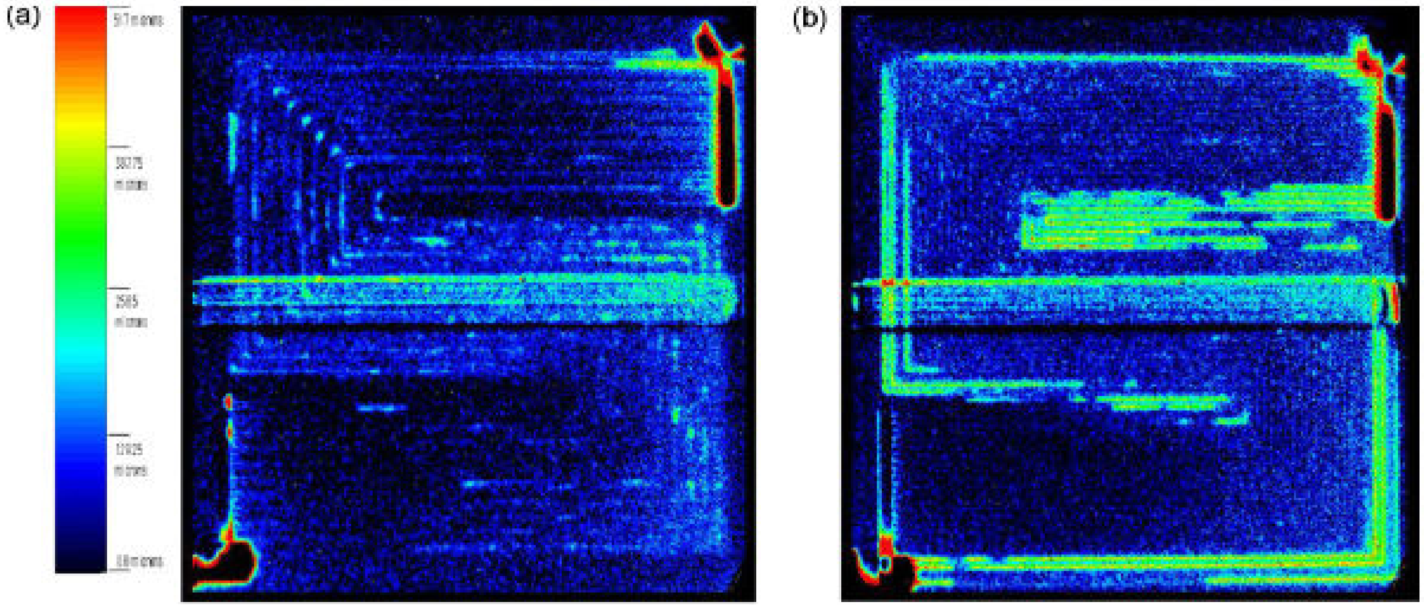


L/C: 1.0x1.5 Cell

L/C: 1.0x0.75 Cell

L:C 1.0 × 1.5					
50 RH		100 RH		Cathode velocity (m s^{-1})	Anode velocity (m s^{-1})
CH (mg)	L (mg)	CH (mg)	L (mg)		
79	73	210	151	1.21	0.93
81	74	240	174	2.41	1.85
79	73	218	161	3.62	2.78
78	73	188	169	4.83	3.70
91	85	158	152	6.03	4.63
71	67	111	122	7.24	5.56
75	70	101	107	8.44	6.48
67	63	104	110	9.05	6.95

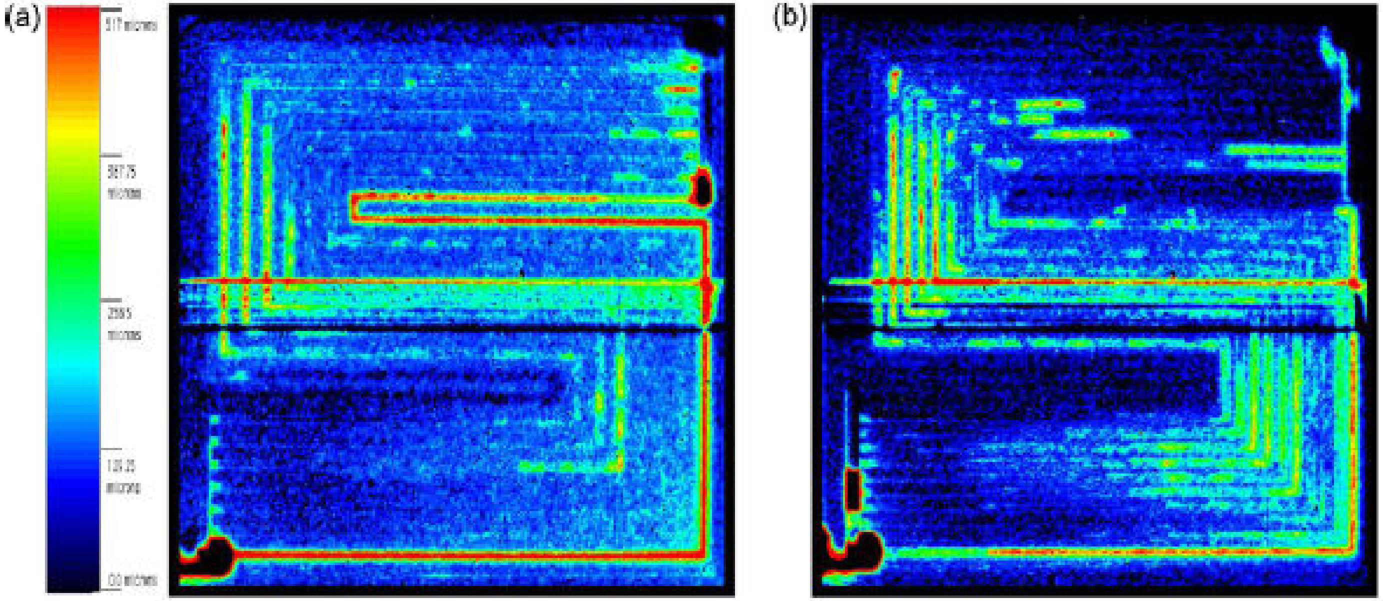
Current density (A cm^{-2})	Cell configuration					
	L:C 1.0 × 0.75					
	50 RH		100 RH		Cathode velocity (m s^{-1})	Anode velocity (m s^{-1})
	CH (mg)	L (mg)	CH (mg)	L (mg)		
0.2	85	126	234	281	1.67	1.28
0.4	86	127	270	301	3.34	2.56
0.6	94	140	412	403	5.01	3.85
0.8	89	133	322	354	6.68	5.13
1.0	98	145	247	306	8.35	6.41
1.2	92	136	205	284	10.02	7.69
1.4	77	115	180	257	11.69	8.98
1.5	72	109			12.53	9.62



L:C 0.5x1.5 cell L:C 0.5x0.5 cell

L:C 0.5 × 1.5					
50 RH		100 RH		Cathode velocity ($m\,s^{-1}$)	Anode velocity ($m\,s^{-1}$)
CH (mg)	L (mg)	CH (mg)	L (mg)		
172	75	254	99	0.90	0.69
81	43	323	119	1.81	1.39
69	38	253	109	2.71	2.08
71	38	193	88	3.62	2.78
60	32	143	68	4.52	3.47
72	39	154	70	5.43	4.17
85	44	124	60	6.33	4.86
		141	67	6.79	5.21

Current density ($A\,cm^{-2}$)	Cell configuration					
	L:C 0.5 × 0.5					
	50 RH		100 RH		Cathode velocity ($m\,s^{-1}$)	Anode velocity ($m\,s^{-1}$)
	CH (mg)	L (mg)	CH (mg)	L (mg)		
0.2	110	152	209	231	1.36	1.04
0.4	113	150	279	292	2.71	2.08
0.6	91	125	242	254	4.07	3.13
0.8	64	100	223	245	5.43	4.17
1.0	53	86	174	215	6.79	5.21
1.2	55	91	164	211	8.14	6.25
1.4	56	91			9.50	7.29
1.5					10.18	7.81

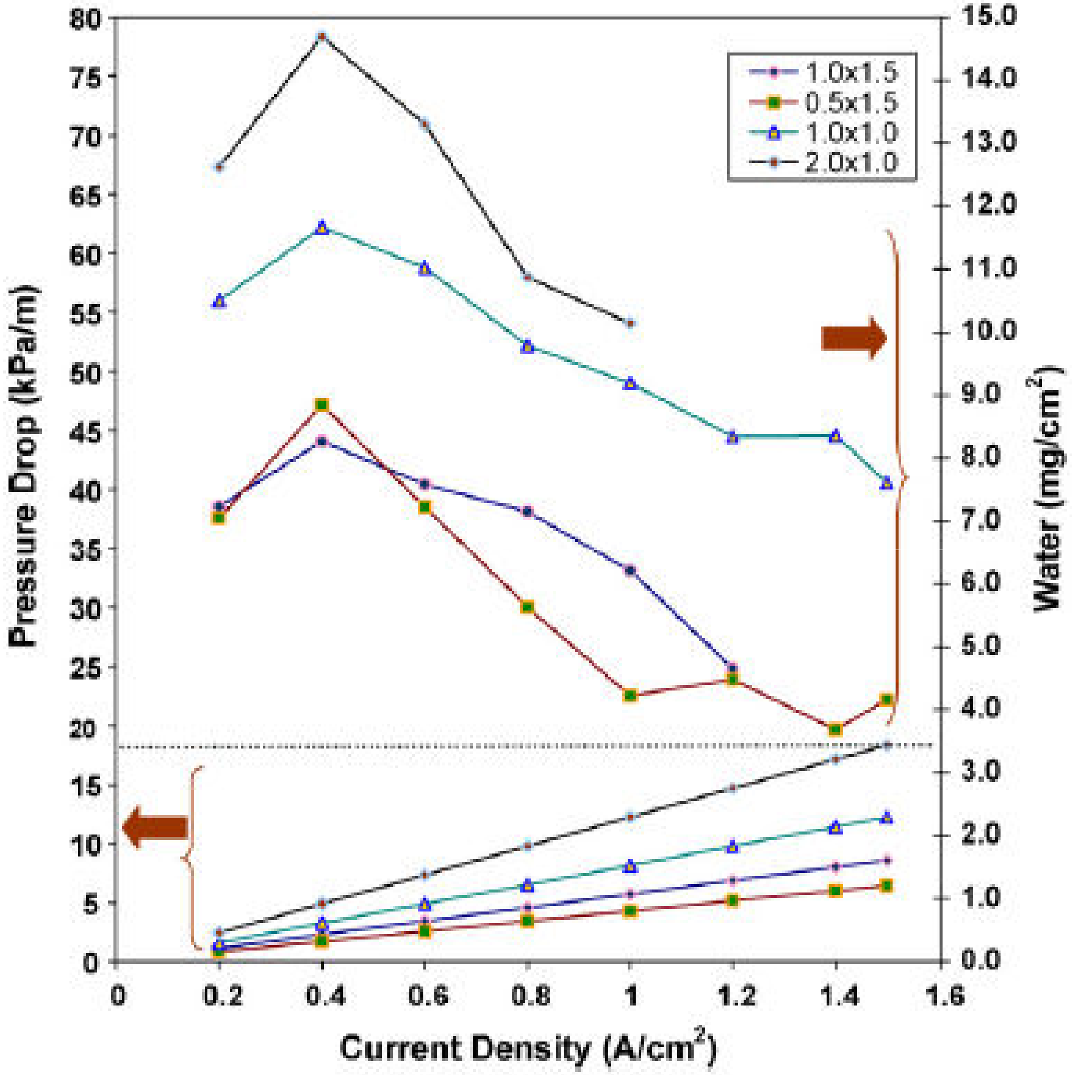


L:C 2.0x1.0 Cell

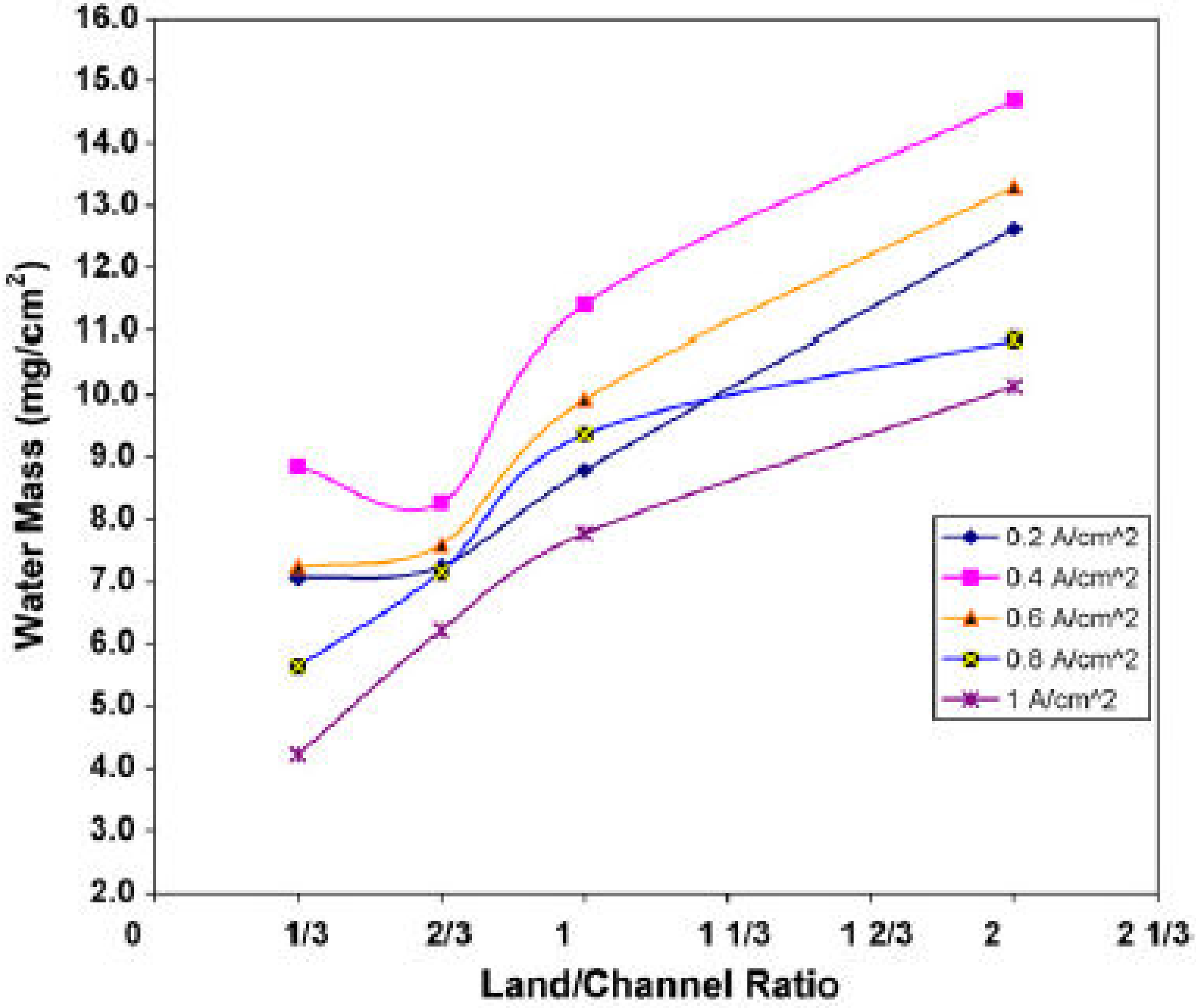
L:C 1.0x1.0 Cell

L:C 2.0 × 1.0					
50 RH		100 RH		Cathode velocity ($m\,s^{-1}$)	Anode velocity ($m\,s^{-1}$)
CH (mg)	L (mg)	CH (mg)	L (mg)		
95	204	268	363	2.04	1.56
76	170	307	428	4.07	3.13
79	182	271	394	6.11	4.69
88	195	190	354	8.14	6.25
90	200	174	333	10.18	7.81
81	179			12.21	9.38
				14.25	10.94
				15.27	11.72

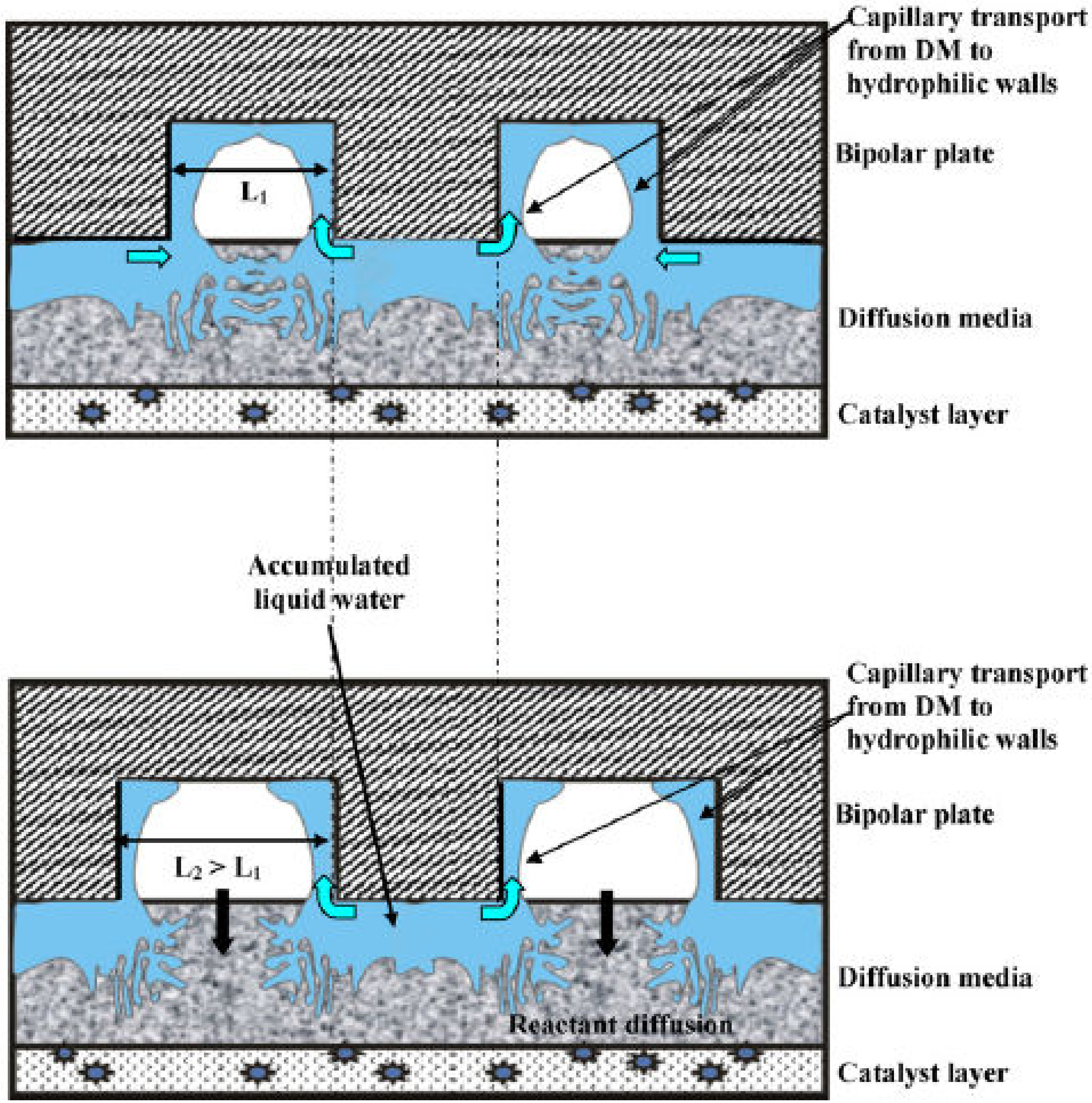
Current density ($A\,cm^{-2}$)	Cell configuration					
	L:C 1.0 × 1.0					
	50 RH		100 RH		Cathode velocity ($m\,s^{-1}$)	Anode velocity ($m\,s^{-1}$)
	CH (mg)	L (mg)	CH (mg)	L (mg)		
0.2	163	167	269	256	1.36	1.04
0.4	94	118	300	283	2.71	2.08
0.6	81	116	273	278	4.07	3.13
0.8	73	110	230	260	5.43	4.17
1.0	56	89	212	247	6.79	5.21
1.2	59	92	189	228	8.14	6.25
1.4	57	90	191	227	9.50	7.29
1.5	55	86	170	211	10.18	7.81



Pressure Drop (kPa/m)
Water (mg/cm^2)
Current Density (A/cm^2)
1.0x1.5
0.5x1.5
1.0x1.0
2.0x1.0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0



16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
Water Mass (mg/cm^2)
0
1/3
2/3
1
1 1/3
1 2/3
2
2 1/3
Land/Channel Ratio
0.2 A/cm^2
0.4 A/cm^2
0.6 A/cm^2
0.8 A/cm^2
1 A/cm^2



Capillary transport
from DM to
hydrophilic walls
Bipolar plate
L_1
Diffusion media
Catalyst layer
Accumulated
liquid water
Capillary transport
from DM to
hydrophilic walls
Bipolar plate
$L_2 > L_1$
Diffusion media
Reactant diffusion
Catalyst layer

Results indicate:

(1) for L:C ratios of one, the liquid water tends to preferentially accumulate under landings rather than in, or under the channels,

(2) water storage is not only a function of diffusion media but also dependent on the flow-field geometry and the number of interfaces for a hydrophilic channel wall,

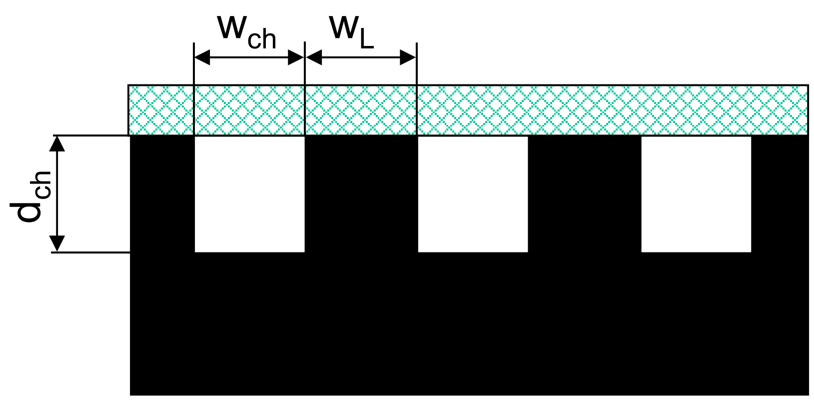
(3) it is possible to obtain similar cell performance at low to moderate current density with vastly different amounts of stored water by tailoring the flow-field geometry,

(4) as the L:C ratio is reduced, the liquid stored in the cell decreases, with an optimal condition for L:C ratios smaller than 2:3,

(5) the number of channel–DM interface for the same L:C ratio has an important influence on water accumulation. Corners are preferred water storage sites and a reduced number of channel–DM interface corresponds to less corners and turns for a serpentine design which results in low water mass in the cell,

(6) at dry operation, a high L:C ratio can be helpful, while at high humidity ratio, a low L:C is preferred.

Pressure drop in channel



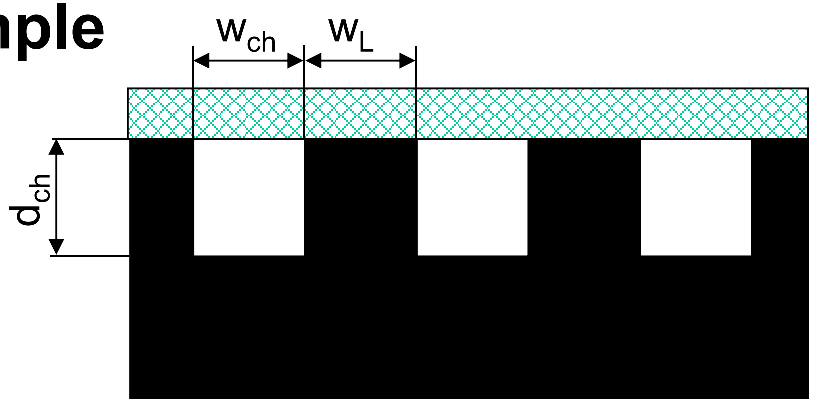
$$\Delta P = f\,\frac{L}{D_H}\rho\frac{\overline{v}^2}{2} + \sum K\rho\frac{\overline{v}^2}{2}$$

f = friction factor
L = channel length, m
D_H = hydraulic diameter, m
ρ = fluid density, kg m^{-3}
v = average velocity, m s^{-1}
K = local resistance (for example in sharp turns)

$$L = \frac{A_{cell}}{N_{ch}\left(w_{ch} + w_L\right)}$$

$$D_H = \frac{2w_{ch}d_{ch}}{w_{ch} + d_{ch}}$$

Velocity in channel - example



Air
$S = 2$
$i = 1\ A/cm^2$
$T = 60^{o}C$
$P = 101.3\ kPa$

$L_{ch} = 10\ cm$
$w_{ch} = 0.1\ cm$
$w_L = 0.1\ cm$
$d_{ch} = 0.1\ cm$

$$v_{ch} = \frac{RT}{P}\frac{Si}{nF}\frac{L_{ch}}{r_L d_{ch}} \qquad \dot{m}_{ch} = S\frac{M_{air}I}{4F}\frac{1}{c_{O2}} \qquad v_{ch} = \frac{RT}{P}\frac{Si}{nF}\frac{1}{c_{O2}}\frac{L_{ch}}{r_L d_{ch}}$$

$$v_{ch} = \frac{8.314 \cdot 333}{101{,}300}\frac{2 \cdot 10{,}000}{4 \cdot 96{,}485}\frac{1}{0.21}\frac{0.1}{0.5 \cdot 0.001} = 1.35\ m/s$$

$$Re = \frac{Dv}{\nu} \qquad D = 4R_h \qquad R_h = \frac{A}{P_m} = \frac{0.001^2}{4 \cdot 0.001} = 0.00025\ m$$

$$Re = \frac{4 \cdot 0.00025 \cdot 1.35}{1.87 \cdot 10^{-5}} = 72$$

$$Re = \frac{\rho v D_H}{\mu}$$

Viscosity of fuel cell gases (at 25°C)

	Viscosity kg m^{-1} s^{-1}	Coefficient C
Hydrogen	0.92×10^{-5}	72
Air	1.81×10^{-5}	120
Water vapor	1.02×10^{-5}	660

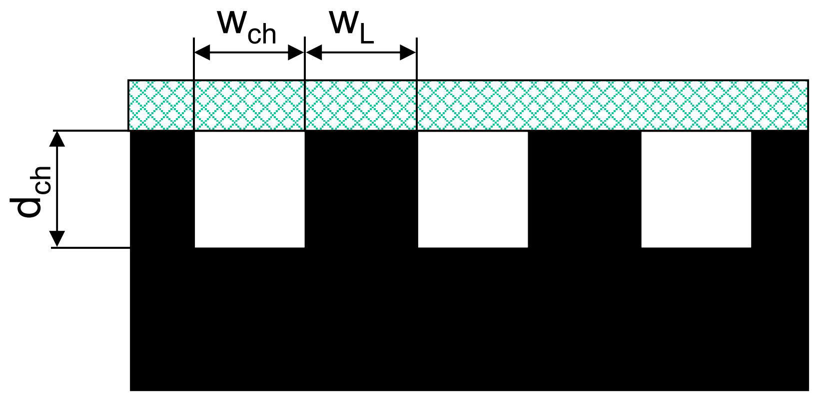
$$\mu = \mu_0 \left(\frac{T_0 + C}{T + C}\right)\left(\frac{T}{T_0}\right)^{\frac{3}{2}}$$

$$\mu_{mix} = \frac{\mu_1}{1 + \Psi_1 \frac{M_2}{M_1}} + \frac{\mu_2}{1 + \Psi_2 \frac{M_1}{M_2}}$$

$$\Psi_1 = \frac{\sqrt{2}}{4}\left(1 + \left(\frac{\mu_1}{\mu_2}\right)^{0.5}\left(\frac{r_2}{r_1}\right)^{0.25}\right)^2 \left(1 + \frac{r_1}{r_2}\right)^{-0.5}$$

$$\Psi_2 = \frac{\sqrt{2}}{4}\left(1 + \left(\frac{\mu_2}{\mu_1}\right)^{0.5}\left(\frac{r_1}{r_2}\right)^{0.25}\right)^2 \left(1 + \frac{r_2}{r_1}\right)^{-0.5}$$

Velocity in channel



$$v_{ch} = \frac{Q_{ch}}{A_{ch}} \qquad \mathbf{A_{ch} = w_{ch} d_{ch}}$$

Volumetric flow rate:

$$Q_{ch} = \frac{\dot{m}_{ch}}{\rho} = \frac{\dot{m}_{ch} RT}{PM}$$

Mass flow rate:

$$\dot{m}_{ch} = S \frac{MI}{nF} \frac{1}{c_{O2in}} \qquad \mathbf{I = iA} \qquad \mathbf{A = L_{ch}(w_{ch} + w_L)} \qquad r_L = \frac{w_{ch}}{(w_{ch} + w_L)}$$

$$\mathbf{A = L_{ch} \frac{w_{ch}}{r_L}}$$

Velocity in channel

For dry air: $$v_{ch} = \frac{RT}{P} \frac{i}{nF} \frac{S}{c_{O2in}} \frac{L_{ch}}{r_L d_{ch}}$$

For humid air: $$v_{ch} = \frac{RT}{P - \varphi P_{vsat}} \frac{i}{nF} \frac{S}{c_{O2in}} \frac{L_{ch}}{r_L d_{ch}}$$

$$\Delta P = f \frac{L}{D_H} \rho \frac{\overline{v}^2}{2} + \sum K \rho \frac{\overline{v}^2}{2}$$

For laminar flow $\quad \mathrm{Re}\, f = constant$

For circular channels (pipes): $\quad \mathrm{Re}\, f = \boldsymbol{64}$

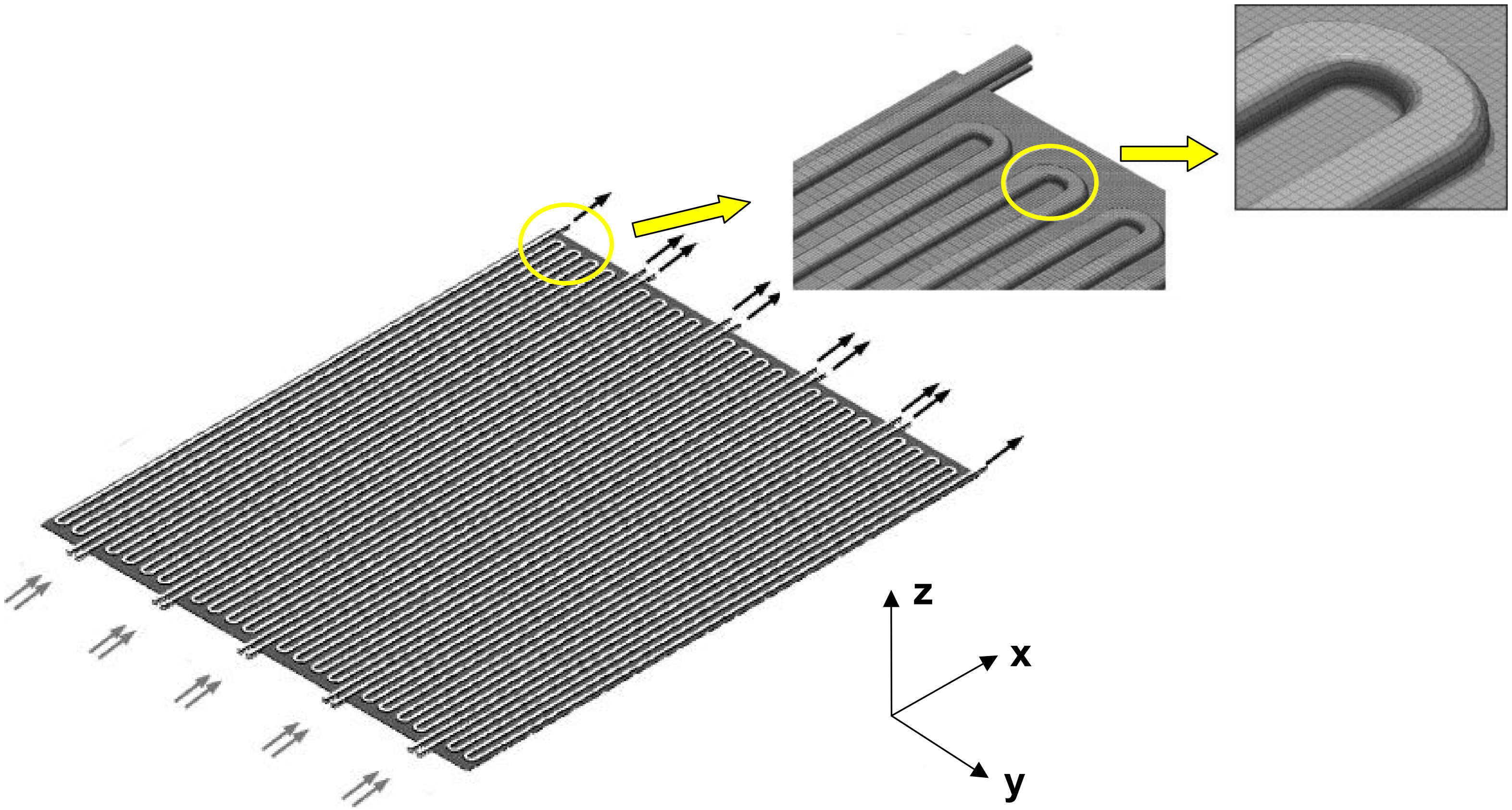
For rectangular channels: $\quad \mathrm{Re}\, f \approx 55 + 41.5\, exp\left(\frac{-3.4}{b/d}\right)$

For square channels: $\quad \mathrm{Re}\, f \approx \boldsymbol{56}$

$$\Delta P = f \frac{L}{D_H} \rho \frac{\overline{v}^2}{2} + \sum K \rho \frac{\overline{v}^2}{2}$$

For sharp turns (90°): $K = 30\,f$

For return bends (180°): $K = 50\,f$



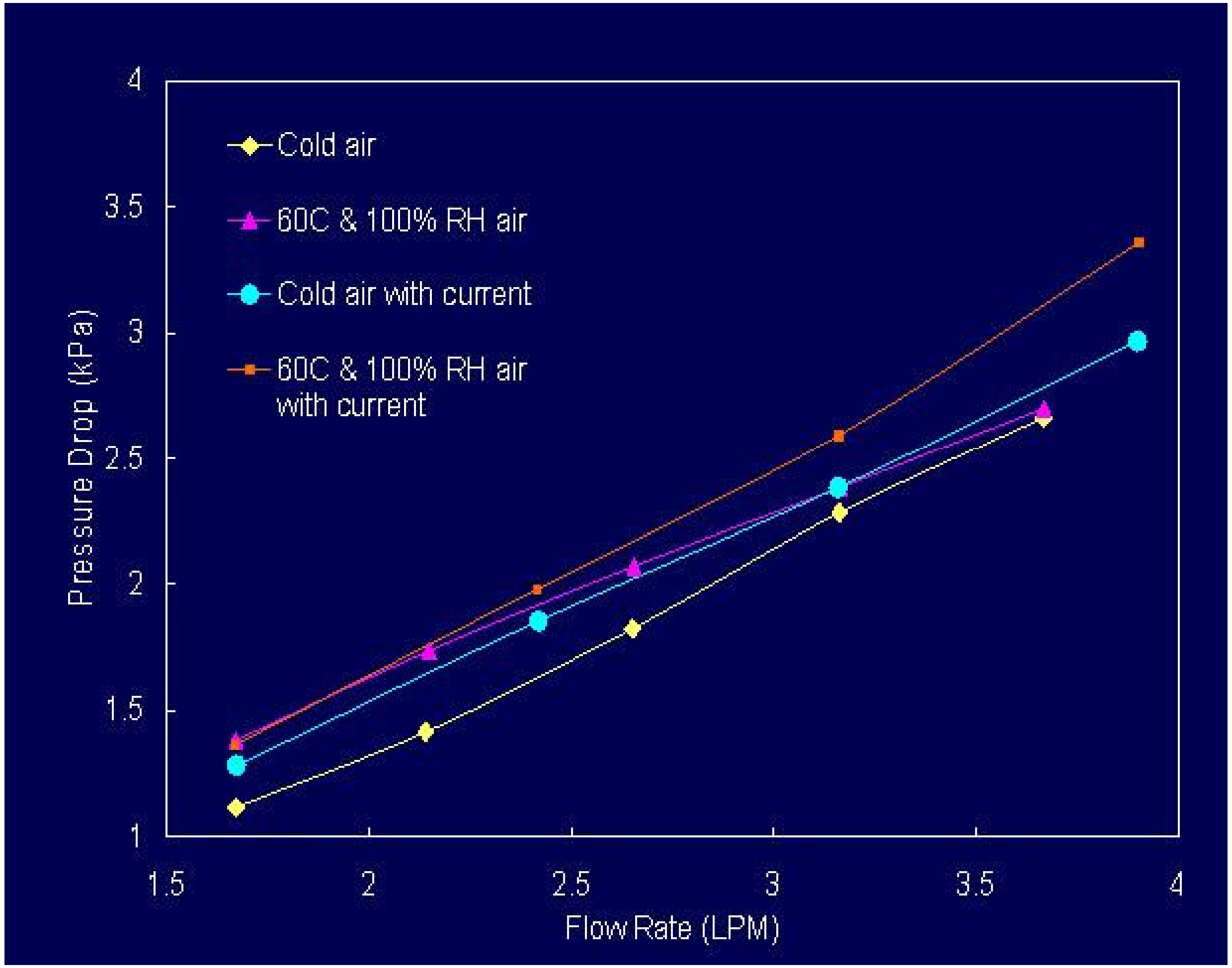
$$Q_{stack} = \frac{I}{4F}\frac{S}{r_{O2}}\frac{RT}{P - \varphi P_{sat}}N_{cell}$$

$$v = \frac{i}{4F}\frac{S}{r_{O2}}\frac{(b + w)L}{bd}\frac{RT}{P - \varphi P_{sat}}$$

$$\Delta P = f \ \frac{L}{D_H}\rho\frac{\overline{v}^2}{2} + \sum K\rho\frac{\overline{v}^2}{2}$$

$$Q_{stack}^{out} = \frac{I}{4F}\left(\frac{S}{r_{O2}} - 1\right)\frac{RT_{out}}{P_{in} - \Delta P - P_{sat}}N_{cell}$$

Pressure drop



- Cathode side pressure drop measured
- Stack at room temperature
- Current drawn proportional to flow rate 1.75 LPM every 10 A

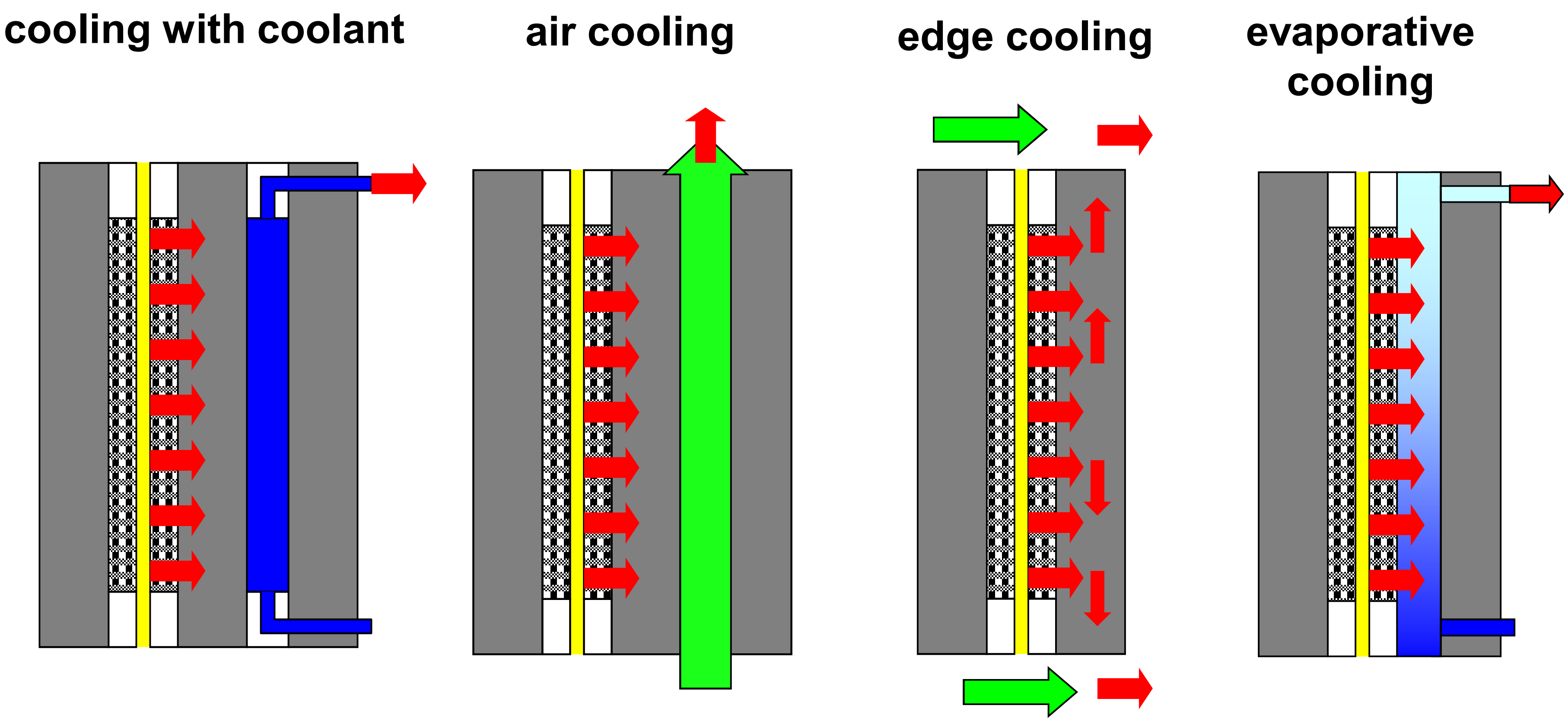
Pressure drop as a function of flow rate and stack inlet conditions for both operating and non-operating stack

Stack design/engineering issues

- Uniform distribution of reactants to each cell
- Uniform distribution of reactants inside each cell
- **Uniform temperature distribution in each cell**

Cooling is required to ensure uniform temperature distribution

Fuel cell cooling schemes



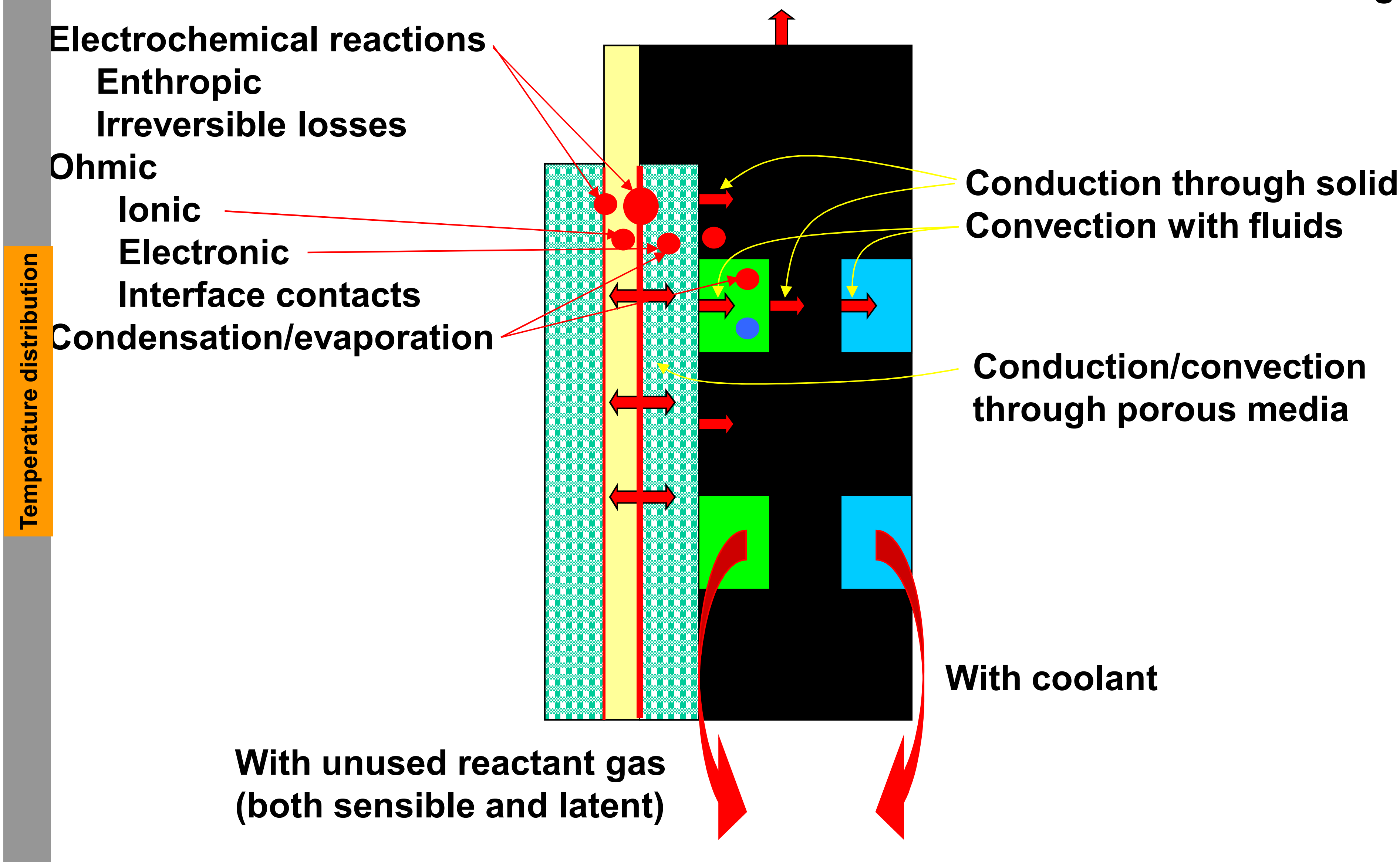
Heat Transfer Paths in Fuel Cell

Sources of Heat in Fuel Cell

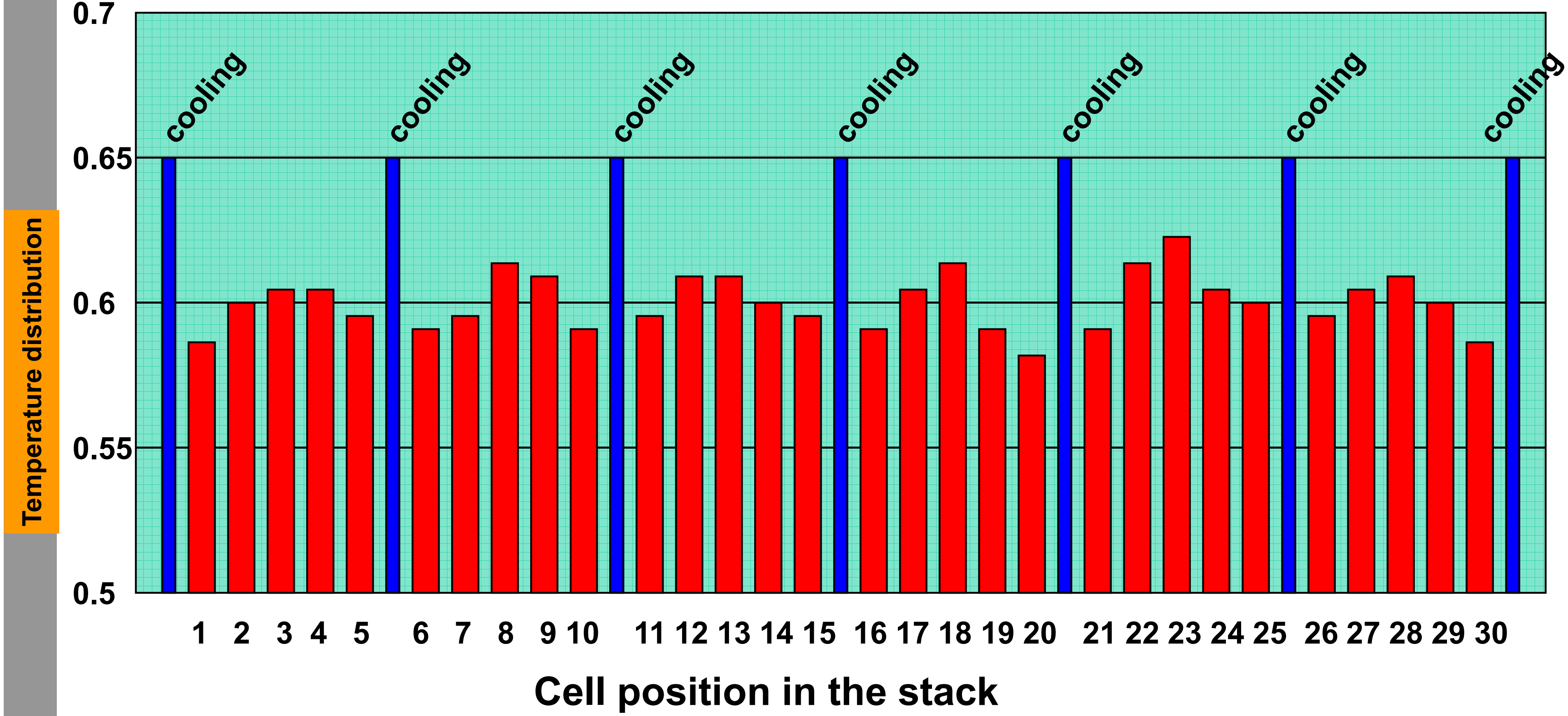
Electrochemical reactions
- Enthropic
- Irreversible losses

Ohmic
- Ionic
- Electronic
- Interface contacts

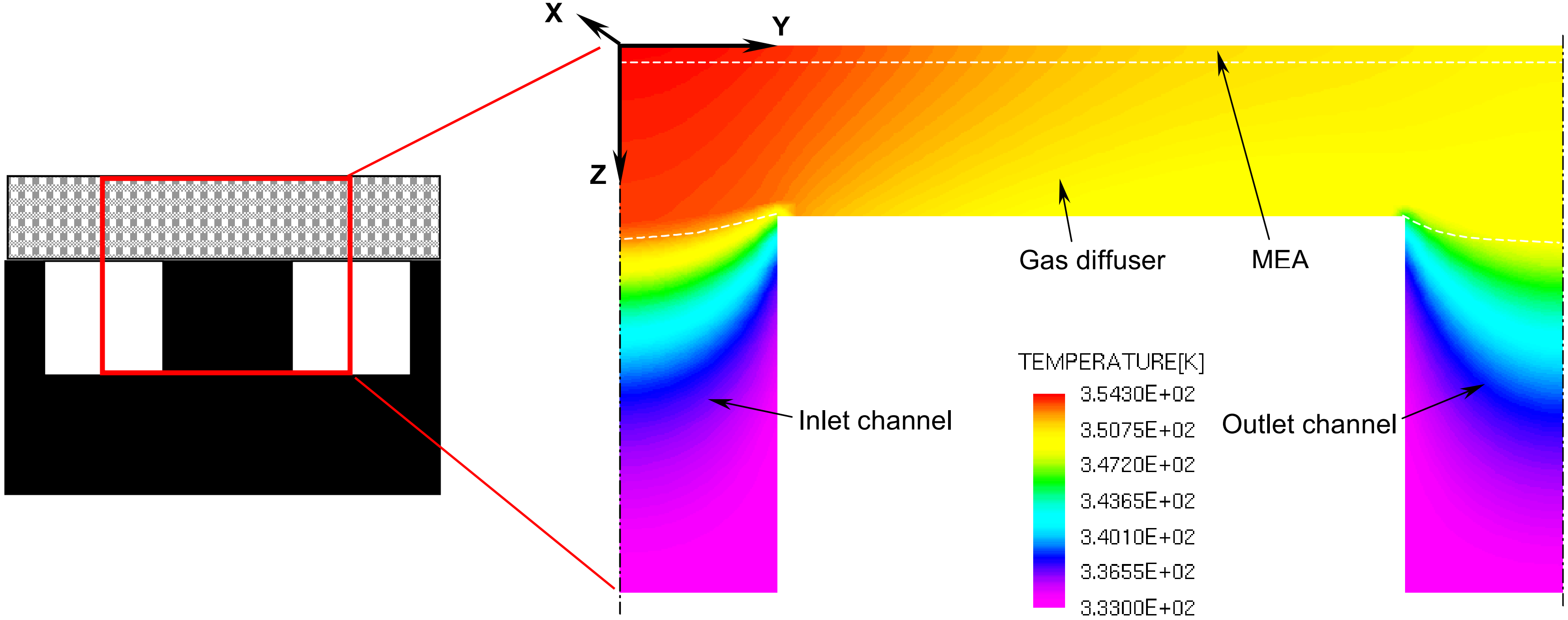
Condensation/evaporation



Effect of cooling cell distribution

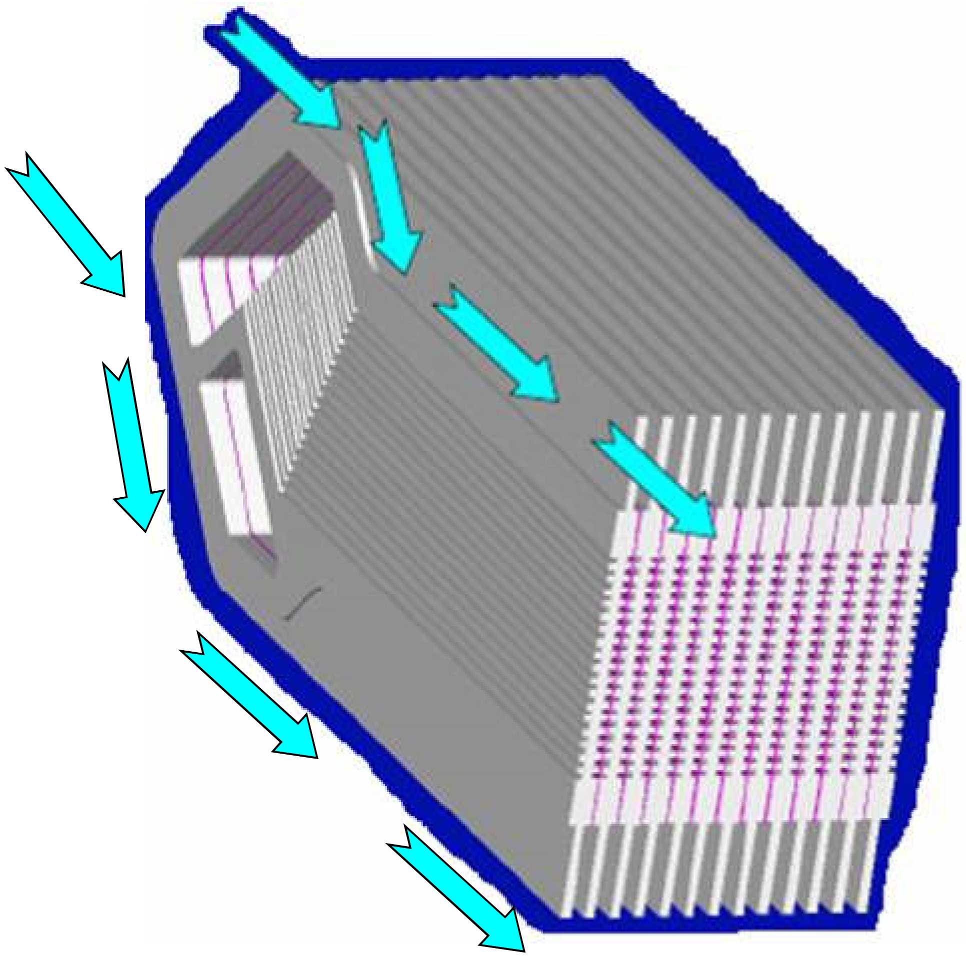


CFD simulation of temperature distribution in a portion of a flow field



Temperature distribution

Edge Cooling



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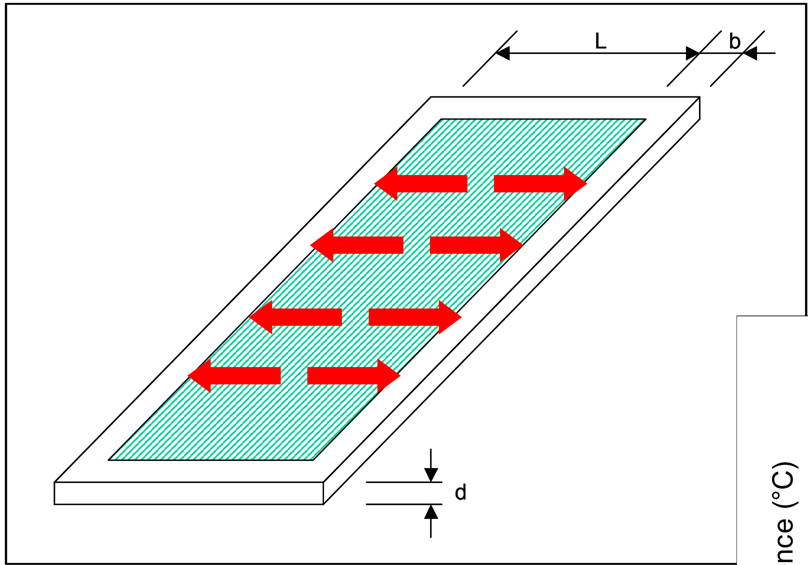
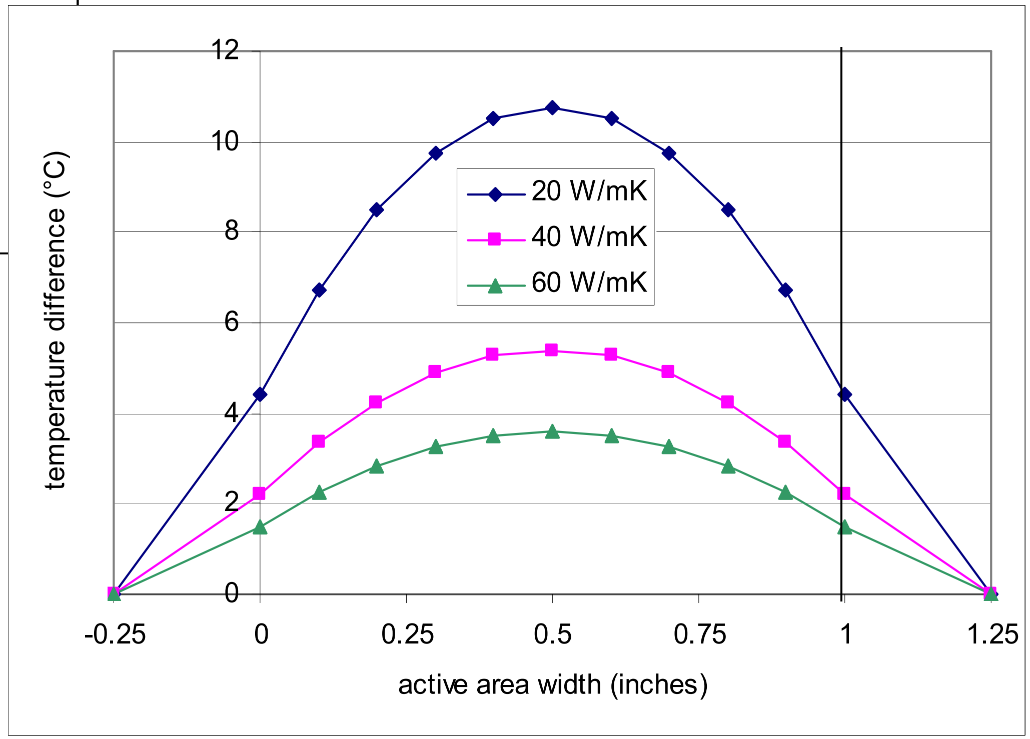
Temperature distribution

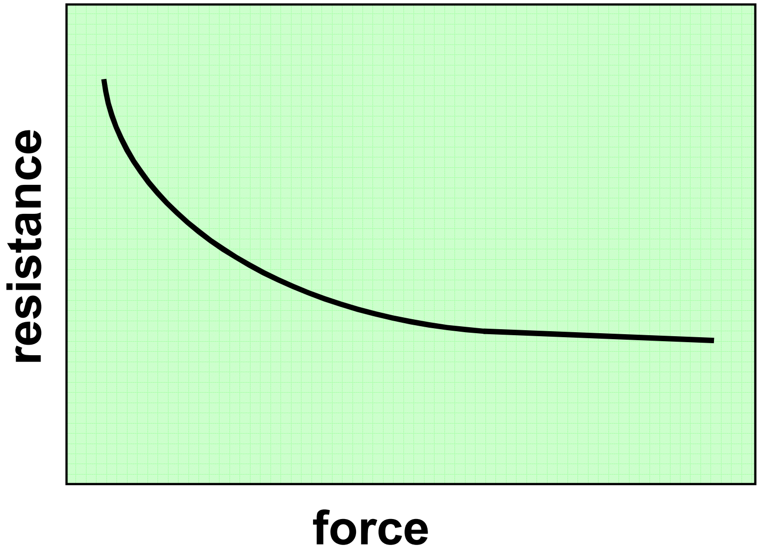
Limitation of Edge Cooling: Conductivity of Material



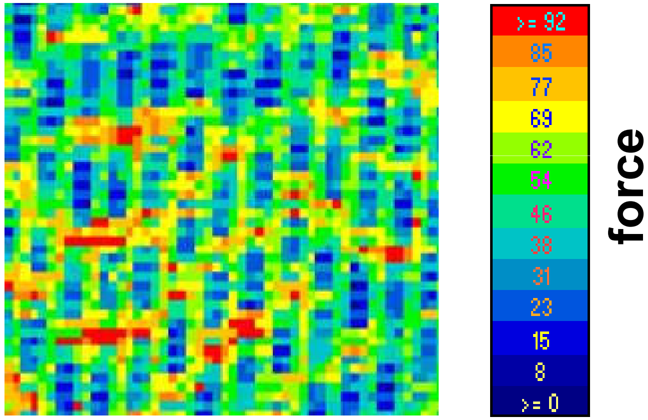


Effect on electrical resistance

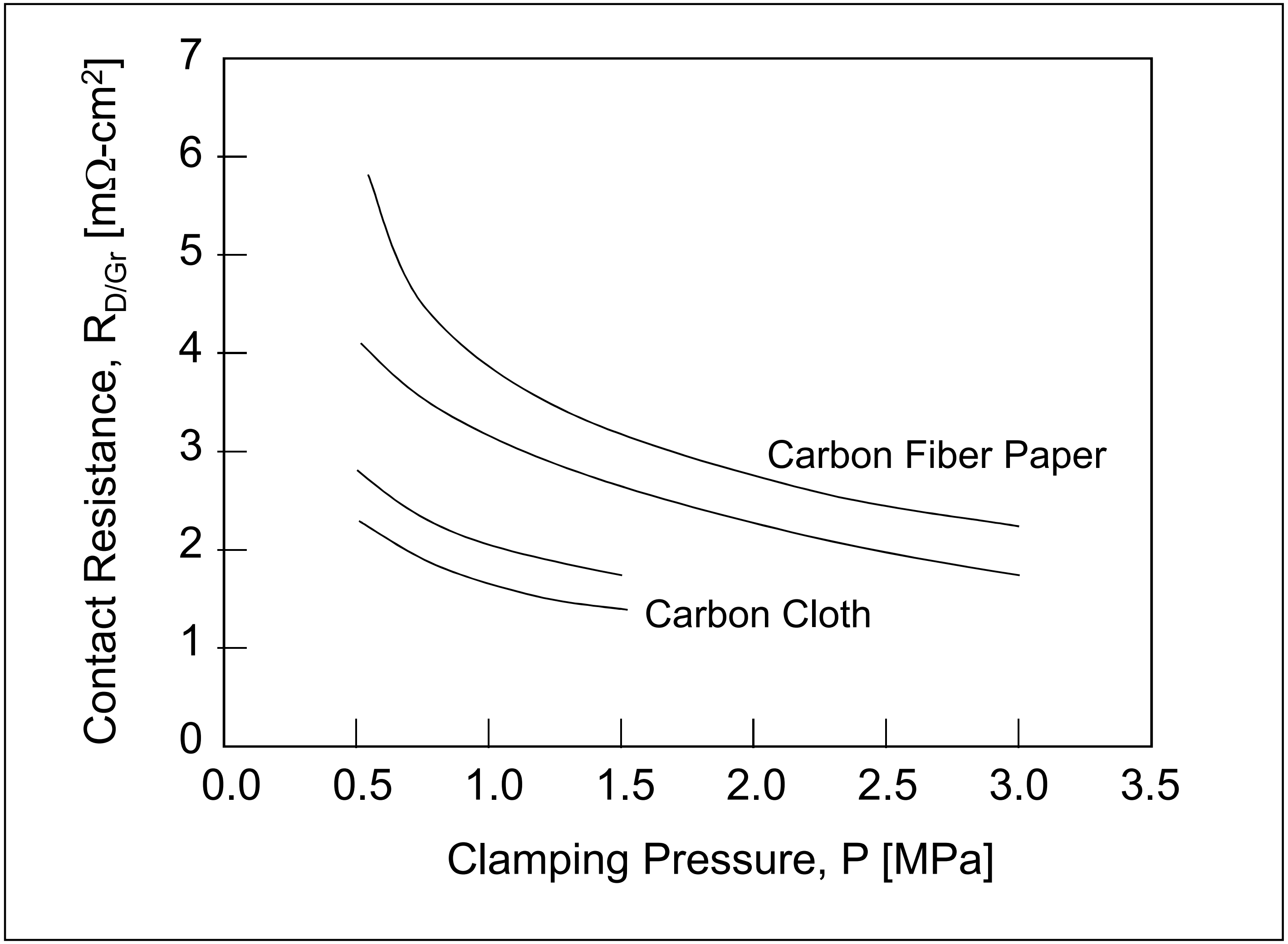
contact resistance



example of pressure distribution

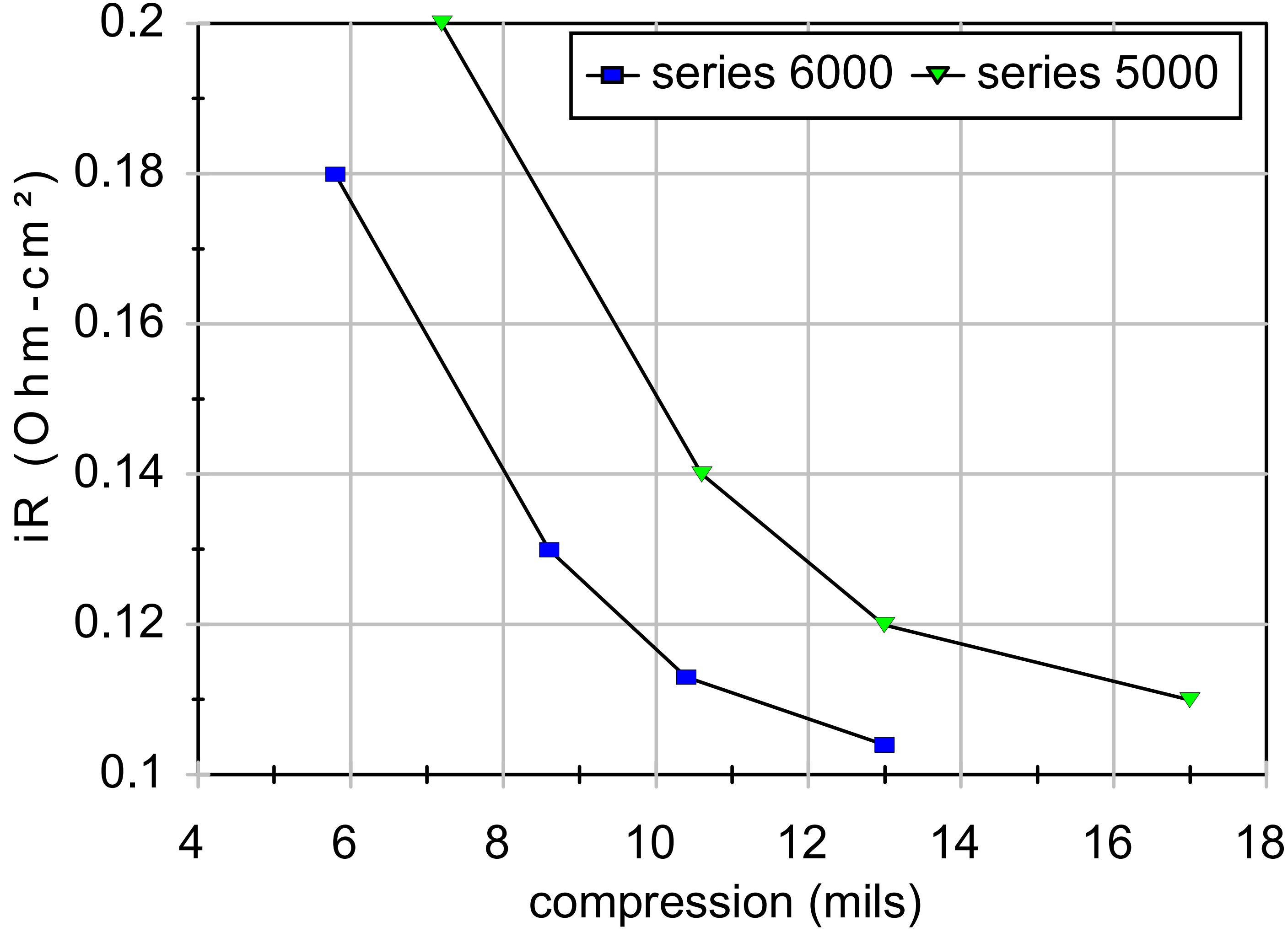


Resistance is a function of clamping force



V. Mishra, F. Yang and R. Pitchumani, Electrical contact resistance between gas diffusion layers and bi-polar plates in a PEM fuel cell, Proc. 2nd Int. Conf. Fuel Cell Science, Engineering and Technology. Rochester, NY, 2004

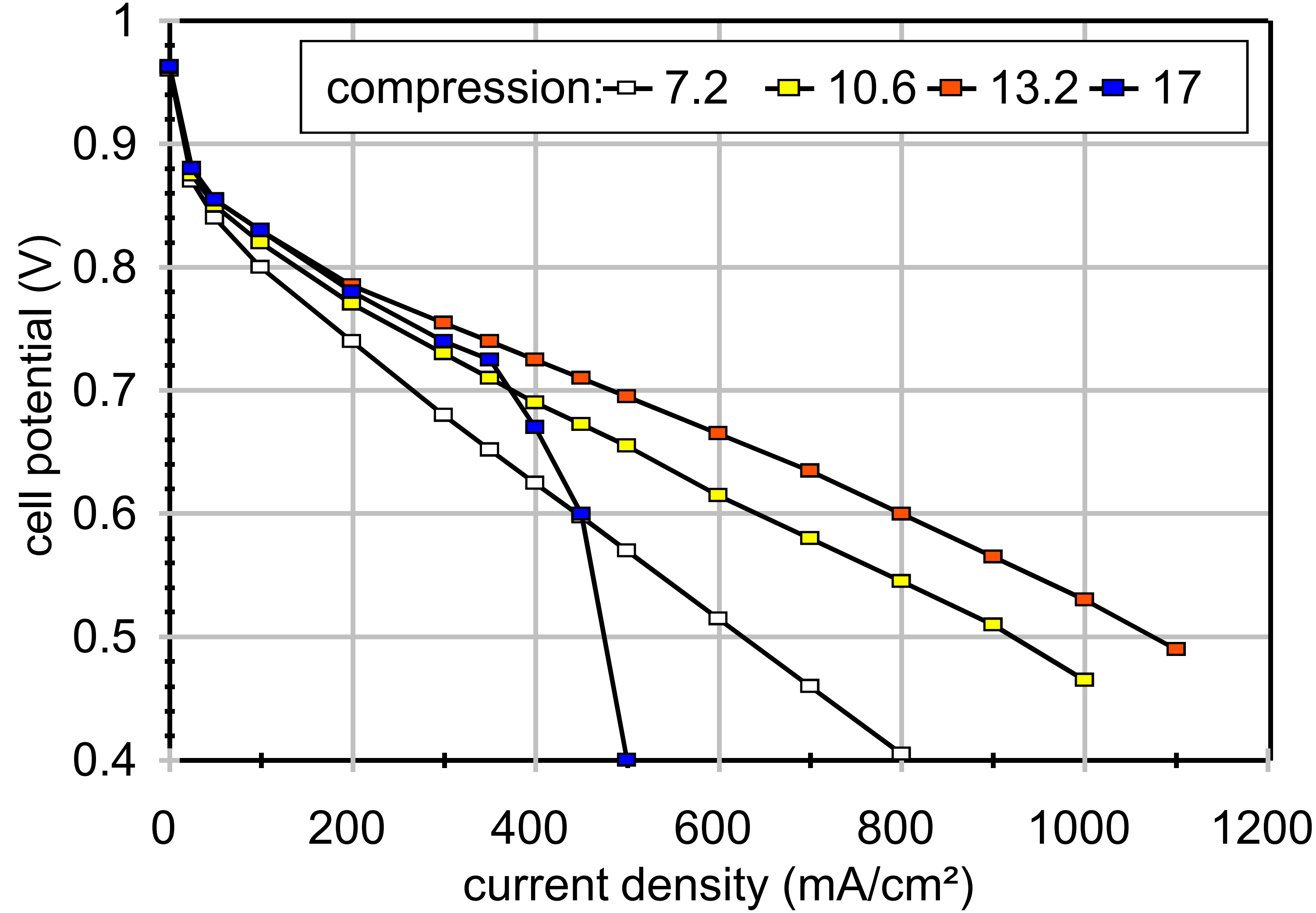
Contact Pressure Investigation



Electrical resistance

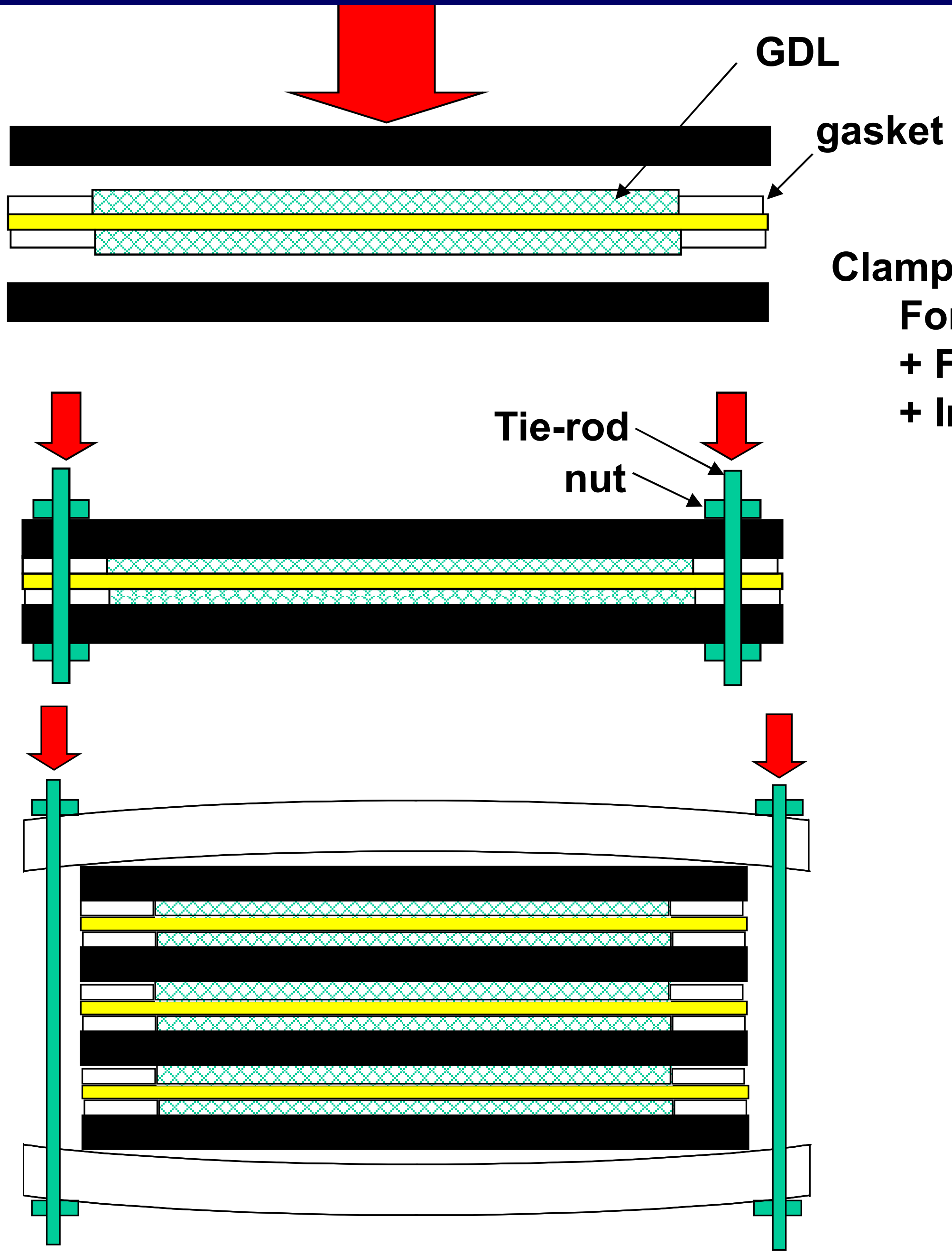
Compression = difference in MEA thickness before and after installation in the cell

Contact Pressure Investigation



(150 cm^2, hydrogen/air, 60°C, 3 bar, H_2 stoich 1.5, air stoich. 3.5, air humidification at 60°C)

Cell compression

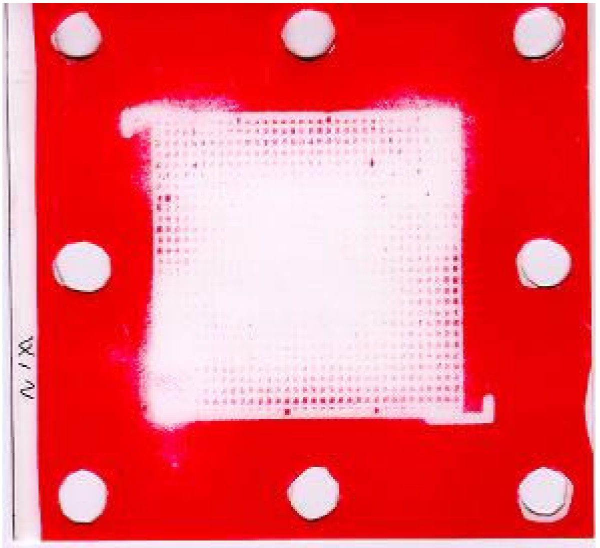


Clamping Force =
Force required to compress the GDL
+ Force required to compress the gasket
+ Internal force(s)

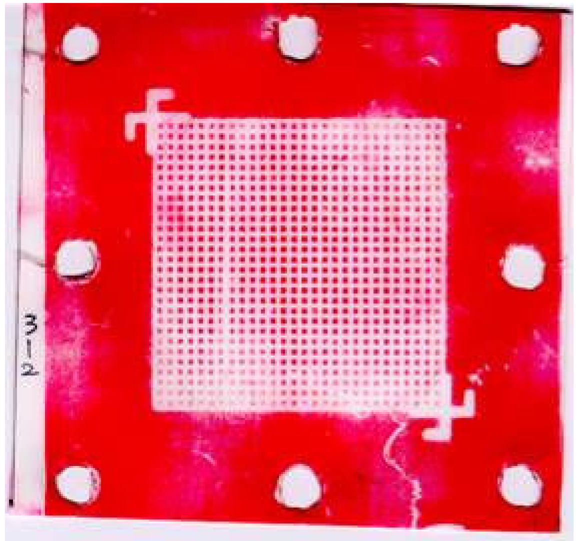
Issues:
- Contact resistance
- Sealing
- Pressure distribution
- End plate bowing
- Internal pressure
- Thermal expansion

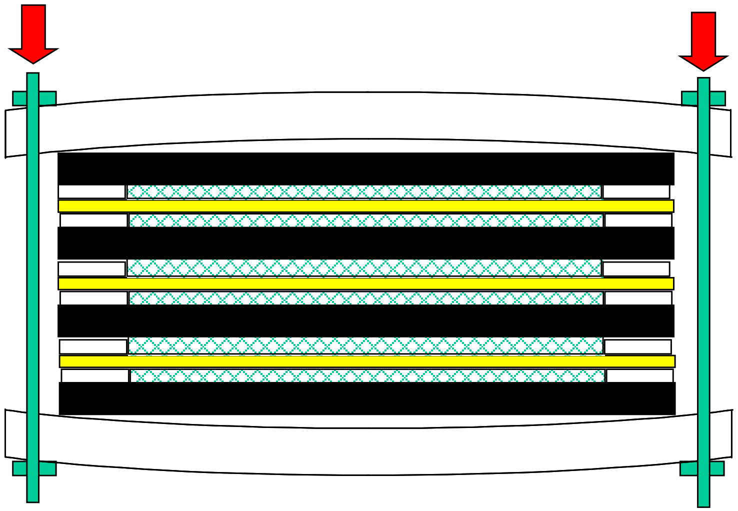
Cell/stack compression

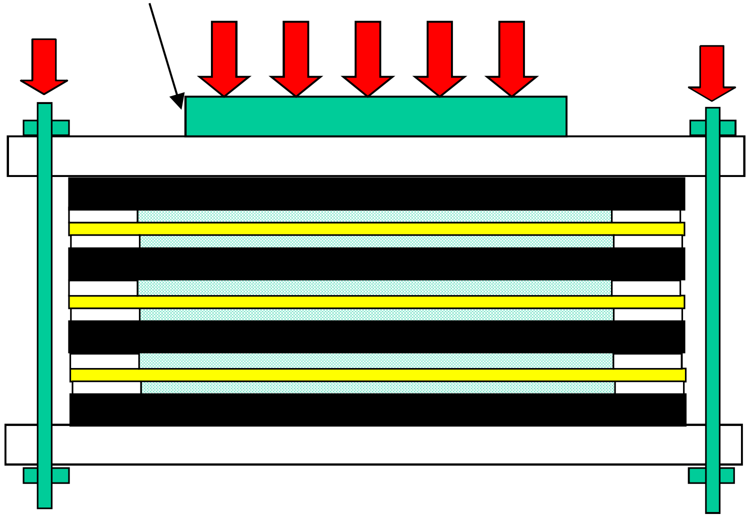
Non-uniform



Uniform

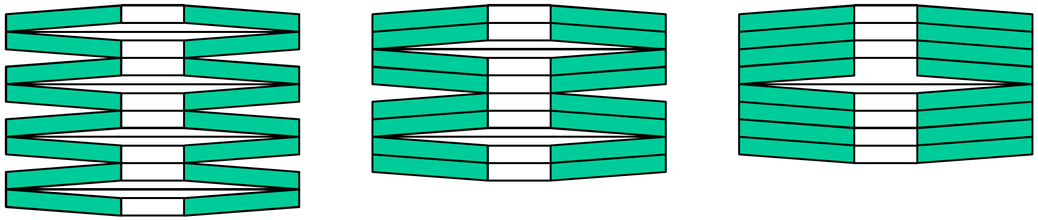


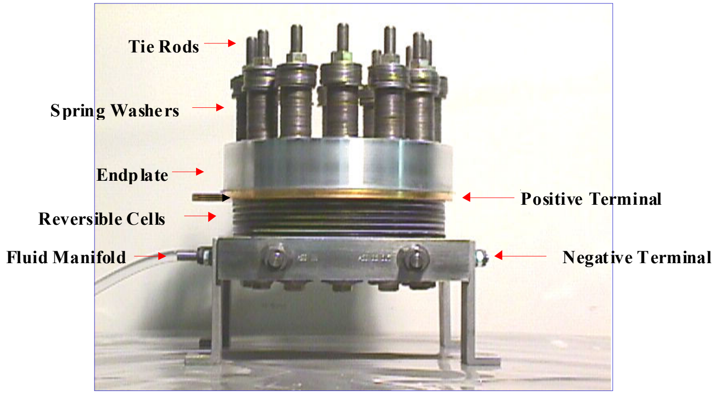




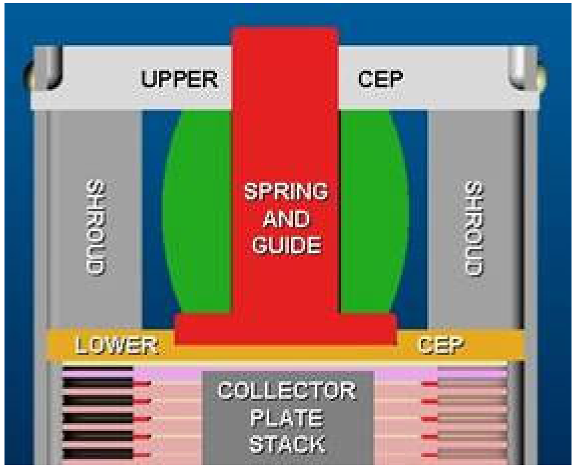
Avoiding loss of stack compression

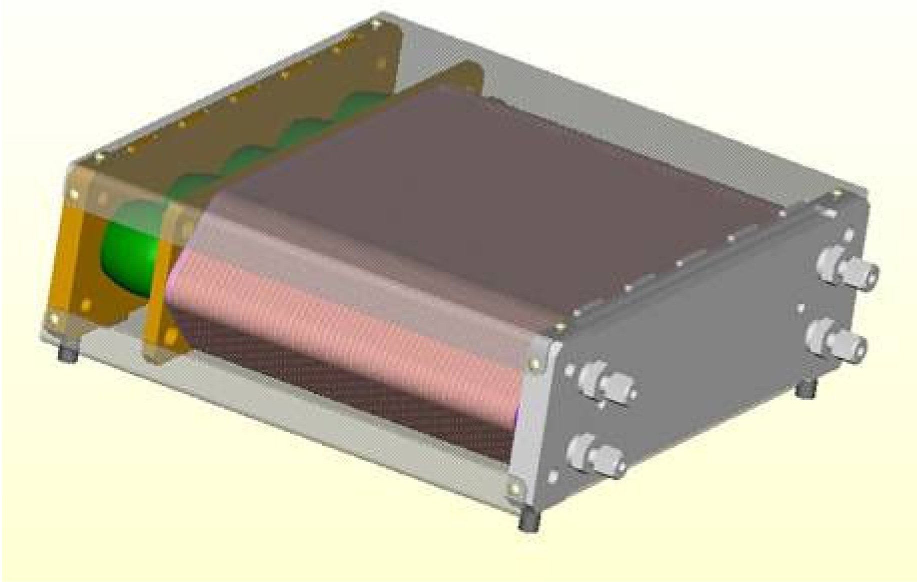
Bellville washers on tie-rods





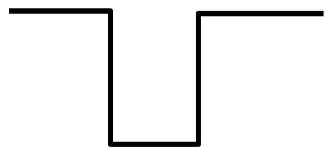
A Novel Approach: springs (coil or polyurethane) – central compression





Stack design/engineering issues

- Uniform distribution of reactants to each cell
- Uniform distribution of reactants inside each cell
- Uniform temperature distribution in each cell
- Minimal resistive losses
  - good electrical contacts
  - selection of materials
- Account for thermal expansion
- No crossover or overboard leaks
- Minimum pressure drop (reactant gases and coolant)
- No water accumulation pockets
- Design for manufacture/design for assembly



Conclusions

- A fuel cell stack is a simple, yet complex device
- Uniformity of local conditions is essential for good design
- Understanding of operating conditions is important
- Information may be gathered through modeling/numerical simulations and experimentally
- Selection of key parameters and conditions must be made from the system perspective
- Good stack design with commercially available MEAs should yield close to 1 W/cm^2

BALLARD®

FCgen™–1020ACS

SPECIFICATION SHEET

PEM Fuel Cell Stacks for back-up power

300 W – 3 kW

PRODUCT SPECIFICATIONS

Type:	PEM (Proton Exchange Membrane) fuel cell stack	
Performance:[1]	Rated Power	42 W/cell
	Rated current	65 Amps
	DC voltage	642 mV/cell
Fuel:	Hydrogen	99.95% or better
	Fuel supply pressure	0.15 to 0.5 bar g
	Fuel flow rate	~0.5 slpm/cell[2]
Oxidant/Coolant:	Coolant	Air
	Coolant flow rate	~70 slpm/cell[2]
Temperatures:	Operating temperature	-20°C to 52°C
	Start up temperature	≥ -10°C
Start Up Time:	Start up to 80% rated power	~20 seconds
Physical Characteristics: (56-cell stack)	Length x width x height	363 x 103 x 351 mm
	Mass	11.0 kg
Product Certification	CAN/CSA-C22.2 No. 62282-2 Fuel Cell Modules	

BALLARD

FCgen™–1030V3

SPECIFICATION SHEET

PEM Fuel Cell Stacks for residential cogeneration

PRODUCT SPECIFICATIONS

Type:	PEM (Proton Exchange Membrane) fuel cell stack	
Performance:	Rated Power	1234 W DC
Fuel:	Reformate	> 72% H2 typical < 10 ppm CO
Oxidant:		Filtered Air
Operating Conditions:	Start-up temperature	> 5° C
	Coolant temperature	57 – 67° C
	Relative humidity	90 – 100%
Durability:	Target lifetime	40,000 hours
	On–Off cycles	4,000
Physical:	Length x width x height	343mm x 153mm x 258mm
	Weight	12kg (dry)
	Volume	17L
Additional Features:	Cover	
	Cell mounting harness	

BALLARD

FCvelocity™–9SSL

SPECIFICATION SHEET

PEM Fuel Cell Stacks for motive power

Material handling: forklift trucks

PRODUCT SPECIFICATIONS

Rated Power [kW][1]	**4.4**	**8.8**	**13.2**	**19.3**
DC voltage (at 300A)[1]	14.6	29.3	44	64.3
Mass (with no coolant) [kg]	7.2	10	13	17
Stack core length [mm]	107	167	228	313
Stack core width [mm]	760	760	760	760
Stack core height [mm]	60	60	60	60

Type:	PEM (Proton Exchange Membrane) fuel cell stack	
Performance:	Maximum current	300A
	Shock and vibration	Automotive[2]
Fuel:	Fuel composition (pre-humidification)	≥ 85% H_2[3] ≤ 15% inert[3]
Oxidant:	Oxidant composition (pre-humidification)	Compressed ambient
Stack Temperatures:	Storage temperature	2 to 40° C (36 to 104° F)
	Start-up temperature	≥ 2° C (≥ 36° F)
	Fluid inlet temperature (operating)	2 to 65° C[4] (36 to 150° F)[1]
	External stack temperature (operating)	-25 to 75° C4 (-13 to 167° F)[4]

BALLARD

FCvelocity™–HD6

SPECIFICATION SHEET

PEM Fuel Cell Stacks for motive power

Bus and Heavy duty

PRODUCT SPECIFICATIONS

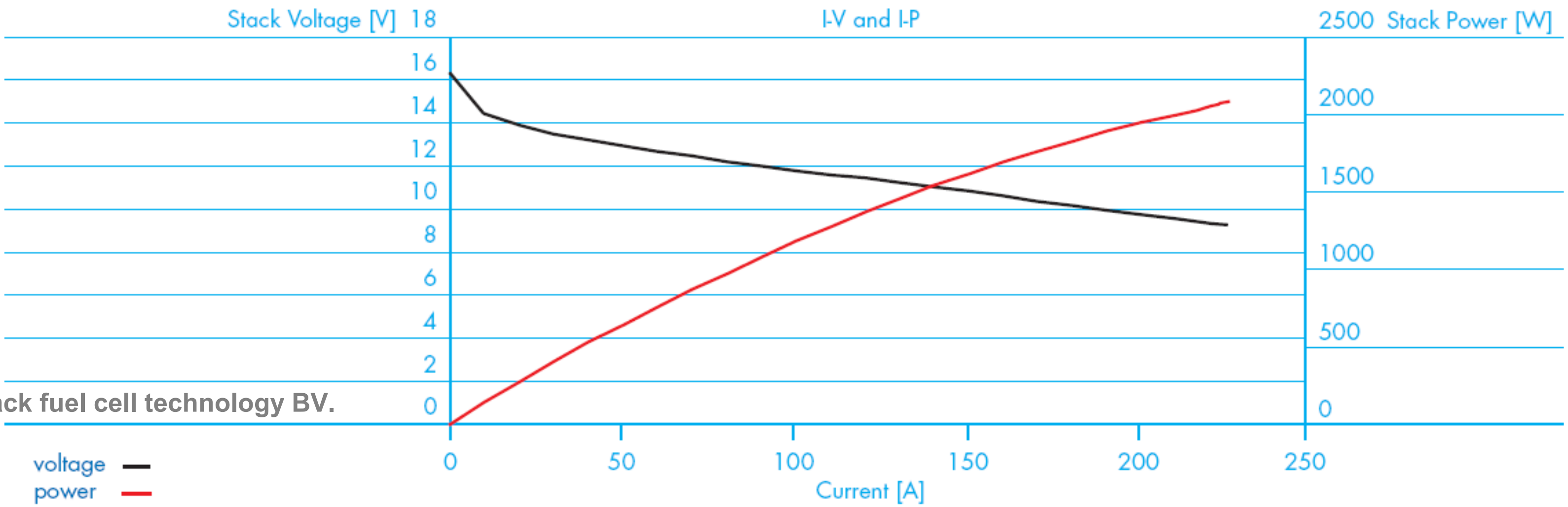
Gross Power:		75 kW	150 kW
Performance:	DC voltage	275 – 400V	550 – 800V
	Maximum current	300A	300A
Physical:	Weight (dry)	< 350 kg (<700 lbs)	< 400 kg (< 990 lbs)
	Length x width x height (without controller box)	1270 x 870 x 505 mm (50 x 34 x 20 in)	
	Volume	0.55m³ (19.6 cubic ft)	
Fuel:	Gaseous hydrogen	Commercial grade (per SAE J2719)	
Oxidant:	Air		
Coolant:	50/50 Pure Ethylene Glycol and Water		
Operating Conditions:	Temperature (nominal)	63°C (149°F)	
	Fuel pressure (minimum)	12 barg	
	Air pressure (nominal)	1.2 barg	
Additional Features:	Control interface	CANbus	
	Enclosure	IP53	

NedStack P2 Product Data

NedStack

Type		NedStack P2 FC stack
Performance	rated peak power	2 kW
	current	>225 A
	output voltage	17 ~ 9 V (DC)
	efficiency	45 – 60 %
Fuel	hydrogen	dry or humidfied
	reformat	80 – 20 mixture, others on request
Oxidant	ambient air	
Operating conditions	temperature	65 °C
	fuel pressure	atmospheric
	air pressure	atmospheric
Physical	dimensions	230 x 190 x 270 mm
	weight	19 kg
Operating lifetime	expected	>20.000 hrs

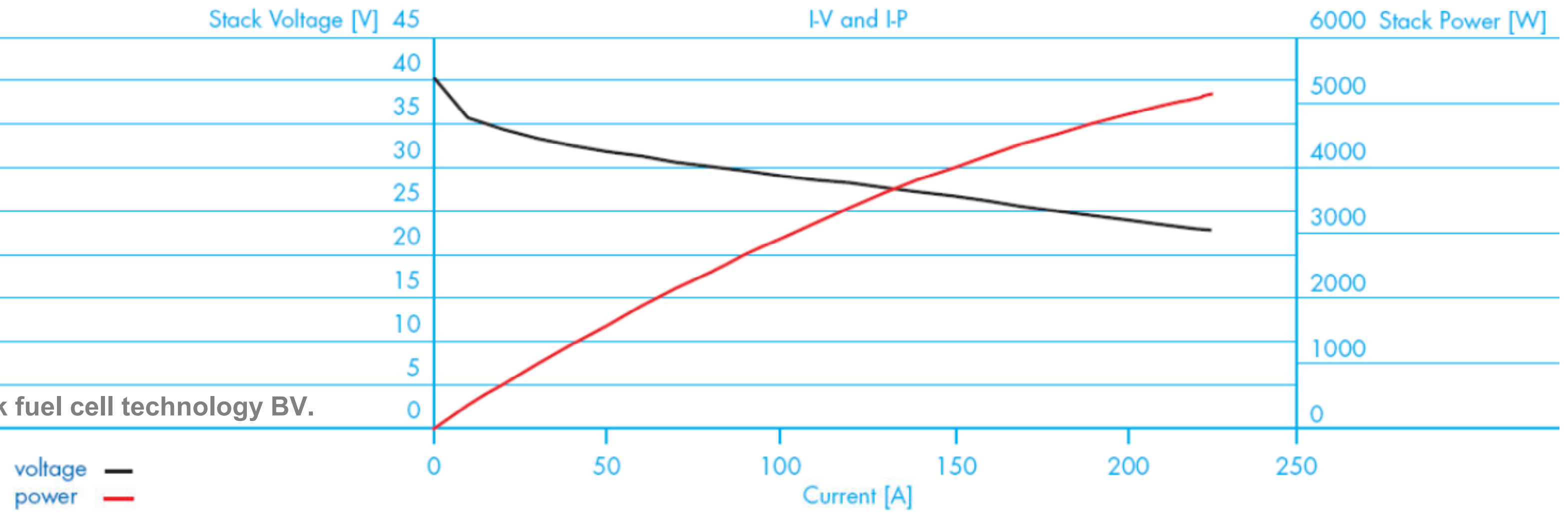
JV-curve NedStack P2



NedStack P5
Product Data

Type		NedStack P5 FC stack
Performance	rated peak power	5 kW
	current	>225 A
	output voltage	42 ~ 22 V (DC)
	efficiency	45 – 60 %
Fuel	hydrogen	dry or humidfied
	reformat	80 – 20 mixture, others on request
Oxidant	ambient air	
Operating conditions	temperature	65 °C
	fuel pressure	atmospheric
	air pressure	atmospheric
Physical	dimensions	370 x 190 x 270 mm
	weight	29 kg
Operating lifetime	expected	>20.000 hrs

JV-curve NedStack P5

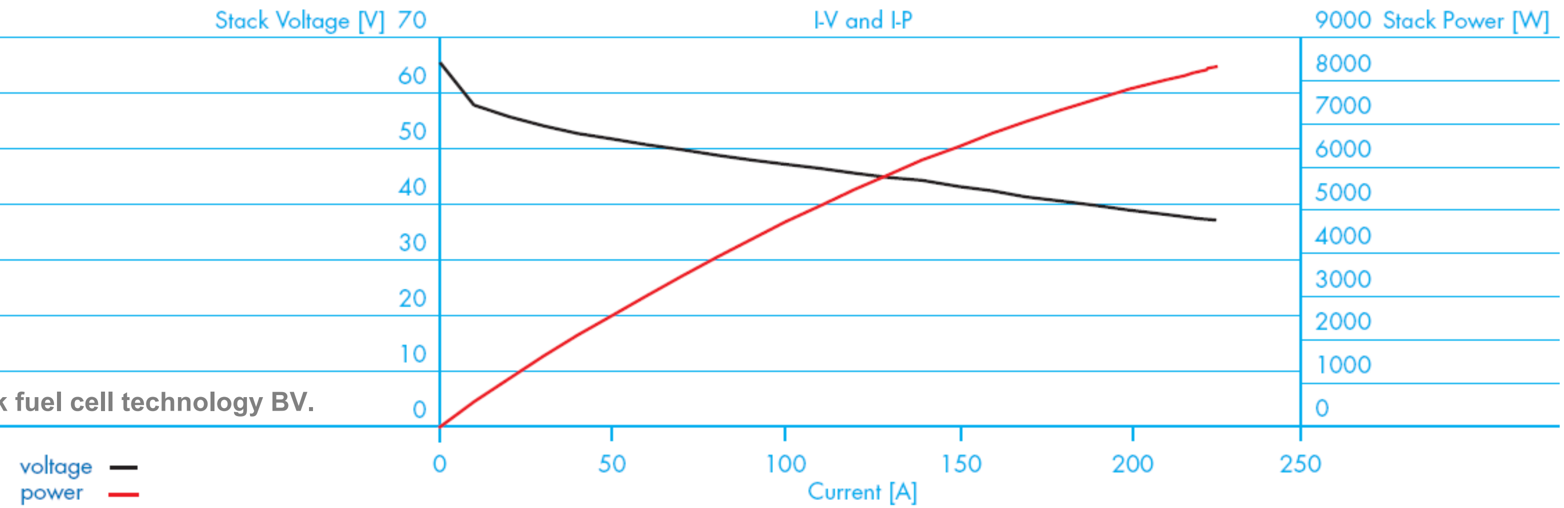


NedStack P8 Product Data

NedStack

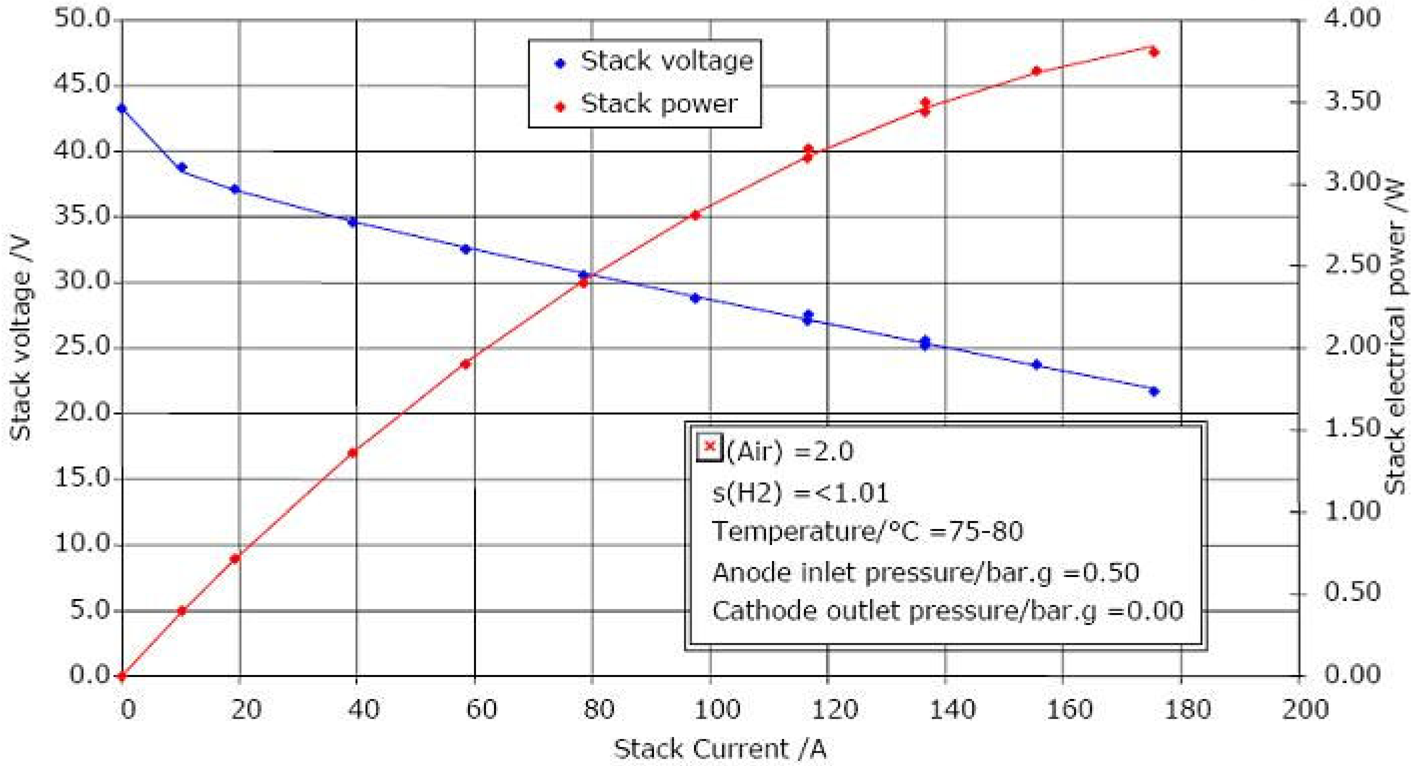
Type		NedStack P8 FC stack
Performance	rated peak power	8 kW
	current	>225 A
	output voltage	68 ~ 36 V (DC)
	efficiency	45 – 60 %
Fuel	hydrogen	dry or humidfied
	reformat	80 – 20 mixture, others on request
Oxidant	ambient air	
Operating conditions	temperature	65 °C
	fuel pressure	atmospheric
	air pressure	atmospheric
Physical	dimensions	520 x 190 x 270 mm
	weight	36 kg
Operating lifetime	expected	>20.000 hrs

JD-Curve NedStack P8



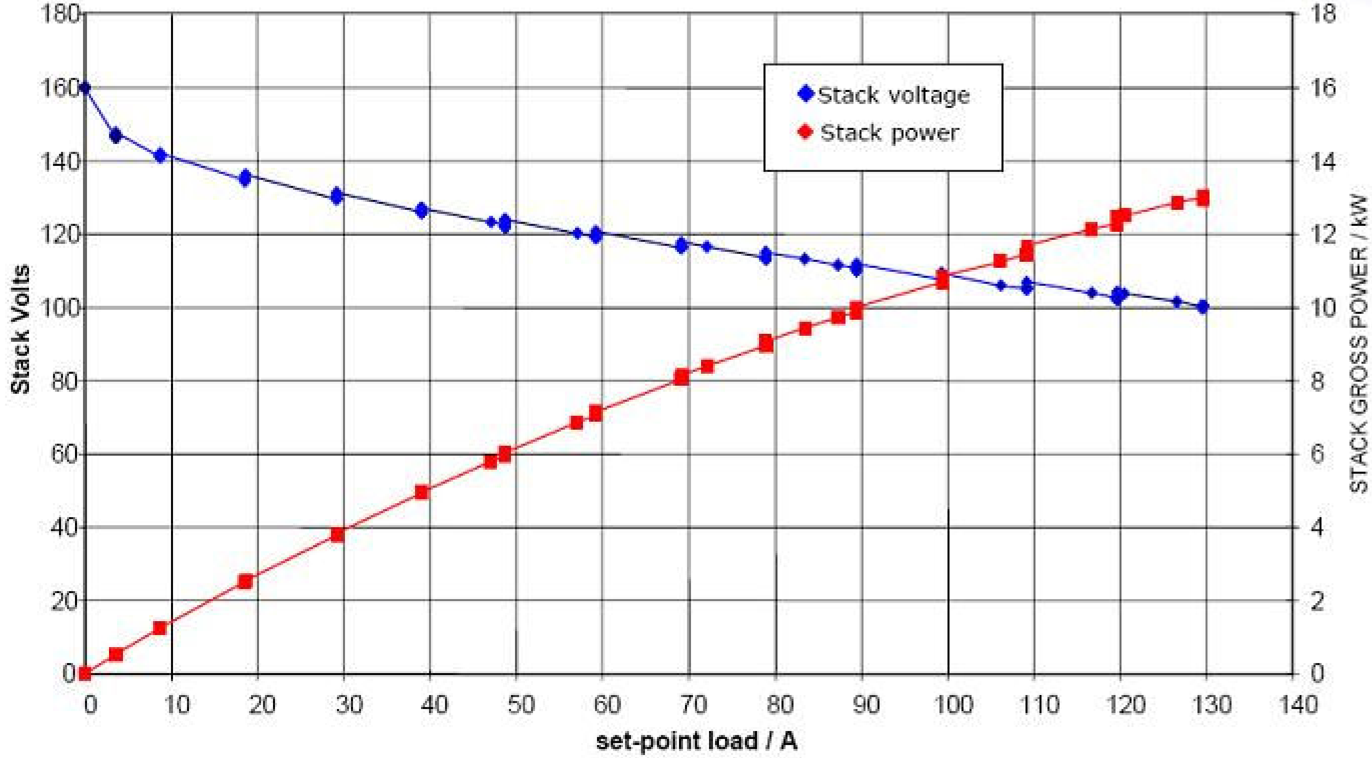
INTELLIGENT ENERGY
Clean fuel and power

48 Cell EC stack (200cm²) Polarisation Curve



INTELLIGENT ENERGY
Clean fuel and power

168 cell EC stack (200cm^2) polarisation curve



NUVERA

FUEL CELLS

ANDROMEDA™

HCS-575 PEM Fuel Cell Stack Series

*384 Cell Stack Shown

Specifications	150 Cell	272 Cell	384 Cell
Stack Power	50kW ± 4	90kW ± 4	127kW ± 4
Stack Operating Voltage	130 – 90V ± 10	235 – 165V ± 10	335 – 235V ± 10
Transient Response	10% - 90% < 2 sec	10% - 90% < 2 sec	10% - 90% < 2 sec
Stack Dimensions	210(h) x 300 x 570 mm	210(h) x 600 x 535 mm	210(h) x 900 x 515 mm
Stack Weight	58kg ± 10kg	107kg ± 10kg	155kg ± 10kg

*custom configurations available

Coolant	150 Cell	272 Cell	384 Cell
Type	Demi Water or Low Conductivity Glycol		
Conductivity	< 5 pS/cm		
Flow Rate	120 lpm ± 6	220 lpm ± 6	310 lpm ± 10
Pressure Drop	400 mbar ± 200		
T In Max	62°C ± 2		
T Out Max	70°C ± 2		

Fuel	
Type[1]	Hydrogen 99.995%
RH% In[2]	Dry Hydrogen Input
H2 Stoich	3 ± 1
H2 Pressure	1.1 – 1.8 bar absolute
H2 Pressure Drop[2,3]	150 mbar ± 50

Oxidant	
Type	Air
Air Inlet Pressure	1.1 – 1.8 bar abs
Air Pressure Drop[3,4]	400 mbar ± 100
Air Stoich @ low current density	2.5 ± 0.5
Air Stoich @ high current density	1.7 ± 0.1
T In	<50°C
T Max Out	70°C ± 2

H-SERIES PEM Fuel Cell Systems

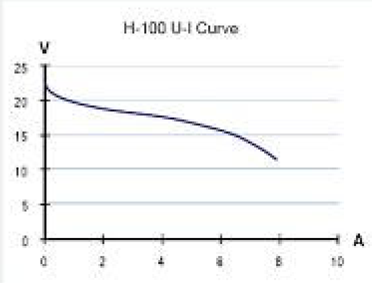
Horizon Fuel Cell Technologies

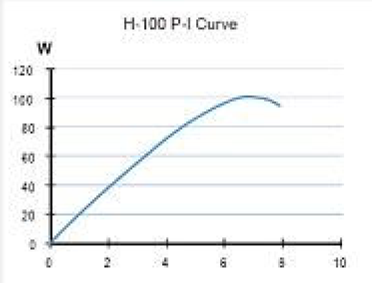
Semi-integrated 100W fuel cell system

Including:
- Connections/Tubing
- Electronic valves
- Electronic control box
- 100W stack with blower
- Fuel cell ON/OFF switch
- SCU ON/OFF switch

H-100
FCS-B100

Type of fuel cell .... PEM
Number of cells...24
Rated power.. 100W
Rated performance..........................14V@7.2A
Output voltage range..........................13V-23 V
Weight (with fan & casing).......... 0.95kg(2.1lbs)
Size..................143x109x94mm(5.6x4.3x3.7in)
Reactants..............................Hydrogen and Air
Rated H_2 consumption.........1.4l/min(83in^3/min)
Hydrogen pressure...... 0.4-0.45Bar(5.8-6.5PSI)
Controller weight........................0.4kg(0.88lbs)
Hydrogen supply valve voltage...................12V
Purging valve voltage.................................12V
Blower voltage..12V
Ambient temperature..............5-35°C(41-95°F)
Max stack temperature................. 65°C(149°F)
Hydrogen purity.......................99.999% dry H2
Humidification........................... Self-humidified
Cooling................... Air (integrated cooling fan)
Start up time................30s (room temperature)
Efficiency of system.........................40%@14V



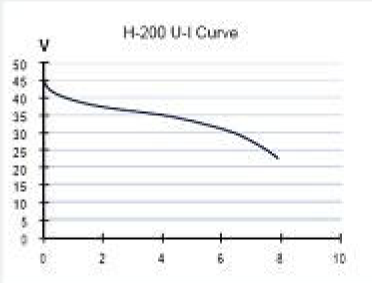


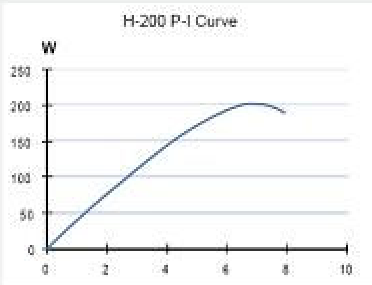
Semi-integrated 200W fuel cell system

Including:
- Connections/Tubing
- Electronic valves
- Electronic control box
- 200W stack with blower
- Fuel cell ON/OFF switch
- SCU ON/OFF switch

H-200
FCS-B200

Type of fuel cell .... PEM
Number of cells...48
Rated power.. 200W
Rated performance......................... 28V@7.2A
Output Voltage range..........................26V-46V
Weight (with fan & casing).............1.5kg(3.3lbs)
Size................. 223x109x94mm(8.8x4.3x3.7in)
Reactants..............................Hydrogen and Air
Rated H_2 consumption.......2.8l/min(178in^3/min)
Hydrogen pressure...... 0.4-0.45Bar(5.8-6.5PSI)
Controller weight......................... 0.4kg/0.88lbs
Hydrogen supply valve voltage...................12V
Purging valve voltage.................................12V
Blower voltage..12V
Ambient temperature..............5-30°C(41-86°F)
Max stack temperature................. 65°C(149°F)
Hydrogen purity.......................99.999% dry H2
Humidification............................Self-humidified
Cooling................... Air (integrated cooling fan)
Start up time................30s (room temperature)
Efficiency of system.........................40%@28V





Horizon
Fuel Cell Technologies

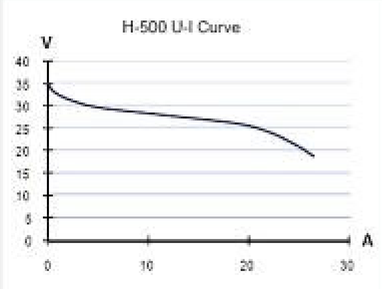
H-SERIES PEM Fuel Cell Systems

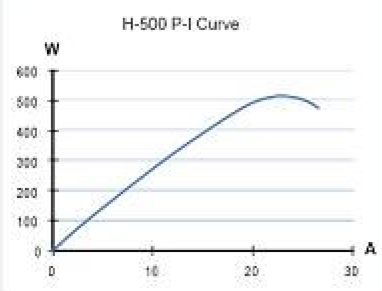
Semi-integrated 500W fuel cell system

Including:
- Connections/Tubing
- Electronic valves
- Electronic control box
- 500W stack with blower
- Fuel cell ON/OFF switch
- SCU ON/OFF switch

H-500
FCS-B500

Type of fuel cell	PEM
Number of cells	36
Rated power	500W
Rated performance	21V@24A
Output voltage range	19V-35V
Weight (with fan & casing)	2.8kg(6.2lbs)
Size	250x190x75mm(9.8x7.5x3in)
Reactants	Hydrogen and Air
Rated H_2 consumption	7l/min(398in^3/min)
Hydrogen pressure	0.5-0.6Bar(7.2-9.4PSI)
Controller weight	0.45kg(0.99lbs)
Hydrogen supply valve voltage	12V
Purging valve voltage	12V
Blower voltage	12V
Ambient temperature	5-30°C(41-86°F)
Max stack temperature	65°C(149°F)
Hydrogen purity	99.999% dry H2
Humidification	Self-humidified
Cooling	Air (integrated cooling fan)
Start up time	30s (room temperature)
Efficiency of system	40%@21V





Semi-integrated 1000W fuel cell system

Including:
- Connections/Tubing
- Electronic valves
- Electronic control box
- 1000W stack with blower
- Fuel cell ON/OFF switch
- SCU ON/OFF switch

H-1000
FCS-B1000

Type of fuel cell	PEM
Number of cells	72
Rated power	1000W
Rated performance	43V@23.5A
Output voltage range	39V-69V
Weight (with fan & casing)	4.2kg(9.3lbs)
Size	324x220x122mm(12.8x8.7x4.8in)
Reactants	Hydrogen and Air
Rated H_2 consumption	14l/min(847in^3/min)
Hydrogen pressure	0.5-0.6Bar(7.2-9.4PSI)
Controller weight	0.45kg(0.99lbs)
Hydrogen supply valve voltage	12V
Purging valve voltage	12V
Blower voltage	12V
Ambient temperature	5-30°C(41-86°F)
Max stack temperature	65°C(149°F)
Hydrogen purity	99.999% dry H2
Humidification	Self-humidified
Cooling	Air (integrated cooling fan)
Start up time	30s (room temperature)
Efficiency of system	40%@43V