MODELLING AND CONTROLLING FC SYSTEMS USING AN ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM STRATEGY

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Korean Danish PEM Fuel Cell Workshop 2013

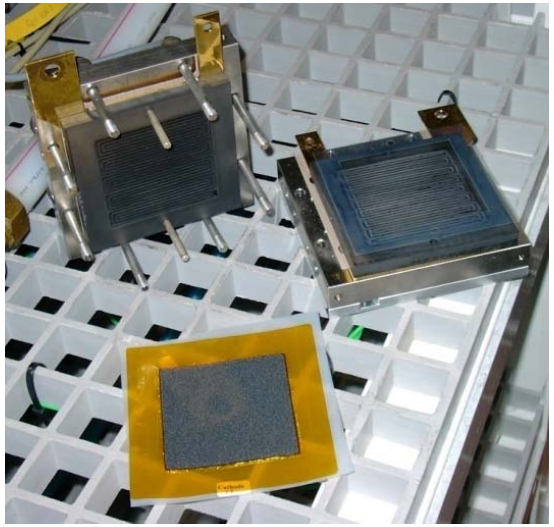
Outline

- Introduction
- Methanol reformers and HTPEM fuel cells
  - Air heat exchange
  - Liquid heat exchange
- Critical system issues
- ANFIS models
- Implementation of ANFIS models
  - Feedforward control
  - Stiochiometry monitoring and control
  - System speed improvements
- Conclusion and future work

Reformed methanol HTPEM fuel cell systems

Advantages

- PBI-based MEAs have a high tolerance to CO
- A liquid fuel, such as methanol is easily accessable and storable
- Heat can be utililzed in fuel conversion
- System energy density increase is ”cheap”



Challenges

- System size and complexity increases
- Impurities are introduced
- System heat-up

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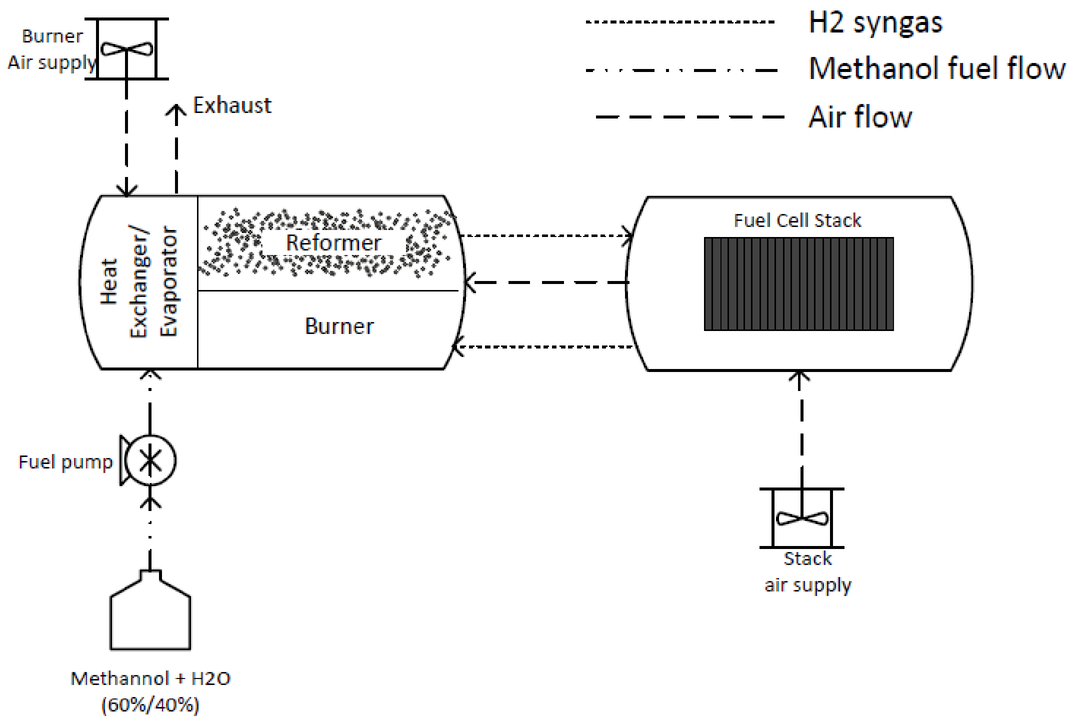
Reformer system - air heat exchange

- Waste heat from cathode air cooled HTPEM Fuel Cell Stacks is used for evaporation of reformer fuel.
- Proper heat integration and design is required to avoid high BoP consumption.
- HTPEM system does not need additional CO clean up.



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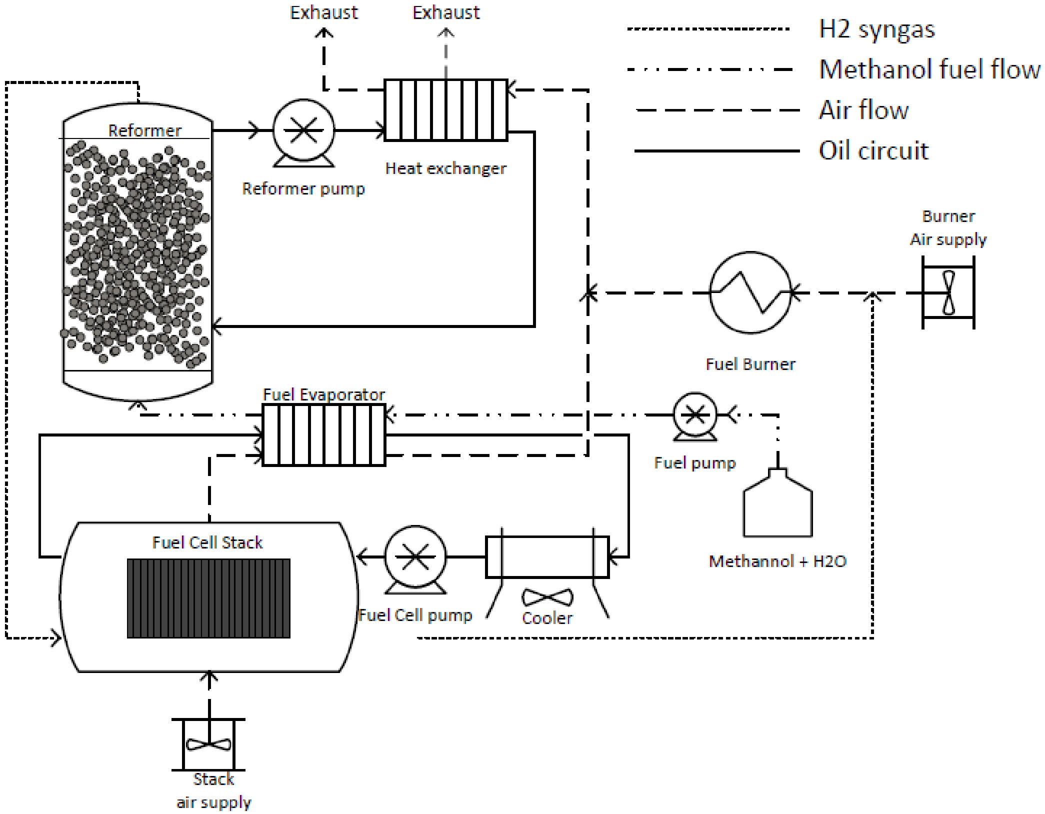
Reformer system - liquid heat exchange

- Liquid heat transfer can minimize system size and BoP power consumption.
- System logistics are more conventional.
- From a control PoV, more variables to manipulate, larger DoF
- Several system topologies are usable depending on application utility heat and demand.



Control development methodology

- Individual system components are characterized ex-situ, such that fuel cell stack and reformer system behaviour can be separated.
- Fuzzy logic / Neural network models of internal system states, can be developed.
- Model based control approaches are implemented in system software and system improvements are quantified.

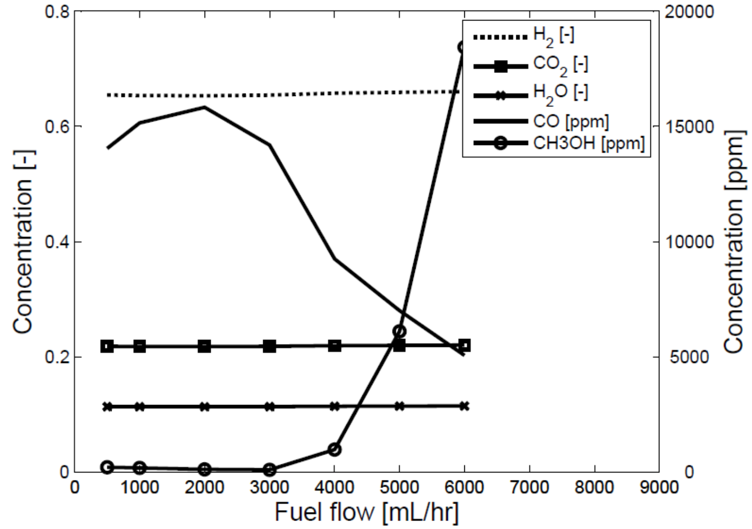
Serenergy H3-350
350W off-grid battery charger
(HTPEM + SR)

Serenergy H3-5000
5kW power system
(HTPEM + SR)

Critical HTPEM system issues

- Hydrogen impurities, CO, unconverted fuel
- Fuel cell stack anode starvation
- System complexity, non-linearity
- System behaviour during load transients, and ambient changes
- System efficiency

$$\eta_{System} = \frac{P_{Electric}}{P_{Chemical}} = \frac{U_{FC} \cdot I_{FC}}{\dot{m}_{CH_3OH} \cdot LHV_{CH_3OH}}$$



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What is ANFIS modelling?

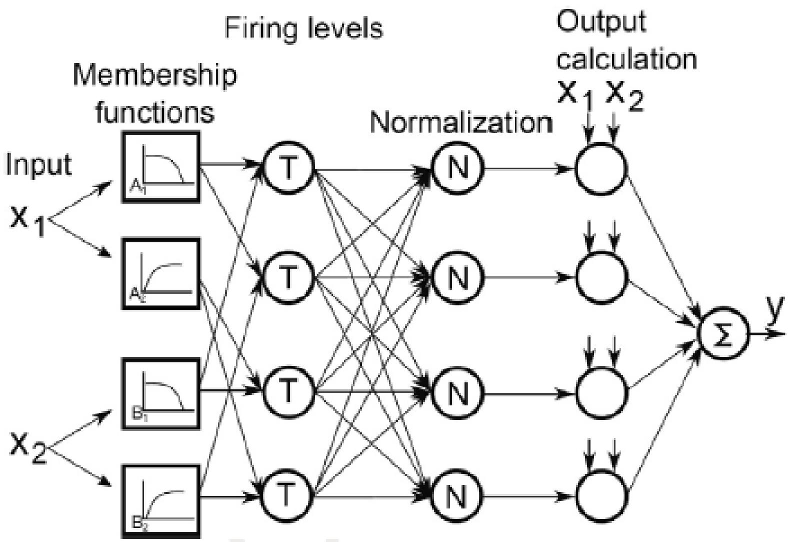
Adaptive Neuro-Fuzzy Inference Systems (ANFIS)

A combination of Fuzzy Inference Systems (FIS) and Neural Networks (NN). The resulting model can be used to describe complex non-linear physical phenomena, such as a fuel cell / reformer system by using a human-like reasoning scheme which learns to imitate a physical system based on experimental data.

Basically the chosen model is learns how to behave from the experimental data it is subjected to.

ANFIS modelling

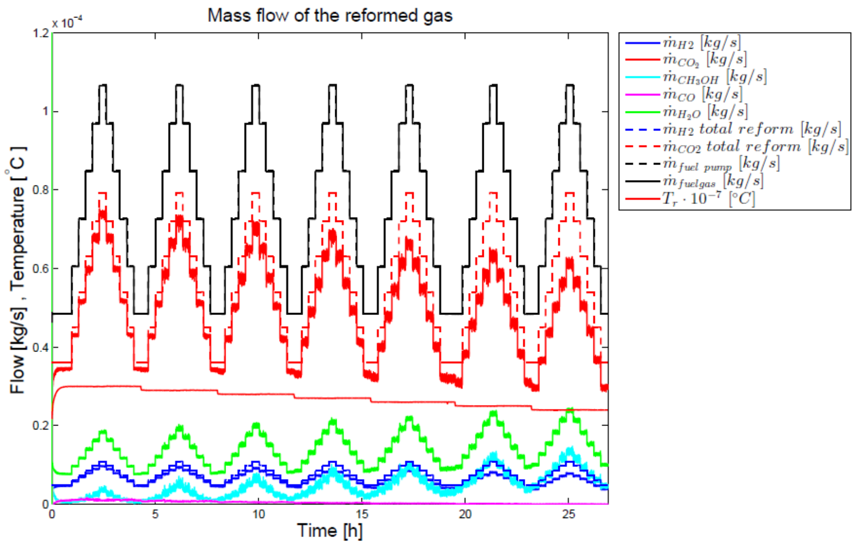
- **Layer 1:** $$O_{1,i} = \mu_{Ai}(x_1) = \frac{1}{1+\left|\frac{x_1-c_i}{a_i}\right|^{2b_i}}$$
- **Layer 2:** $$O_{2,i} = w_i = \mu_{Ai}(x_1)\cdot\mu_{Bi}(x_2)$$
- **Layer 3:** $$O_{3,i} = \overline{w}_i = \frac{w_i}{\sum_{i_2=1}^{n} w_{i_2}}$$
- **Layer 4:** $$O_{4,i} = \overline{w}_i \cdot f_i = \overline{w}_i \cdot (p_i \cdot x_1 + q_i \cdot x_2 + r_i)$$
- **Layer 5:** $$O_5 = y = \sum_{i=1}^{n} \overline{w}_i \cdot f_i$$



Gas composition modeling in a reformed Methanol Fuel Cell system using adaptive Neuro-Fuzzy Inference Systems, Int. Journal of Hydrogen Energy, 2013, K.K.Justesen,S.J.Andreasen,H.R.Shaker,M.P.Ehmsen, J. Andersen, In Press

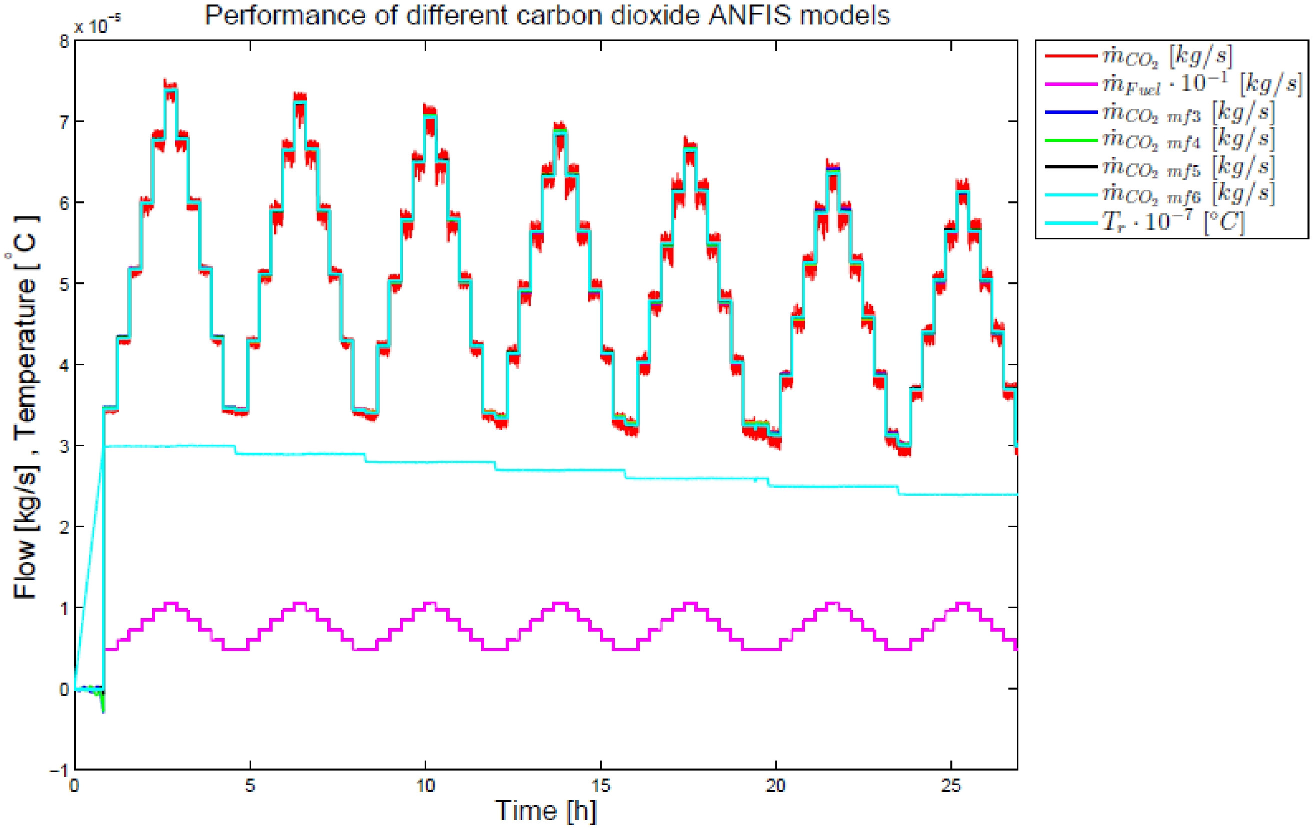
Experimental analysis

- Example: Extensive ex-situ reformer output gas measurements using gas analyzers create the foundation for ”learning” system behaviour by an Adaptive Neuro-Fuzzy Inference System (ANFIS) model.
- Proper prediction of gas composition, anode stoichiometry, etc. can enable higher efficiency, reliability and lifetime.



Modelling precision

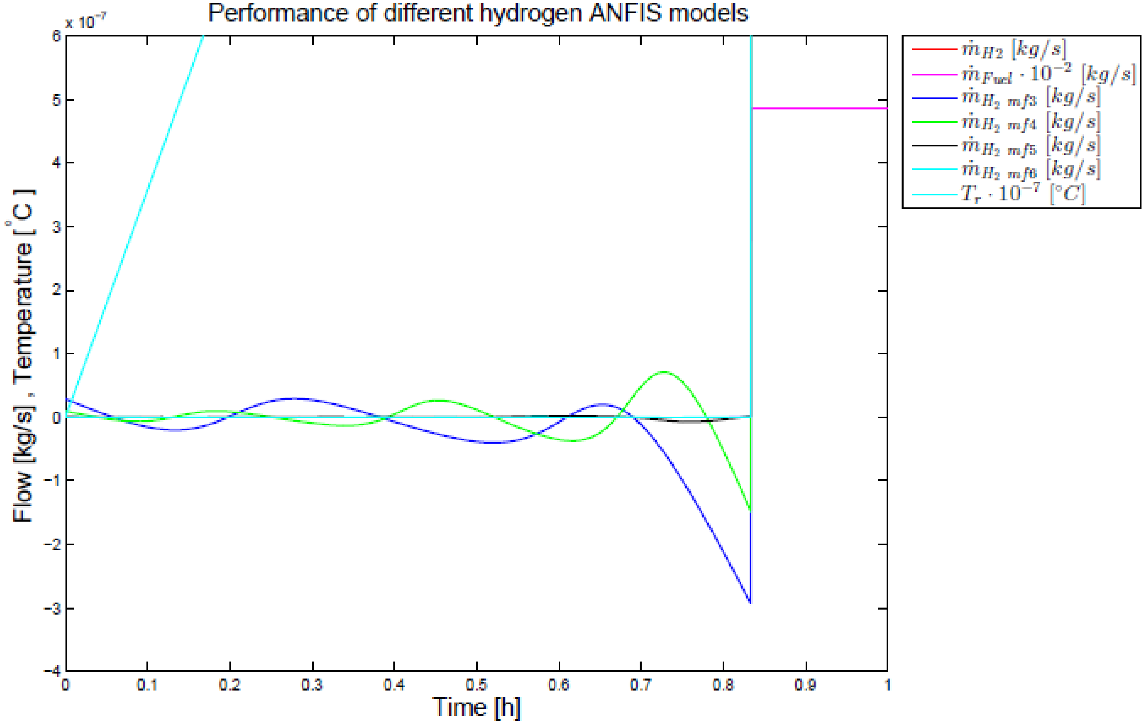
- The model predicts each species flow with a good precision. Carbon Dioxide shown here



Modelling precision

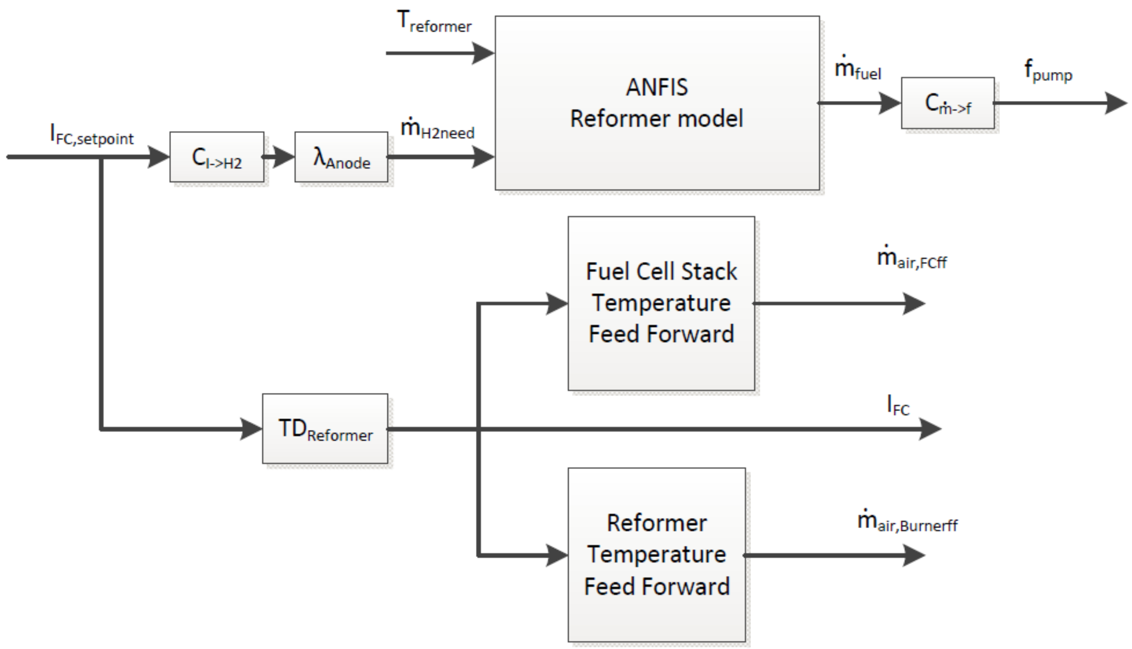
- Choosing the number of membership functions. Consider no-flow output, precision etc. Notice numerical differences in the extremes.

# membership functions	3	4	5	6
MAE %	5.31	4.56	4.5	4.3



System control challenges

- Pump flow determines usable hydrogen flow in the FC anode, but fuel evaporation and conversion need to be considered.
- A model based approach can be used for proper feedforward contol and determination of system setpoints.
- For example ANFIS modelling can provide high prescision state prediction based on experimental results avoiding undesired system operating conditions.



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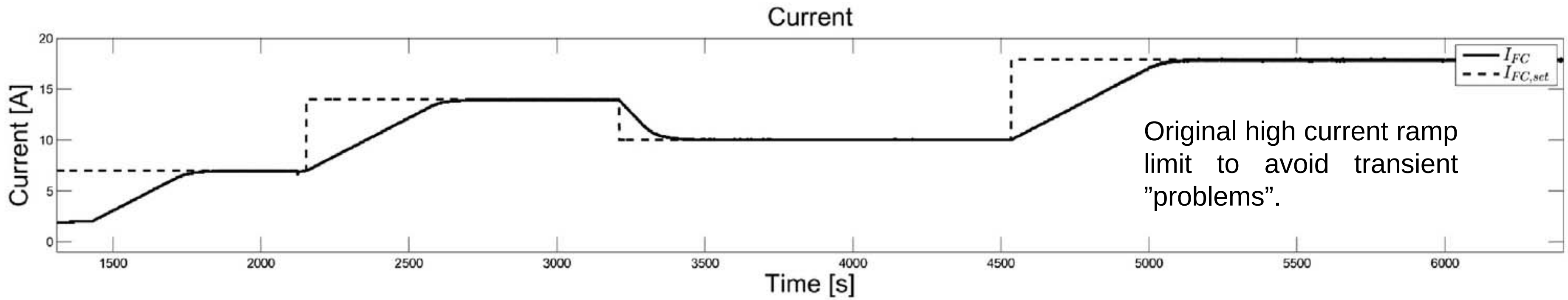
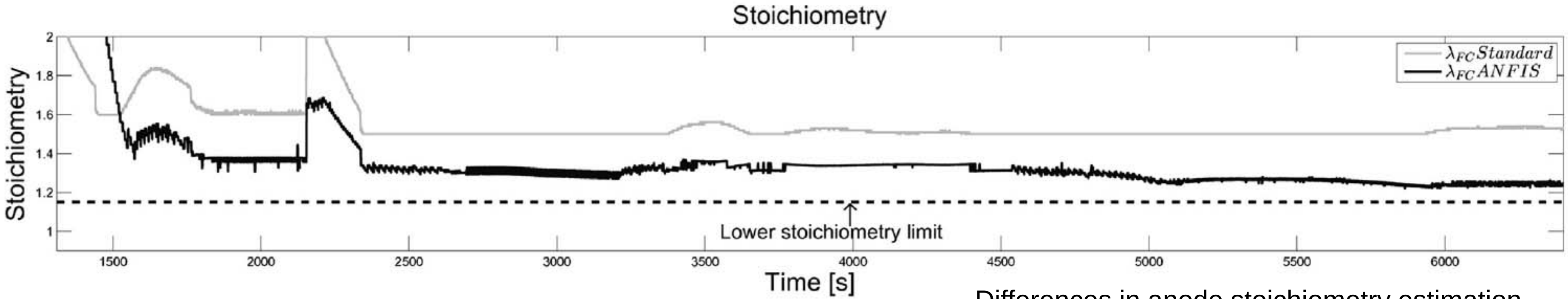
Implementation results





Differences in anode stoichiometry estimation comparred to ideal fuel conversion.

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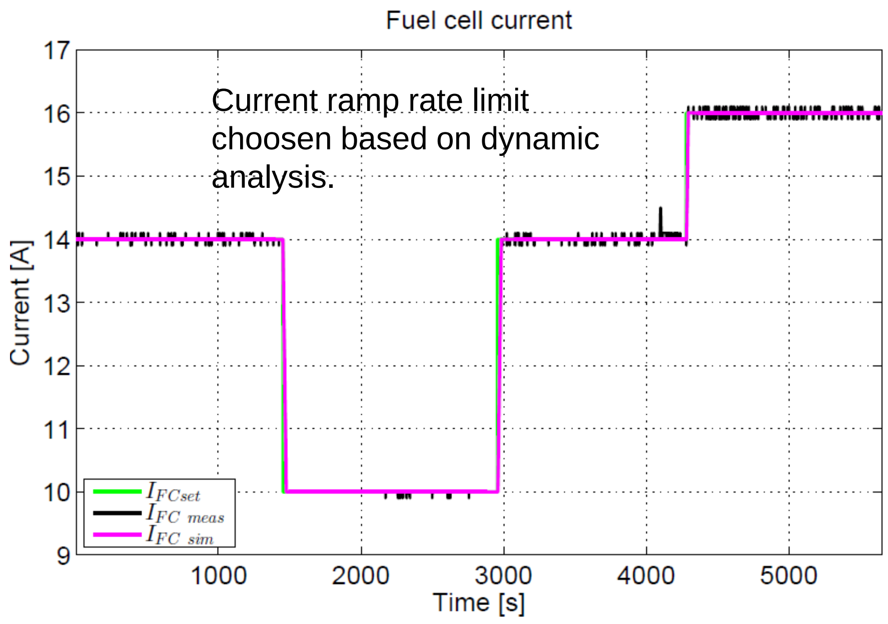
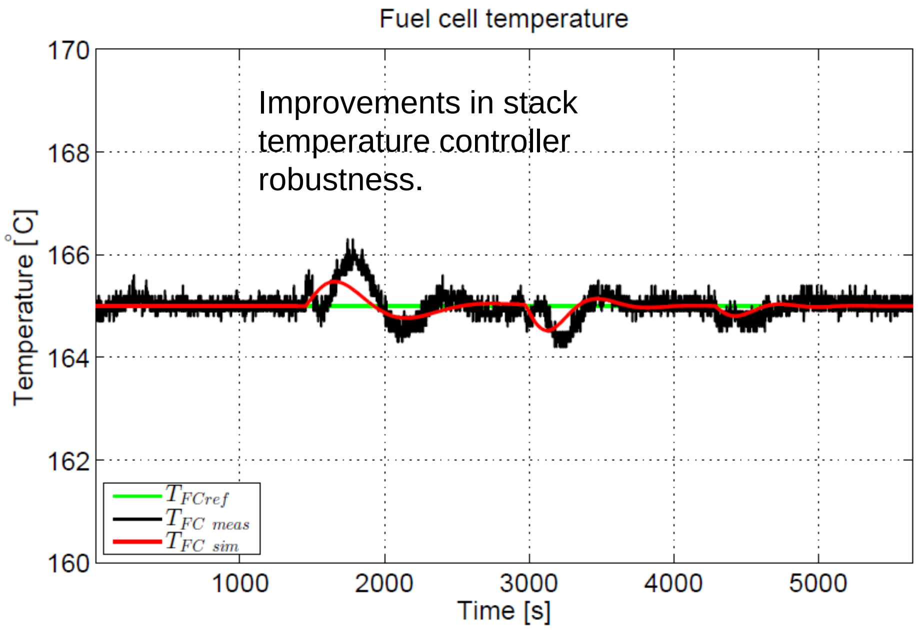
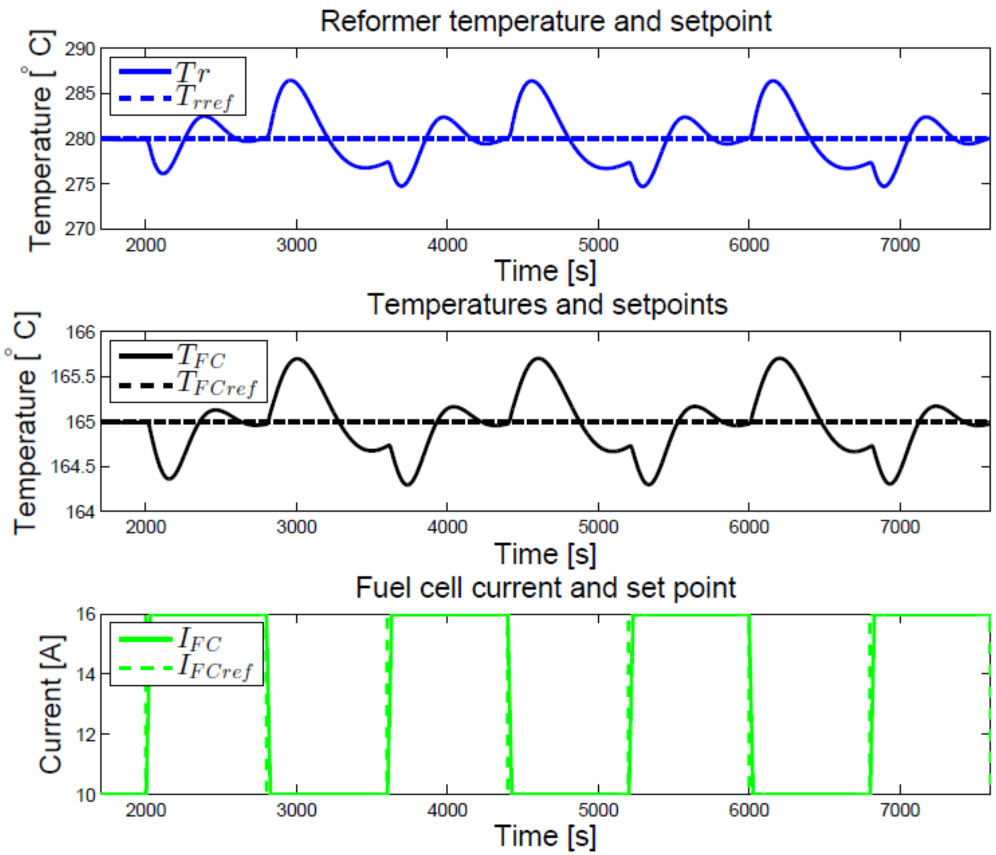




System simulation

Simple system models can be used to optimize system control in ”extreme” cases.

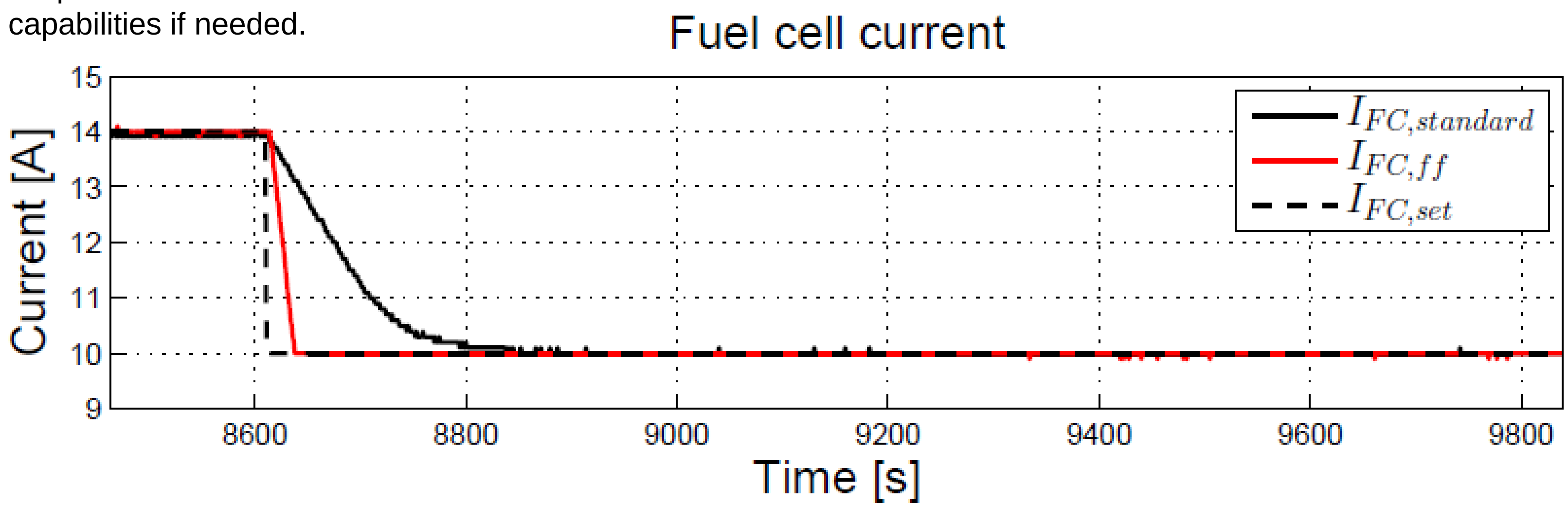
Normally negative current steps would result in burner overheating, but with detailed control such critical temperature excursions can be avoided.



Improvements in load following capabilities

Fuel cells are great part load performers, but reformer systems often remove this advantageous feature.

Proper control can restore som of these capabilities if needed.



Conclusions

- Efficient and reliable HTPEM fuel cell systems are at a development stage, where control becomes increasingly relevant.

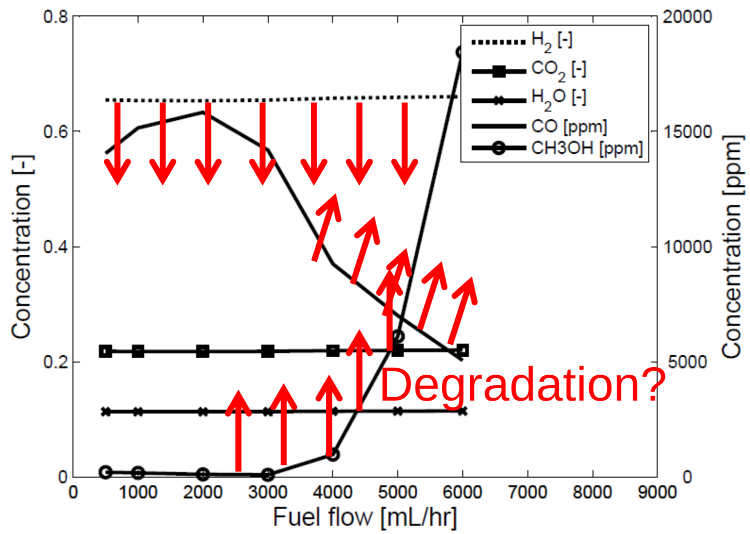
- Fuel cell systems are excellent part load performers, but lag, complex systems dynamics and expensive state monitoring can limit load following capabilities and system performance.

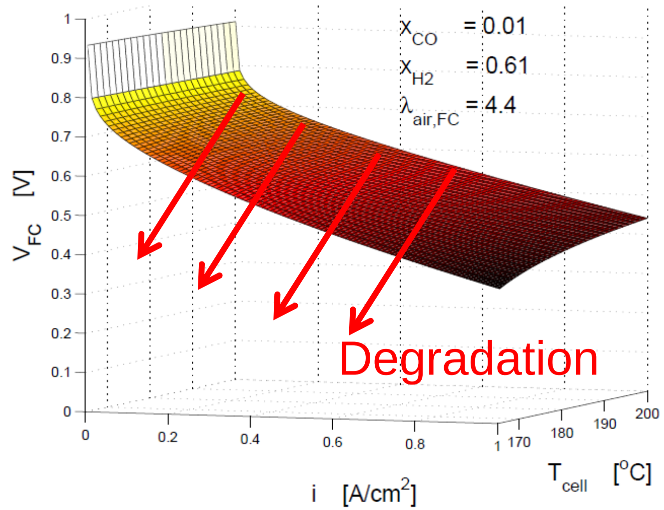
- Knowledge from detailed experimental analysis and experience can effectively be used in advanced control strategies (such as ANFIS based approaches) that are implementable in real systems.

- Advanced system control can be used to improve performance, i.e. system efficiency, transient performance, load following capabilities and eventually lifetime.

Future work

- How can knowledge of system lifetime be used to improve system lifetime?
- To what extent can we train adaptive models by using degradation information for both reformer and fuel cell stack, and can we change operating setpoints accordingly to potentially increase lifetime?





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