Некоторые физические проблемы, связанные с функционированием и диагностикой топливных элементов

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INSTITUT P'

Research Institute in Materials, Mechanics and Energetics

Application to Transport, Energy and Environmental Engineering

Director : Yves GERVAIS
Vice Director : Jean-Claude GRANDIDIER

- Institute of the CNRS : INSIS et *INP*
- Section CNRS (Chercheur) : *5, 9 et 10*
- Section CNU (Enseignant Chercheur) : 26, 28, 30, 60, 62, 63 et 74
- Component of affectation : UFR SFA, ENSIP, IUT 86, IRIAF, IUT 16 et l'ENSMA

Where is Poitiers ?

An Old Medieval City (Roman Art) ...

... of cheese and wine !

INSTITUT P'

Research and Education Context

Research and Education

School of Engineers in Aeronautics

Within the ISAE Toulouse group

Faculty of Sciences (Physics and Mech Engg)

School of Engineers ENSIP (environment)

Faculty of Sports Sciences

The Pprime Institute

- **People** : ~ **600 personnes**

Academic staff	Technical staf	PhD students	Contractual (post-doc, engineers, …)
199 (58 % d'HDR)	101	156	> 150

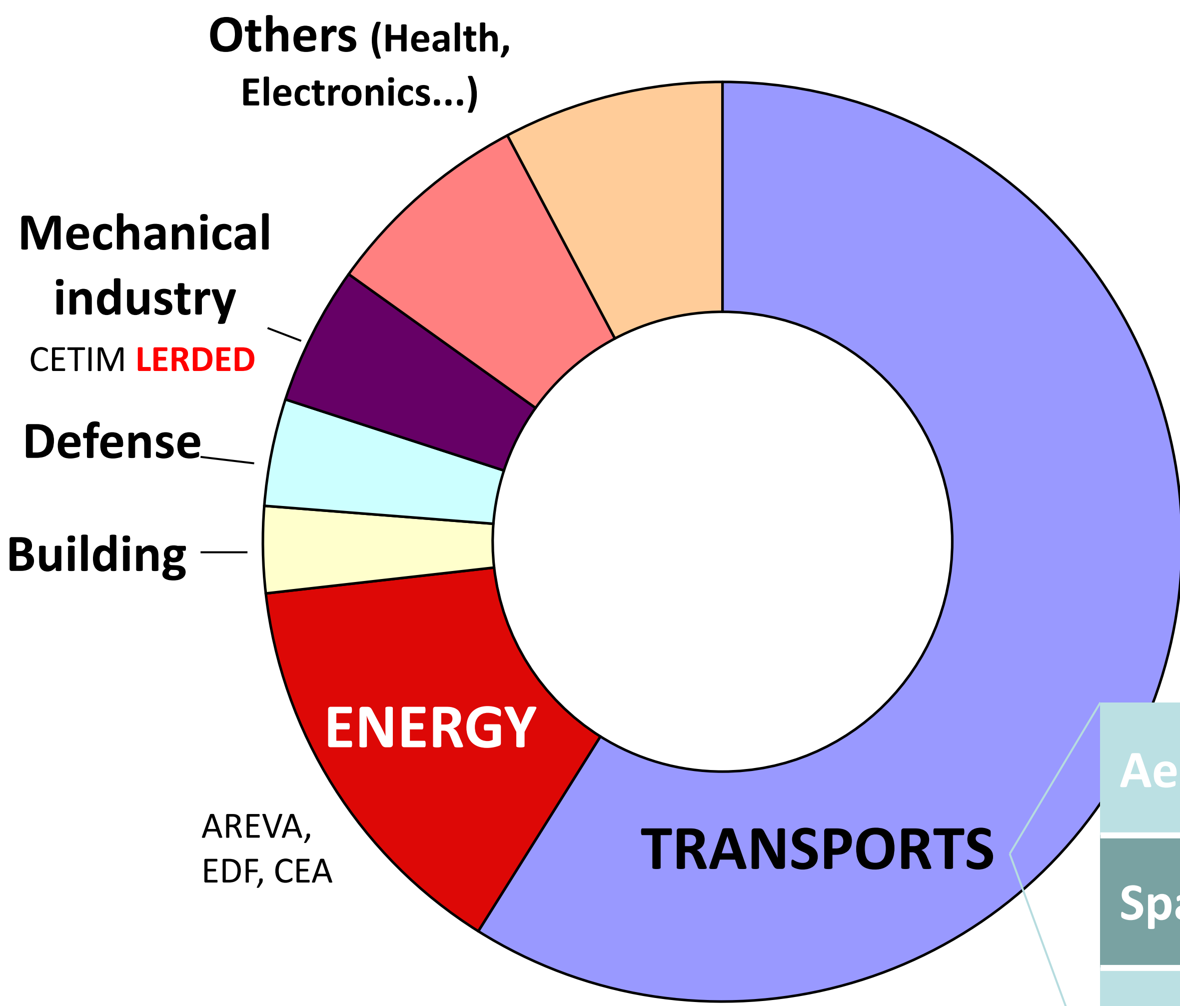
- **Annuel Budget : ~ 25 M€**

Salaries	Government annual fundings	Local (regional) funds CPER, FEDER	Grants, Industrial sponsors and contracts
14,5 M€	1,5 M€	2 M€	7 M€

- **Scientific and Technical Production** : **250 international publications/year (+ about 500 communications) ; 45 ANR; 1 FUI ; 9 FP7 in progress, ~ 15 active patents**

Connected Industrial Sectors

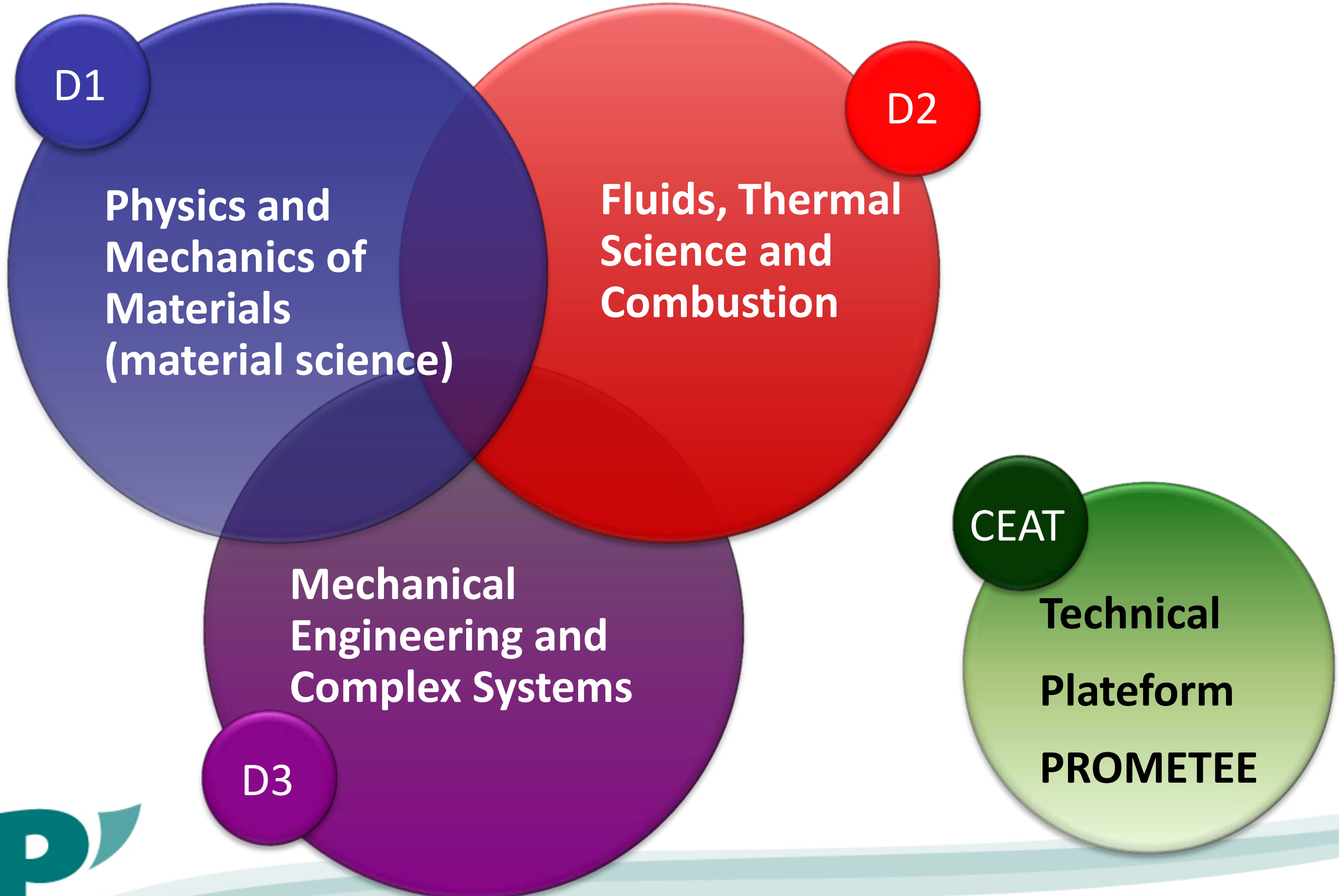
~ 4 M€/year



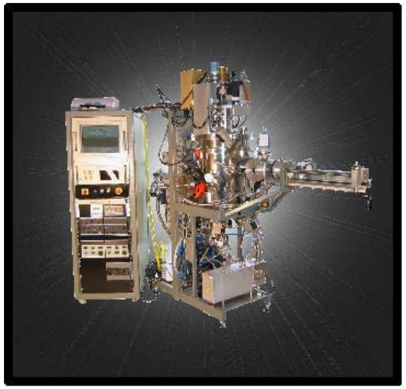
Aeronautics	60%	SAFRAN, EADS, ONERA
Spatial	15%	CNES
Automobile	20%	PSA **OpenLab**, Renault, Valéo, Leroy Somer

Industry sponsoring over 2010-2014

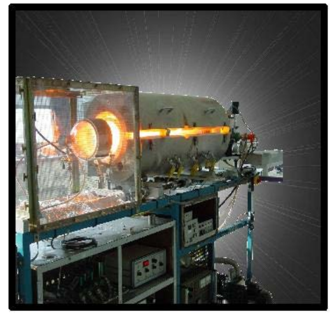
3 Scientific Departments



Dept. Physics and Mechanics of Materials



Elaboration



Surface plasma treatments

Ion implantation

Equipment

Elaboration-treatment-Characterization

calculations

Nano,
microindentation

DMA DSC

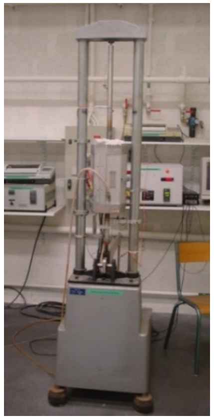
X-ray analysis

INSTITUT

Dept. Physics and Mechanics of Materials

Fatigue apparatus under controled environment (gas)

Fatigue (thermal)



Creep under environment

Vibrophore

≠ thermomechanic loading & ≠ Environnements

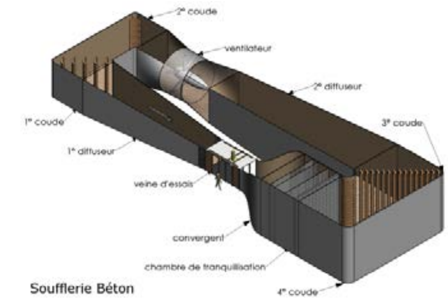
Deformation under gas or hydrostatic pressure

Fatigue apparatus (temperature and bi-dimensional)

Dept. Fluids, Thermal Science, Combustion

Test bench : Martel *High speed, high temp. aeroacoustic 2400K,M 2-3*

Wind tunnels *Supersonic, Anechoic*

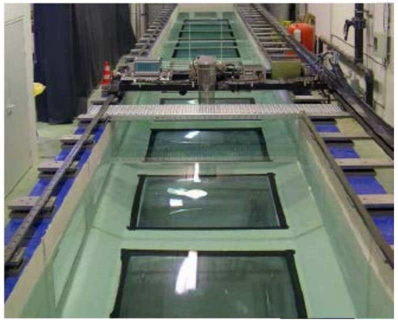


Subsonic Wind Tunnels

*Béton: 2.4*2.6m^2, 50m/s*

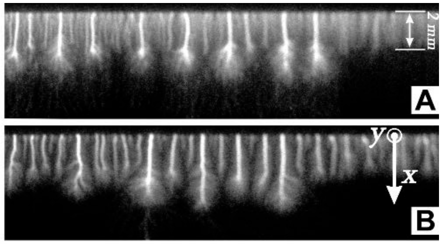
Bois: 1 m^2, V_{max} : 80m/s

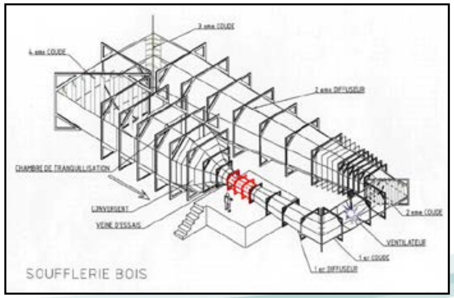
FTC :
Some Large experimental facilities

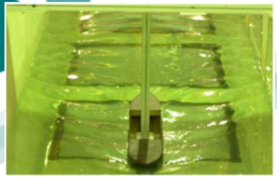


Towing Tank

Length: 20m ; Width: 1.5m





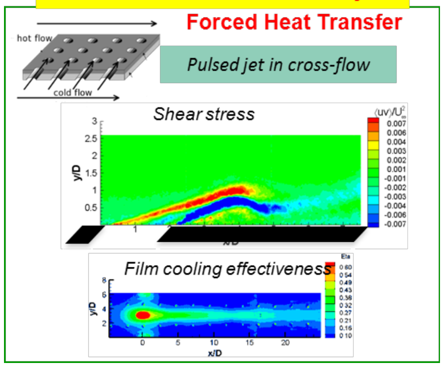


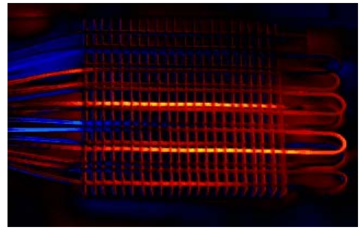
Test benches :

Plasma actuators in flight conditions

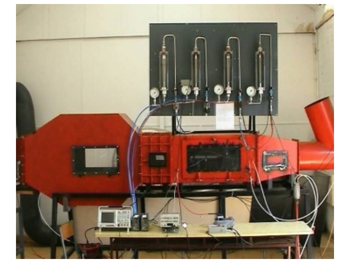
Dept. Fluids, Thermal Science, Combustion

EQUIPEX « GAP » : BATH Project





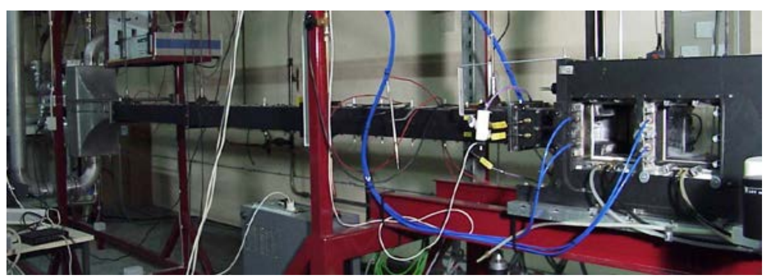
Heat Drains *From Lab to industrial scale*



Pulsed detonation engine

FTC :
Some Large experimental facilities

Cavity Ra=10^{11}



Oracle Test Bench
Partially premixed combustion

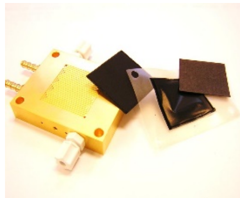
Rotating detonation engine

EQUIPEX « GAP » : RDE Project

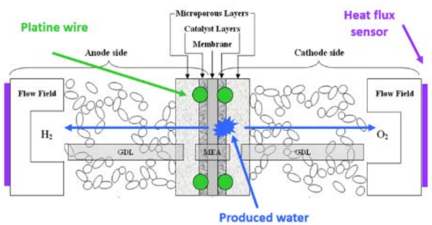
EDE Team Research Activities

Fuel Cells / Electrolyzers

MEA optimization
Cell Test & Systems
Mechanical Effects / Durability



Membrane
Electrode
Assembly

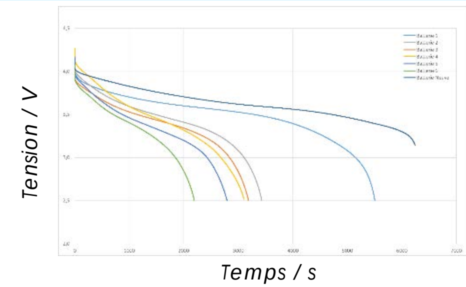


Electrical, Fluid & Thermal Metrology within Fuel Cells

Batteries / Supercapacitors

Lithium Battery Supercapacity

Electrochemical Noise
Aging Tests
Diagnosis / Prognosis



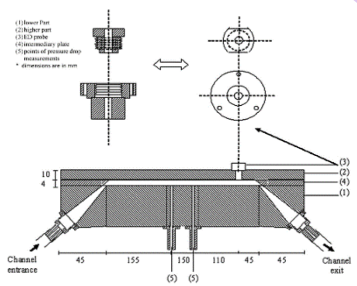
Dispersion in discharge curves

Electrical, Thermal & Fluid Metrologies – Sensors - Multiphysical Modelling & System approach -

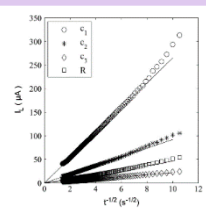
Coupled Charge, Heat & Mass Transfer in electrolyte

Liquid / Solid Deformable Interface

Mass Transfer in Turbulent Flow



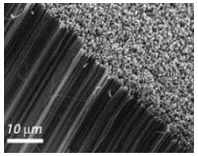
Flow loop with μ-electrodes



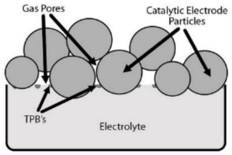
Diffusion limit current

Modelling –Electrodiffusion Effects

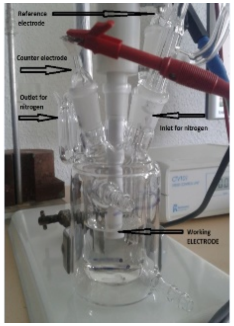
Interface Structuring / EDL



Carbon Nanotubes



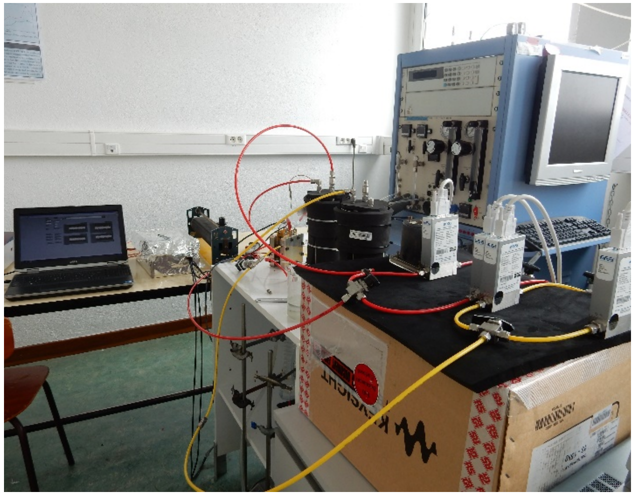
Triple phase boundary



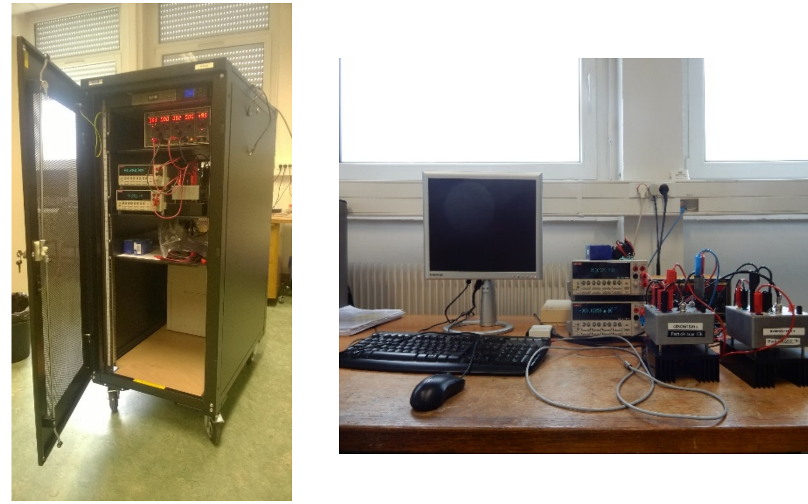
3 electrodes cells

Nanostructure / Electrical Double Layer
Cyclic Voltammetry - Impedance

Experimental Resources

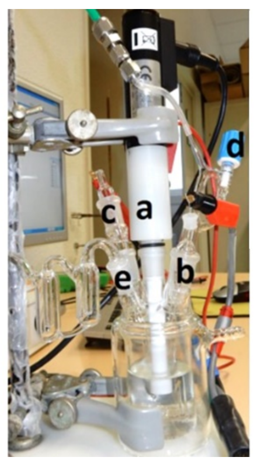


2 Fuel Cell bench



2 Lithium-ion bench

1 electrodiffusion loop

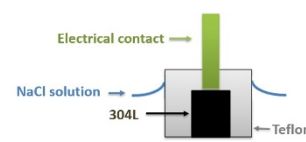


(a) Working electrode :
- polished 304L
- fixed in a Teflon holder
- 0.196 cm² area exposed to **NaCl solution (0.01 M)**

(b) Counter electrode : Pt solid : large surface area (2 cm^2)

(c) Reference electrode : Ag wire/AgCl (saturated KCl)

(d) / (e) Nitrogen flushing

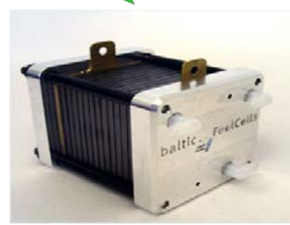


One analysis bench and electrochemical cells

Intermitent Renewable Energy

Electricity

O_2



Fuel Cell

Smart Grid

Li-ion battery

Electrolyzer

H_2

H2 vector Conversion & Storage Energy

→ Electrochemical Storage of Intermitent Renewable Energy (Electrolyzer + Fuel Cell + Batteries)

→ Power generation for isolated sites (Household Cogeneration Electricity / Heat)

→ Power for transportation and mobile applications

Exemples

TOYOTA

- Mirai commercialized since 2015
- Production capacity = 3,000 / yr
- 30,000 / yr from 2020

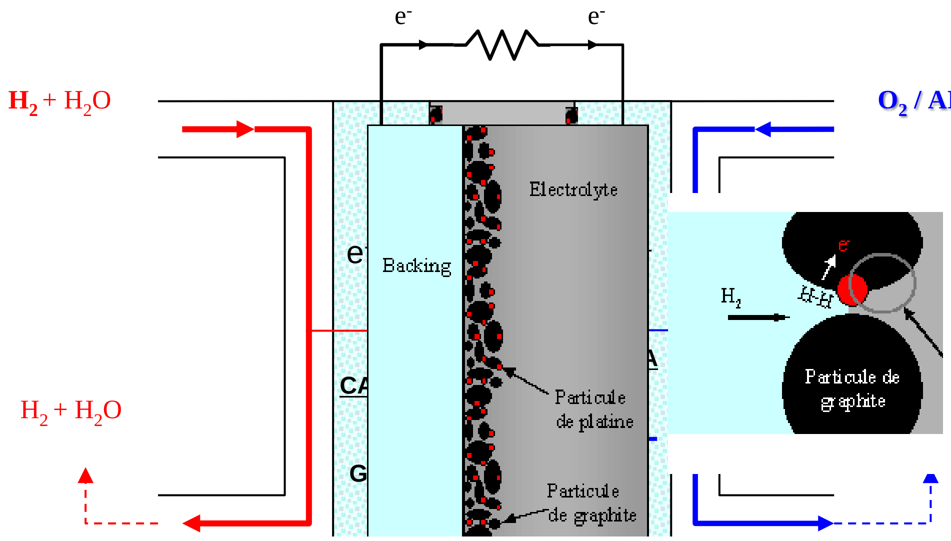
- Tucson commercialized since 2014
- Production capacity = 1 000 / yr
- 6,000 / yr from 2018

HYUNDAI

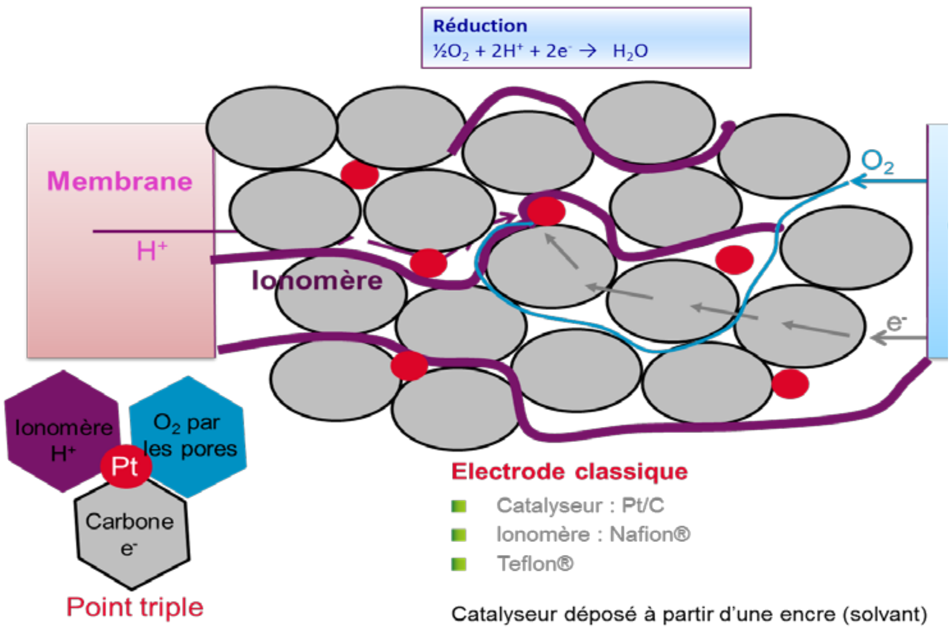
HONDA

- Clarity commercialized since 2016
- Production capacity = 1,000 / yr

Triple phase boundary



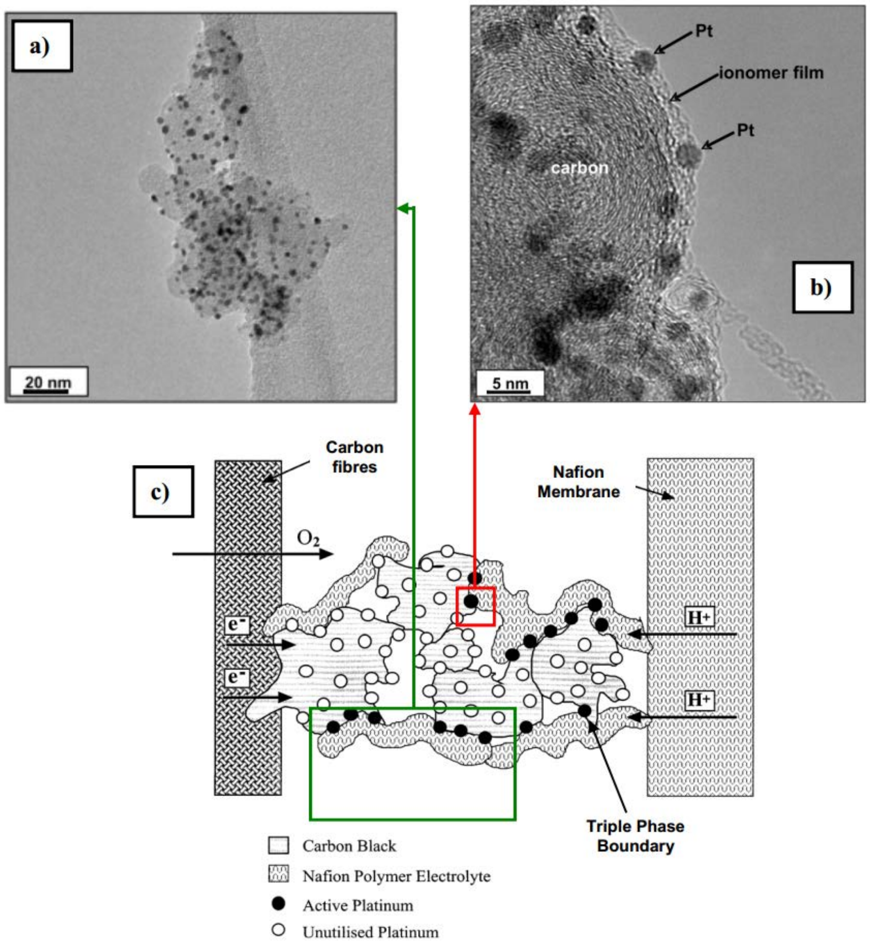
Problème de la Catalyse à la cathode



Electrode classique

- Catalyseur : Pt/C
- Ionomère : Nafion®
- Teflon®

Catalyseur déposé à partir d'une encre (solvant)



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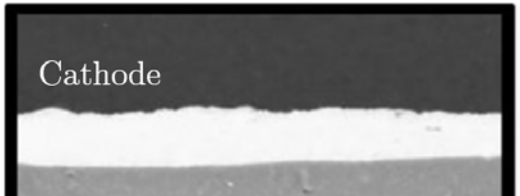
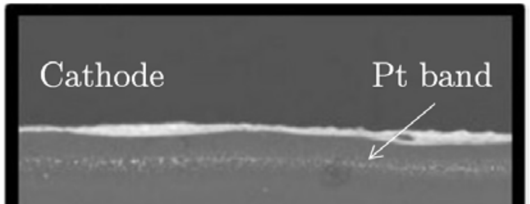
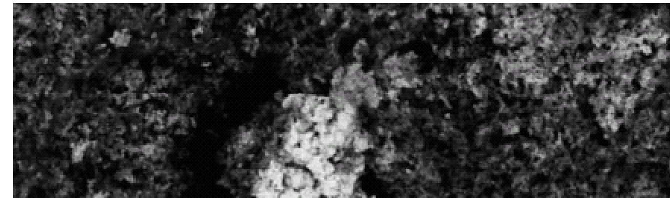
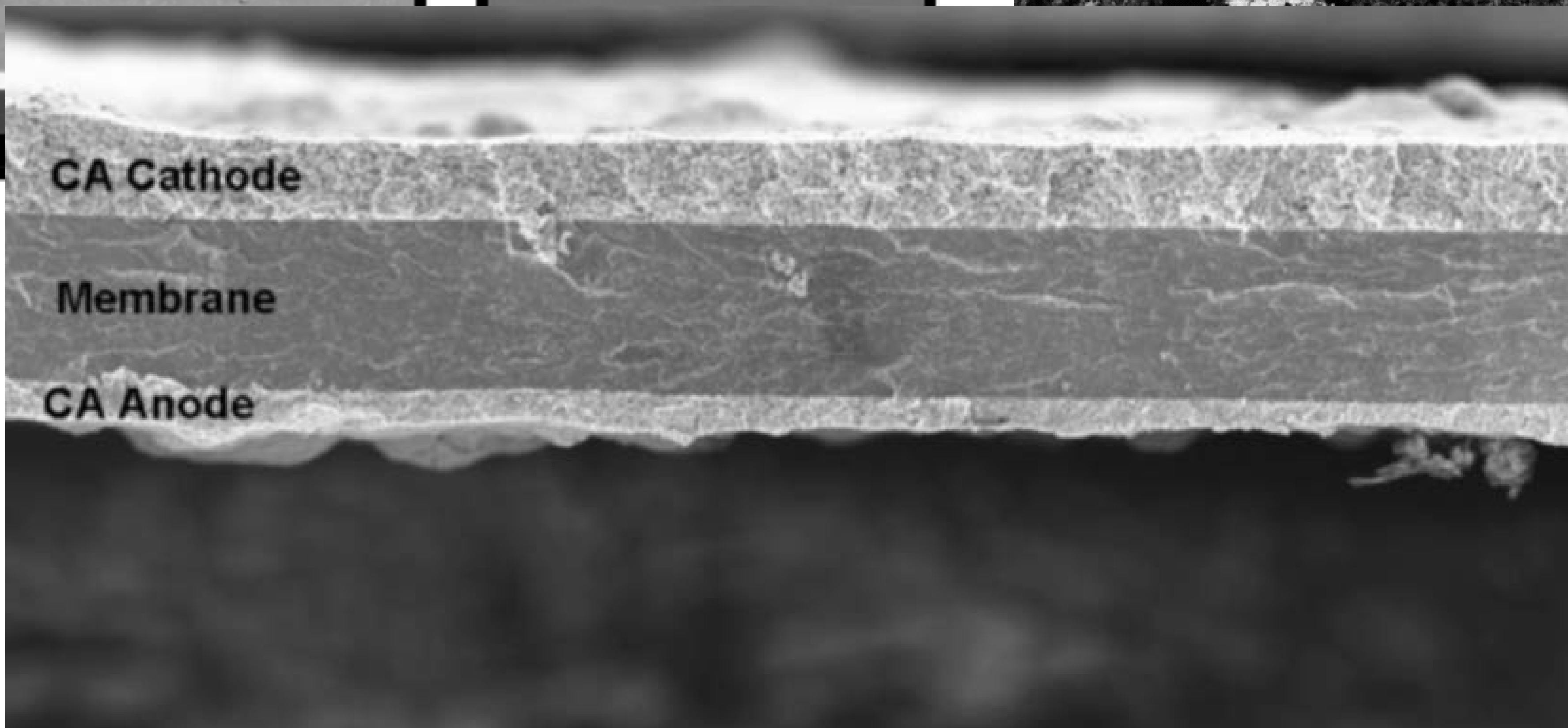
Only 20-30% activate Pt

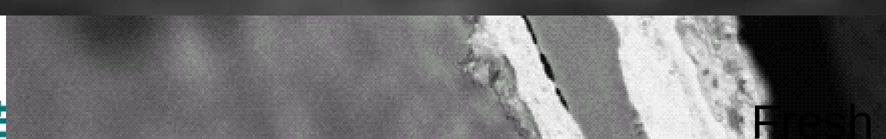
Durability in MEA



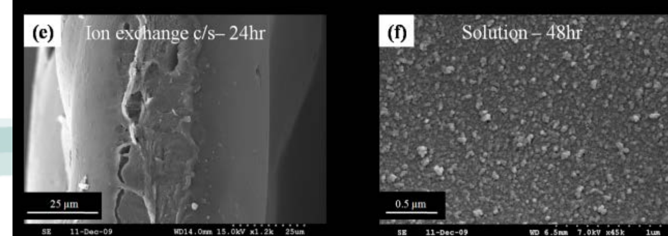








Fresh MEA



Delamination – mechanical stress

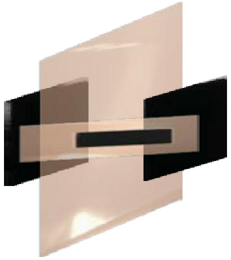
→ Structured and Robust MEA

Membrane cracks (humidity changes)

Actual method to make MEAs

Hot pressing

- Simple method
- Control 3 parameters : Temperature, Pressure and Time
- Ensure a good interface between CL - membrane



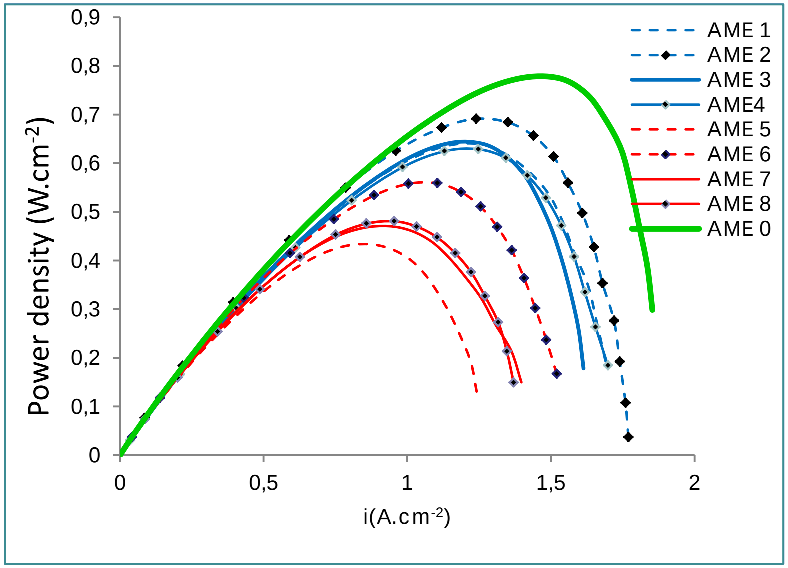
Prospects

- Objective 1 : Robustness and Stability of MEA
- Objective 2 : Industrialization (automatisation) of the process
- Control mechanical and thermal behavior
- Optimize MEA manufacturing like in batteries area
- Use similar process than microelectronics area (PVD – CVD, Lithography,…)

[1] V.A. Ilie, « Contribution à l'optimisation des AMEs et au développement des métrologies spécifiques pour les piles à combustible PEMFC et SAMFC », Thesis 2010

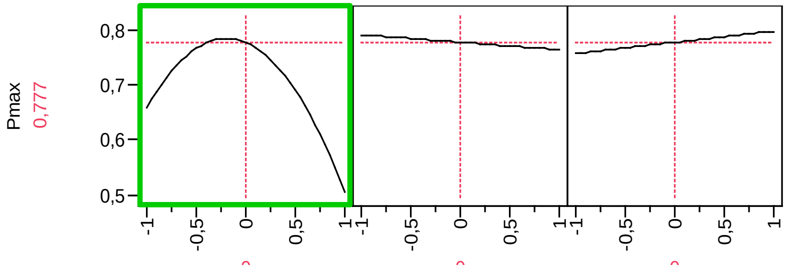
Parameter influence (T,P,t) on electrical performance

MEA	$T_{pressing}$ (° C)	$P_{pressing}$ (kg / cm²)	$t_{pressing}$ (s)	P (mW/cm²)
1	100	50	90	638
2	100	50	180	684
1	100	100	90	670
4	100	100	180	639
5	130	50	90	470
6	130	50	180	589
7	130	100	90	468
8	130	100	180	495
9	115	75	135	760
10	115	75	135	753
11	115	75	135	812



Domain of study

Level	T (° C)	P (kg / cm²)	t (s)
-1	100	50	90
0	**115**	**75**	**135**
+1	130	100	180

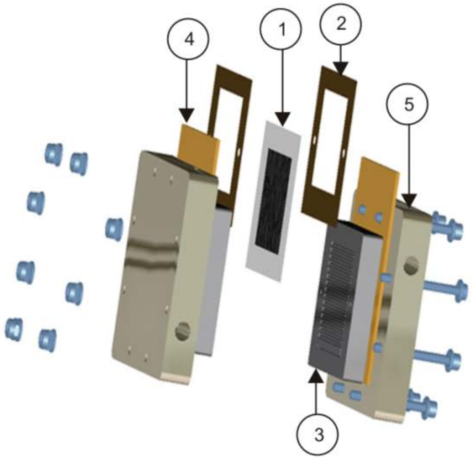


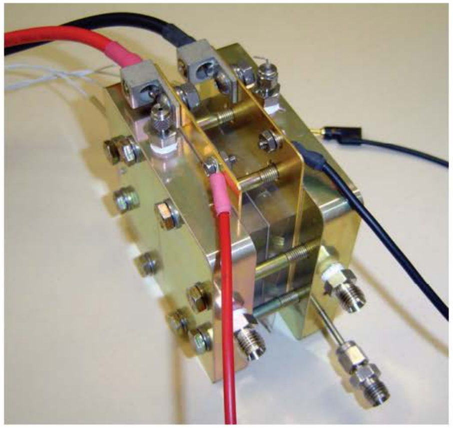
- **Increase of 25% to 50% electrical performance with good control of temperature**

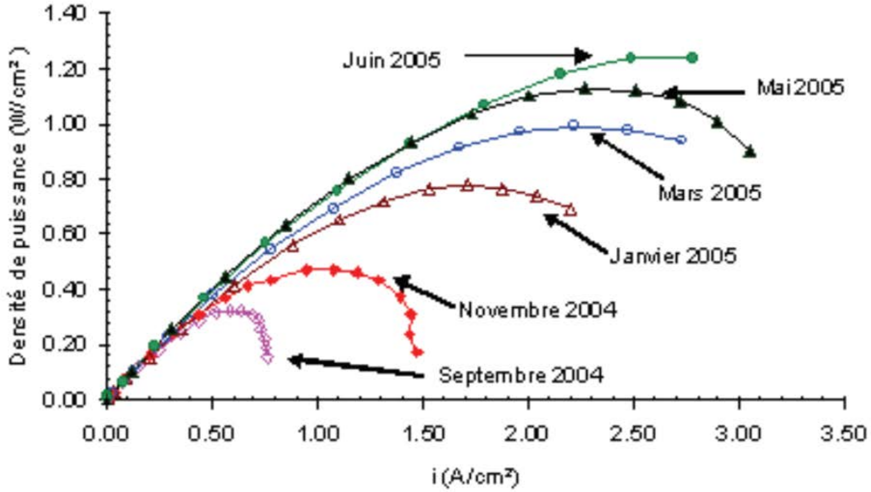
  $T_{pressing}$ ~ T_{glass} (little cooler 115° C < 117° C)

[1] V.A. Ilie, « Contribution à l'optimisation des AMEs et au développement des métrologies spécifiques pour les piles à combustible PEMFC et SAMFC », Thesis 2010

Fuel cell electrical performance

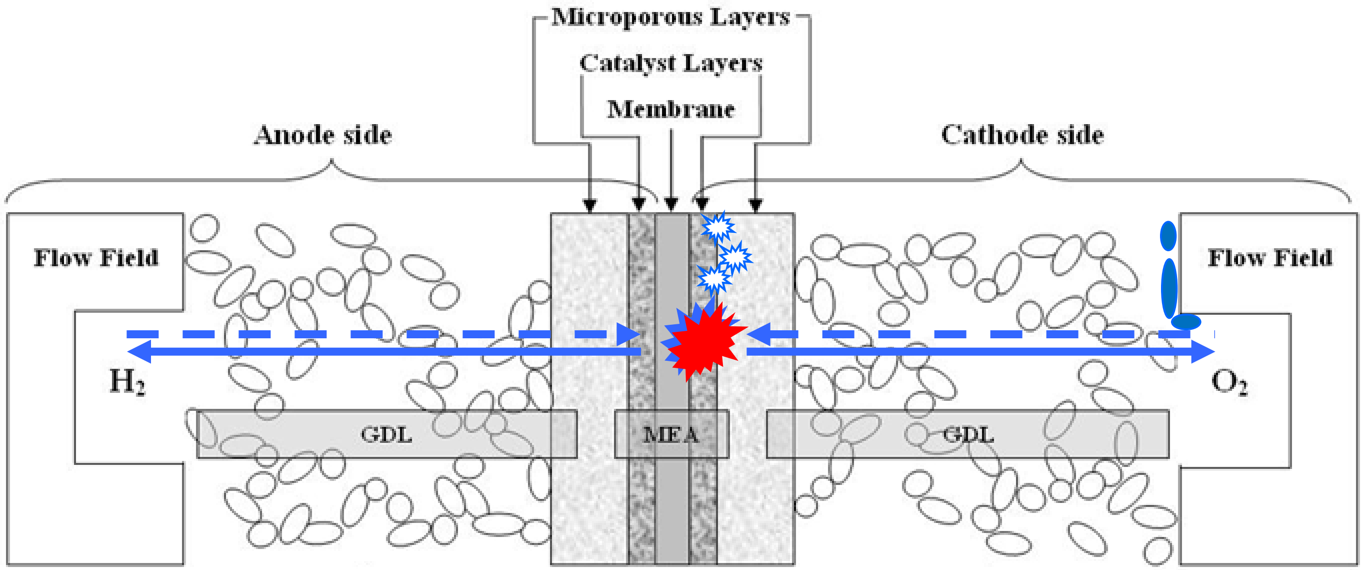






	AME – L.A.C.C.O.			
	Membrane / épaisseur (µm)	GDL/epaiseur (µm)	Charge en Pt / poids mg/cm² / %	Solution de Nafion %
Septembre 2004	Nafion 117 / 180	Papier de carbone/220	0,5 / 20	25
Novembre 2004	Nafion 117 / 180	Papier de carbone/220	0,4 / 20	25
Janvier 2005	Nafion 115 / 100	Tissu de carbone /270	0,35 / 30	25
Mars 2005	Nafion 112 / 50	Tissu de carbone /270	0,35 / 40	25
Mai 2005	Nafion 112 / 50	Tissu de carbone /270	0,35 / 40	25
Juin 20056	Nafion 112 / 50	Tissu de carbone /270	0,35 / 40	25

Heat and water transfer - Background



Water management :

- Good hydration of membrane => good proton conductivity
- Flooding issues on CL and GDL with the presence of liquid water

Thermal management :

- High temperature →Hydration and deterioration problems
- Low temperature→ increased risk of flooding

Objective : To understand mechanisms of heat and water transfer

Usually, fuel cell is supposed isothermal and thermal regulation is provided by thermocouples in flow field plates.

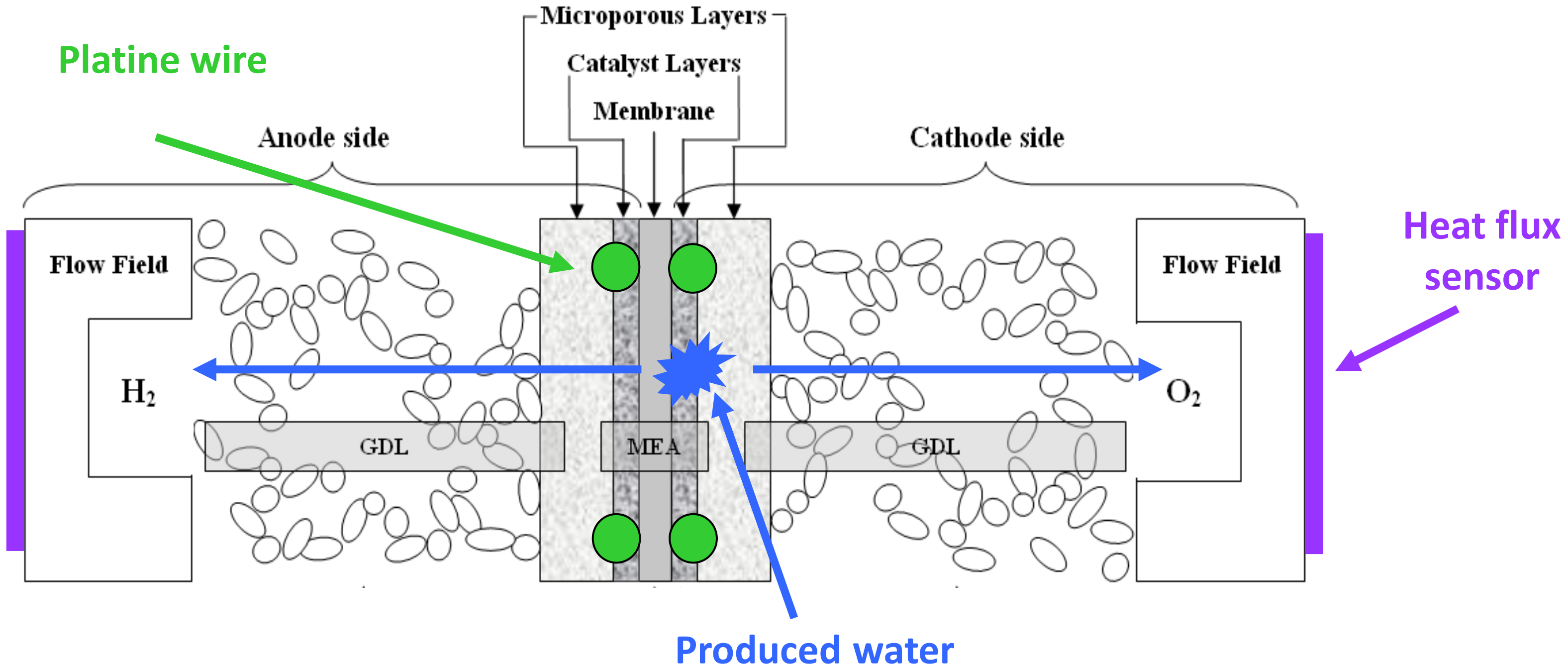
Originality of complementary measurements

Three complementary water/heat measurements

Electrode temperature → Temperature profile in the thickness direction

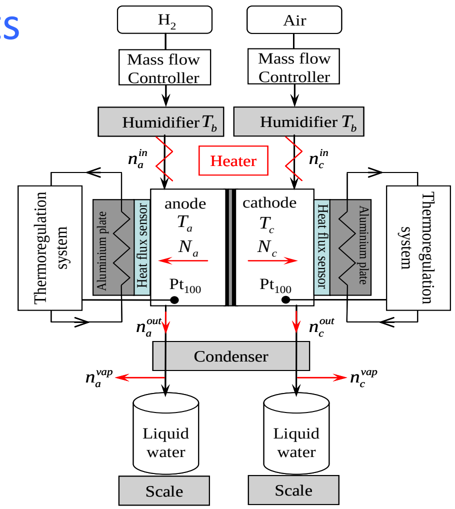
Heat fluxes → Heat fluxes through the GDLs

Water fluxes → Effect of temperature profile on water transport



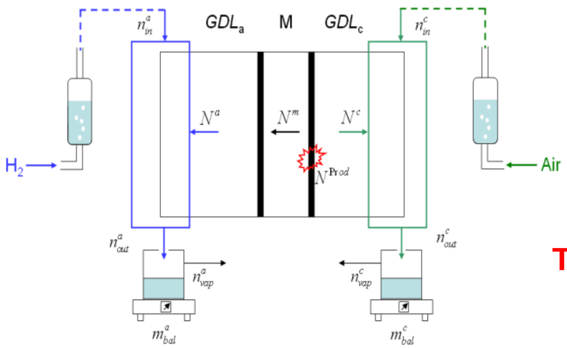
Metrology used

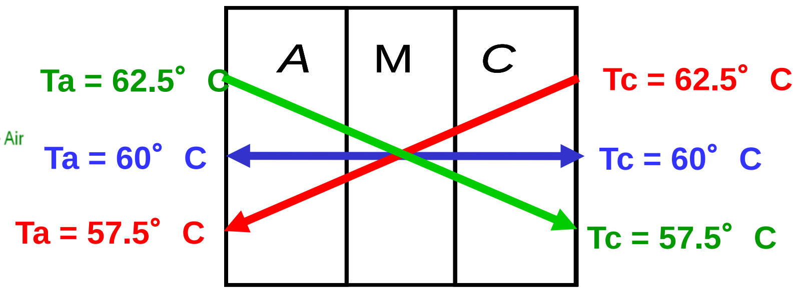
Three complementary water/heat measurements



Water fluxes

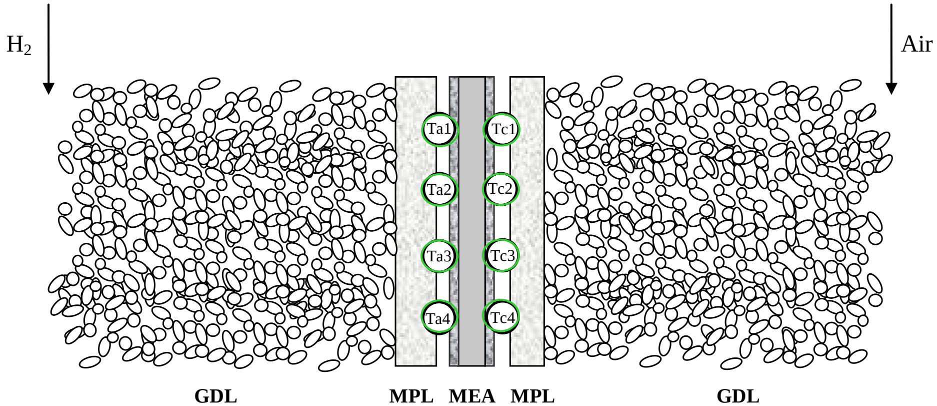
→ Effect of temperature profile on water transport





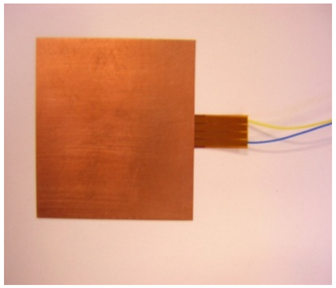
Electrode temperature

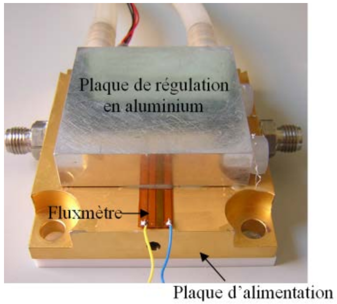
→ Temperature profile in the thickness direction



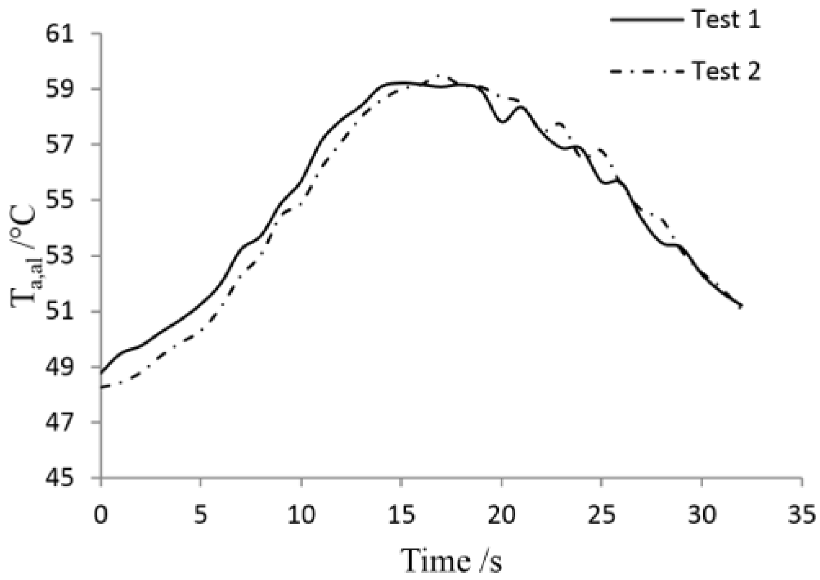
Heat fluxes

→ Heat fluxes through the GDLs

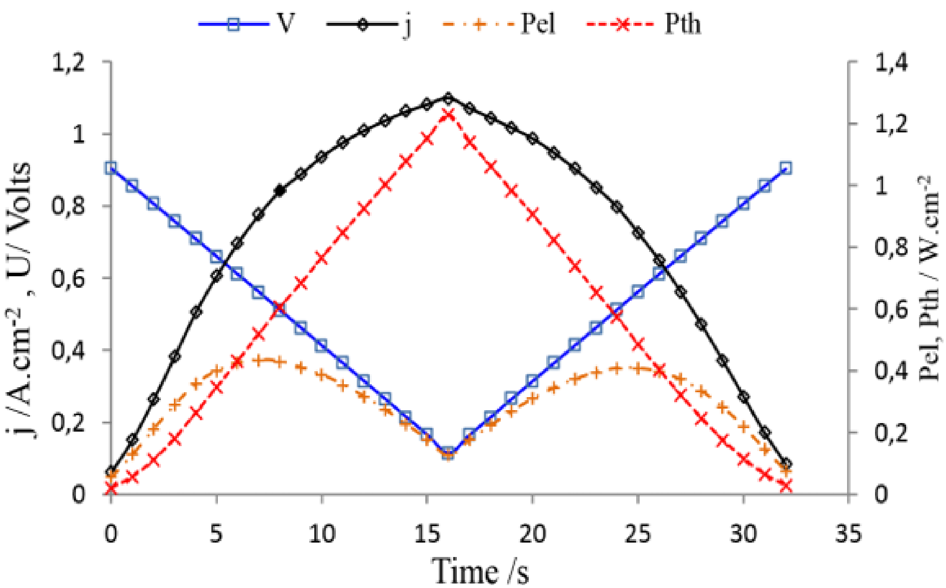




Electrode Temperature results



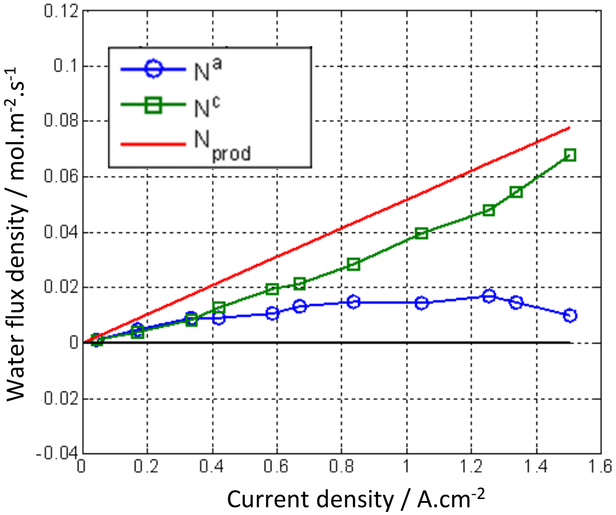
(a)



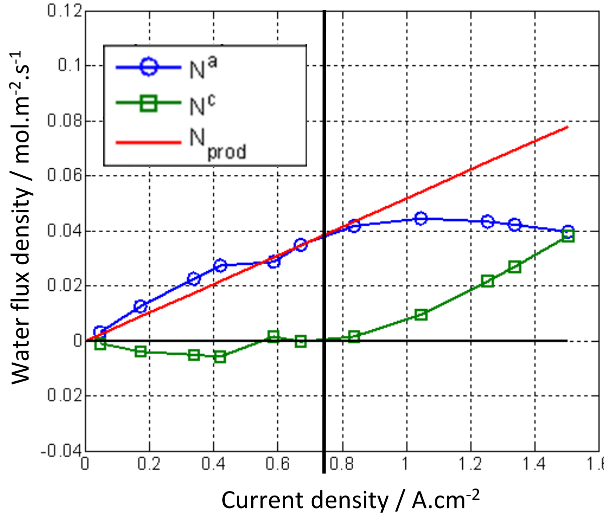
(b)

Water and Electrode Temperature results

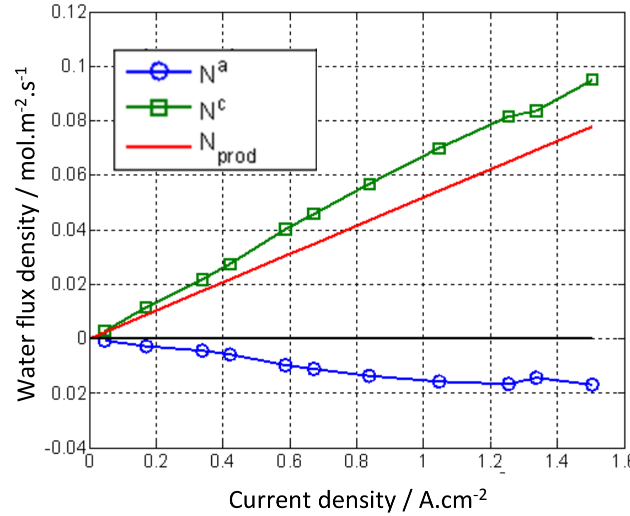
$(i) \quad T_c = T_a = 60°C$

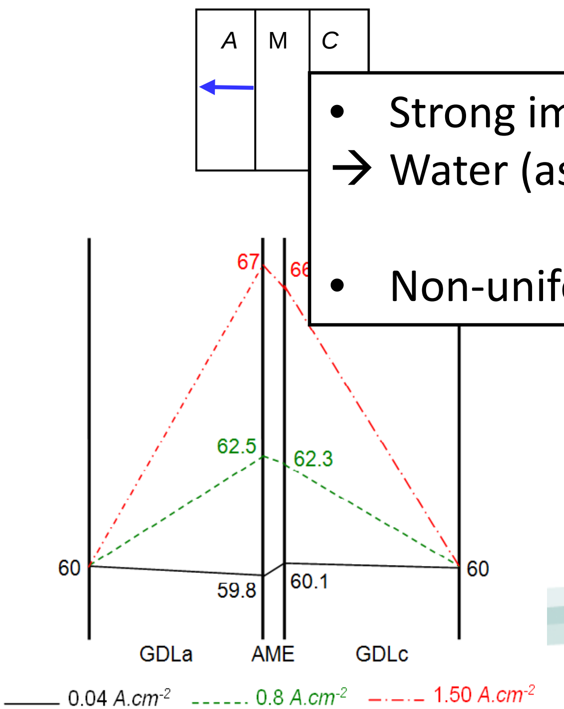


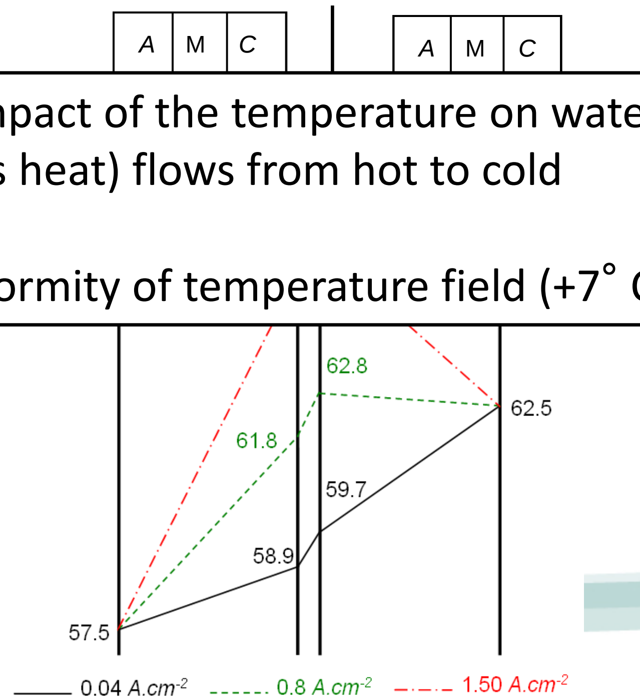
$(ii) \quad T_c = 62.5°C > T_a = 57.5°C$

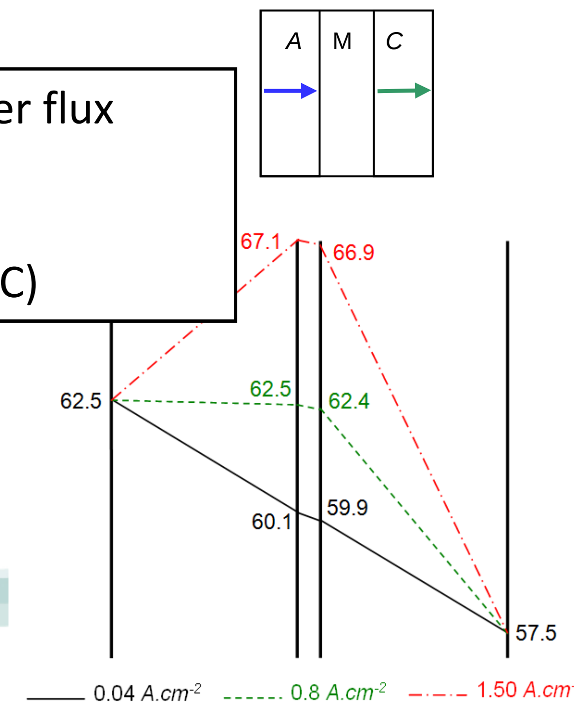


$(iii) \quad T_a = 62.5°C > T_c = 57.5°C$









- Strong impact of the temperature on water flux
→ Water (as heat) flows from hot to cold

- Non-uniformity of temperature field (+7° C)

■ The main goals related with studying of mechanical effects

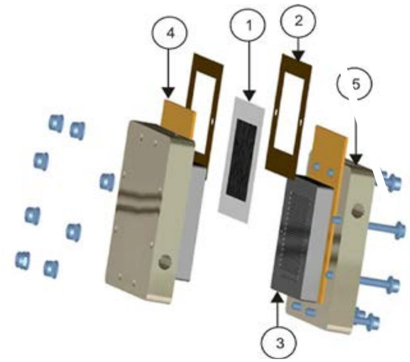
1. Influence of compressive stress on the fuel cell performance

2. Mechanical damages of MEA

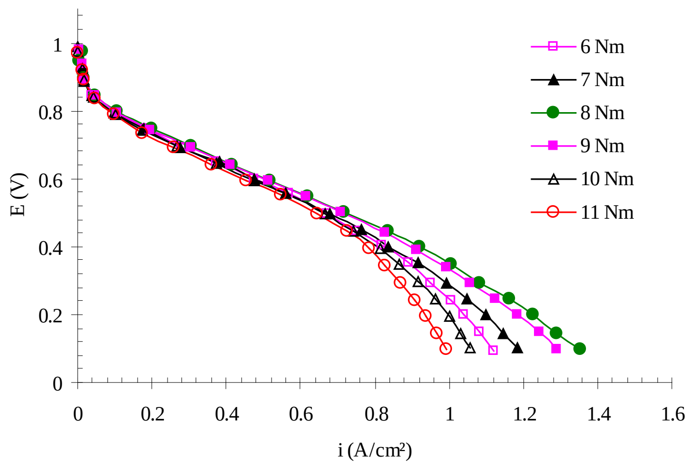
Why study mechanical stress ?

⇨Bolts torque Effects ?

MEA with carbon cloth

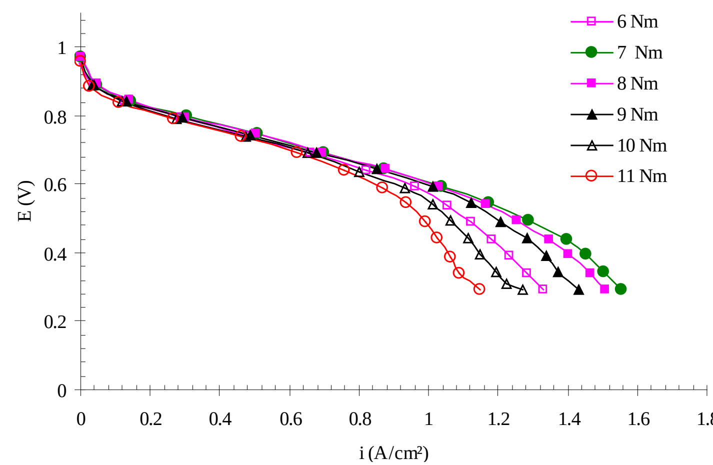


MEA with carbon paper



performances of the cell assembled with MEA-carbon cloth

T_{cell}=70° C, T_{huma}=T_{humc}=80° C, d_a=500 ml/min, d_c=1000 ml/min, p_a=p_c=1 bar

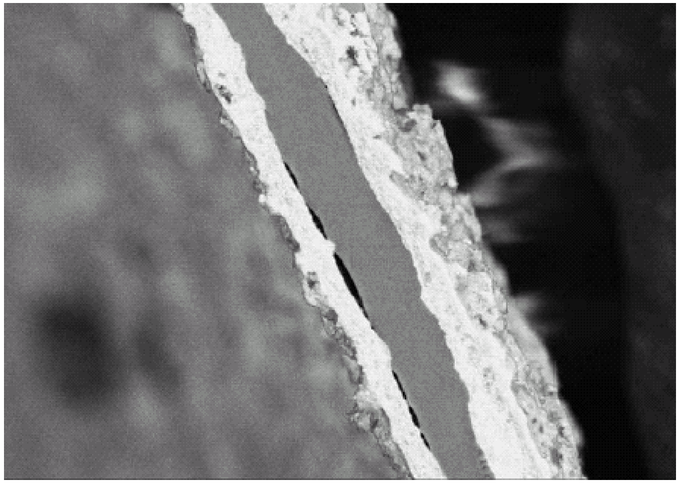


performances of the cell assembled with MEA-carbon paper

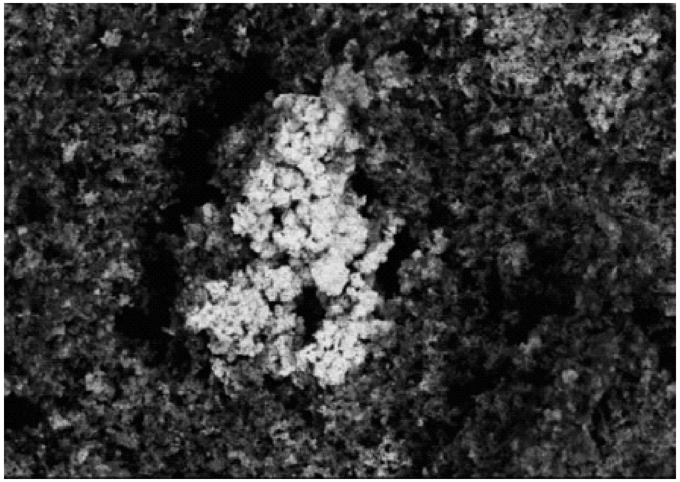
T_{cell}=70° C, T_{huma}=T_{humc}=80° C, d_a=800 ml/min, d_c=2000 ml/min, p_a=p_c=3 bar

Durability

- Delamination between membrane and catalyst layer



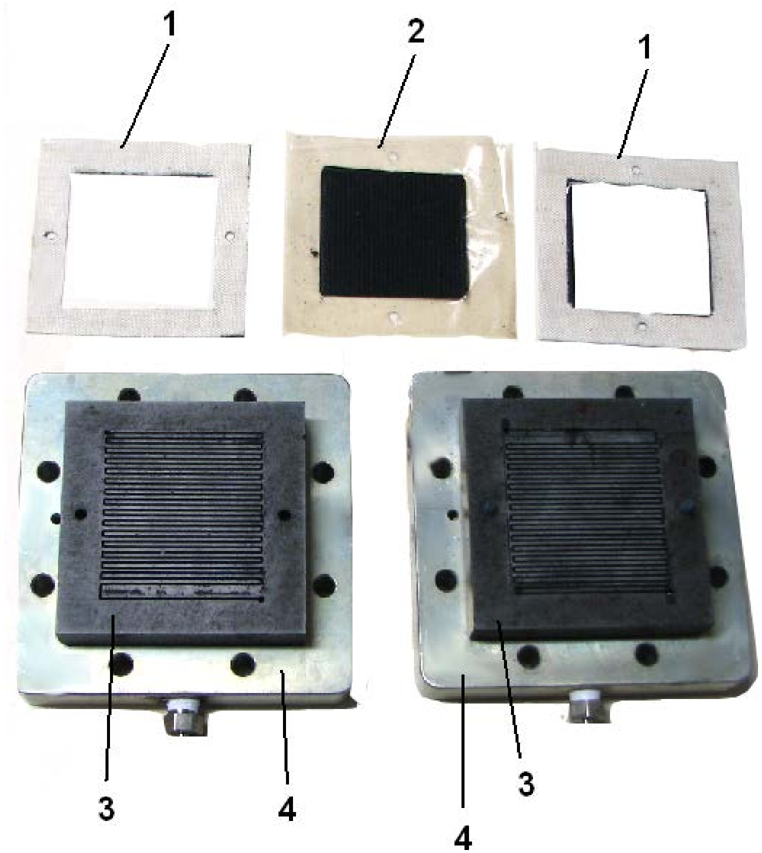
- Holes in the membrane



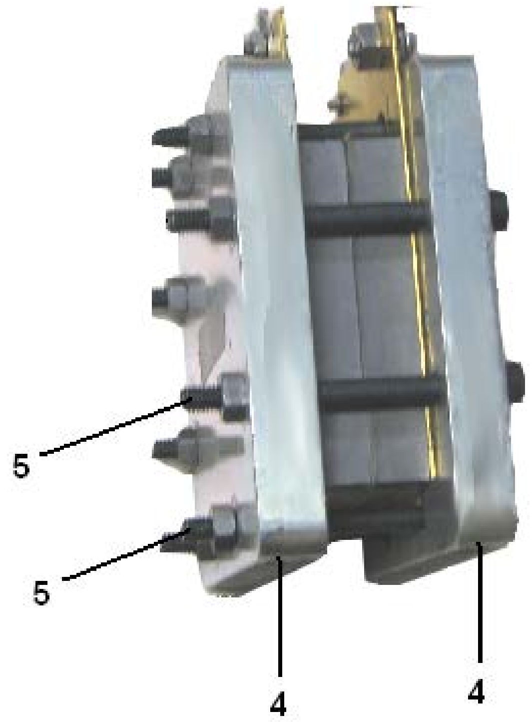
Modelling of mechanical effects

- **Using tools**
  - ✓ Numerical calculations of stress distribtions in fuel cell by means of ABAQUS code
  - ✓ Realistic modelling of the applied mechanical load
  - ✓ Modelling of the single tooth / channel structure (local approach)
  - ✓ Modelling of the entire fuel cell (global approach)

Fuel cell components



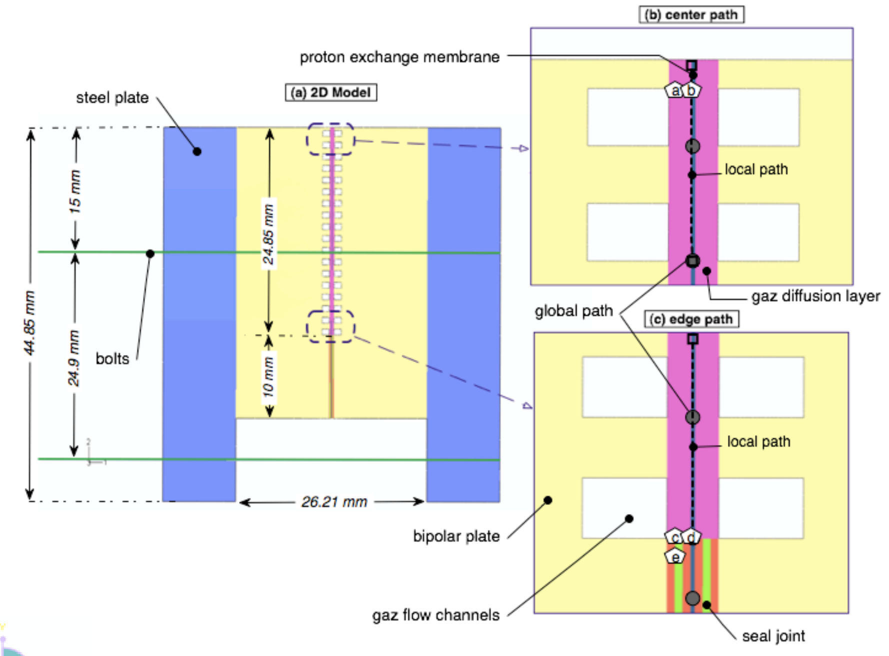
The Assembled fuel cell

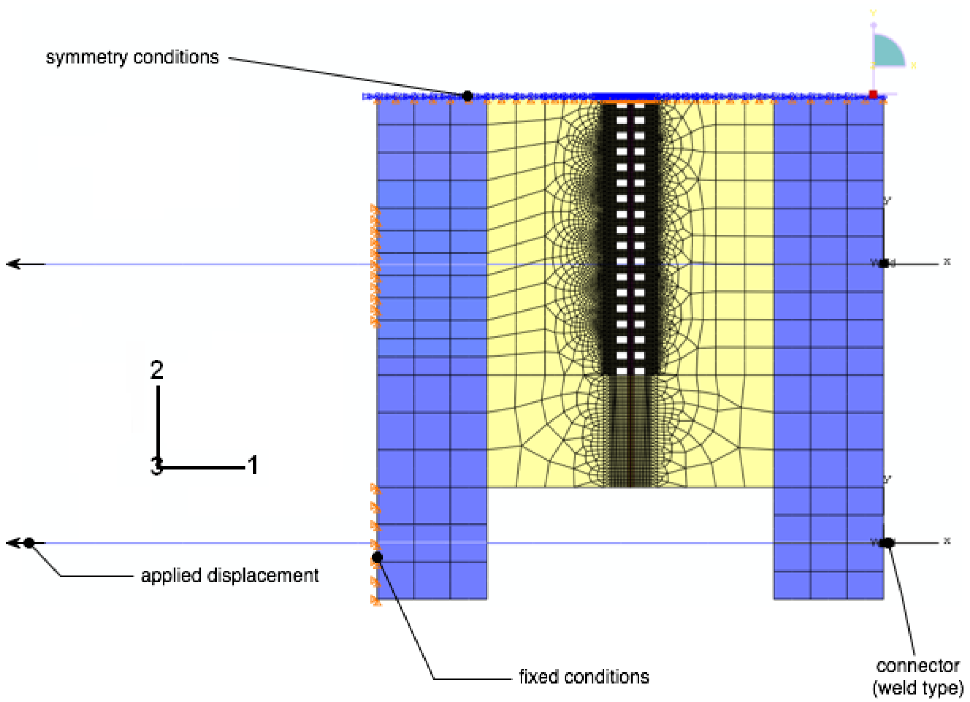


1 - Seal joints, **2 -** MEA, **3** – Graphite plates,
4 - Steel plates, **5 -** Bolts.

The model of fuel cell

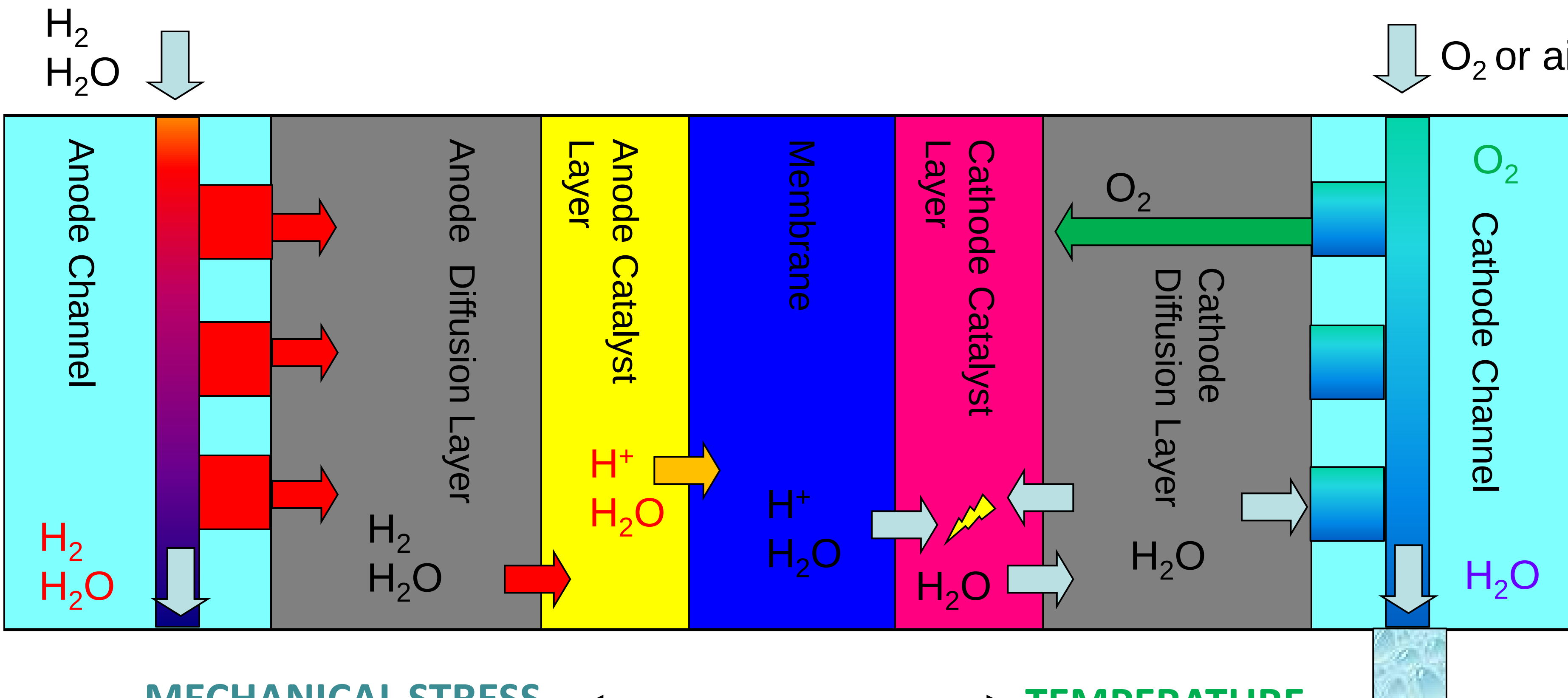
The seal joints,
The membrane,
The graphite plates,
The steel plates,
The bolts.





The global and local scales

2D Model



MECHANICAL STRESS ⟷ **TEMPERATURE**

→ **Clamping effect on electrode, GDL and membrane (compression)**

→ **Swelling effect (humidity)**

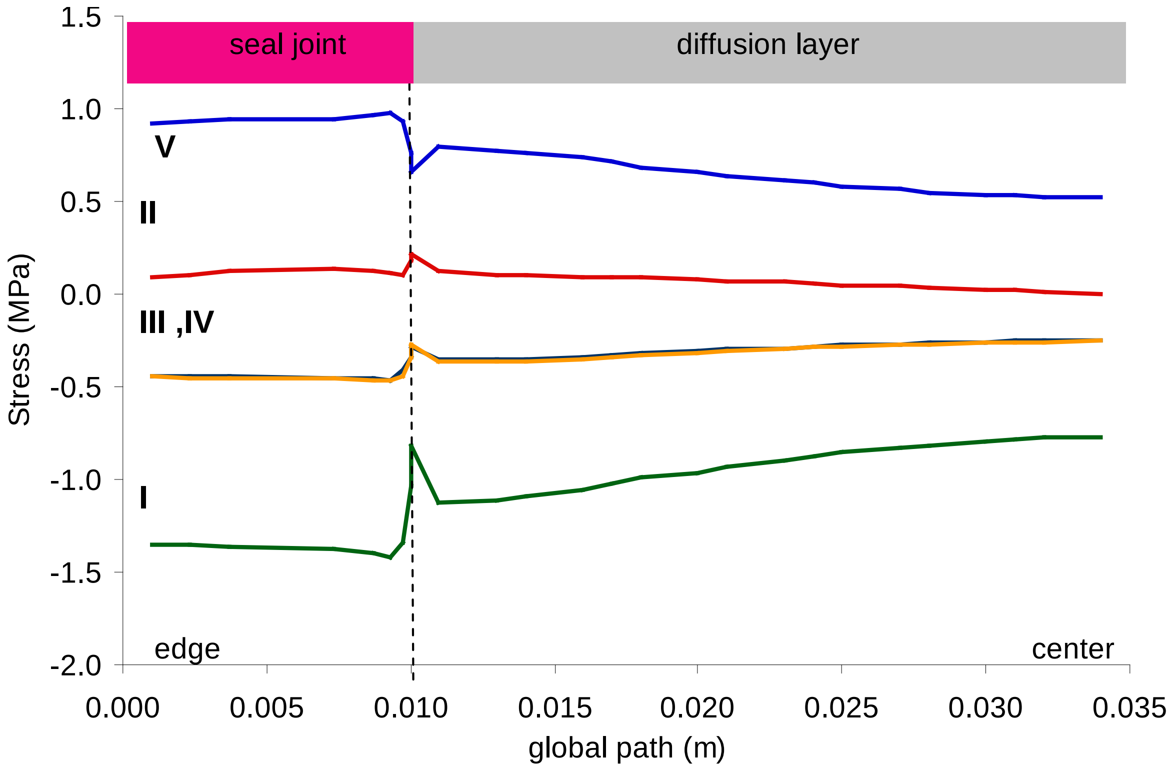
→ **Exothermic reaction**

→ **Joule effect**

Modification on mechanical & thermal properties

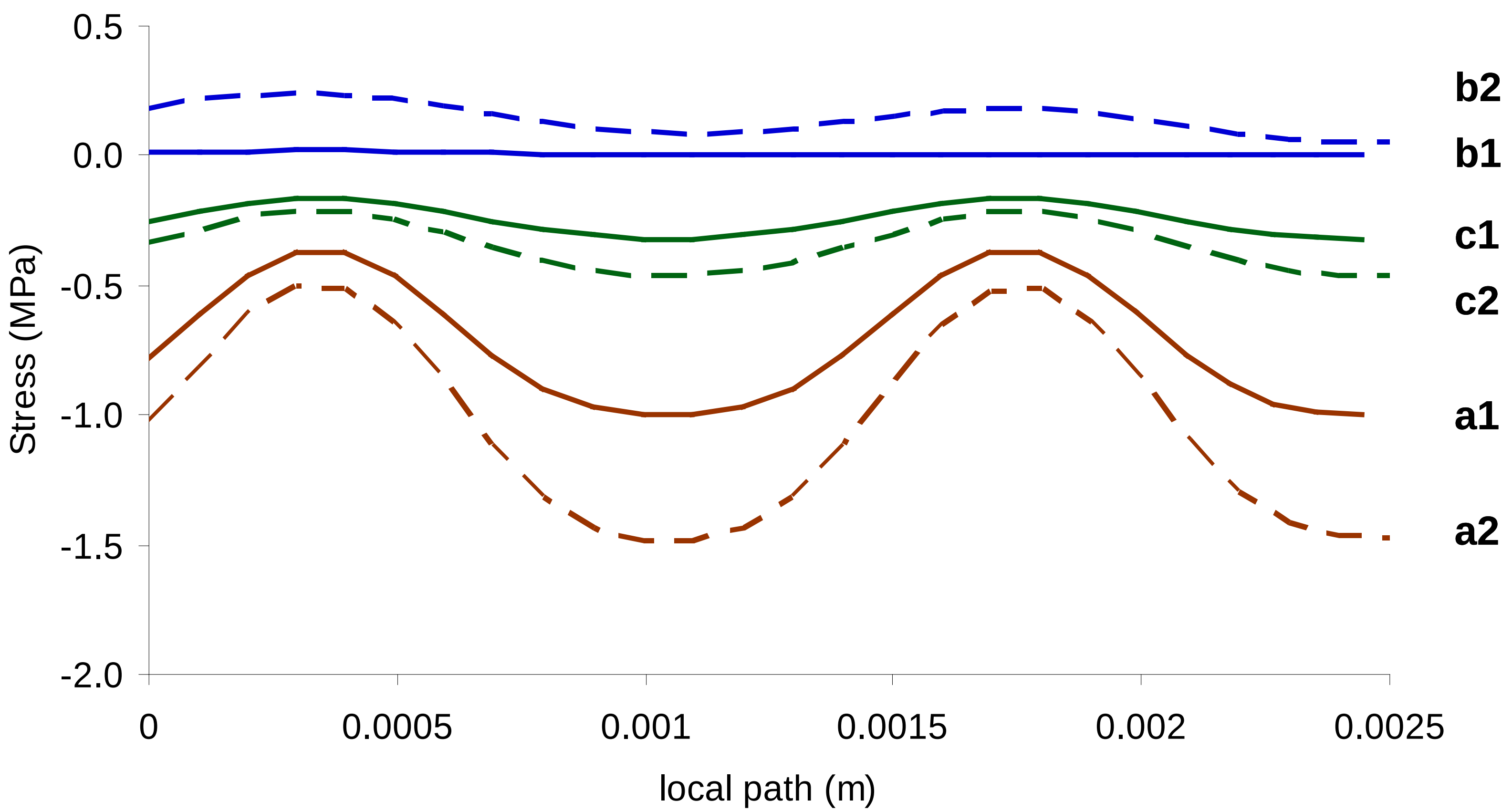
[7] D. Bograchev, M. Gueguen , J.C. Grandidier, S. Martemianov, Journal of Power Sources, 2008 180, 393-401
[8] D. Bograchev, M. Gueguen , J.C. Grandidier, S. Martemianov, International Journal of Hydrogen Energy, 2008 33, 5703-5717
[9] J.C. Grandidier, S. Martemianov, M. Gueguen, D. Bograchev, M. Hamour, CFM, 2009

Cold assembly (global scale in the membrane)



I - Normal Stress , II – Shear stress, III – Tangential stress out of plane, IV –Tangential Stress, V – Misses stress.

Cold assembly (local scale in the membrane)

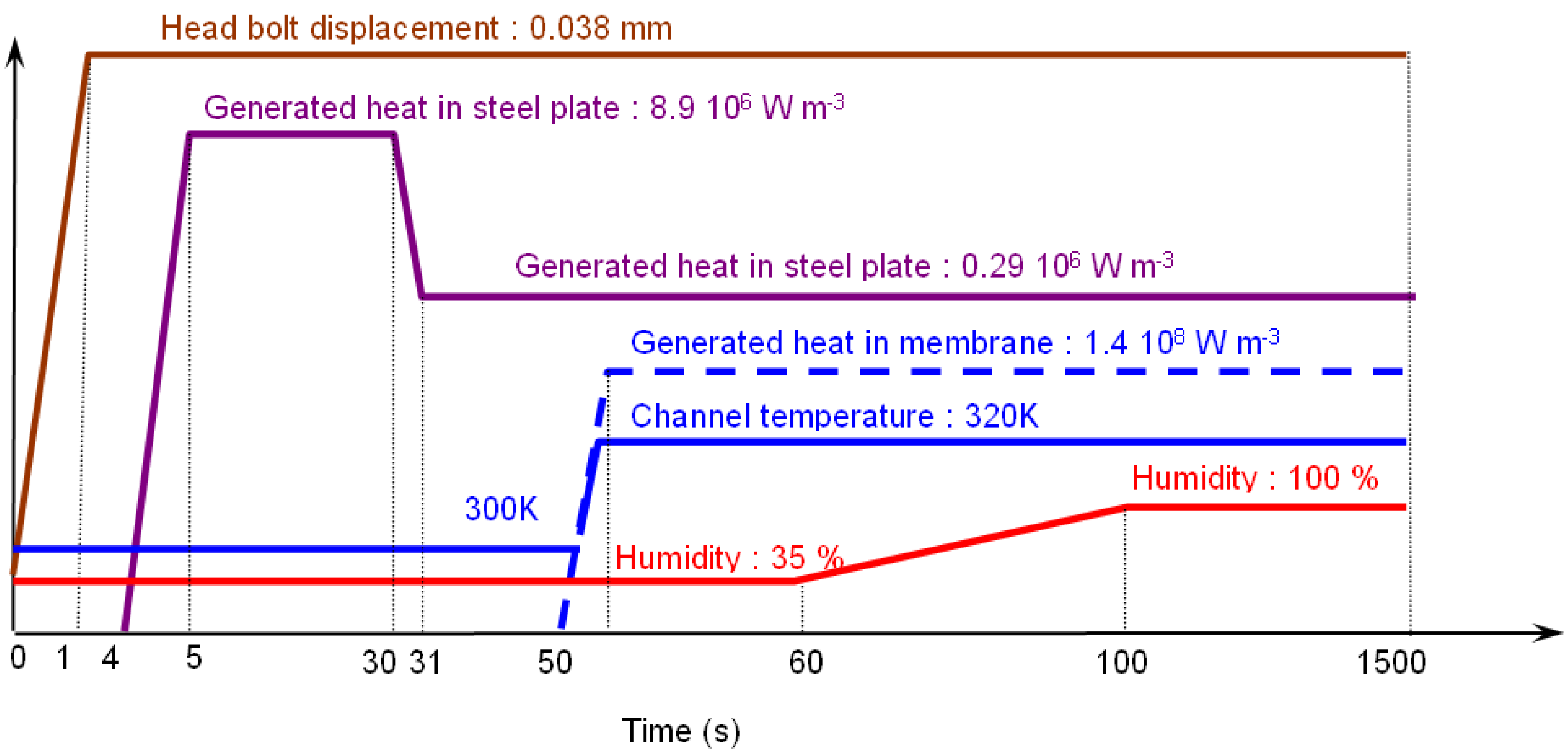


The normal (a), shear (b), and tangential (c) stresses distribution
Centre (1) and at edge (2) region of membrane.

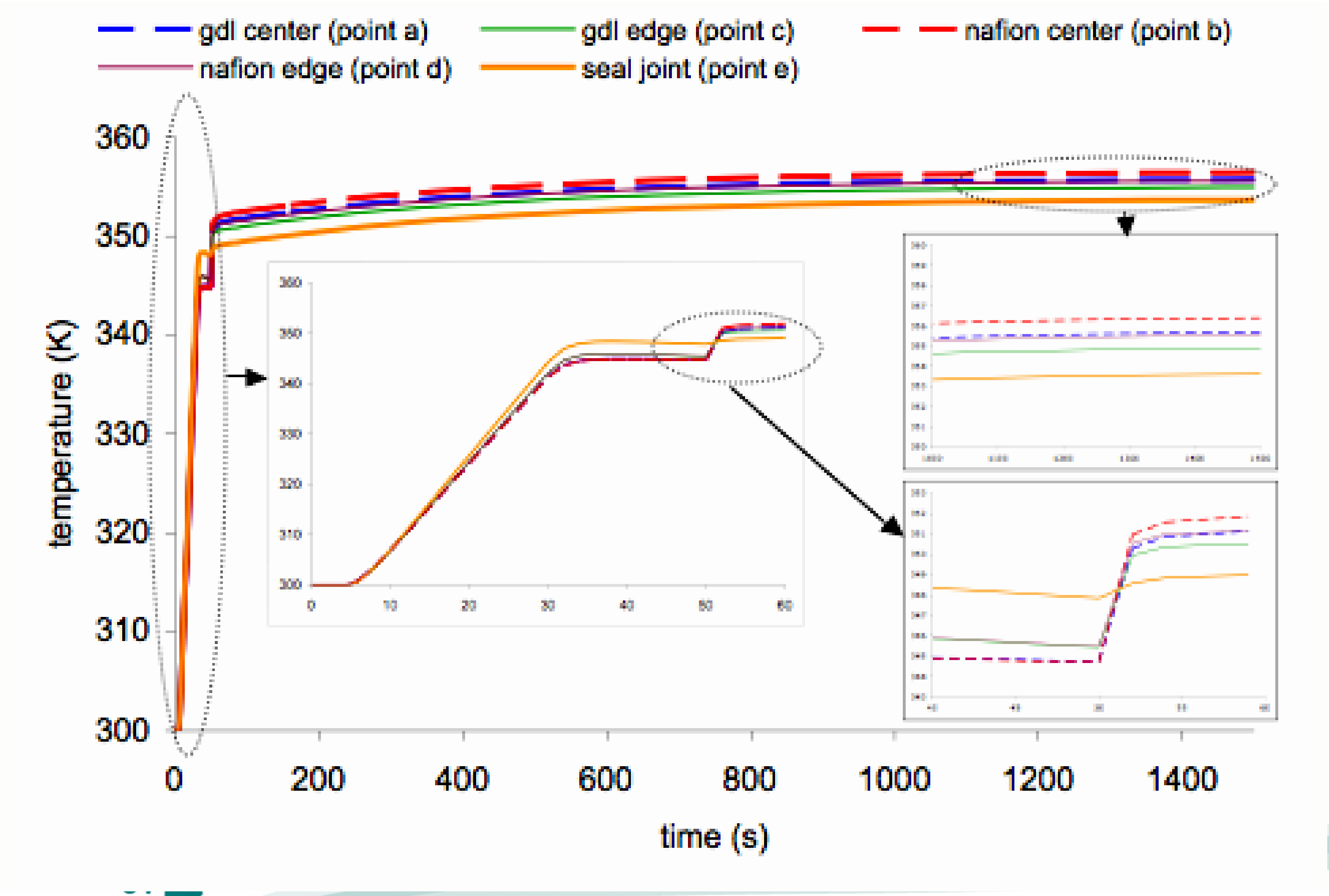
Conclusions for «cold» model

- stress distributions on the local and the global scales are determined
- there is a zone with strong heterogeneous stresses in the membrane under the junction seal joint/graphite plate
- difference between stiffness of seal joint and gas diffusion layer is very significant factor
- membrane does not reach the plasticity at the applied mechanical load corresponding to 1MPa

Hygro-thermal loading: running fuel cell

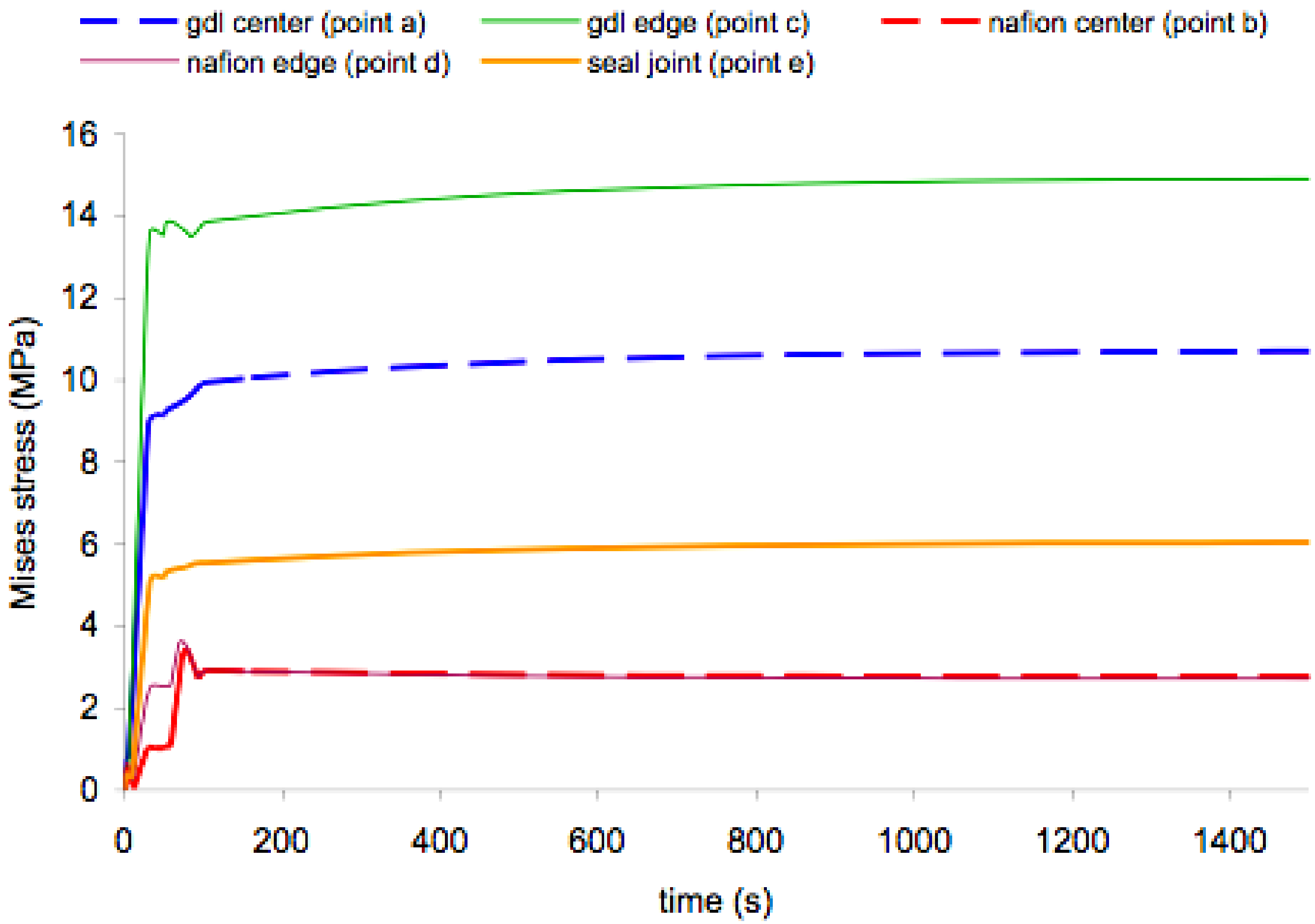


After fuel cell turn-on
Time evolution of temperature



- The steady-state regime is achieved after about 1400s
- The highest temperature is in the membrane (center region), then GDL
- The seal joint temperature grows faster but reaches less level in comparison with membrane and GDL
- Characteristic temperature difference in MEA is about 5 °C

After fuel cell turn-on
Time evolution of the Mises stresses

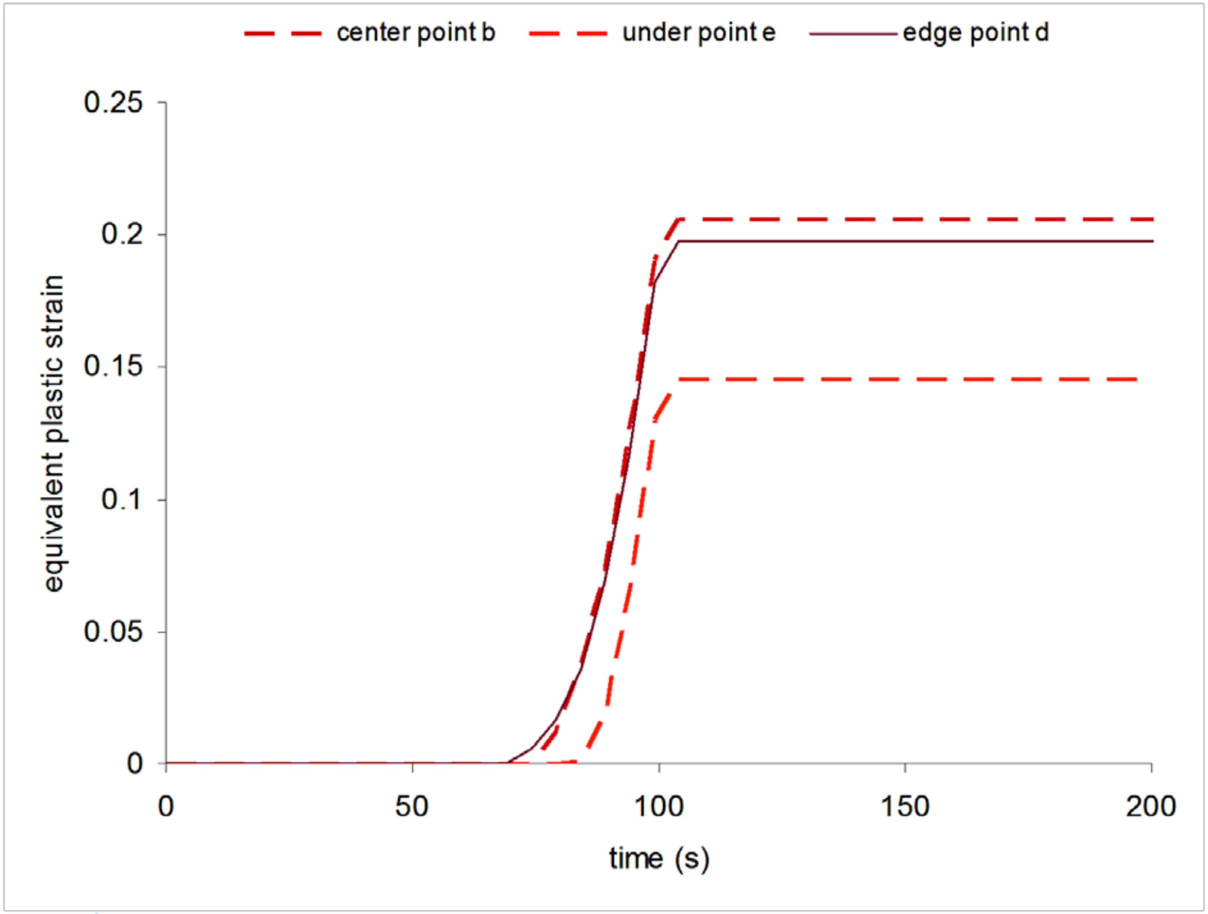


- The stresses change strongly during the first 100 seconds of the cell running, afterwards they stabilize with the achievement of the temperature steady-state regime

- The highest level of Mises stress is reached in the GDL, but plasticity effects don't occur in this zone

- From the other hand, the critical value of yield stress is achieved in the membrane and plasticity deformations arise

After fuel cell turn-on
The time evalution of the eqivalent plastic strain



- The first plastic deformations in the membrane emerge only during the stage of the humidification

- The plastic deformation in the centre of the membrane arises later; however, it reaches a higher level

- The plasticity appears also in the membrane under the seal joint

- The plastic deformation remains constant at the end of the humidification stage

- It is important to note that its level is very high.

- The stress distribution along the membrane has a complex character during the transient phase
- This distribution stabilizes at the end of the humidification step and becomes quasi-homogeneous when the temperature field reaches steady-state
- It can be noted that the maximal stresses (higher than 3.5 MPa) occur during the humidification step
- These peak stresses are localized under the joint/GDL interface; especially in this part of MEA the failures are often observed.

Conclusions

Mechanical phenomena play very important role in fuel cell technologies influencing on cell performance and durability

In particular, one of the reasons of **membrane pinholes can be caused by accumulation of plasticity deformations** during work cycles

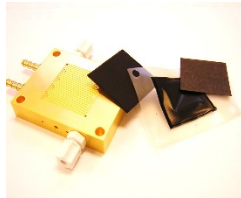
There is **strong coupling between mechanical, thermal and humidification effects**: numerical modelling shows that arising in MEA **stresses depends on heat and humidity load regimes**

Arising in MEA **stresses reach important peak values (3 time more than applied during assembly mechanical load)** in transient regime during humidification step

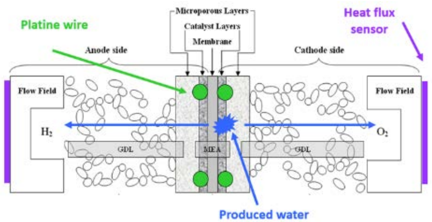
EDE Team Research Activities

Fuel Cells / Electrolyzers

MEA optimization
Cell Test & Systems
Mechanical Effects / Durability



Membrane
Electrode
Assembly

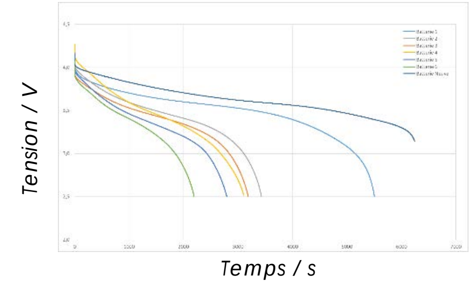


Electrical, Fluid & Thermal Metrology within Fuel Cells

Batteries / Supercapacitors

Lithium Battery   Supercapacity

Electrochemical Noise
Aging Tests
Diagnosis



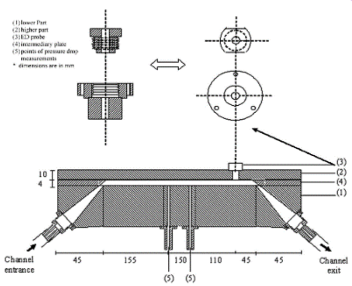
Dispersion in discharge curves

Electrical, Thermal & Fluid Metrologies – Sensors – Multiphysical Modelling & System approach –

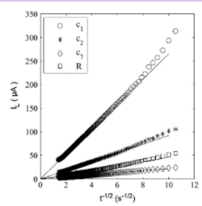
Coupled Charge, Heat & Mass Transfer in electrolyte / systems

Liquid / Deformable Solid Interface

Mass Transfer in Turbulent Flow



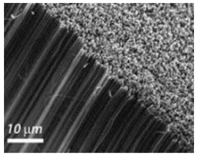
Flow loop with µ-electrodes



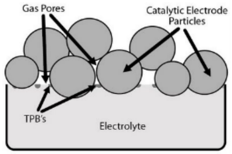
Diffusion limit current

Modelling –Electrodiffusion Effects

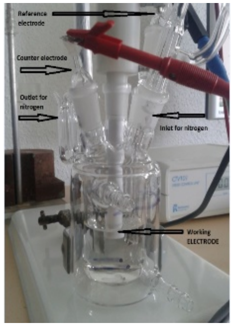
Interface Structuring / EDL



Carbon Nanotubes



Triple phase boundary

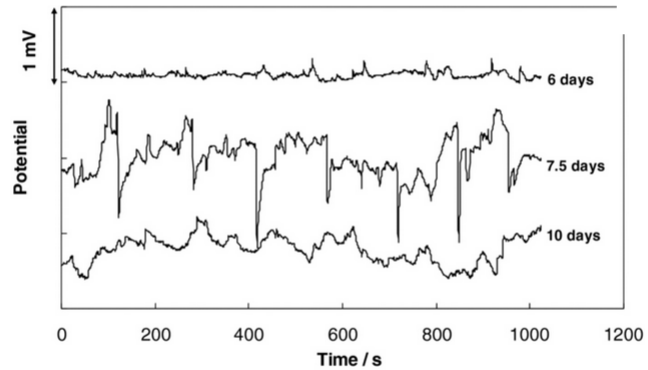


3 electrodes cells

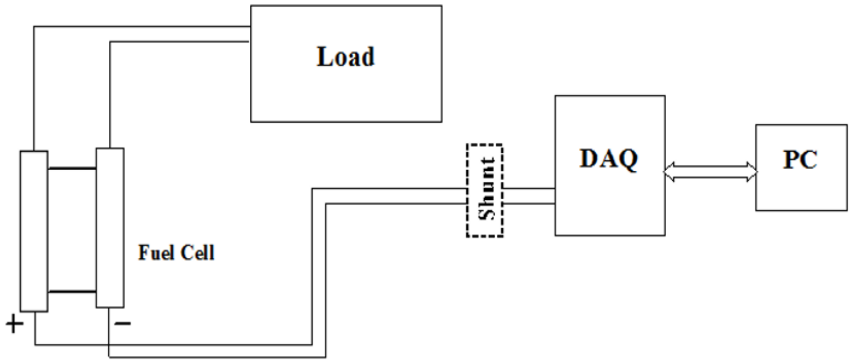
Nanostructure / Electrical Double Layer
Cyclic Voltammetry - Impedance

Electrochemical Noise = stochastic fluctuations of voltage (or current)
generated by mechanical and/or chemical degradations (cracks, dissolution, gas bubble formation,…)

Mostly use in Corrosion at metal-solution interface



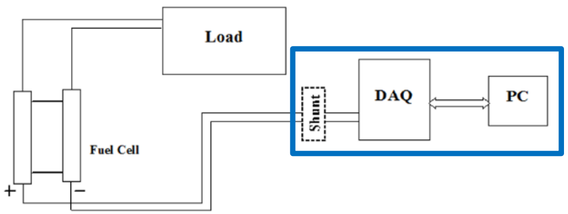
Experimental setup

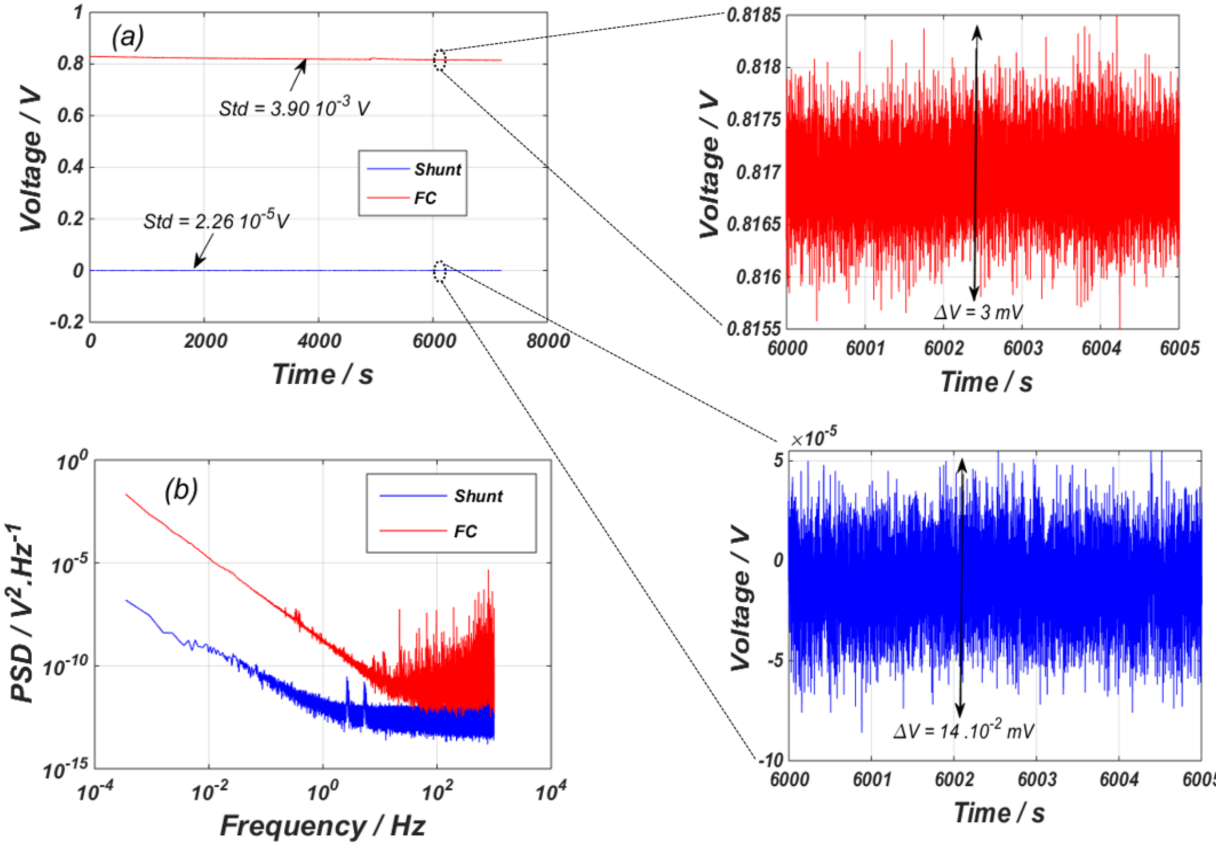


→ Direct measurement
No analog filter / No amplifier
Additional elements can impact final results

- *PEMFC single cell* Commercial MEA Nafion® 211 (25 cm²) 0,3 mg.cm^{-2} Pt / Sigracet ® GDL 25BC
- *Fixed flow rate* H2 : 122 ml.min^{-1} and Air : 622 ml.min^{-1}
- *Tcell = 60 °C / Tbubblers (60 °C or more)*
  4 humidities : RH_{H2} = 100% / RH_{Air} = 0%
  RH_{H2} = 100% / RH_{Air} = 100%
  RH_{H2} = 50% / RH_{Air} = 50%
  RH_{H2} = 20% / RH_{Air} = 20%
- *NI DAQ 9239* 24 bits (good accuracy) / anti-aliasing-filter sampling rate 2kHz
- Load = 0,1 Ω - 8 Ω Resistor
- *Shunt* : Intrinsic noise of experimental setup

Intrinsic noise of experimental setup





Voltage fluctuations measurements during 7200s at 2 kHz

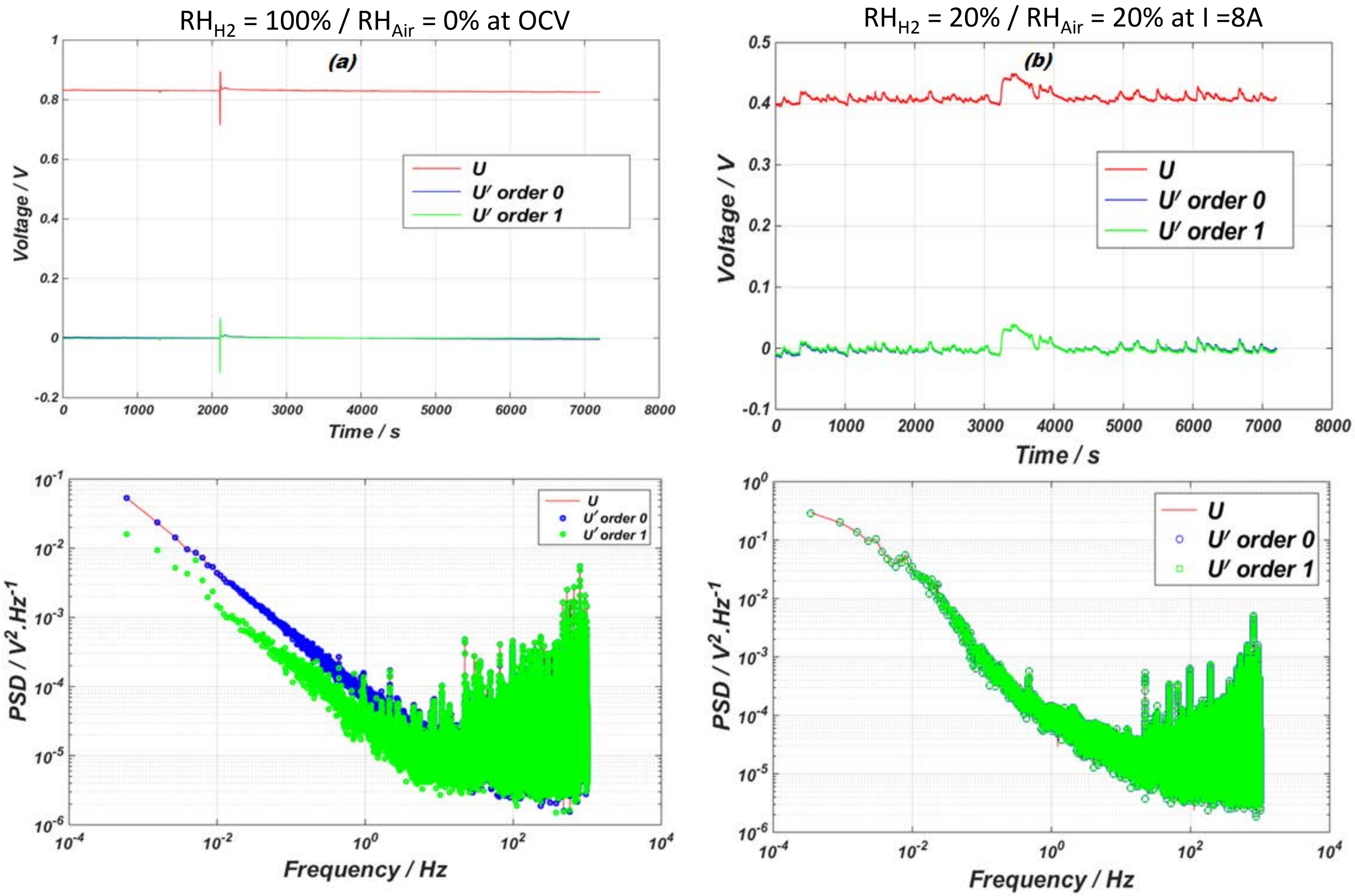
- *Fuel cell voltage fluctuations = 3 mV* **>>**$_{x20}$ *Shunt voltage fluctuations 0,14 mV*
- STD_{FC} **>>**$_{x180}$ STD_{Shunt}
- *Spectrum amplitude*$_{FC}$ *>> Spectrum amplitude*$_{Shunt}$ *at low frequency range (f < 100 Hz)*

Intrinsic noise of experimental setup two order smaller than electrochemical noise of the fuel cell

Methodology of Spectral Noise Analysis

Apply FFT analysis to calculated Power Spectral Density (PSD) to:

- *Raw signal U*
- *Signal fluctuations U' = U – Ū extracted with polynomial removal drift constant (order 0) or linear (order 1)*



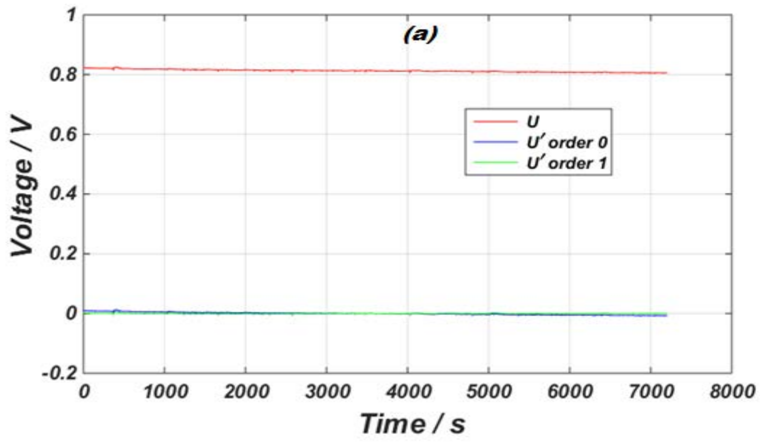
If PSD non-sensitive to drift removal → Quasi-stationarity of signal

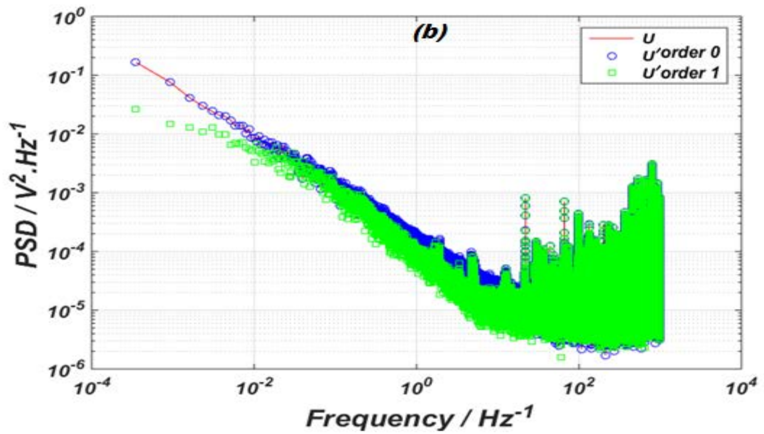
Methodology of Spectral Noise Analysis

Apply FFT analysis to calculated Power Spectral Density (PSD) to:

- *Raw signal U*
- *Signal fluctuations U’ = U – Ū extracted with polynomial removal drift constant (order 0) or linear (order 1)*

RH_{H2} = 100% / RH_{Air} = 100% at OCV





Higher drift (5mV.h^{-1}) → preconditionning, flooding?

Changes appear in spectrum signatures *:*

→ Two linear slope U’ order 1 (linear polynomial) at very lo frequency (f < 1Hz)

Signal cannot be condiser as stationary

Drift signal involves distorsion of the results

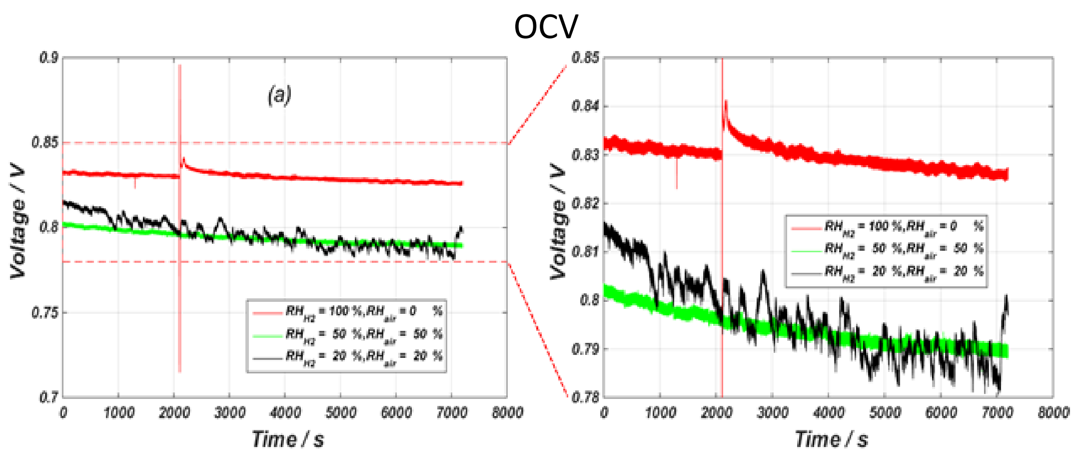
Perform another drift removal procedure (piece-wise analysis – short term analysis)

For all results we apply this methodology and present only quasi-stationary signals

Results — *OCV*

3 operating point : OCV, 2.5A and 8A

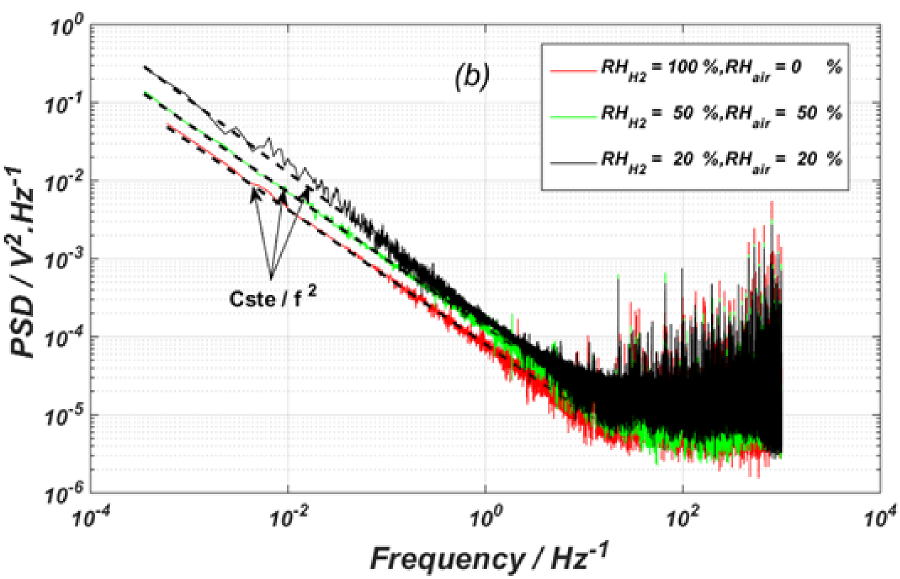
4 relative humidities **RH_{H2} = 100% / RH_{Air} = 0%** - **RH_{H2} = 100% / RH_{Air} = 100%** - **RH_{H2} = 50% / RH_{Air} = 50%** - **RH_{H2} = 20% / RH_{Air} = 20%**



Voltage curves decrease smoothly

- RH_{H2} = 100% / RH_{Air} = 0% highest and stable voltage
- RH_{H2} = 50% / RH_{Air} = 50% less stable
- RH_{H2} = 20% / RH_{Air} = 20% **the noisiest**

*Fluctuations appears roughly **6 times larger***



All Power Spectral Density at OCV have the same shape :

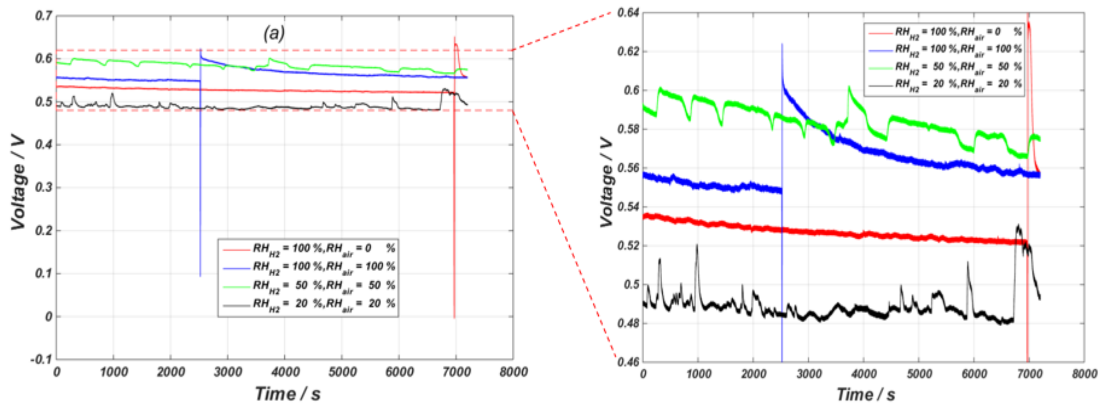
- PSD highlight **linear slope $1/f^{\alpha}$** with α = 2 (red noise) at low frequency

  (f < 100 Hz).

→ Fuel cell signature

I = 2.5 A

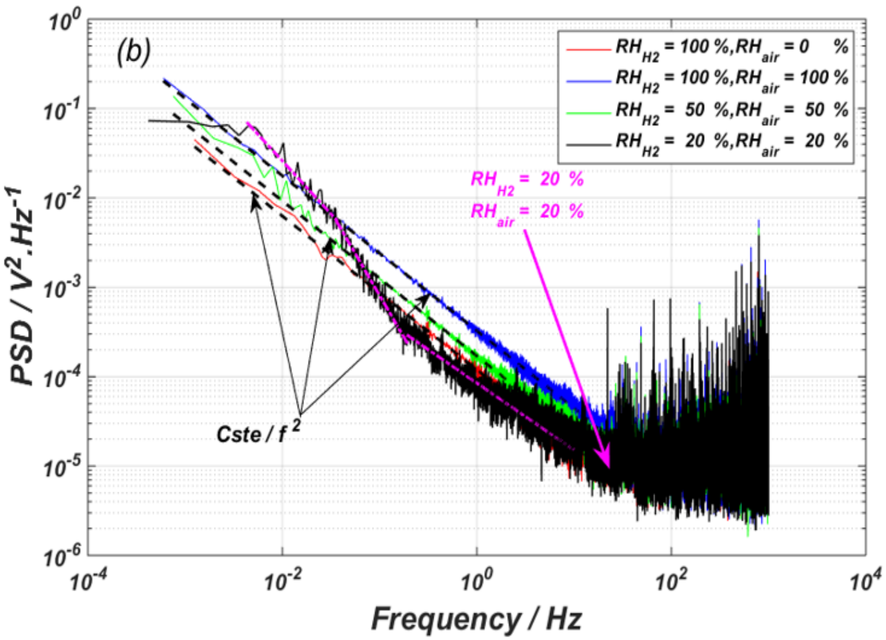
I = 2.5 A



As previously

- RH_{H2} = 100% / RH_{Air} = 0% highest and stable voltage
- RH_{H2} = 20% / RH_{Air} = 20% **the noisiest**

100% / 0% and 100% / 100%
potential peak drop (flodding phenomena)



All Power Spectral Density at 2,5 A have the same linear shape **except 20% /20%**:

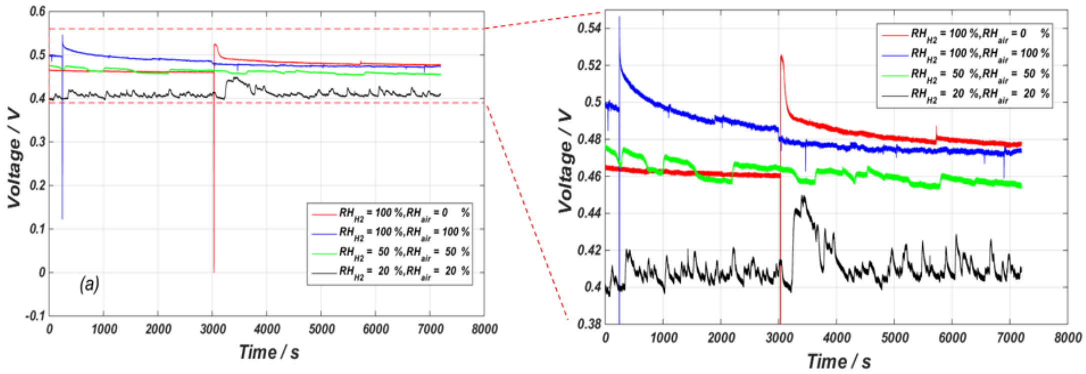
PSD 20% / 20% highlights **3 linear slopes**

→ Dry membrane signature

(spectral descriptor)

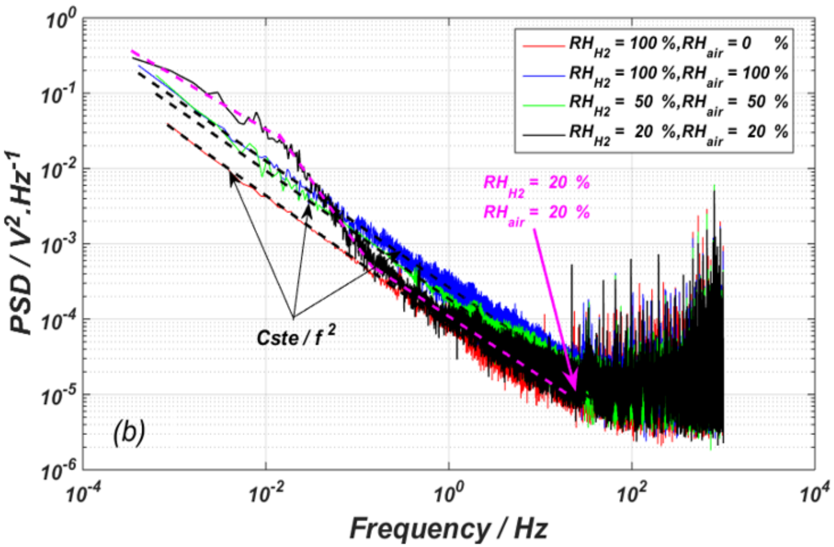
I = 8 A

I = 8 A



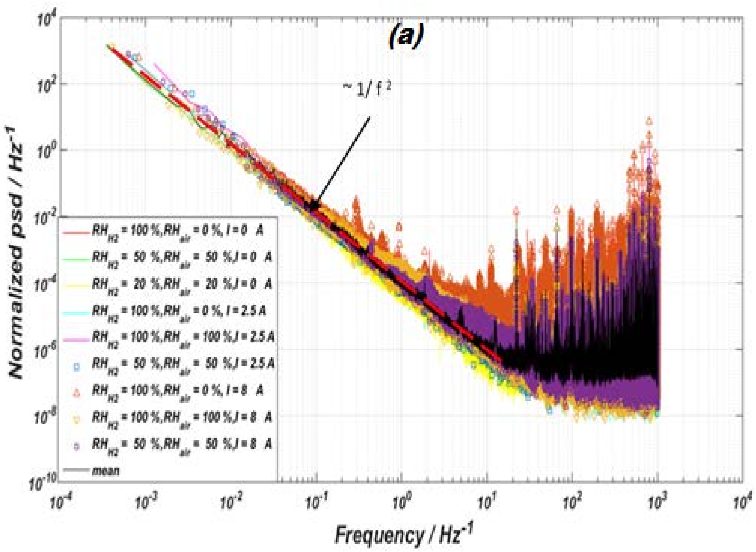
Increase of the voltage fluctuations

Increase of the **3 linear slopes** for PSD at 20% / 20%



→ **Dry membrane signature**

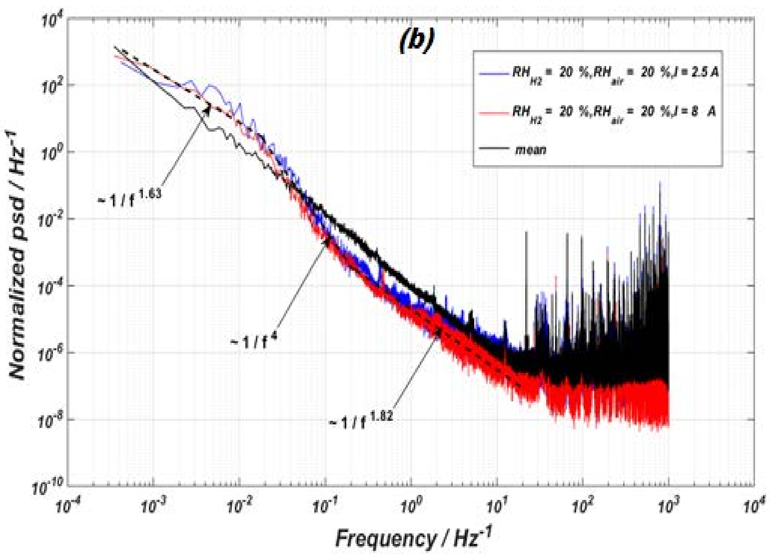
(spectral descriptor)



All normalized PSD for ≠ humidities except 20% / 20% for all operating point

Linear slope of α = 2 (red noise)

→ Fuel cell signature



RH_{H2} = 20% / RH_{Air} = 20% for 2.5A and 8A

Three linear slope

→ Dry membrane signature

PSD can be a spectral descriptor of drying membrane and diagnosis tool

Conclusions

- Electrochemical Noise Analysis (ENA) performed on PEMFC
  - *4 relatives humidities*
  - *3 operating point (OCV, 2.5A and 8A)*

- Spectral signature of fuel cell : linear slope $1/f^{\alpha}$ with $\alpha = 2$ at low frequency ($f < 100$ Hz)

- EN is sensitive to water management
  - *Three linear slope in dry conditions (higher mass & charge transfer resistance)*

- Methodology proposed to evaluate quasi-stationarity
  - *Non-sensitivity of spectrum for polynomial drift removal (order 0 & 1)*

- ENA is an interesting tool for the diagnosis of PEMFC
  - *Complete impedance spectroscopyand interrupt current methods*

- Remarkable advantage of ENA is its non-destructive nature
  - *Apply in on-line industrial application (prognotics)*

- **Bejaia**
  - Durability, Water & Thermal management of fuel cells systems

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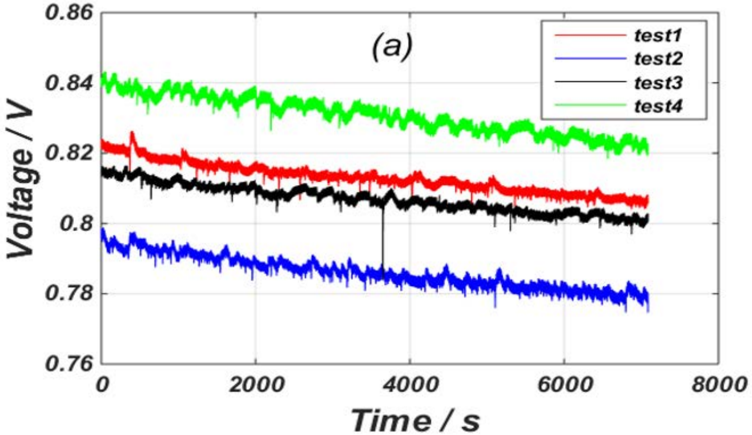
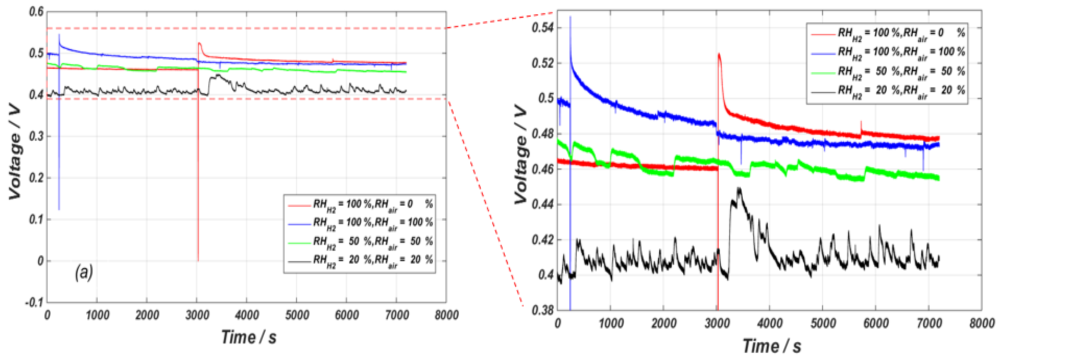
Université de Béjaïa

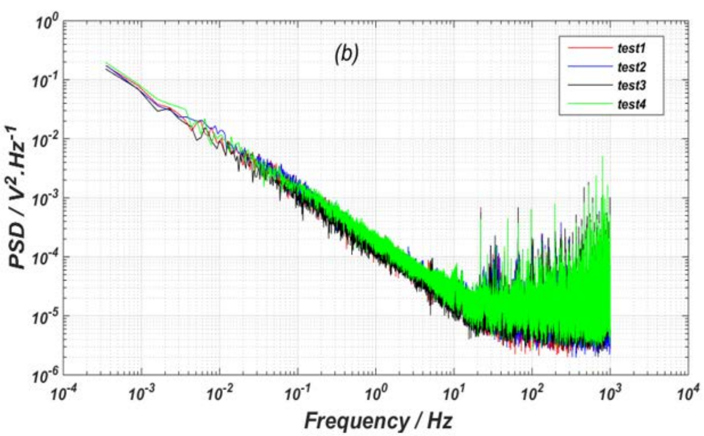
OCV



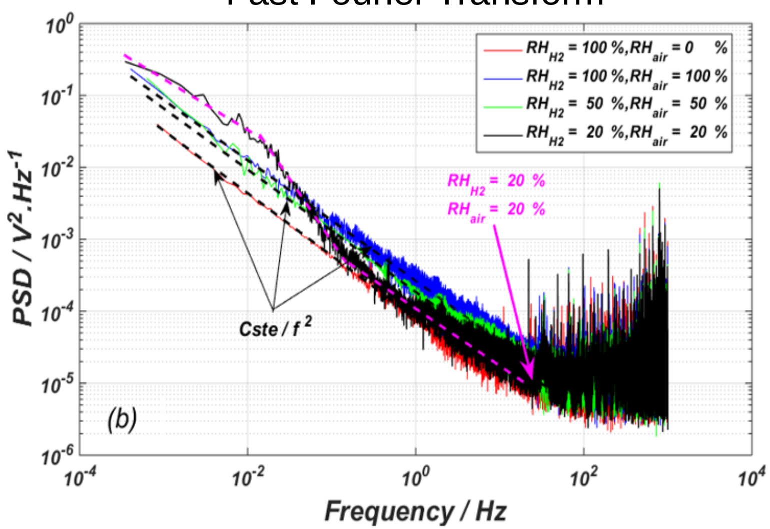
I = 8A



Fast Fourier Transform



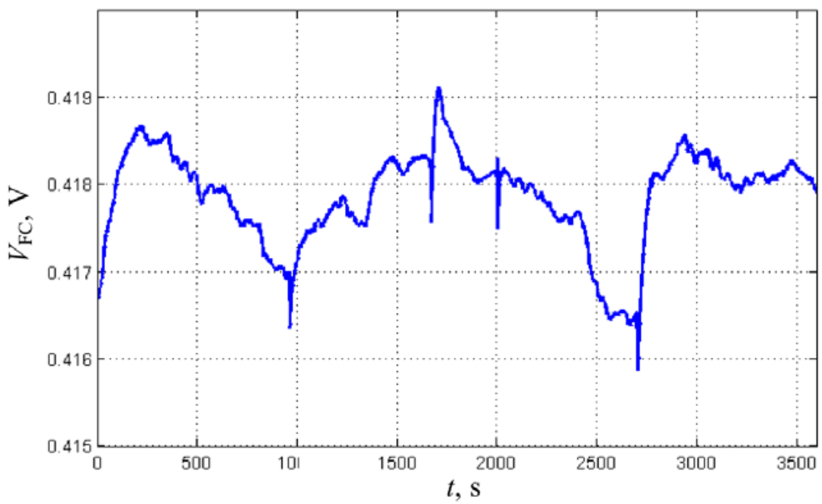
Fast Fourier Transform



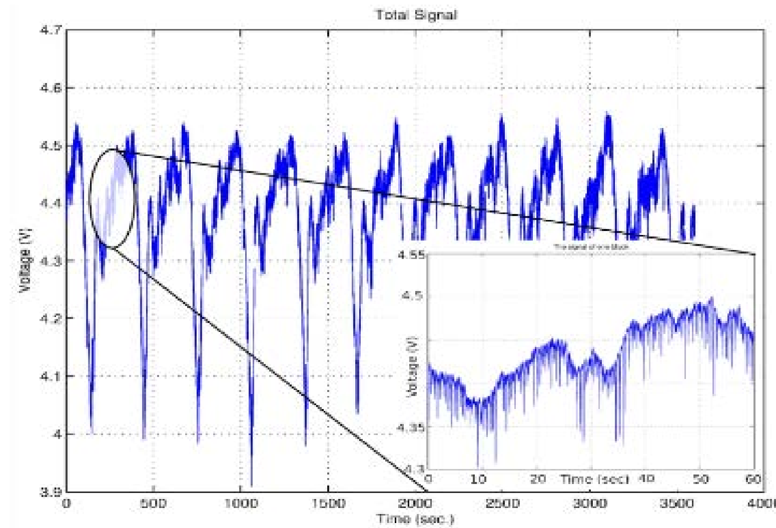
→ **1** Franco-Algerian cosupervision Thesis : R. Maizia (2017)

- **Kazan National Research Technical University (Russia)**

  - Durability, Diagnostics & Prognostics of fuel cell systems



Denisov 2011 - One cell system (25W)



Adiutantov 2015 – Stack system 8kW

→ **2** Franco-Russian cosupervision Thesis : E. Denisov (2012) & N. Adiutantov (2016)

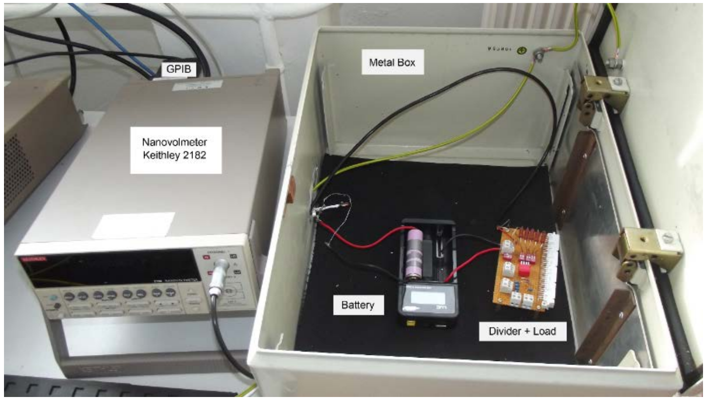
→ **1** International Exploratory Cnrs Project (Pics – 2010)

→ **1** French ANR Project (Propice 2013 – Femto Belfort)

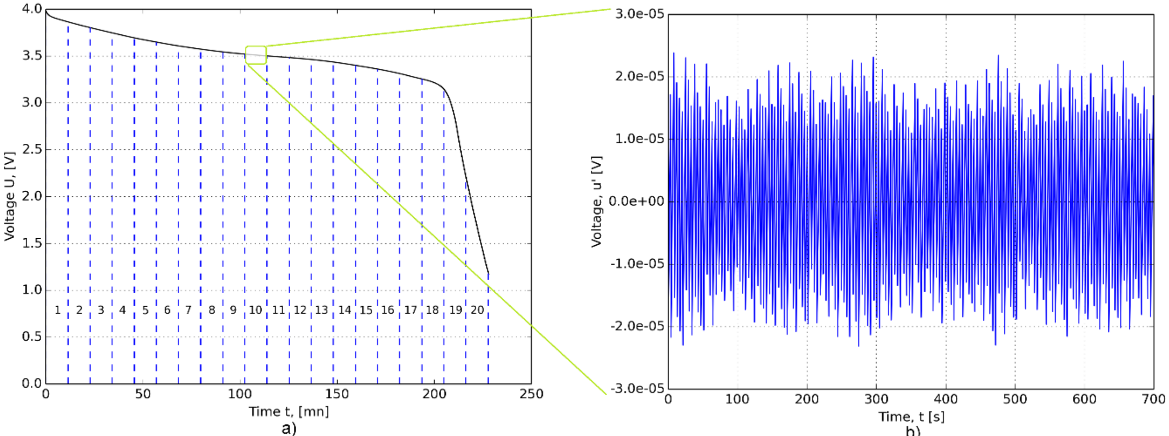
Electrochemical Noise = stochastic fluctuations of voltage (or current)
generated by mechanical and/or chemical degradations (cracks, dissolution, gas bubble formation,…)

Why use EN? Non intrusive method *(compare to impedance spectroscopy or current interruption)*

Battery Applications : → Safety (prevent battery explosion)
→ Generate descriptors for diagnostics & pronostics



Voltage measurements in commercial ICR 18650 Lithium ion battery
Non stationary signal



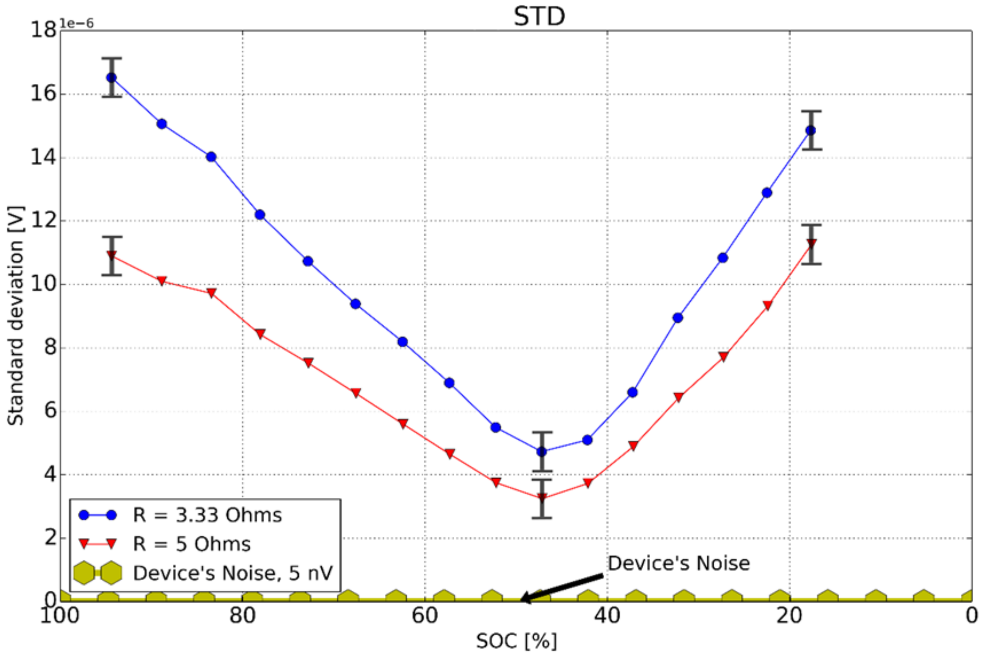
Discharge curve

Voltage fluctuations u'

$$u' = U - \bar{U}$$

Piece-Wise-Polynomial method to calculate $\bar{U}$

Standard deviation of u' with State-of-charge (SOC)



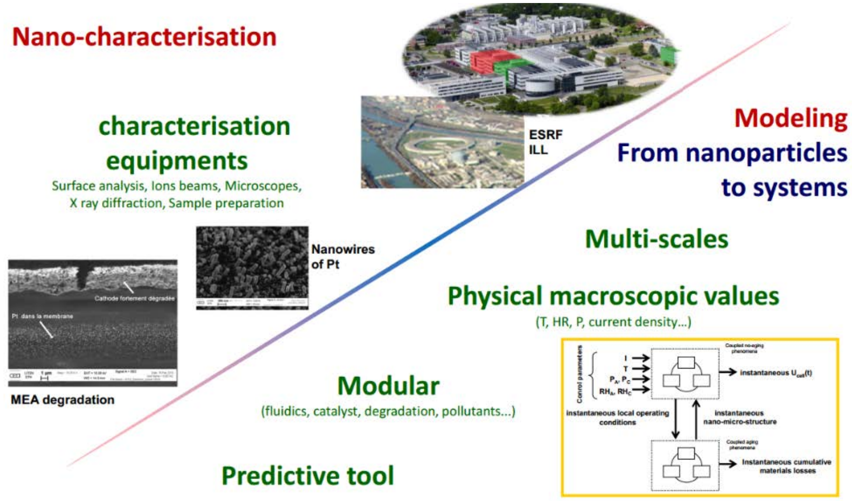
V-shape curve

→ Minimum of 3.5 µV for 5.5 Ω load

→ Minimum of 5 µV for 3.3 Ω load

around 45% of SOC

- **New and innovative metrologies & systems** *(Sensors, Reactor & Cells Designs)*
- **Modelling** *(Multiphysics, Multiscales, Modular, Predictive)*
- **Applications** *(Energy storage, Mobility, Green chemistry)*



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Thank you for your attention