Optimising topologies of fuel cell hybrid drive trains for working machines – final report

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Confidentiality: Public

Report's title	
Optimising topologies of fuel cell hybrid drive trains for working machines – final report	
Customer, contact person, address TEKES, Martti Korkiakoski, PL 69 00101 Helsinki	Order reference 89/31/2010
Project name Optimising topologies of fuel cell hybrid drive trains for working machines	Project number/Short name 41909/TopDrive
Author(s) Timo Keränen, Jari Ihonen, Henri Karimäki, Kaj Nikiforow, Samu Kukkonen, Luis Martinez, Jaana Viitakangas, Pertti Kauranen, Pauli Koski, Mikko Kotisaari, Heidi Uusalo, Sonja Auvinen, Samu Aalto, Matti Koponen	Pages 51/
Keywords PEMFC, hybridization, simulation, hydrogen quality	Report identification code VTT-R-05605-12

Main focus of this research was to study hybrid electric drivetrains involving polymer electrolyte membrane fuel cells and finding ways to optimize the efficiency, lifetime and cost of these systems within the framework of non-road mobile vehicle applications. TopDrive-project was, in fact, two parallel projects coordinated by Aalto University and VTT, both with solid foundation of experimental work to support the development of simulation tools to perform analysis of different drivetrain topologies for various vehicle duty cycles.

Experimental work was conducted from operating full scale hybrid drivetrains in Aalto Hyblab laboratory to stack fuel efficiency optimization studies in VTT test benches and further cell level measurements to determine the effects of impurities like carbon monoxide to fuel cell behaviour. High temperature polynezimidazole (PBI) fuel cells were also studied in a novel cell design based on a composite material developed in-house at VTT.

Technology follow-up was an important part of the project, as well, and in this work, focus was placed especially on standardization, hydrogen quality and safety analysis related issues. A researcher exchanges took place during the project in the form of an exchange from VTT to CEA, France in 2011 and from University of Porto, Portugal to VTT in 2010 and 2012.

In conclusion, the project reached the majority of its goals in increasing domestic knowledge in PEM-based fuel cell technologies and building the foundations to support the industry in introducing fuel cells as the prime mover in industrial mobile machinery.

Confidentiality	Public

Espoo 28.8.2012

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Preface

The project “Optimising topologies of fuel cell hybrid drive trains for working machines” (TopDrive), was conducted in 2010-2012 with aim to develop competence needed to support Finnish industry in a future effort to commercialize PEMFC based energy systems in non-road mobile industrial vehicle applications. The project was conducted as two parallel projects carrying the same name; One coordinated by VTT and the other coordinated by Aalto University. This report summarizes the results of the TopDrive VTT -project.

The steering group of the project consisted of the following members:

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VTT wishes to thank Tekes and the industrial partners involved for financial support and interest in the project.

Espoo 28.8.2012

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1 Introduction

In the times of increasing prices on traditional energy sources and with environmental awareness becoming an increasingly important factor, machine manufacturers are looking into ways to improve the energy and cost efficiency of their products.

Electrifying the traction drivetrain of non-road mobile machinery is seen as the first step towards taking advantage of alternative energy sources; Electric motors provide high efficiency and low emissions, if only sufficient amount of electricity can be stored on-board the vehicle. Advances in battery technologies has been a hot topic in the recent years, but in the foreseeable future even the state-of-the-art batteries struggle with weight and volume when facing the traditional internal combustion engine. Fuel cells are considered to be one potential alternative to ICE-based generators in drivetrains of automotive and other mobile machinery, with real potential to be competitive in the drivetrain energy density.

TopDrive-project focused on experimental studies and development of simulation tools to support introduction of fuel cell technology into the non-road mobile vehicle industry in Finland.

In order to be able to develop a PEMFC based drivetrain, one must understand the fundamental principles of how the fuel cell works and what potential technical, economical and safety related risks are involved in using this technology. This knowledge comes from experience in operating these systems in controlled environments and identifying the limitations and possible pitfalls from operator point of view. In TopDrive-project, experimental work, both on system and cell level, has formed the basis of building the domestic know-how on PEMFC and related technologies.

While experimental work should form the basis of designing a fuel cell system, considerable cost and time savings can be achieved through utilizing modern simulation tools in system design. Because of this, system level models of the fuel cell stack, BoP and the electric drivetrain have been studied extensively in TopDrive.

When technological and economic issues surrounding the fuel cells are tackled, the final obstacle in the way of wide scale commercial adaption will be the ability to ensure their safe and reliable operation. This has been also part of the project in the form of participating to standardization workgroups and reviewing of existing literature.

2 Goal

A general objective of the project was to develop fuel cell knowledge in Finland in all parts of the fuel cell value chain. This supports and enables new business activities in the field of fuel cell technologies. These business opportunities include materials, fuel, stacks, systems and integration to other products.

The TopDrive-project continued the experimental activities that started during the WorkingPEM-project and aimed to develop tools and train researchers in model based design of fuel cell hybrid drivetrains. When the heavily experimental and demonstration oriented WorkingPEM-project finished, it was seen that to support possible product development work of the participating industry in the future, simulation-based evaluation of system topologies, combined with strong experimental background to enable validation of these tools would be a cost-efficient path to follow.

2.1 Objectives

Objectives for different work packages of VTT part of the project, as defined in the project plan, are listed here.

WP1:

- Experimental knowledge in hybrid fuel cell systems with different electrical system topologies
- Experimental knowledge in commercial fuel cell systems
- Knowledge base for fuel cell system integration (in power range of 50-80 kW)

WP2:

- Experimental knowledge in main fuel cell balance of plant (BoP) system components
- Semi-empirical models for BoP components
- Knowledge about system components for 50-80 kW system

WP3:

- A dynamic model for unpressurised fuel cell system with low pressure drop on the air side enabling system design and performance optimization
- Reduced order models of the system that can be executed online with the real process and control algorithms to take advantage of the models
- System models that can be used for estimation of process parameters when working with limited amount of information (minimal instrumentation)
- A model for fuel cell hybrid power source that can be used in optimizing topologies and component sizing. This model is developed together with Aalto University

WP4:

- A durable and cost-efficient liquid cooled PBIFC stack optimized for operation between 160 and 180 °C
- An innovative oil cooled PBIFC stack optimized for high cooling oil outlet temperature and large internal temperature differences
- Successful demonstration of domestic component (bipolar plate composite) in PBIFC stack, that enables commercial launch of the composite

WP5:

- Knowledge that enables definition of filtering and fuel quality requirements for working machines in different applications
- Evaluation of impurity tolerance of both PBIFC and PEFC enabling comparison of technologies in highly polluted environment

WP6:

- Understanding safety and reliability issues of fuel cell hybrid power sources at the level that enables use of information in cost optimization studies
- Implementing hydrogen safety engineering knowledge to traditional safety and reliability studies in order to develop efficient methods for fuel cell hybrid power source safety and reliability studies in the future

2.2 Content, methods, phases and international co-operation

In this research project modeling and experimental work were combined. Experimental work was done with both commercial and in-house fuel cell systems and hybrid power sources enabling high quality data collection.

In addition, progress in the field was followed using scientific literature and participating in conferences and fairs.

International co-operation was essential part of TopDrive. International co-operation of the VTT part of the project included a six month researcher exchange to Grenoble, France, where CEA Liten hosted Jaana Viitakangas from December 2010 to June 2011. In addition, Luis Martinez from University of Porto, Portugal spent a total of six months at VTT in two different occasions during the project.

2.3 Results and deliverables

The project had several results and deliverables planned that are listed below:

Models and simulation tools

- A simulation model for the PEFC system
- A simulation tool for the optimization of the PEFC hybrid fuel cell system

Hardware and software

- A new version of 8 kW PEFC system
- An upgraded version of 16 kW with higher power level

Scientific publications and thesis

- 5 Scientific articles that are also included different PhD. thesis
- 3 MSc. thesis works

Demonstration of Finnish technology

- Demonstration of high temperature BP plate material, developed in Finland

Other deliverables

- Knowledge for integration of commercial systems
- Knowledge base for commercial production of unpressurised fuel cell systems, with low pressure drop stacks
- Fuel quality understanding for both PBIFC and PEFC
- Safety and reliability information packages for both fuel cell systems and fuel cell hybrid power sources

2.4 Work Packages, time schedule and milestones

Structure of the VTT's part of the project is presented in the following figure.

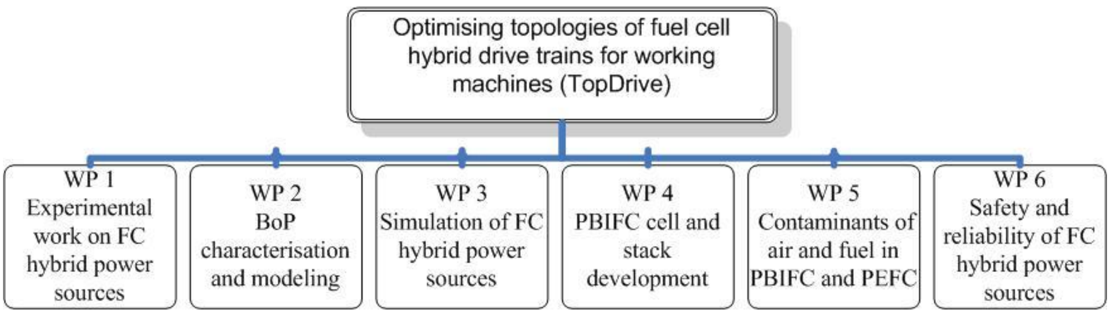

Figure 2-1. Project work package structure

Project was divided in work packages that have relatively high independence. Reasoning was that this would secure the progress in each work package in case there would be delays in other packages.

There were a number of common work packages with Aalto University's part of the project. A separate project plan document about common work between parallel projects was prepared and submitted during the project proposal phase. A structure is shown in following Figure 2-2.

The project duration in project plan was defined to be two years. TopDrive (both VTT and Aalto parallel projects) officially started in spring 2010 and was closed in spring 2012.

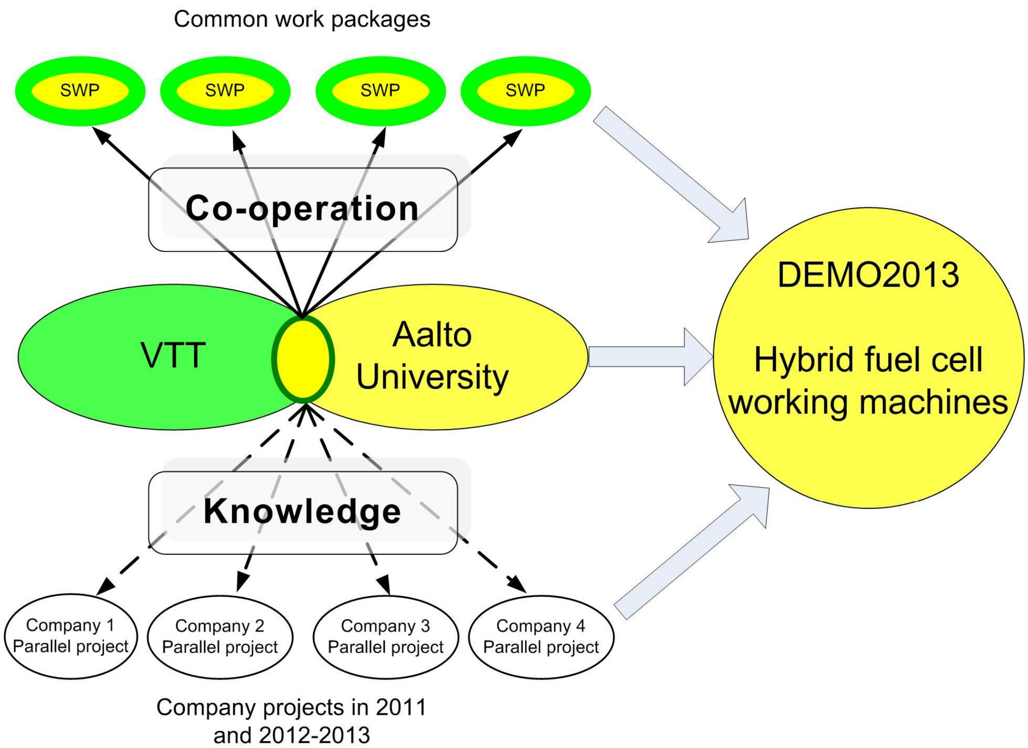

Figure 2-2. Linking of VTT and Aalto parallel projects to industry projects and a long term goal

3 Description of facilities, simulation tools and methods

3.1 PEMFC stack and BoP testbench

One of the tasks in TopDrive-project was performing a major revamp to the old stack and BoP testbench. The previously integrated and movable 8kW power module was rearranged and assembled under a fume hood, allowing more flexible swapping of stacks and system components, see **Error! Reference source not found.** [1]. In addition to moving the system under a fume hood, system instrumentation was increased considerably. Figure 3-2 shows the current PI-diagram of the testbench.

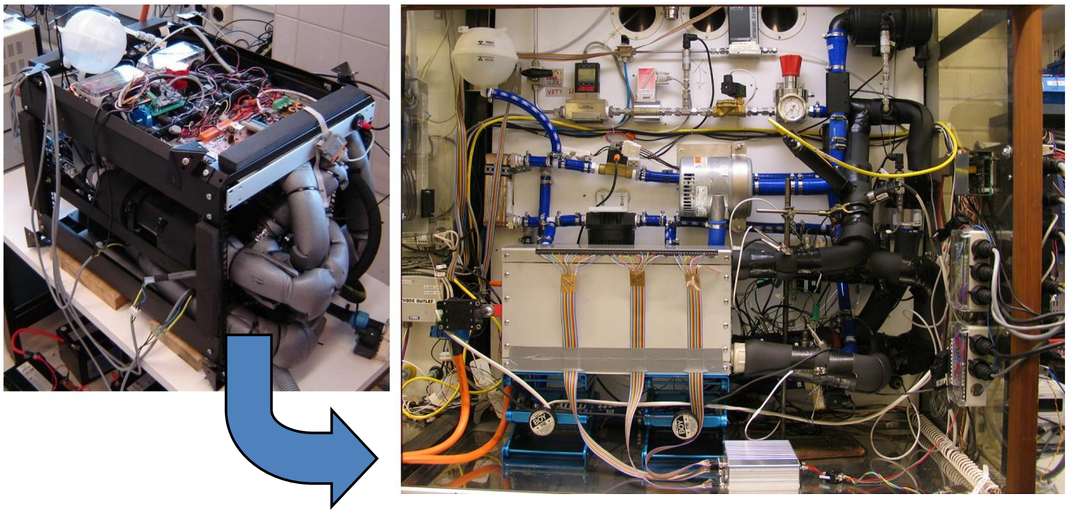

Figure 3-1. The integrated PEMFC power pack was rebuilt into a fume hood.

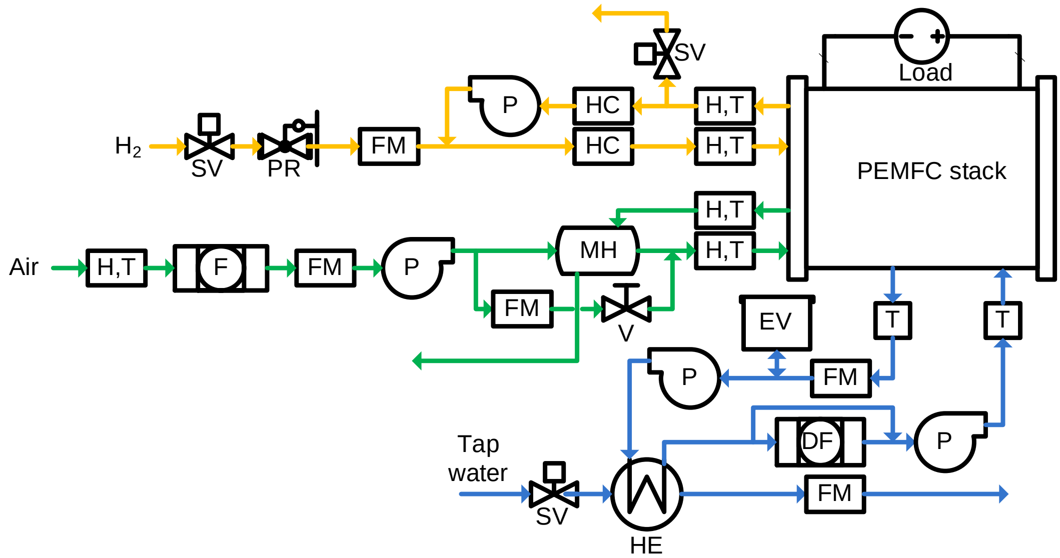

Figure 3-2. PI-diagram of the PEMFC testbench. (SV=solenoid valve, PR=pressure regulator, FM=flow meter, HC=H2 concentration, H,T=humidity,temperature, F=filter, P=pump, MH=humidifier, HE=heat exchanger, DF=deionization filter

The PEMFC stack and BoP testbench is dimensioned for PEMFC systems with a gross power of approximately 8 kW at most. By replacing the most critical component, i.e. the air blower, with a more efficient one, somewhat more powerful PEMFC stacks can be tested.

Much effort has been put on being able to measure quantities during fast transient occurring in PEMFC stack, especially during the anode purge. These quantities include the volume of anode gas purged and the mole fraction of hydrogen in the purged anode gas. The measurement of these quantities is possible due to a fast hydrogen flow meter, hydrogen concentration sensors both in anode inlet and outlet, and a data acquisition system capable of acquiring data at a rate of 50 Hz.

The old NutDAC control data acquisition system [2], based on the Ethernut microcontroller, was retained and the previously developed software continued to be utilized during TopDrive-project. Because of the large amount of measurements, a data acquisition system based on FieldPoint and implemented with LabView is used in parallel with the NutDAC based system.

3.2 Simulation tools utilized

In the spring 2010, different software tools for performing the planned modelling activities were searched and evaluated. By the summertime Matlab/Simulink [3] and Modelica/Dymola [4] were considered the two main candidates. Both would require some additional toolboxes to fulfil the needs of TopDrive-simulation activites. In case of Simulink the SimScape and SimPowerSystems add-ons were required in addition to Thermolib [5], a third-party fuel cell specific components library from EUtech. In case of Dymola, various model libraries related to power train components, vehicle dynamics and process plant simulation were needed.

After evaluation and receiving quotations of the two options, Matlab/Simulink was selected mainly due to VTT Fuel Cells research groups existing competence using Matlab-based software and more convincing connectivity to other software and hardware at the time. For the favour of Modelica-based simulation environment, it was seen as technically more advanced in addition to being based on open source code. Furthermore, cost of the Matlab-based solution with the required add-ons was somewhat cheaper than its competitor, partly due to better existing license agreements between Mathworks and VTT.

Possibilities to utilize APROS [6] were also looked into, but this was abandoned mainly due to lack of PEMFC related software module, which would have required close cooperation with the APROS developers.

Thermolib is a Simulink library of fundamental thermodynamic functions and ready-built system components (e.g. pumps, compressors, stacks). Fluid dynamics in Thermolib is calculated iteratively using pressure feedback. Although Thermolib has not ready-implented models for very specific phenomena (e.g. water transport), the software support (updates, bug fixes) offered by EuTech has been proven to be valuable.

3.3 Co-operation with Aalto University Hyblab

Part of the experimental testing within the project was carried out in co-coperation with Aalto University Hyblab. This work included:

- Hydrogenics HyPM HD 16 fuel cell power module characterization using a directly coupled electric motor load
- Prisma ecotech 15 kW DC/DC converter characterization and testing together with the Hydrogenics fuel cell power module
- Hybrid drivetrain experimental work with a hybrid system combining Hydrogenics fuel cell power module, Prisma DC/DC converter and Maxwell supercapacitor module.

This joint experimental work was done in Aalto Hyblab testing facilities. The series-hybrid test bench consists of several drivetrain components and enables testing of different drivetrain topologies. Equipments utilized for testing were Active Front-End (AFE) converter from Vacon as a power supply and different electric traction drives from e.g. Siemens as a load. The test bench configuration used in the hybrid drivetrain testing can be seen in Figure 4-4.

In addition to the experimental work, also modelling and simulation work was done jointly with Aalto University. This co-operation included:

- Exchange of both actual models of electric drivetrain components (DC/DC converter, Li-ion battery pack, PEFC system) and modelling expertise
- Studying the use of fuzzy control in controlling power flows within a hybrid drivetrain comprising PEFC, DC/DC converter and Li-ion battery pack
- Arranging a modelling workshop to demonstrate the modelling tools developed during the project

The experimental testing and modelling and simulation work have been described more in detail in Chapters 4.1.1 and 4.3.

3.4 Greenlight G60 single cell and short-stack testing facilities

The G60 test station was purchased to replace the old Arbin test station for single cell testing. After purchasing and commissioning of the G60, the dead end mode did not work as expected, and it needed a lot of additional work and some parts were sent back for repairs and modification. After the repairs, the system has been used for single cell testing with both open anode and in dead end mode with anode gas recirculation.

The G60 test system includes a gas feeding system that is able to control fuel and oxidant humidity, temperature, flow rate and pressure. Load unit is Dynaload XBL 50-150-800 which is equipped with Gamry FC350 EIS impedance analyser. In addition, cell voltages, pressure, temperature and humidity monitoring is done within the same system, controlled by al LabView-based control and data collection software (HyWare). The software also incorporates an automated scripting language (HyAL).

In contrast to common fuel cell testing routines the G60 test station is also capable to operate fuel cells in dead-end mode, which better corresponds to commercial systems. The system was also fitted with additional equipment to quantify the effects of gas impurities. These include a precision mass flow controller, that mixes the impurities (e.g. CO) on-line to the hydrogen feed, and a gas chromatograph (GC) to analyze the exhaust gas. For the GC, it is also necessary to remove excess water form the gas stream, which was achieved with a membrane dryer. The system diagrams for open-anode and dead end operation are shown in Figure 3-3.

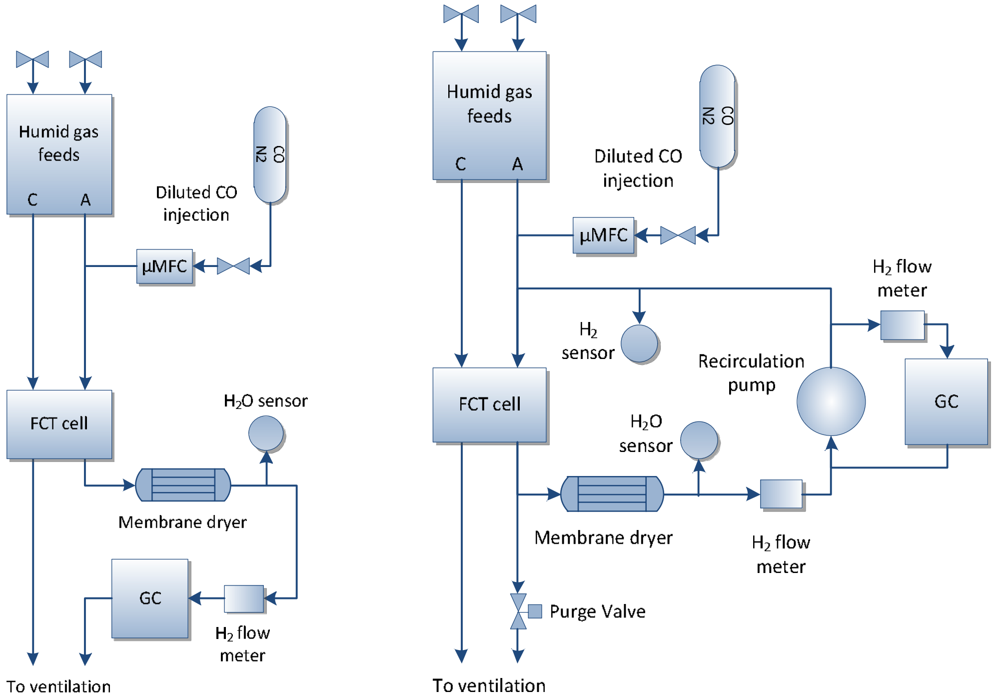

Figure 3-3: Normal G60 setup (left) and dead-end setup (right)

3.4.1 Dead-end operation with recirculation loop

The additional components installed within the recirculation loop include a diaphragm pump, hydrogen flow meters and hydrogen concentration sensors. The circulation system works with a KNF-PM24948-86.12 diaphragm pump providing 0.6 bars of pressure and flow rates up to 5 nlpm. Due to the pressure pulsations of the pump, the recirculation flow is monitored with a hydrogen rotameter, that effectively averages the flow over pulsations.

3.4.2 CO-injection

The contamination injections are done with a Sierra µTrak mass flow controller (MFC) to mix the contaminants to hydrogen feed “on the fly”. To function properly µTrak MFCs require high inlet pressure (10-15 bar). For this purpose, a high pressure vessel (150 bar) of 900 ppm CO diluted in N_2 was used. The flow controller is able to achieve steady flows down to 0.5 sccm rates.

3.4.3 Gas chromatography

To analyse the exhaust gases from fuel cell anode, a gas chromatograph (GC) was installed on the side of the G60 test station. The Agilent 6890N chromatograph was fitted with a methanizer (Agilent G2747A Nickel Catalyst kit) to allow detection of CO and CO_2 levels. The methanizer is able to convert CO and CO_2 to methane which is visible on flame ionization detector (FID). A 6 ft Porapak Q column was installed for the system. To get sufficient separation of the peaks, the oven was operated at low temperatures (from 40 °C to 80 °C).

4 Results

Results related to each work package are presented in this section. These include the experimental work with PEMFC systems and stacks (4.1), BoP component characterization and simulation (4.2), fuel cell and hybrid drivetrain modelling (4.3), PBI stack development (4.4), Hydrogen quality (4.5) and Safety and regulations (4.6).
Most of the results have been reported in separate, cumulative internal reports during the project.

4.1 Experimental work on PEMFC systems and stacks

Main results related to experimental work include the PEMFC anode subsystem studies performed at VTT BoP testbench and on the other hand, cooperation between VTT and Aalto in characterization and hybridization of the commercial Hydrogenics power module.

4.1.1 Commercial PEMFC system experimental work

The Hydrogenics HyPM HD 16 power module was tested in Aalto Hyblab together with a Prisma Ecotech galvanically isolated DC/DC converter. A hybrid drivetrain consisting of the HyPM module, Prisma DC/DC converter and a Maxwell supercapacitor module was also experimentally studied in the test bench.

Hydrogenics HyPM HD 16 testing highlights:

- An I-V curve was recorded for the HyPM module with the DC/DC converter (see Figure 4-1) to test the functionality of the two devices together. A maximum current of 330 A was reached before the maximum DC/DC conversion ratio started to limit the current. In these experiments the DC bus voltage was set to 650 V.

- The HyPM response delay to current draw transients was measured at different current steps (see Figure 4-2).

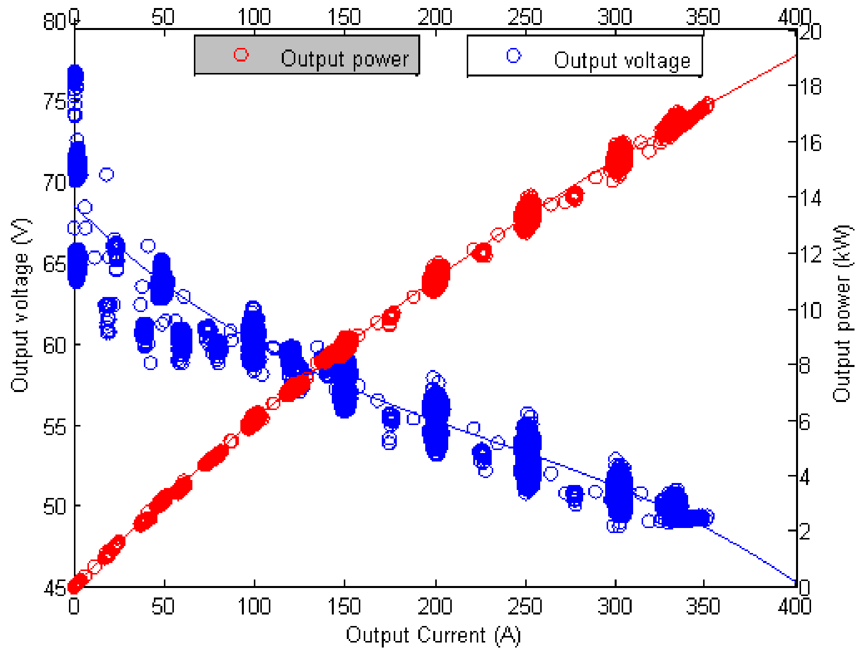

Figure 4-1. I-V curve recorded with PEMFC connected to Prisma DC/DC converter

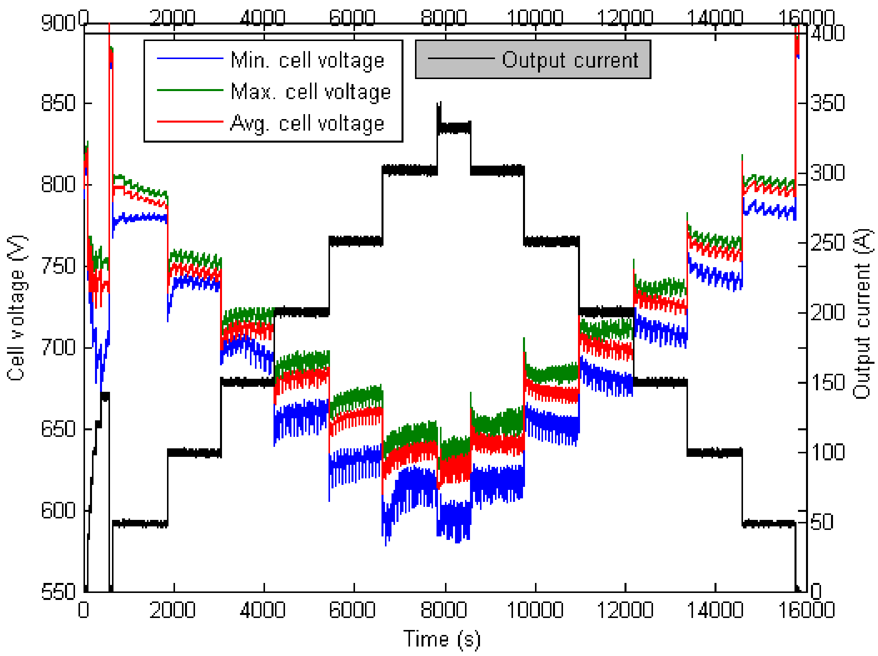

Figure 4-2. Hydrogenics HyPM HD 16 cell voltages during I-V curve experiment

4.1.1.1 Prisma DC/DC converter characterization

The Prisma DC/DC converter was characterized together with the HyPM power module.

Prisma DC/DC converter testing highlights:

- Efficiency of the converter was measured within HyPM's operation range (see Figure 4-3) at 650 V DC bus voltage. Efficiency stayed almost throughout the operation range above 92%, while maximum efficiency was 95% at 4-5 kW fuel cell power.

- Converter control delay was determined using a step response test. It was found to be approximately 35 ms.

- Current ripples on both input and output sides were recorded and analysed. Both high frequency and low frequency ripple components were found. They are most probably caused by the grid inverter (high frequency ripple) and unstable behaviour of the cathode blower (low frequency ripple).

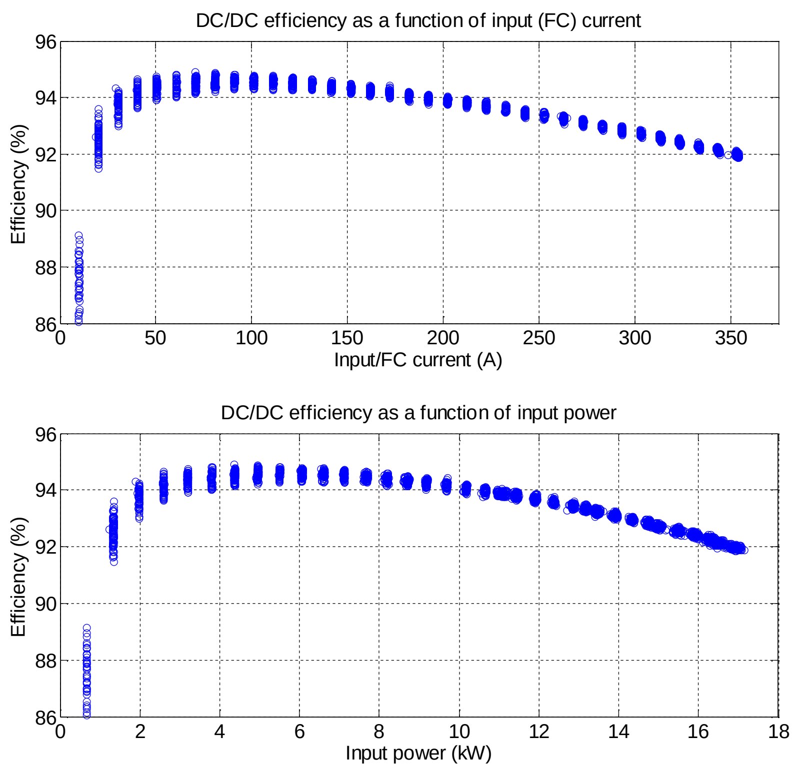

Figure 4-3. Converter efficiency when coupled with Hydrogenics HyPM HD 16

4.1.1.2 Hybrid drivetrain experimental work

A hybrid drivetrain (see Figure 4-4) was built by connecting a Maxwell supercapacitor bank passively in parallel with the HyPM + DC/DC converter combination. Performance of the drivetrain was tested using the fuel cell hybrid forklift load cycle recorded at VTT during winter 2010. The load cycle was scaled down between 10% to 99% of the original load cycle, and separate tests were run with each scaling (example from 99% cycle in Figure 4-5). In these experiments the DC bus voltage was set to 300-350 V depending on the test due to maximum voltage limit of the supercapacitor module.

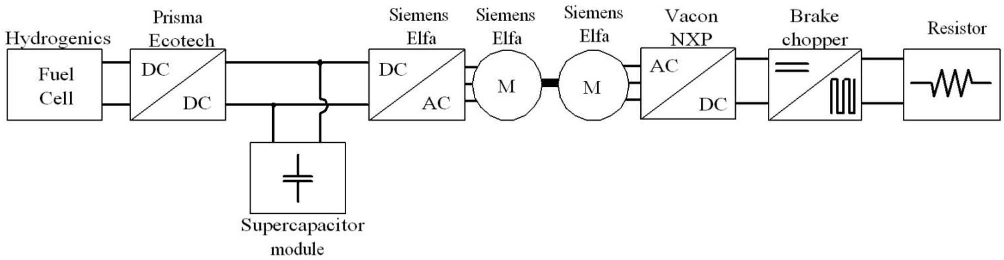

Figure 4-4. Hybrid drivetrain topology used in the experimental tests

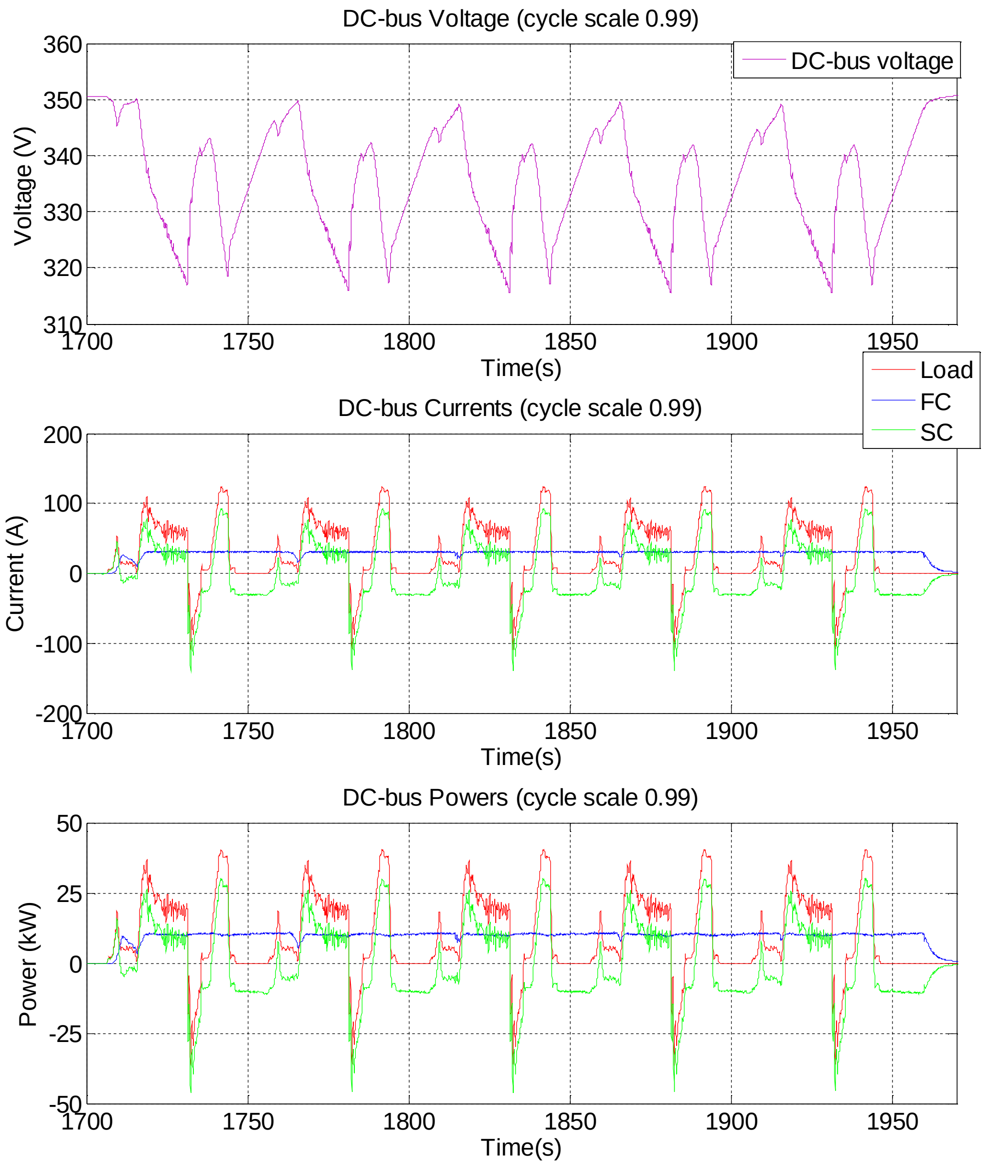

Figure 4-5. Example of the hybrid drivetrain test data with the forklift load cycle

4.1.2 PEMFC system studies

The PEMFC test bench has been used to characterize stacks from different manufacturers: Nedstack, PowerCell, and Ballard. The gross power of the stacks tested has been in the range 3…8 kW. By testing stacks from different manufacturers, knowledge and experience about BoP dimensioning and operating PEMFC stacks has been gained.

When comparing results given in this section, it should be remembered that the test bench is dimensioned for Nedstack P8 stack. Moreover, the authors have by far the most experience in operating stacks from Nedstack.

Besides characterizing stacks, the PEMFC test bench has been used for studying the anode purging strategy. These tests were carried out using the NedStack P8-series 64-cell stack and the PowerCell SX-series 30-cell stack.

Methodology and system setup utilized in these measurements has been presented in article "The use of on-line hydrogen sensor for studying inert gas effects and nitrogen crossover in PEMFC system", published in International Journal of Hydrogen Energy [7].

4.1.2.1 Nedstack P8-series 64-cell stack characterization

The Nedstack P8-series 64-cell stack was characterised at 62 °C. The polarization curve is shown in Figure 4-6 and the pressure drop as a function of air flow rate on the cathode side is shown in Figure 4-7.

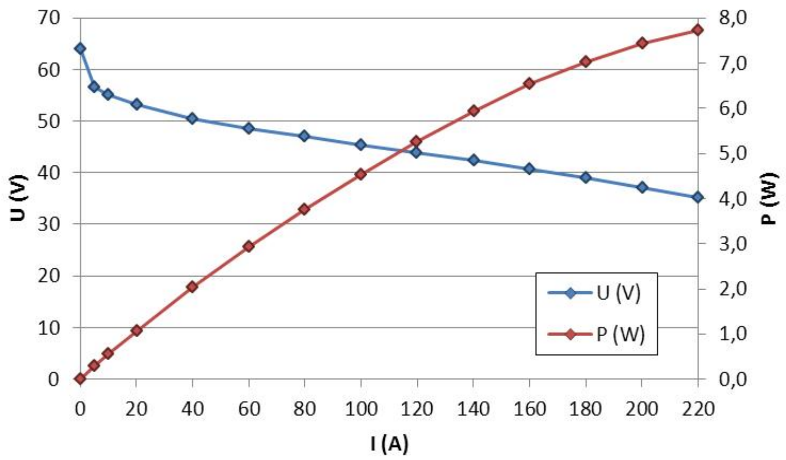

Figure 4-6. Polarization curve of the Nedstack P8-series 64-cell stack measured at 62 °C

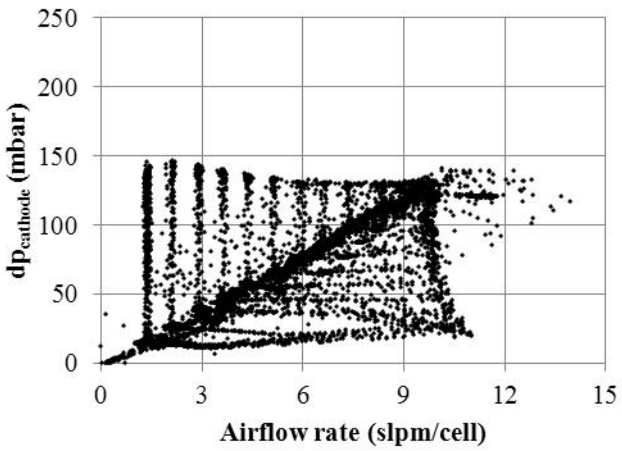

Figure 4-7. Cathode pressure drop of the Nedstack P8-series 64-cell stack as a function air flow rate at 62 °C

The characterization runs showed that the Nedstack P8 stack has a low pressure drop on the cathode side (lowest of all four tested stacks). It was observed that cell close to the end plates flood more easily than the other cell. The Nedstack P8 stack has shown to work reliably at all power levels as long as the humidity level is proper.

4.1.2.2 PowerCell S1-series 35-cell stack characterization

The PowerCell S1-series 35-cell stack was characterised at 62 °C. The polarization curve is shown in Figure 4-8 and the pressure drop as a function of air flow rate on the cathode side is shown in Figure 4-9.

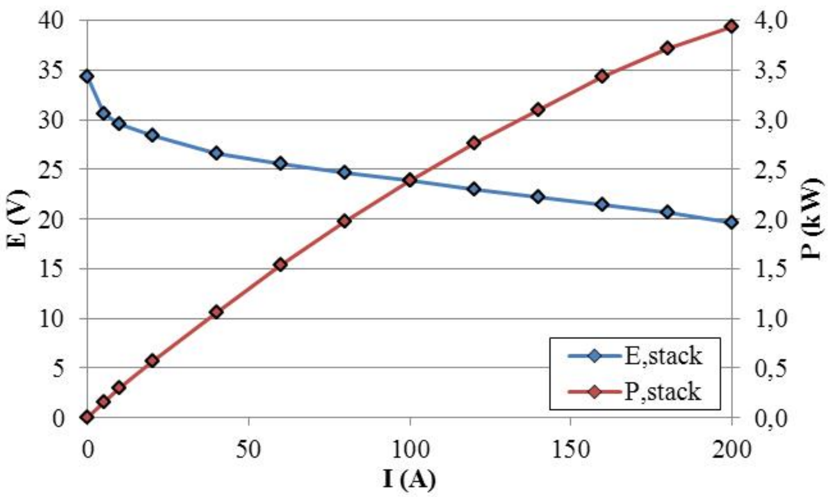

Figure 4-8. Polarization curve of the PowerCell S1-series 35-cell stack measured at 62 °C

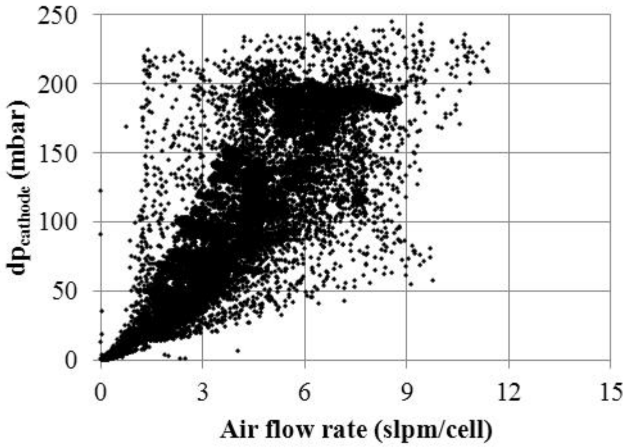

Figure 4-9. Cathode pressure drop of the PowerCell S1-series 35-cell stack as a function air flow rate at 62 °C

The characterization runs showed that the PowerCell S1 stack has a quite high pressure drop on the cathode side. Moreover, uneven distribution of air between cells in the stack caused the voltage of some cells to drop whenever a water droplet or slug entered the stack. Especially the cells close to the end plates showed to be sensitive towards liquid water entering the stack.

4.1.2.3 PowerCell SX-series 30-cell stack characterization

The Powercell SX-series 30-cell stack was characterised at 62 °C in co-flow mode, and at 80 °C in co- and counter-flow mode. The polarization curves are shown in Figure 4-10 and Figure 4-11, and the pressure drops as a function of air flow rate on the cathode side are shown in Figure 4-12.

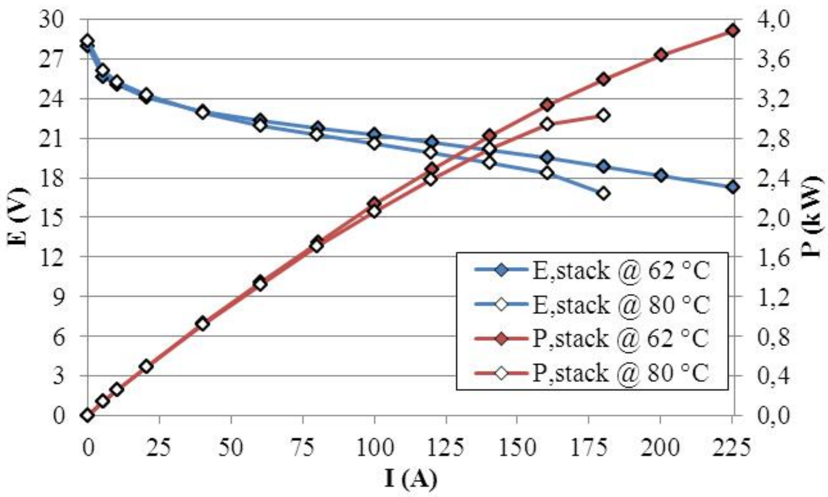

Figure 4-10. Polarization curve of the PowerCell SX-series 30-cell stack measured in co-flow mode and at 62 °C and at 80 °C.

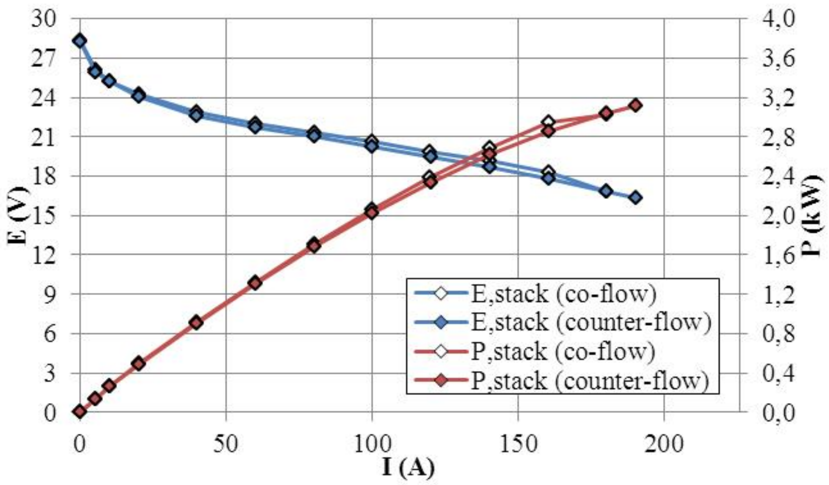

Figure 4-11. Polarization curve of the PowerCell SX-series 30-cell stack measured at 80 °C and in both co-flow and counter-flow mode.

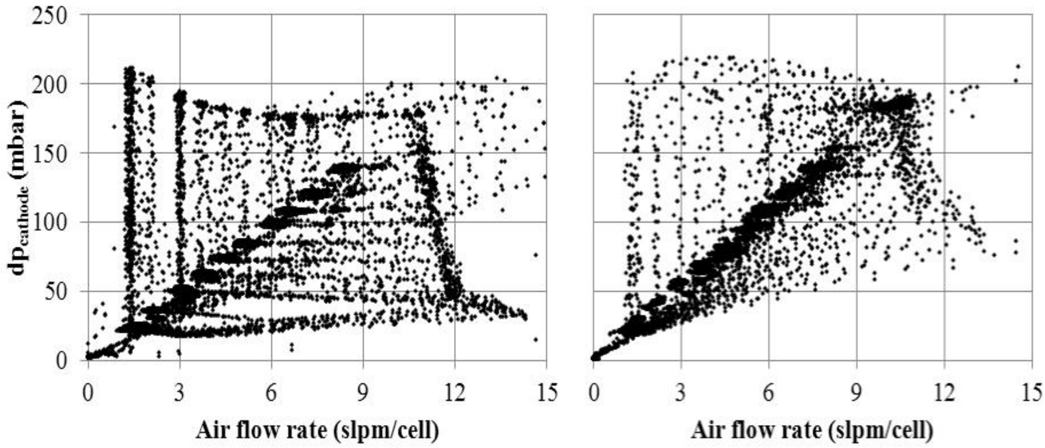

Figure 4-12. Cathode pressure drop of the PowerCell SX-series 30-cell stack as a function of air flow rate a) at 62 °C and b) at 80 °C.

The characterization runs showed that the PowerCell SX stack has a low pressure drop on the cathode side (same level as Nedstack P8). The reason for not running the characterization runs on full power (225 A) at 80 °C is that the cell voltages approached the safety limit (500 mV) of the control system.

Unlike the other stacks characterized during TopDrive-project, the SX-series is still under development and therefore, not a commercial product at the time performing the experiments. Nevertheless, the PowerCell SX stack worked reliably and no flooding of particular cells was observed.

4.1.2.4 Ballard FCgen1310 50-cell stack characterization

The Ballard FCgen-1310 50- cell stack was characterised at 60 °C and a) keeping the cathode inlet dew point temperature constant at 58 °C and b) letting the cathode inlet dew point temperature change with the current load. The polarization curves are shown in Figure 4-13 and the pressure drops as a function of air flow rate on the cathode side are shown in Figure 4-14.

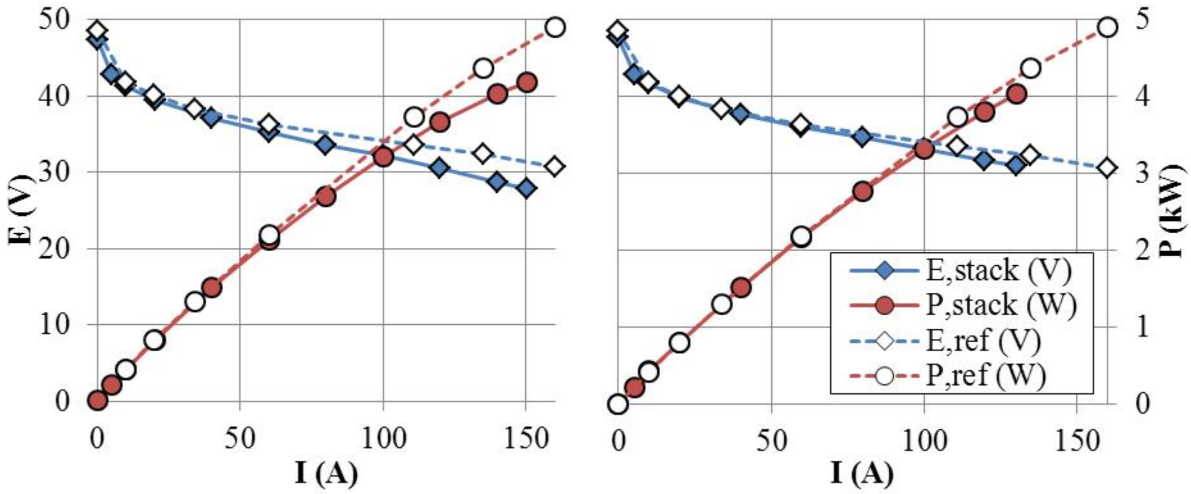

Figure 4-13. Polarization curve of the FCgen-3010 50-cell stack measured at 60 °C and a) cathode inlet dew point temperature at 58 °C, and b) cathode inlet dew point temperature not controlled. E_{ref} and P_{ref} are the stack voltage and stack power, respectively, reported by the manufacturer.

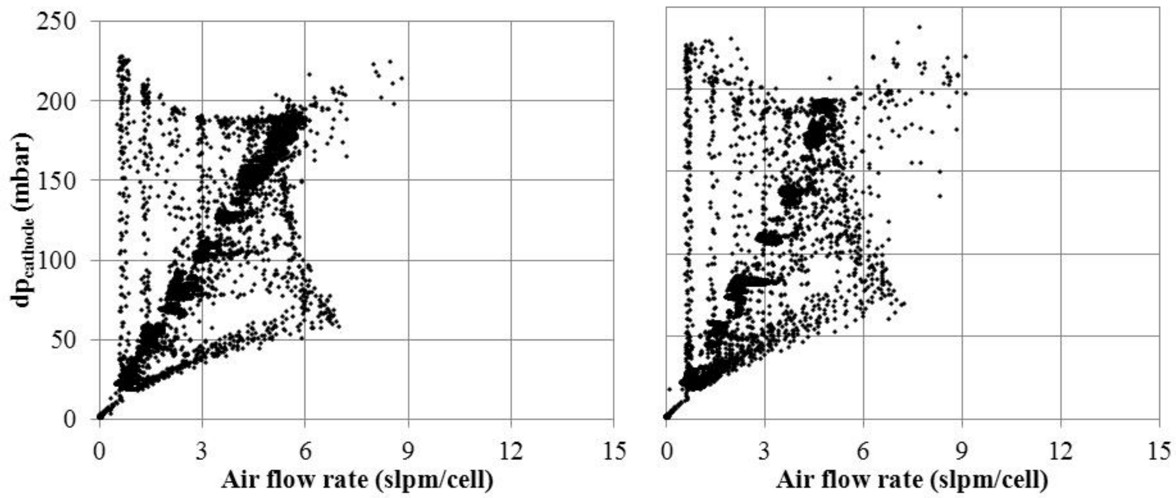

Figure 4-14. Cathode pressure drop FCgen-3010 50-cell stack as a function of air flow rate at 60 °C and a) cathode inlet dew point temperature at 58 °C, and b) cathode inlet dew point temperature not controlled.

The characterization runs showed that the Ballard FCgen-1310 stack has a high pressure drop on the cathode side. The reason for not running the characterization runs on full power (160 A) is the underdimensioned air blower. The Ballard FCgen-1310 stack worked reliably and no flooding of particular cells was observed even under humid conditions.

4.1.2.5 Purge strategy optimization studies

Experimental work has been carried out to determine the optimal anode purging strategy (purge triggering voltage drop and purge type) on different stack humidity levels. The experiments were run with the Nedstack P8 stack in steady-state conditions.

In Table 1 the different humidity levels, purge types (single 200 ms and 400 ms purges, double 200 ms purge) and triggering voltage drops can be found. The table also indicates the reliability of the data gathered during experiments.

Table 1. Experimental matrix and the reliability of the results

		Purge type								
		t_{purge} = 2 x 200 ms			t_{purge} = 200 ms			t_{purge} = 400 ms		
		$T_{dew\ cathode\ in}$			$T_{dew\ cathode\ in}$			$T_{dew\ cathode\ in}$		
		52 °C	55 °C	58 °C	52 °C	55 °C	58 °C	52 °C	55 °C	58 °C
dU_{avg} purge trigger V	3 mV	strong	strong	poor	strong	strong	strong	strong	strong	strong
	6 mV	strong	average	failed	strong	failed	failed	strong	strong	failed
	9 mV	strong	poor	failed	strong	failed	failed	strong	strong	failed

strong: 8-10 subsequent purge cycles under steady conditions
average: 4-8 subsequent purge cycles under steady conditions
poor: 1-4 subsequent purge cycles under steady conditions
failed: no reliable data due to stack flooding

Regardless of the flooding at the higher humidity levels, interesting data was gained. This type of data is always stack and system dependent, but it can be used as a guideline for purge optimization of different systems also. Data analysis is currently under work. A scientific article about the findings has been submitted for evaluation to Journal of Power Sources.

4.2 BoP components characterization and simulation

Aim of the PEMFC BoP component studies was to develop a simulation environment to support design work and optimization on system level. All the subsystems were modelled with a specific attention to certain anode side components and fuel efficiency.

A fuel cell system model has been built with MATLAB Simulink and Thermolib. Using the same simulation environment as with the hybrid drivetrain studies enables, in principle, coupling the two together when more accurate results are desired and computation time is not an issue. A flow diagram of the modeled system is shown in Figure 4-15 and the Simulink model is shown in Figure 4-16.

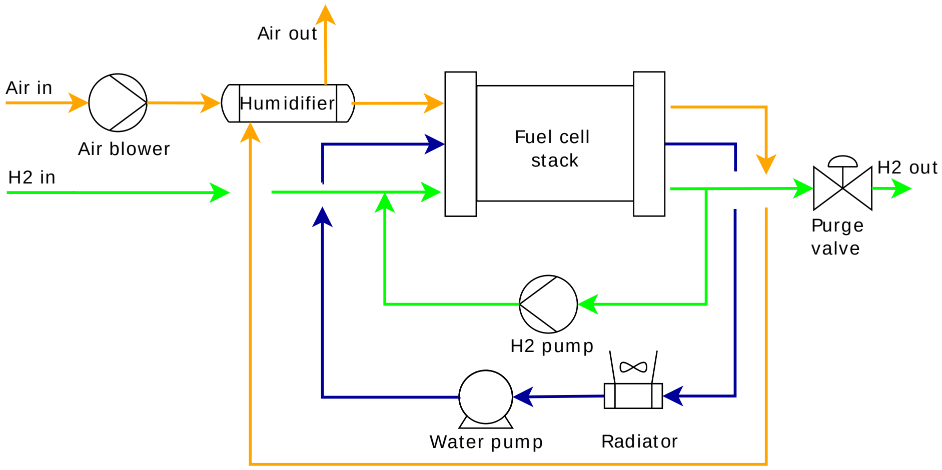

Figure 4-15. PEMFC BoP model flow diagram

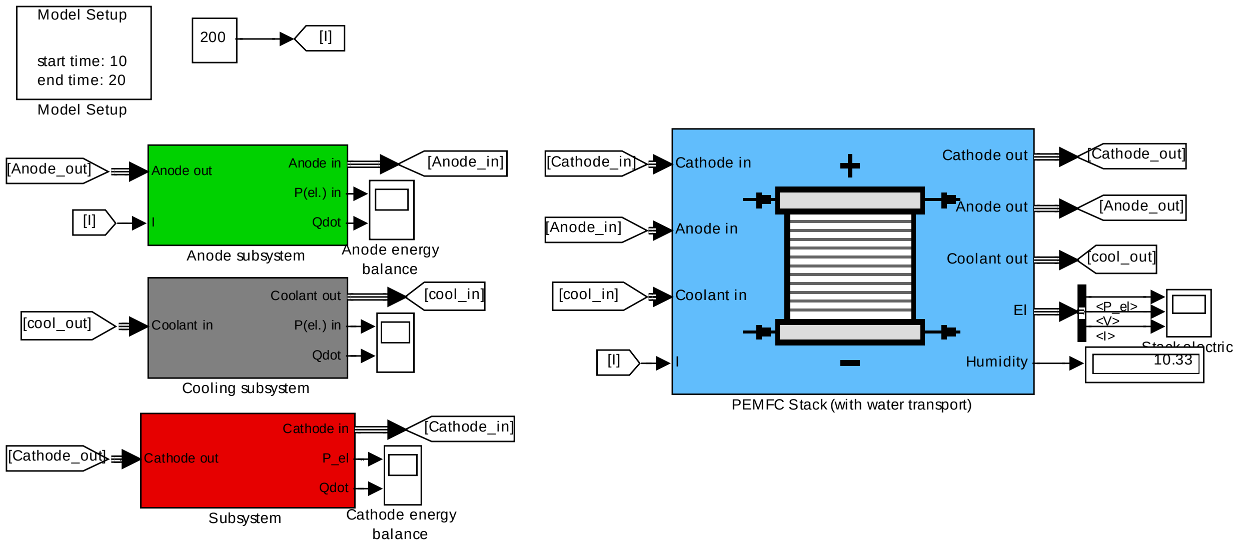

Figure 4-16. PEMFC system model Thermolib implementation

Some of the components used in the model seen in Figure 4-16, are available in the Thermolib library. Other components not included in the Thermolib library and needed in the model, have been implemented in-house and included in a Simulink library. Next, the in-house implemented components are presented.

4.2.1 PEMFC stack model

The PEMFC stack is identical to the stack model in Thermolib, except for the calculation routine for the water transport. Next, this routine is presented briefly.

Water transport in stack due to diffusion and electro-osmosis are calculated using an approach presented in [8]. This is an analytic approach that enables modeling water transport in different stack with different water transport properties by fitting the parameters affecting the solution.

4.2.2 Cathode subsystem

In the cathode subsystem ambient air is compressed, then fed through a humidifier (where it gets humidified) to the stack and back to the humidifier and then out. Next the components implemented to model this process are described.

Air compressor compresses ambient air and outputs it at a rate determined by the pressure feedback information, and at a pressure determined by lookup table data. Also, the ambient humidity is taken into account when solving the output flow.

Pipes are used to calculate the pressure drop due to friction with pipe walls, and heat exchange to the environment. Modeling pipes with a volume is also implemented by currently not suitable to be used many such pipes in series because of unsteady behavior.

Membrane humidifier uses the same calculation routine as the stack in calculating the water transport due to diffusion from the wet side to the dry side.

4.2.3 Anode subsystem

In the anode subsystem hydrogen is fed from a hydrogen tank to the stack at a rate at which it is consumed. Before entering the stack, the fresh hydrogen is mixed with a recirculation stream. When the purge valve located after the stack opens for short period of (this happens periodically) the flow rate from the tank increases to a value determined by pressure feedback information. Next the components implemented to model this process are described.

Hydrogen tank outputs a stream at a rate that corresponds to the hydrogen consumption in the stack and flow rate calculated from the pressure feedback information combined. The composition of the stream is given as parameter.
Pipes are used here for the same purpose as in the cathode subsystem.

Volume is used in the anode subsystem as a separate component instead of using it in the pipes (due to reason mentioned earlier) to model the build-up of inert gases and water in the recirculated stream. The build-up of inert gases causes a decrease in hydrogen concentration, which causes a decrease in cell voltages. This can be avoided by purging the anode periodically.

Purge valve is opened periodically, which causes fresh hydrogen from the tank to flow through the system, thus increasing the hydrogen concentration and increasing cell voltages. Excess purging will decrease the fuel efficiency of the system.

Recirculation pump recirculates the stack output gas to the input at a pressure given as a parameter. Based on the pressure increase (depends on pressure losses through the system) and the flow rate (equal to the stack exit stream except during purges), the pump calculates its power consumption.

4.2.4 Cooling subsystem

Cooling water is recirculated in a closed loop between the stack and a heat exchanger. The cooling water is kept at a predefined temperature by feeding air to the other side of the heat exchanger. Next the components implemented to model this process are described.

Pipes are used here for the same purpose as described above.

Fan supplies air to the heat exchanger at a rate that is necessary to keep the temperature of the coolant water at a predefined level. The pressure of the air supplied by the fan is calculated from the pressure drop of air flowing through the heat exchanger, i.e. the pressure of the air exiting the heat exchanger is close to ambient pressure. Using the air flow rate and the pressure supplied by the fan, the power consumption is calculated assuming some fan efficiency.

4.2.5 Example simulations

Although the components in the model are implemented, the parameters are not tuned for any specific system, and thus the examples presented here are not correct although they model the general trends correctly.

Below, the effects of purge interval on hydrogen mole fraction in the recirculated gas (Figure 4-17) and the stack voltage (Figure 4-18), and the effects of humidifier size on stack membrane average water content (Figure 4-19) and stack voltage (Figure 4-20) are shown.

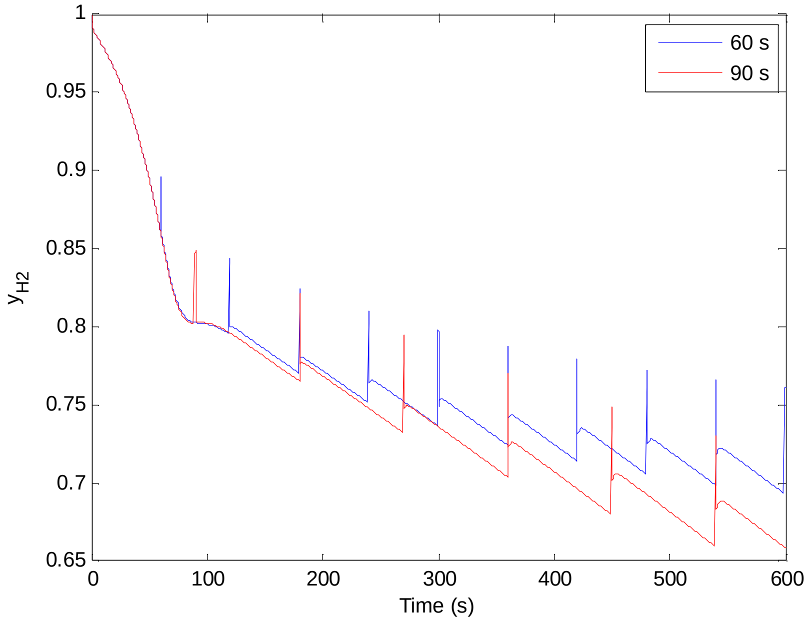

Figure 4-17. Comparison of purge interval (60s vs. 90s) - H_2 mole fraction

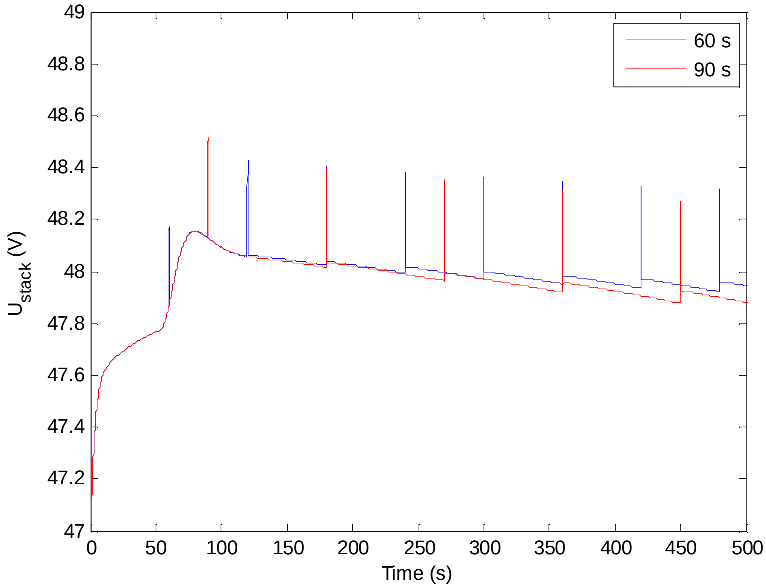

Figure 4-18. Comparison of purge interval (60s vs. 90s) - stack voltage

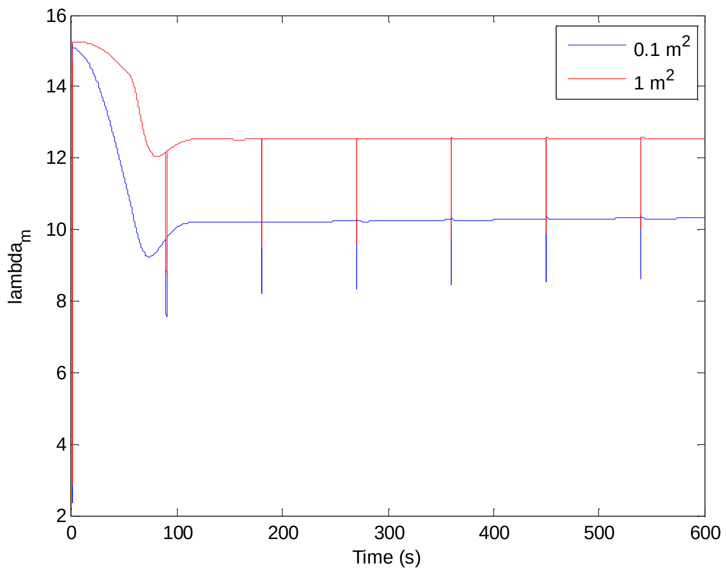

Figure 4-19. Comparison of humidifier size (0.1 m^2, 1 m^2) - stack membrane water content

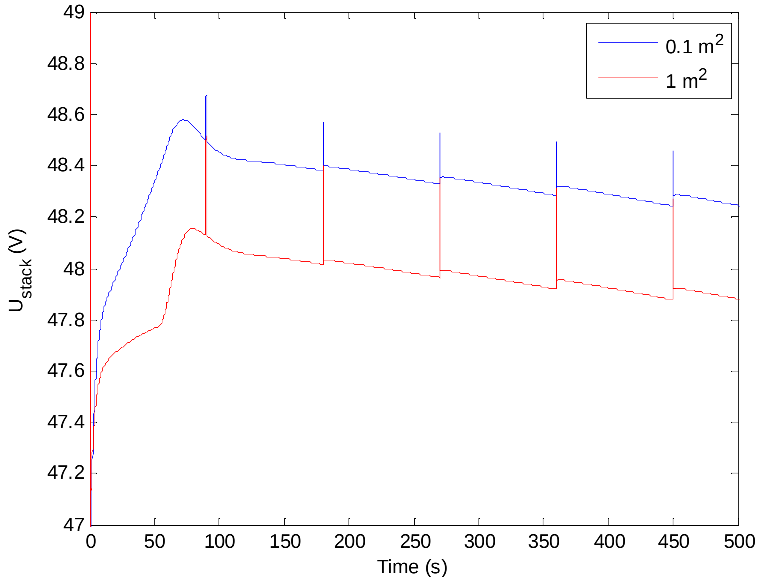

Figure 4-20. Comparison of humidifier size (0.1 m^2, 1 m^2) - stack voltage

The simulation times greatly depends on (1) how small time steps are used (the smaller time steps, the more accurate are the result), (2) how accurately the water transport is modelled (i.e. how many integration steps are used in the calculation), and (3) how much data is saved to the workspace during simulation. The above simulations are carried out with a time step of <0,1 s (with much larger time steps the simulation becomes unstable), relatively many integration steps when solving the water transport (1000 in the stack, 100 in the humidifier), and saving quite much data in the workspace. With these choices of accuracy and amount of data, the system simulates at a rate of approximately 2 s/s. By choosing integration steps of 200 and 50 for the stack and the humidifier, respectively, the simulation rate increases to about 3 s/s.

The fuel cell system model will be utilized in upcoming projects to support the design of PEMFC balance-of-plant.

Combining the Thermolib model with the hybrid drivetrain model is planned once the PEMFC stack and BoP component models are working and properly tuned. This enables the investigation of how the PEMFC BoP system dynamics, like cathode blower delay and system thermal mass etc. affect the hybrid drivetrain component sizing and control strategy development, which leads to better confidence in what the real fuel cell system performance is going to be prior to actually constructing it.

4.3 Fuel cell and hybrid drivetrain modelling

A hybrid drivetrain model was developed for the purpose of fuel cell and energy storage capacity optimization to a defined load cycle and experimentation with different strategies to control the energy flows between the drivetrain components.

The model interface was selected to be the intermediate bus, not including the motor inverters. Later in the project, off-the-shelf SimPowerSystems components were utilized to include electric motor and vehicle chassis dynamics into the simulations.

4.3.1 DC/DC Converter Modeling

The original hybrid fuel cell powertrain simulation model developed during WorkingPEM-project has been expanded to include DC/DC converter models. This expansion was done because a practical hybrid powertrain demands DC/DC converters to control the energy flows. The powertrain model is built in SimScape environment. This and the interest in investigating the stability of the converters (and the whole system) resulted in creating DC/DC converter models using basic electrical building blocks found from SimScape library. This resulted in very accurate converter models but made them also very time consuming to simulate.

Another approach on DC/DC converter modeling was taken at Aalto University. Their DC/DC converter model is based on efficiency test data of a practical converter built by MSc Electronics. The converter model is based on scaling the input current with conversion ratio with appropriate efficiency corrections to create an output current. This makes the model very fast to simulate but it does not accurately model the dynamics of a practical converter. The model was built in Simulink environment.

4.3.1.1 SimScape DC/DC Converter Model

The SimScape converter model is based on electrical building blocks as seen in Figure 4-21. The main circuit is a basic bidirectional converter i.e. a simple boost converter in one direction and buck converter in the other direction. The control system controls the converter direction and the duty ratio of the switches based on the reference current and feedback signal. The main circuit was designed for the specific application and is therefore purely theoretical in nature. The control system is a double PID-controller with an individual controller for each direction. The controllers were designed using proper loop-shaping techniques. The control system has appropriate logics for choosing the correct operating direction. The switching frequency is 20 kHz which makes it necessary to use a simulation step time in the microsecond range making the model very slow.

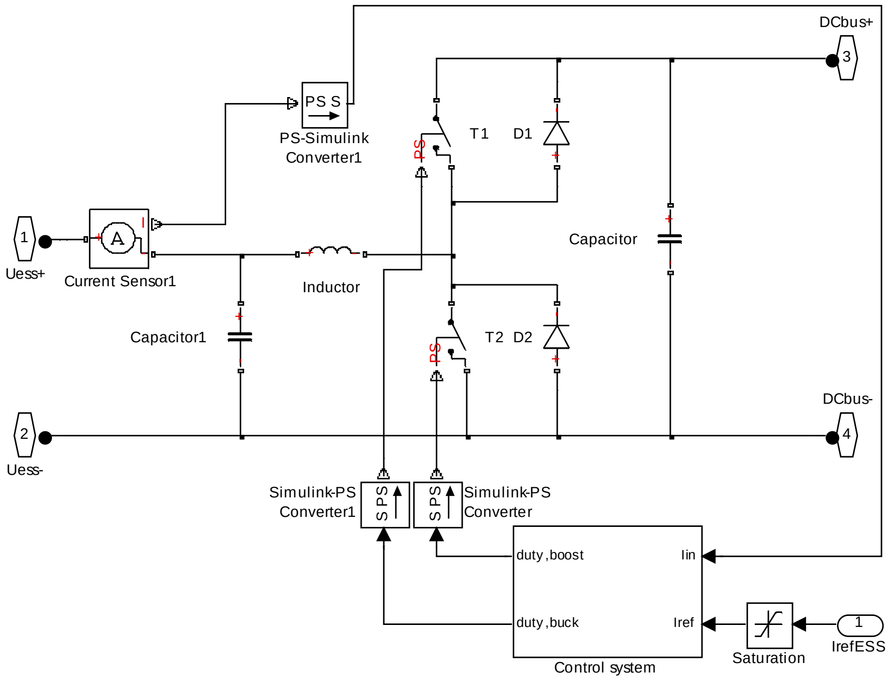

Figure 4-21. Bidirectional SimScape DC/DC converter model

The accurate modeling of the switching actions and the proper design of the control system ensure accurate modeling of the converter dynamics. This makes the model useful in investigating stability and transient behavior. However, this much accuracy is not needed (at least at first) when investigating power management strategies, component sizings etc. A less accurate model with fast simulation speed would be more ideal for those needs. More details on the high frequency SimScape DC/DC converter model can be found in Master's thesis by S. Kukkonen [9].

4.3.1.2 Simulink DC/DC converter model

The Simulink converter model was built at Aalto University. The model is based on MSC200DCDC750 DC/DC converter manufactured by MSc Electronics. The clear advantage of this model is that it is based on very simple mathematical operations making the model very fast to simulate. The disadvantage is the lack of accurate modeling of the DC/DC converter dynamic behavior. The high frequency accuracy of the model is therefore questionable. However, the model was designed with up to 20 Hz bandwidth in mind and the model has been validated to be accurate up to this frequency.

4.3.1.3 Model integration

Simscape blocks have been substituted with Simpowersystem blocks resulting in greatly increased simulation speed and usability of the model. Fuel cell and battery models have been replaced with models from Simpowersystem's library. This has been done to shift the focus of the modeling more to control system design and to improve simulation speed. After the control system design is finished, more accurate fuel cell and battery models are easily incorporated. The latest work in progress hybrid drivetrain model is presented in Figure 4-22.

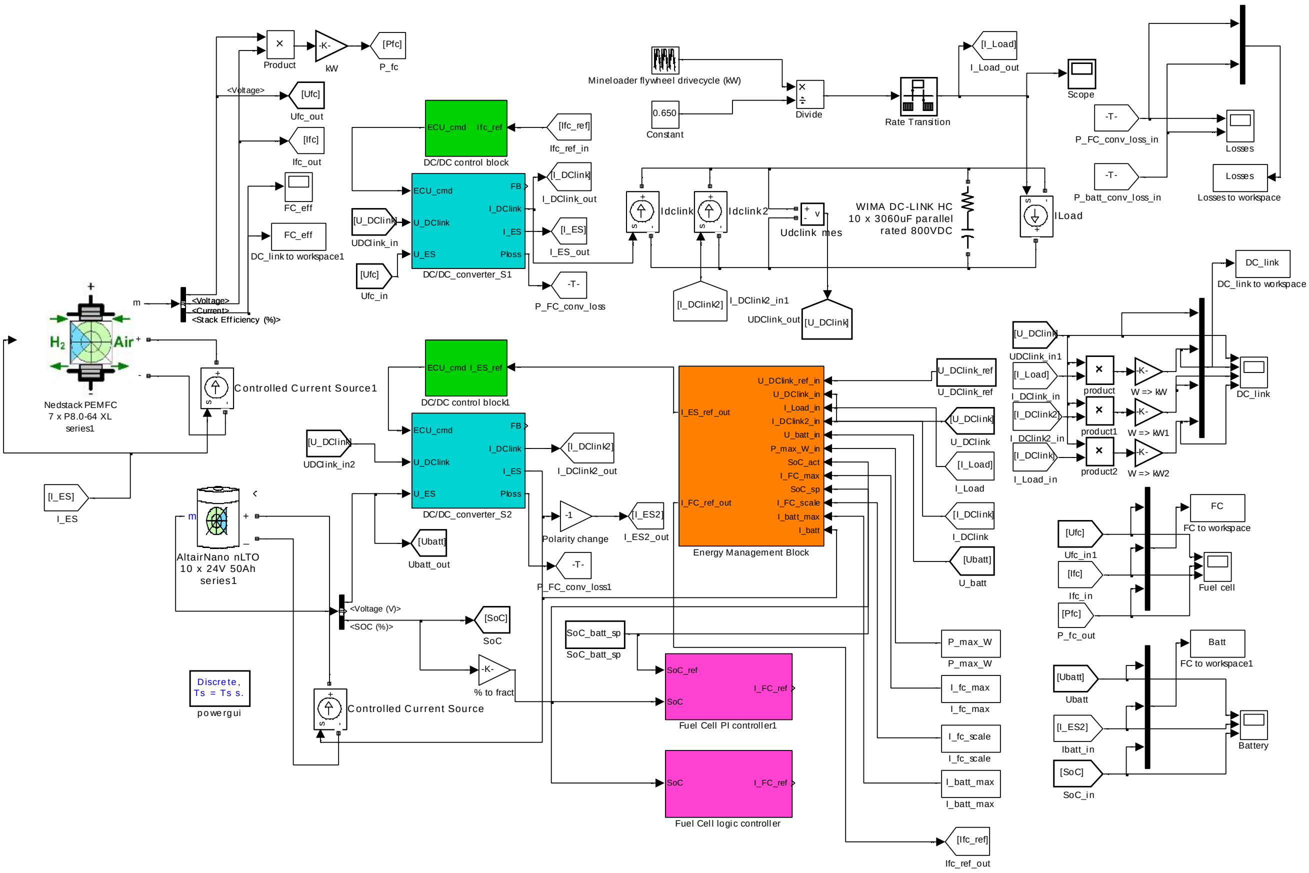

Figure 4-22. Simulink implementation of the hybrid drivetrain

The latest model has a simulation speed of ~2s/s which is a lot faster than the previous ~0.01s/s. Fast simulation speed is needed in the control system design which is simulation intensive. In an addition to increased simulation speed, the latest model uses fixed step in contrast to earlier variable step. The model gives the possibility to use real drive cycles mesured from different workmachines. The fuel cell and battery models are modeled after Nedstack P8 fuel cell and Altairnano 24 Volt modules respectively. Validation of system components is partially completed with Nedstack P8 experimentally measured and Altairnano modules waiting to be characterized at Aalto University. The Nedstack P8 stack calibration is shown in Figure 4-24. below.

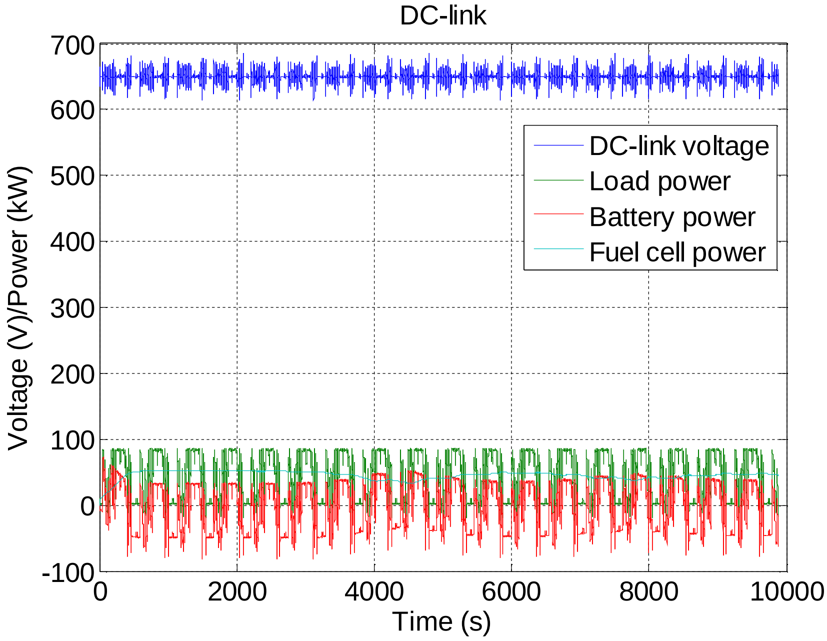

Figure 4-23. Simulation results with the hybrid drivetrain model

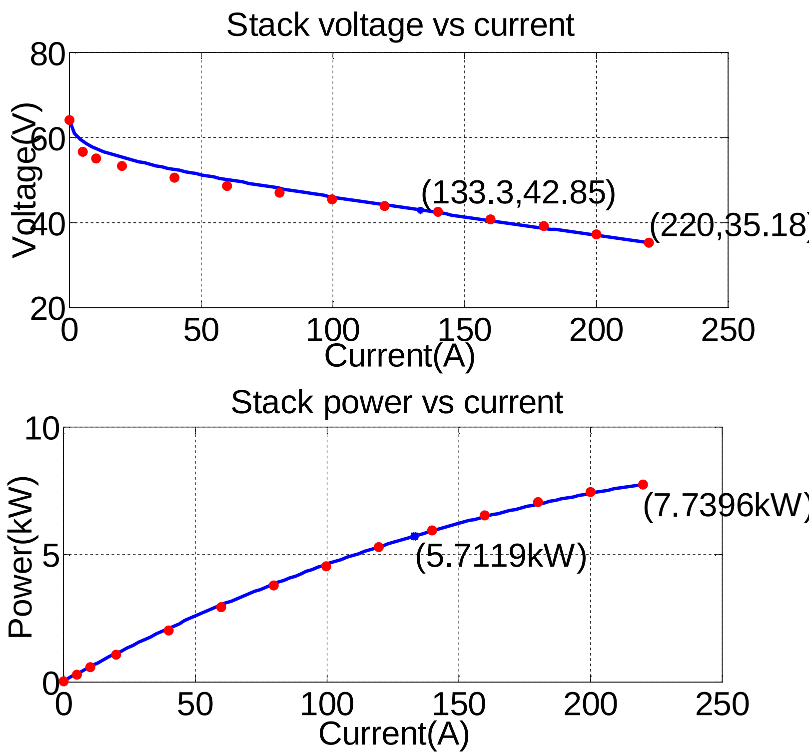

Figure 4-24. Calibration of SimPowerSystems PEMFC model with experimental data

4.3.2 Power flow control

The control strategy is developed so that the battery converter controls the DC-link voltage and the fuel cell converter controls the battery state-of-charge.This means that the battery is supposed to buffer the load transients and absorb the regenerative braking energy, while fuel cell operates in near steady-state mode.

The battery converter control can be implemented with traditional PI controller, when the device is operated in voltage control mode. However, in order to achieve fast enough control, a disturbance compensated PI controller needs to be incorporated. Fuel cell current and load current can be thought of as disturbances affecting the DC-link voltage, which can be compensated by the controller. Figure 4-25 describes the DC-link voltage controller that gives current reference for the battery converter. The current reference is given as battery side current and therefore appropriate scaling has been implemented into the controller.

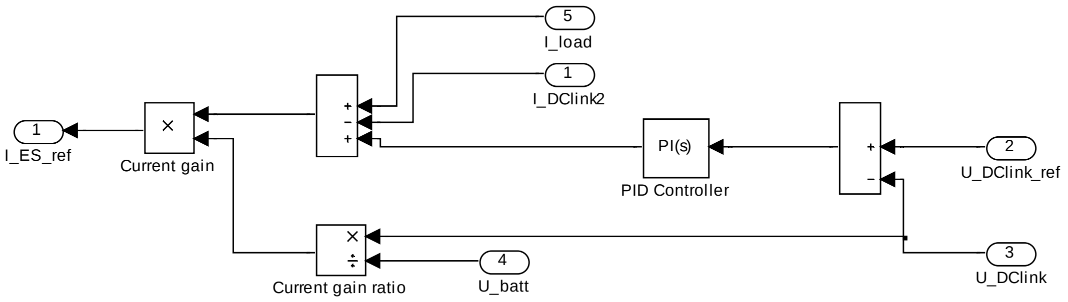

Figure 4-25. DC-link voltage controller

The battery state-of-charge control is problematic to achieve with a traditional PI-controller because of the control requirements of the fuel cell. Nevertheless, a PI-controller was designed to handle this task and later on logic based and fuzzy logic based approaches are evaluated to inspect the improvement over traditional PI-control.

Fuzzy logic has the prospect of producing better performance in complex multivariable control problems compared to traditional PID control. Compared to some other model based approaches, a fuzzy logic controllers are relative easy to develop and do not require much processing power when implemented on a real control hardware. A downside is that numerical optimization of a fuzzy inference system is less straightforward than, for example with the parameters of a PID controller.

In the case of hybrid drivetrain model developed, two different ways to utilize fuzzy control have been experimented. A pure fuzzy logic controller, which takes multiple input signals and produces directly the control signal for the actuator is used to control the PEMFC converter, while a cascade controller consisting of fuzzy controller feeding the reference signal for a traditional PID-controller is in use with the battery converter. A way to visualize the fuzzy logic decision making in the case of PEMFC DC/DC converter control is shown in Figure 4-26.

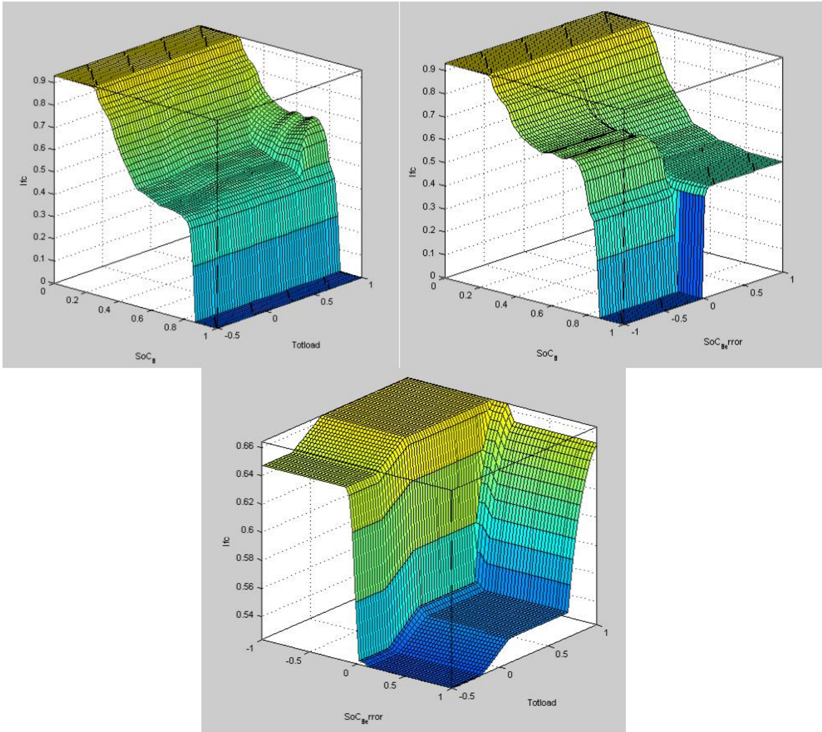

Figure 4-26. Fuzzy logic control surfaces for PEMFC controller with three input signals and one output

Figure 4-27 andFigure 4-28 show the first results from comparison of hysteretic (static limit values) control, traditional PI control and fuzzy logic control on fuel cell power demand and battery state-of-charge. The fuzzy logic controller is still a work in progress, but it can be seen from the figures that

1) The FC power and battery SoC variation is roughly equivalent to well tuned PI controller
2) The fuzzy logic controller is able to stabilize the battery SoC around the setpoint almost as fast as the hysteresis based controller
3) Fuzzy logic controlled fuel cell peak-to-peak load variation in the mineloader workcycle is much less than with PI controller

By this early comparison, it seems like the fuzzy controller is able to combine the good features of the two methods it is being compared to.

Results of this work have been presented in [10].

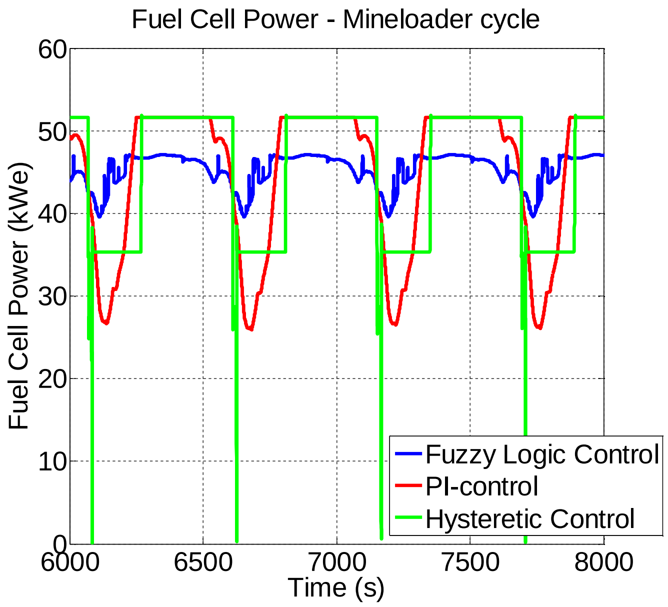

Figure 4-27. FC power curve with different control methods of FC DC/DC converter

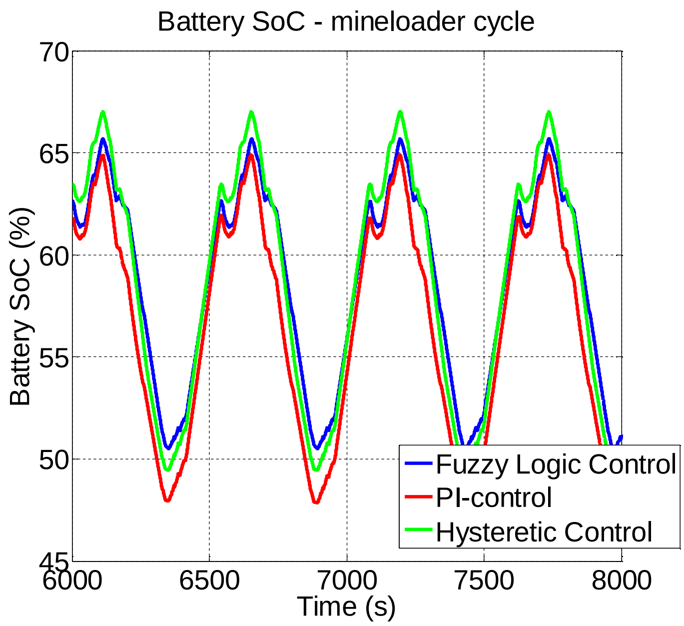

Figure 4-28. Battery SoC curve with different control methods of FC DC/DC converter

4.3.3 Modelling workshop with Aalto University parallel project

A workshop was arranged for the project partners to demonstrate the modelling tools developed during the TopDrive-project at Aalto University and VTT. VTT:s contribution consisted of a presentation of the detailed fuel cell BoP model implemented using the Thermolib-library for Simulink and presenting the hybrid electric drivetrain model used for studying fuzzy control of the fuel cell DC/DC converter.

4.3.4 Passenger car hybrid FC range extender simulations

A case study of simulating a passenger car with a hybrid FC drivetrain was done based on specifications defined by Powercell. The system to be simulated consisted of a vehicle chassis resembling the Volvo C30 Electric car, a battery module, and a small fuel cell range extender. Also the electric motor and fuel cell DC/DC converter models were included. Goal of the work was to define the range of such vehicle with 5kg of hydrogen onboard when driving the new european drive cycle (NEDC), which is a standard cycle for passenger cars.

Table 2. Vehicle chassis parameters used in simulation

Weight (kg)	2073
Drag coeff. (Cd)	0,31
Gear ratio	7,2
Trnsm. Inertia (kg*m^2)	0,5
Wheel inertia (kg*m^2)	0,5
Wheel radius (m)	0,25

Most of the parameters in the model are quite roughly estimated, but according to the simulations, a 10kW FC range extender is sufficient for the NEDC cycle and for strictly urban driving, the 5kW FC could be enough also. On the otherhand, even the 10kW PEMFC was not enough to maintain the SoC of the battery module on the highway part (EUDC) of the NEDC profile. Therefore, for highway capable vehicle either the fuel cell system has to be more powerful or the battery capacity needs to be higher. The latter case would probably mean that limitations to operating range would need to be accepted.

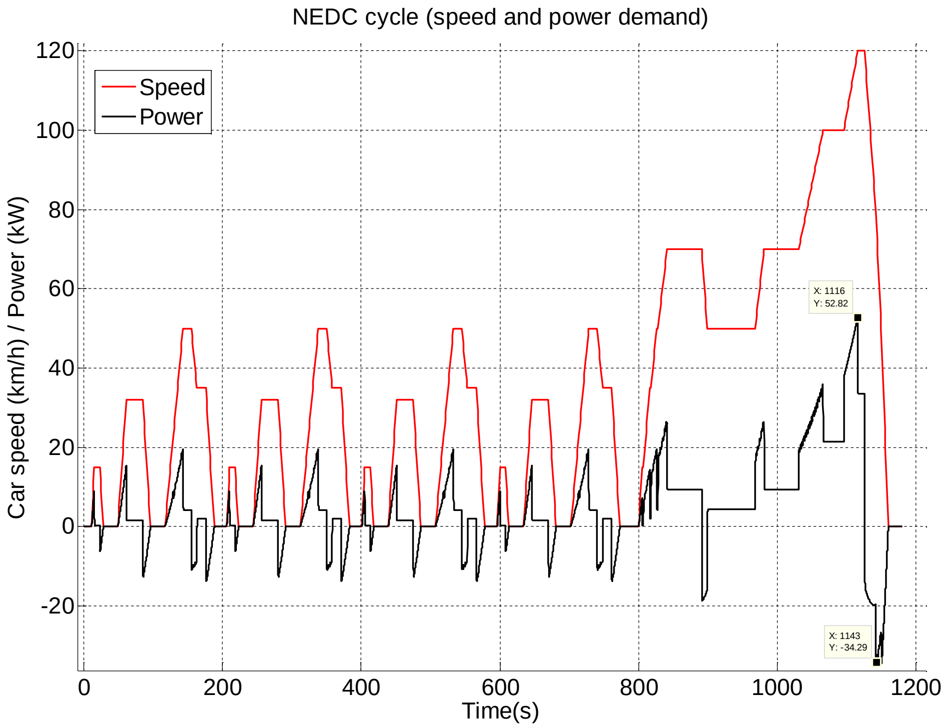

Figure 4-29. NEDC cycle and the vehicle chassis power demand

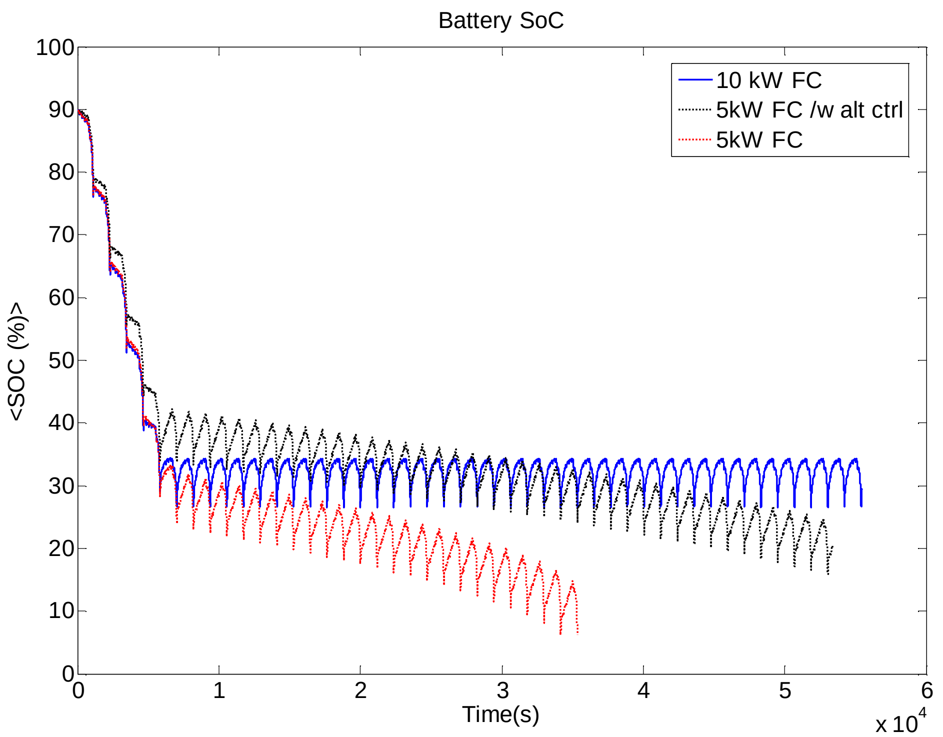

Figure 4-30. Battery SoC during repeated NEDC cycling

Table 3 below summarizes some performance parameters extracted from simulation data. The second 5kW case involved an alternative control method with different limit values and controller reference signal selection logic based on battery SoC instead of constant value.

Table 3. Simulation results summary

	5kW FC	5kW FC alt	10kW FC
Distance (km)	326	493	511
Max ΔI (A/s)	2,81	45,98	2,78
Eff. stack (%)	44,80 %	50,19 %	54,72 %
Min SoC (%)	6,20 %	15,88 %	26,60 %

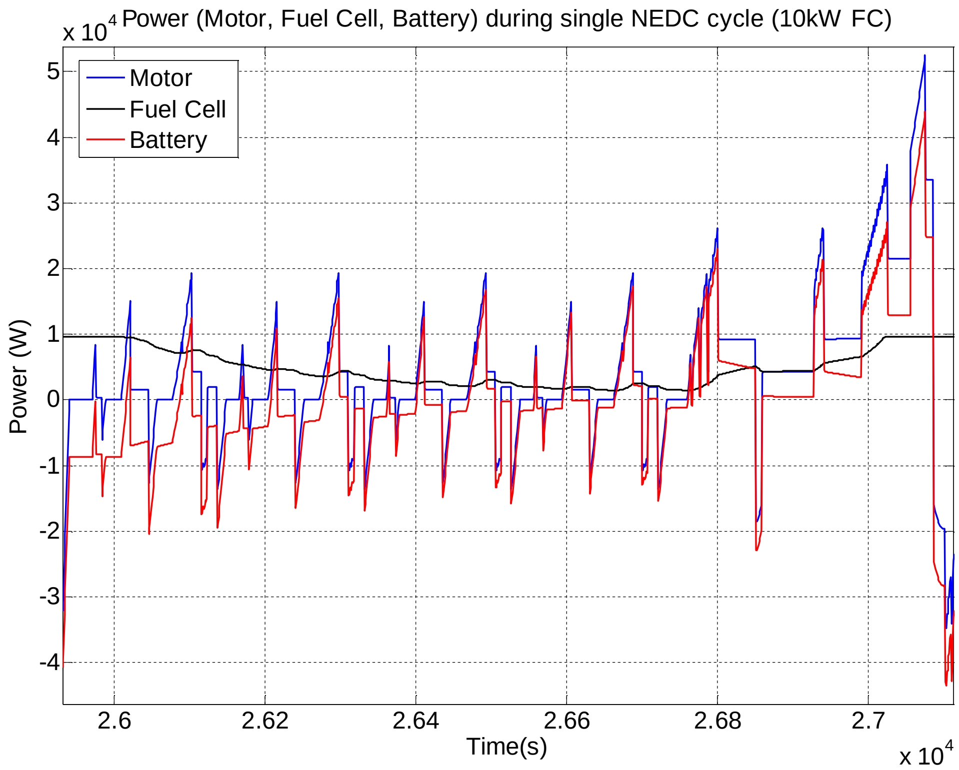

Figure 4-31. Power distribution between battery and fuel cell during NEDC cycling (10kW FC)

According to simulation results, the 10kW range extender would be sufficient to complete repeated NEDC cycling with these vehicle chassis parameters. Vehicle range with 5kg hydrogen storage would then lead to operating range of approximately 500km.

4.4 PBIFC stack development

PBI (polybenzimidazole) fuel cells are essentially PEM fuel cells, but operate in comparably high temperature of 160°C-200°C. The high temperature brings along many simplifying aspects both in the cell level chemistry as on the system level. One of the biggest benefits is the high tolerance against fuel impurities, especially CO. On the system level many balance-of-plant components could be cut out and savings could be achieved in size and cost. Moreover, the operation temperature of PBIFC just about reaches the reforming temperature of methanol, which makes methanol-PBI system an interesting future candidate for vehicles. In the scope of the project, PBI research included development work for construction of a laboratory scale stack.

Goals of the work package were set as

- A durable and cost-efficient liquid cooled PBIFC stack optimized for operation between 160 and 180 °C
- An innovative thermo-oil cooling design in the stack, optimized for high cooling oil outlet temperature and large internal temperature differences, to study the effect of phosphoric acid circulation in the MEA.
- Successful demonstration of domestic component (bipolar plate composite) in the stack, that enables commercial launch of the composite

4.4.1 Bipolar plate design

An essential motive behind the work package was demonstration of a stack component called bipolar plate, distributing the reactant gases to MEA and conducting the electric current. The bipolar plate was planned to be made of an in-house graphite composite material, developed in earlier projects by VTT Materials applications team in Tampere. The bipolar plate was the scientifically interesting and new component in the stack design – other components were planned to be ordered from suppliers. For instance, custom dimensions for MEAs and gaskets according to the bipolar plate design presented below were agreed with the supplier BASF.

4.4.1.1 CAD design for a new bipolar plate

A new plate with manifolds and flowfields was designed using CAD. The mold for the manufacturing process (compression molding) of the blank plate was made in VTT Materials applications. The dimensions of the plate were 205x110x5 mm. The blank plates were molded in VTT Tampere and were planned to be machined according to the CAD design.

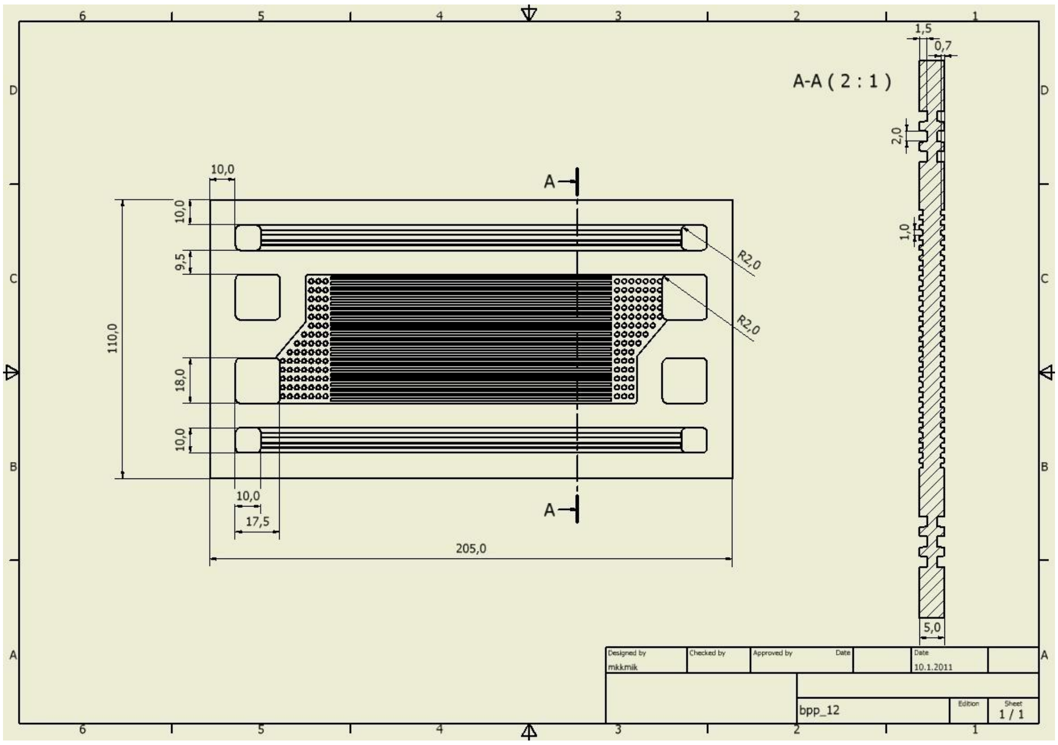

Figure 4-32. The new bipolar plate design, top view and cut view enlarged

4.4.1.2 Heat transfer modelling in the bipolar plate

Modelling was used as a tool to evaluate if the work package objective is realistic, and how it could be reached. The modelling was done with Comsol Multiphysics, a commercial partial differential equation solver software based on the finite element method.

The goal values for gas inlet and outlet temperatures are 220 °C and 160 °C, respectively. This is a large temperature difference to have in a small cell.

A preliminary model was built on the following assumptions:

- All fluid flow is laminar
- Heat transfer to ambient air is not significant i.e. the stack is well insulated
- MEA, GDLs and insulation layers are so thin that they do not have a significant impact on the heat transfer and have thus been excluded from the model
- Geometrical simplifications such as excluding the cylindrical supports structures at the gas inlets and outlets
- The cell is in an infinitely long stack i.e. here is no heat transfer through the cell
- Current density is constant on the active area

Table 4 below lists the most important parameters used in the modelling.

Table 4. List of the most important parameters used in the modelling

Density of oil at 160 °C, kg/m^3	827
Thermal conductivity of oil 160 °C, W/K m	0.112
Specific heat capacity of oil 160 °C , J/K	1760

Dynamic viscosity of oil at 160 °C, Pa*s	0.00347
Thermal conductivity of the bipolar plate x,y direction, W/K m	45
Thermal conductivity of the bipolar plate z-direction, W/K m	19
Density of the bipolar plate, kg/m^3	1820
Specific heat capacity of the bipolar plate, J/K	940
Oil inlet temperature °C	140
Air inlet temperature °C	220
Ambient temperature °C	100
Cell current density, A/m2	6000
Active area m^2	0.00561
Stoichiometry of the air flow	2
Stoichiometry of the hydrogen flow	1.10

An illustration of the temperature distribution in the cell as calculated by the preliminary model is presented below (Figure 4-33). The image shows that the inlet temperature is close to what is desired and the ends of the gas channels are around 170 °C, somewhat higher than desired. Increasing the oil flow rate in the cooling channels decreases the temperature.

According to the preliminary modeling results, accomplishing a suitable temperature difference on the active area with the current geometry and oil and gas temperatures is possible.

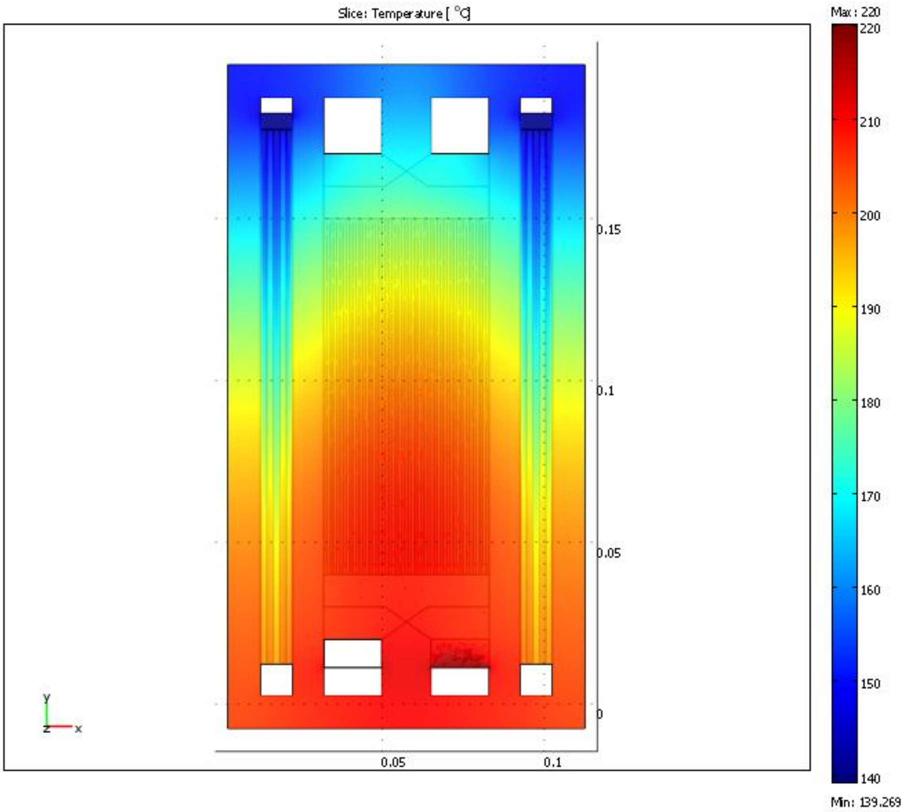

Figure 4-33. Illustration of the temperature distribution

4.4.2 Outcome

Initially, 15 blank plates was supposed to be molded in VTT Advanced Materials. The molding encountered big problems, e.g. part of the machinery broke down. In the end, four plates were molded during January 2011.

Specifications became the following

- compound *Marapoke 1056* from a previous project
- dimensions 205*110*5 mm
- density ~ 1,86 g/cc

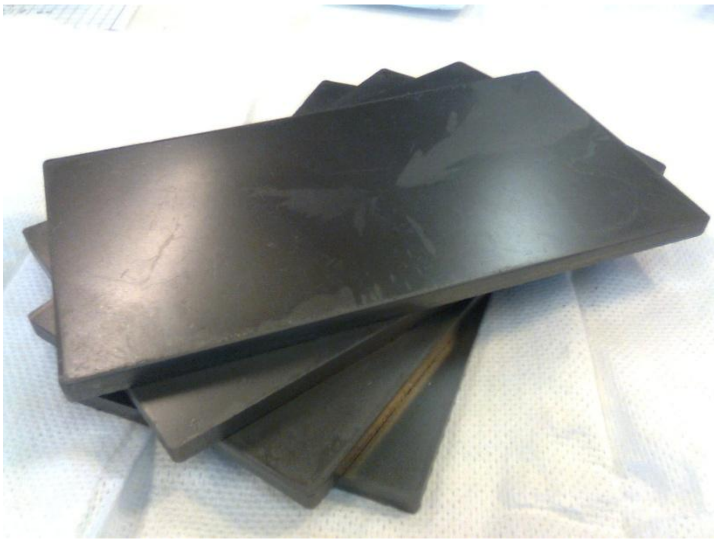

Figure 4-34. Blank plates compression molded in VTT Tampere.

Because of setbacks and the limited time in the project, the original new bipolar plate design was abandoned. Instead, an old plate design by Thomas Tingelöf was taken into use. The goal was no more to study the phosphoric acid circulation in the MEA, but simply to test the graphite composite material suitability as the bipolar plate material and build a 3-cell stack.

During the final 6-month period there was a attempt to compression mould blank plates (185 mm x 185 mm x 5 mm) by an external partner capable of machining the plates, as well.

Molding of the PPS turned out to be a challenging task. The external partner made 7 plates. 6 of the plates have densities below 1.8 g/cm3. The last plate had a density of 1.87 g/cm3. Each plate took 10 hours to make due to the long heating/cooling time and there was no more molding capacity for further trials. Hence, molding of the plates was unsuccessful. VTT has decided to upgrade its molding press in order to be able to mould more plates in future projects.

In the end, no bipolar plates were machined and the stack could not be built. Eventually, the initial goals of the WP in the project plan were not met and the resources of the WP have been used in the other WPs.

During the period Pertti Kauranen attended 1st international expert workshop “High Temperature PEM fuel cells“ 27.03.2012 - 28.03.2012 in Duisburg. Workshop was organised by Zentrum für Brennstoffzellen Technik.

4.5 Hydrogen quality

In this work package air and fuel quality requirements were studied. Theoretical part of the work, which considers anode side contaminants, was reported 2010 in[11].

This work has been done in co-operation with Luis Martinez, who is PhD. guest researcher (PhD. student) from University of Porto.

The main focus has been to study the effect of CO residence time on the performance of PEMFC in a single cell level using also gas analysis. Work has been started with open anode mode, but will be continued with recirculation mode.

The goal of this work was to study how the residence time of gas affects the CO tolerance in hydrogen fuelled PEFC.

If there is improved CO tolerance due to more even distribution, this would affect both cell and system design as well as system operation.

In principle, if CO is more evenly distributed on the anode surface, then internal air bleed (oxygen from cathode) would be more effective as more electrode area would be used. However, as residence time increases further, part of the CO will pass the cell without oxidation and in recirculation mode it is recycled back to inlet.

4.5.1 Description of the work

Two cells (cell A and B) have been used to perform controlled CO poisoning experiments using Arbin FC test station. The description of the cells and corresponding test bench is given below.

Cell A - description

- 25 cm^2 active area. (MSC gen 2)
- The MEA (IRD) has 0.15 mg $Pt \cdot cm^{-2}$ on both anode and cathode. The membrane thickness is 18 µm.
- The gas diffusion layers (GDL) are Sigracet 35 BC (SGL Group). The thickness is 325 µm.
- Freundenberger 35 FC-PO100 gaskets are used.
- Single channel serpentine flow fields at anode and cathode.

Cell B - description (Fuel cell technologies cell)

- 25 cm^2 active area.
- The MEA (Gore series), the anode and cathode catalyst loading is 0.4 mg $Pt \cdot cm^{-2}$ and 0.6 mg $Pt \cdot cm^{-2}$ respectively. The membrane thickness is 35 µm.
- The gas diffusion layers (GDL) are Sigracet 35 BC (SGL Group). The thickness is 325 µm.
- Freundenberger gaskets 35 FC-PO100 are used.
- Single channel serpentine flow fields at anode and cathode.

4.5.2 Test bench description

- Air and fuel fed in counter flow mode.
- A liquid cooling loop is used to control the temperature of the cell.
- Neat H_2 (reference) and H_2-CO mixtures are fed to the cell.
- Fuel exhaust is dehumidified using a FC 100 80 6MKK membrane humidifier (Permapure LLC). Dry N_2 is fed in counterflow mode to humidifier at Q_{N_2}=10 $l \cdot min^{-1}$. N_2 is passed through a heated pipe; the temperature is set to 75 °C.
- One EX2020R (TTi) power supply and a LD300 electronic load (TTi) for potentiostatic control and current monitoring.
- H_2 concentration is measured with an HPS 100 hydrogen process sensor (Applied Sensor).
- Relative humidity of dried gas is measured with an HMP 110 relative humidity and temperature probe (Vaisala).
- Gas chromatography (GC) is performed using a 6890N gas chromatograph (Agilent Technologies).
- H2 and air flow rate, humidity control and data logging with Arbin FC test station.
- CO is fed using a three-way valve placed at the anode inlet. CO is taken from 10 bar pressurized mini bottles (AGA) with a nominal CO concentration of 1000 ppm (N_2 balanced). The CO flow rate is controlled with two mass flow rates (Bronkhorst), the first with 0-1 $ml \cdot min^{-1}$ and the second with 0-100 $ml \cdot min^{-1}$ nominal flow rate.

4.5.3 Results of CO poisoning experiments

This chapter describes some interesting results from a typical series of experiments performed in the spring of 2012 with the Greenlight G60 testbench.

On March 6 and 7 the reproducibility of experiments with cell A was studied. Figure 4-35 shows the results. The experimental conditions are showed in the upper right box. It is important to highlight:

- The first CO injection of both days had different shape. The time to reach V=250 mV was at least five times bigger for the first injections. Consequent injections showed good reproducibility.

- The CO concentration was too high, C_{CO}=24.9 ppm, for the operating temperature T_{cell}=65 °C.

- The actual temperature of the humidifiers was corrected after these experiments; there is a difference of approx. 7 °C between the actual and measured value. Because of this, the relative humidity of the anode and cathode was 65 %, not 90 % as planned.

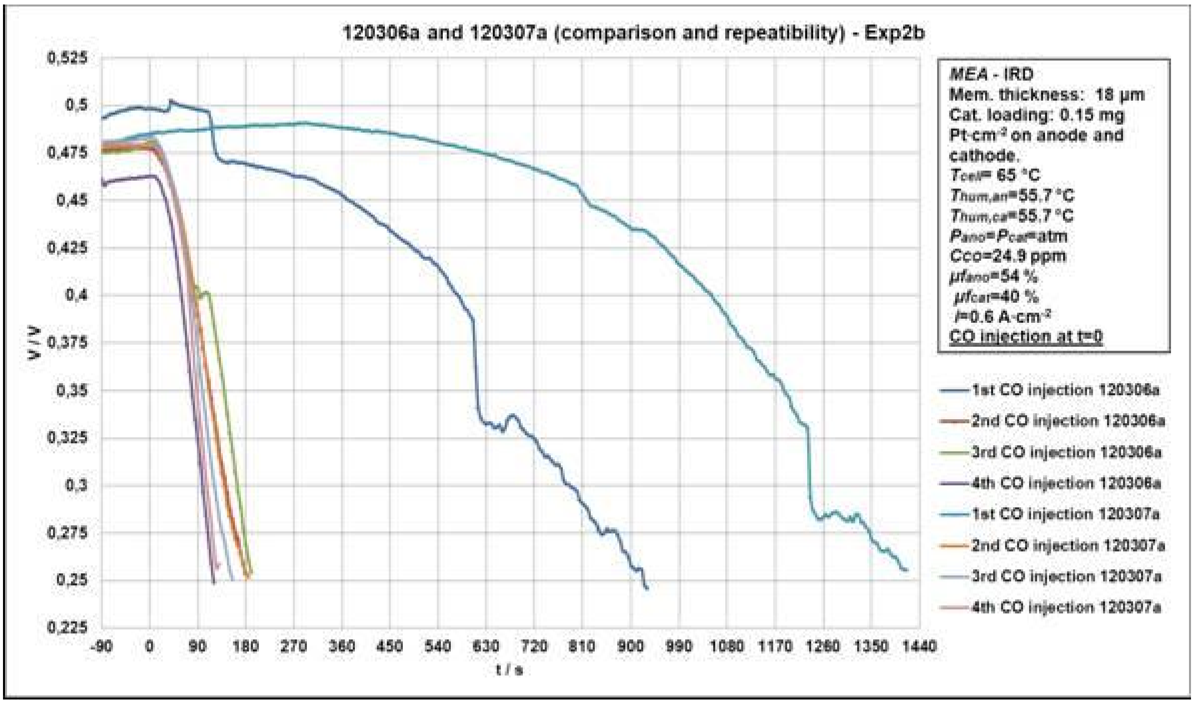

Figure 4-35. Comparison and repeatability of experiments with cell A

On March 8 cell A was replaced by cell B due to low performance. Cell B was conditioned. An experiment was conducted using different fuel utilizations. Figure 4-36 shows the results. It is important to highlight:

- The first CO injection also showed a different shape.
- The time to reach V=550 mV doubled for the low fuel utilization (high flow rate); however, the CO concentration was also reduced. This resulted from the constant CO molar rate injected.
- Not even recovery processes were responsible for different V at the moment of CO injection.
- After this experiments the fuel utilization was corrected for 0.6 A·cm-2. The fuel utilization was being calculated for 0.1 A·cm-2.
- The RH of the anode and cathode was close to 90%.
- High CO concentrations were used (18.1 and 6.1 ppm)

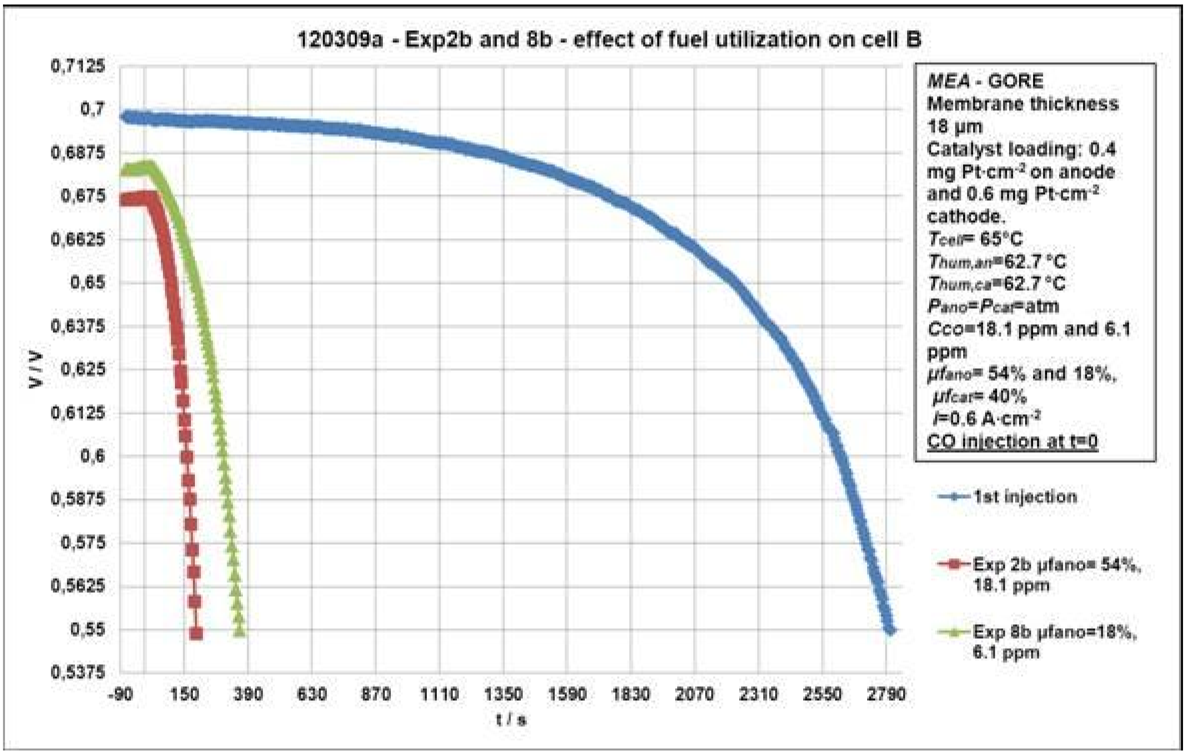

Figure 4-36. Effects of fuel utilization on cell B

On March 13th experiments with lower CO concentrations were performed with cell B. Figure 4-37 shows the results. It is important to highlight:

- CO injections started to take more time (4.5 hours) to achieve the desired voltage value, in this V=650 mV.
- After these experiments, the RH of the anode was decreased to 80 % to prevent flooding.
- The experiment “second CO injection 14mar2012” was aborted, however, it seems that the cell was about to start a steady state poisoning process.

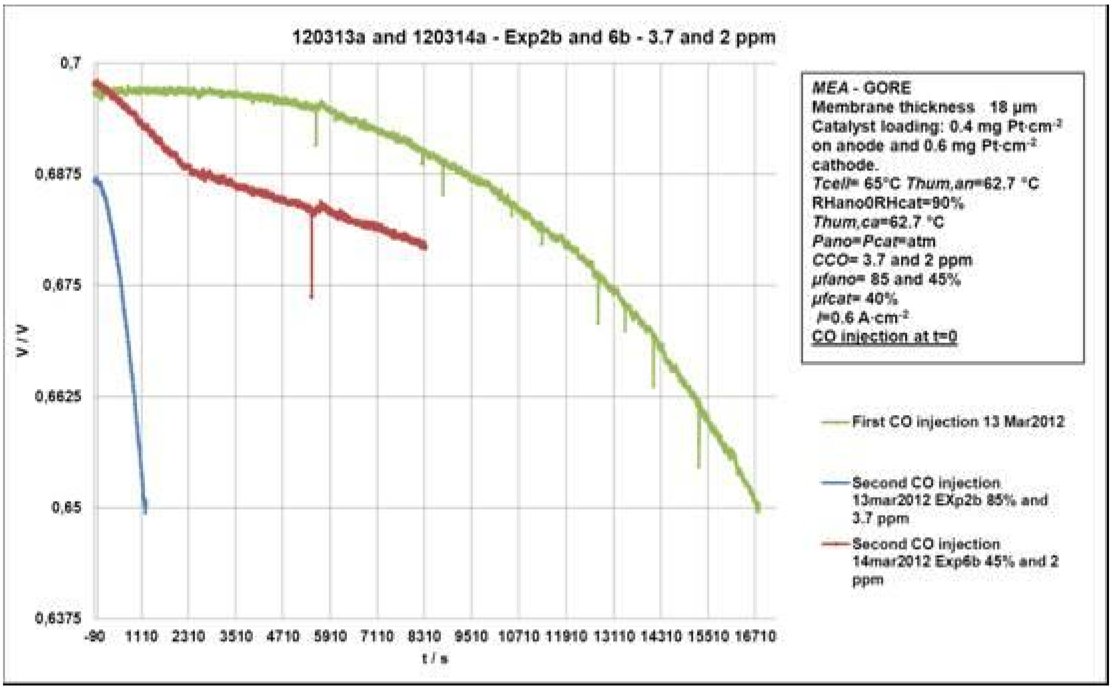

Figure 4-37. Comparison and repeatability of experiments with cell B

On March 16th, four experiments were performed. The objective was to reproduce the experiments using relatively low CO concentrations. Figure 4-38 shows the results. It is important to highlight:

- It was not possible to reproduce the experiments. The main reason may be the lack of a standard recovery process between them.

On March 27th, one experiment was performed. The objective was to steady state CO poisoning process. Figure 4-39 shows the results. It is important to highlight:

- A steady state CO poisoning process was observed for the first time, it took about 5 hrs to achieve it.
- The steady state was achieved at V≈425 mV.

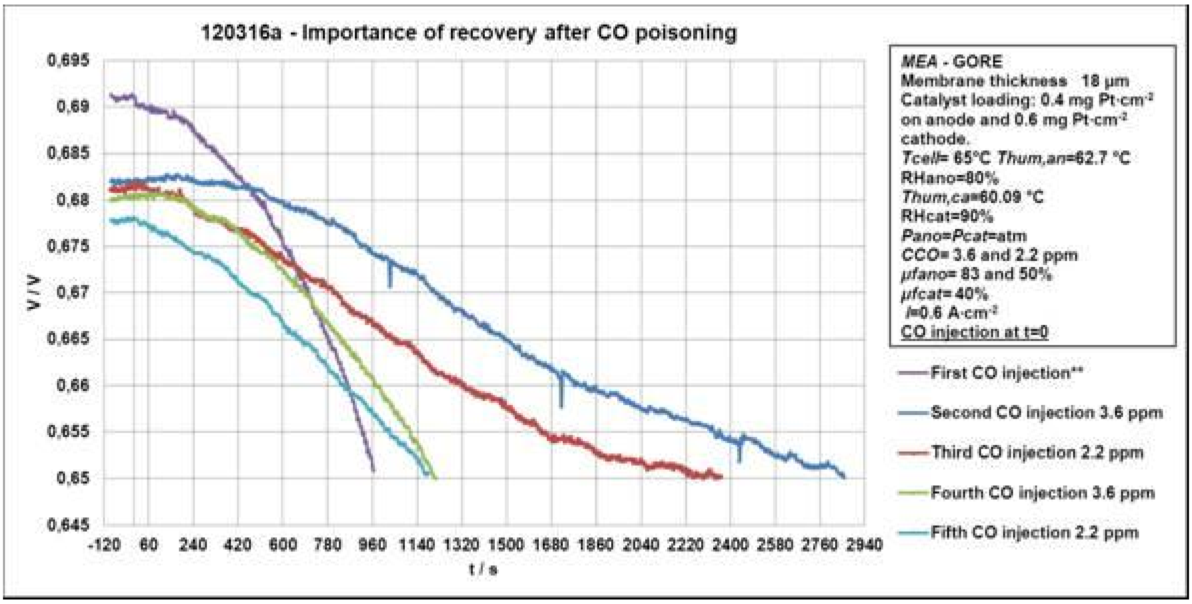

Figure 4-38. Cell B recovery after CO poisoning

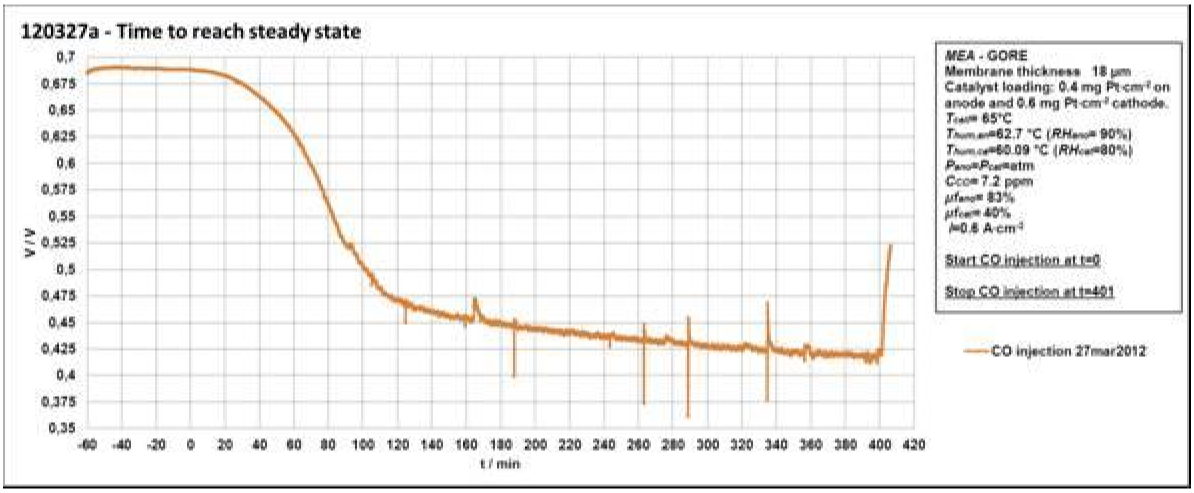

Figure 4-39. Cell B time to reach steady-state

Single cell experiments - constant CO concentration (11 Abr 2012)								
		Anode				Cathode		
Experiment	Tcell (°C)	RH (%)	Pano (bar)	uf (%)	CO (ppm)	RH (%)	Pcat (bar)	uf (%)
1 (Ref)	65	90	1,01325	80	0	80	1,01325	40
2	65	90	1,01325	83	7,2	80	1,01325	40
3	65	90	1,01325	55	7,2	80	1,01325	40
4	65	90	1,01325	42	7,2	80	1,01325	40

Single cell experiments - constant CO molar rate (11 Abr 2012)								
		Anode				Cathode		
Experiment	Tcell (°C)	RH (%)	Pano (bar)	uf (%)	CO (ppm)	RH (%)	Pcat (bar)	uf (%)
1 (Ref)	65	90	1,01325	80	0	80	1,01325	40
2	65	90	1,01325	83	7,2	80	1,01325	40
3	65	90	1,01325	55	4,8	80	1,01325	40
4	65	90	1,01325	42	3,6	80	1,01325	40

4.6 Safety and regulations

Main goal for the work package was to find suitable set of methods analyzing the safety and reliability of fuel cell systems.

4.6.1 Literature review - Safety and reliability analysis methods for PEMFC systems

Literature review about methods which have been used in PEM fuel cell systems for safety and reliability analysis has been conducted.

Due to a fact that fuel cell systems and needed fuelling infrastructure are complex systems, risk assessment tools need to be carefully selected. Methods successfully used for PEM fuel cell system risk assessments found in literature are collected in the review.

Reliability is one of the primary barriers for the large-scale commercialisation of PEM fuel cell system. The reliability of fuel cell system depends on the reliability of the stack and the reliability of all the other components within the system. Even a single cell failure in stack may require the entire fuel cell system to be shut down or failures of upstream components can lead to premature stack damage and failure. The durability and the degradation of fuel cells are major reliability problems. Methods used to analyse reliability found in literature are collected to the literature review.

4.6.2 Standard development work

Development work for the new standard “Fuel Cell Technologies – Part 4-101: Fuel cell power systems for propulsion other than road vehicles and APUs – Industrial electric trucks – Safety” for industrial trucks has started. VTT is participating in the IEC TC105 WG6, which develops the standard. From 13th to 14th of September first Working Group 6 meeting was held in Geneva. During the meeting outline of the standard was developed. First draft of the standard is now under commenting. Comments for the first draft have been collected in January 2012.

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