Taylor PEM Phase 1

Development of tools for tailored Danish PEM fuel cells stacks for the early marked

EUDP Project J. No 64009-0016

Period Oct-2009 to Dec-2013

Project responsible:

IRD Fuel Cells

Kullinggade 31

5700 Svendborg

CVR No. 28308523

Project partner:

SENER, Spain

Report edited by:

Steen Yde-Andersen, June 2014

Indhold

1. SUMMARY

State of the art for fuel cells stacks on the market have been stacks which technically have had good performance and durability, but not aimed for mass production. The result is high production prices and not scalable power outputs. Furthermore these "early" stacks are engineered to optimize the fuel cell technology. Not to fulfill specific customer demands.

The TailorPEM project has with its new research, modeling of the dynamic processes followed by new design and process engineering decreased production price to meet the Danish 'Road Map' targets as defined in the Danish PEM strategy.

Given this technology level at the current market, the project has enabled IRD and partners to be in the forefront in the growing commercial fuel cell market. Given the market size and growth potential, this is a great opportunity for the consortium and Denmark.

The project partners have supplemented each other very well with their experience in stack development and manufacturing as well as system integration and market knowledge in the different market segments. And the quality of the manufactured fuel cell stacks has been sufficient to fulfill the demands of very demanding system integrators.

The outcome of the project opens new possibilities as the FC stack and module can be custom made and produced for an affordable cost in small scale production and with a potential of high cost reductions on large scale production.

The overall results of the TailorPEM project are the establishment of a design tool together with efficient and optimised production methods with the potential for automated production in larger scale. The outcome of the project has decreased production cost of IRD's fuel cell modules even in small scale production. The design tool has enabled stacks to be tailored for different applications and demands. This is changing the product design from research/supply driven to a customer demand driven.

Cost efficient production methods for small scale stack and module manufacture with the additional objective to automate stack assembly and manufacture has been obtained in the TailorPEM project. These results include

- Design specifications of graphite flow plate moulds reducing tooling and fabrication cost for flow plate production
- Low cost mould material and low cost polishing process especially suitable for small scale flow plate production
- Low cost seal design and seal process suitable for both small scale production and large scale automated production
- Design and production process stack end plates, 2 types, either end plates with no deflection in the stack (developed within associated EUDP project) or a low weight end plate for transportable application .
- All polymer infra-structure for stack module for easy assembly

2. PROJECT STRUCTURE

The TaylorPEM phase I project, EUDP Project J. No 64009-0016, was organized in 5 work packages, addressing the coordination, the specification, the modelling, the prototype process development and the test and validation. The project included a review in August 2011. This report covers the entire span of the project. The overall objectives of the project are listed below, followed by a brief record of the final status on the project milestones. Subsequently a detailed report on each work package is provided.

2.1 PROJECT OBJECTIVES

The overall objective of the TailorPEM project phase I is to establish a design tool and a cost efficient production method, decrease production cost of fuel cells even in small scale production and adressing automated stack manufacture. This design tool will enable stacks to be tailored for different applications and demands even in small-scale productions. That will change the possible product design from research/supply driven to a customer demand driven. Meeting end-user demand and decreasing production price will give a unique first mover advantage in the fuel cell marked. The project has been divided in two phases, the present report concerns Phase I only.

2.2 PROJECT BACKGROUND

Fuel cells convert fuel and air directly to electricity, heat and water in an electrochemical process. It is an essentially clean technology that uses hydrogen (from its fuel source) and oxygen (from the air) to generate electricity and heat without pollution. The only basic emission is water.

In principle a fuel cell operates like a battery. However, unlike a battery, it is continuous charged when supplied with fuel and air.

There are several types of fuel cells, such as Solid Oxide Fuel Cells (SOFC), Molten Carbonate Fuel Cells (MCFC), and Polymer Exchange Membrane Fuel Cells (PEM FC); the latter includes the Direct Methanol Fuel Cell (DMFC).

All types of fuel cells share the basic design of two electrodes (a negative anode and a positive cathode) separated by a solid or liquid electrolyte that carries electrically charged particles between them. Hydrogen is passed over the anode and oxygen over the cathode, which produce, respectively, hydrogen and oxygen ions that can combine to form water and produce the electric current. Catalytic coatings on the electrodes are generally used to speed up reactions.

Fuel cells are classified according to the nature of their electrolyte which also determines their operating temperature. Each type of fuel cell has particular materials requirements. And in theory all can use a wide range of fuels providing that the fuel contains hydrogen.

Today stacks designs on the market are early generation fuel cells. Technically they have good performance and durability, but they are not developed for low cost and mass production.

For IRD the two most mature technologies are in focus: PEM FC. and DMFC (Direct Methanol Fuel Cell) The Direct Methanol Fuel Cell is a further development of the PEM FC. It use the same type of membrane. Instead of using gaseous hydrogen as fuel, methanol is directly converted to hydrogen by a catalytic process in the hydrogen electrode.

2.3 PROJECT

A solid understanding of the dynamic behaviour of a Proton Exchange Membrane Fuel Cell under load changes and variable sizes is crucial for reliable, optimised operation and durability. The dynamic behaviour of a fuel cell is highly complex. The power of a PEM FC strongly depends on operating conditions such as flow rates, relative humidity and temperature of the gases as well as ambient temperature. Mathematical modelling is essential for understanding and handling this complexity. Non-linear Model Predictive Control (NMPC) and online optimisation of dynamic processes have attracted increasing attention over the past decade in the fuel cell industry.

In contrast to empirical control strategies based on experimental observations and extensive testing, a model-based control allows faster system development and optimal system operation over a wide range of operating conditions. As a prerequisite, NMPC requires detailed non-linear process models.

The TailorPEM project will research and model the dynamic processes in the PEM Fuel Cell design. In this process, also decrease production price according to the Danish 'Road Map' targets as defined in the Danish PEM strategy.

2.4 STATE-OF-THE-ART AND PROJECT OUTCOME

Over the past two decades, fuel cell technologies has been extensively studied because they represent one of the most promising ways of energy production for transportation (propulsion and/or auxiliary power units), mobile devices (mobile phones, computer, emergency) and stationary systems. Indeed, fuel cells convert directly and continuously the fuel (hydrogen) chemical energy into electric power, heat and water, without limitations due to the Carnot theorem and polluting evolutions. PEM FC (Proton Exchange Membrane Fuel Cells) using solid polymer membranes and working at low temperatures (≤100ºC) are the subject of worldwide priority research. However, only the niche markets have accepted the very high fuel cell cost. The low turnover and the high cost of stack development entails that the FC stack manufacturers have had a very narrow product line.

Therefore the overall objective of the TailorPEM project has been to establish a design tool (Phase I) and an automated production method (Phase II) that enables construction and production of affordable PEM and DMFC stacks tailored for a range of different applications and demands even in small scale production (>50 stacks). This project goal has been obtained by a substantial effort with the following areas:

- PEM FC stack CFD-modelling which has obtained a solid understanding of the dynamic response of the PEM FC stack under steady state- and transient loads. Because the dynamic behavior of a fuel cell is a highly complex phenomenon, as it involves different physical and time scales. Furthermore, the power of a PEM FC depends on operating conditions such as fuel purity, flow rates, relative humidity, temperature, and pressure of the feed gases. The mathematical modelling is therefore a powerful tool in this respect, and the only proper tool for understanding and handling this complexity. The result is a solid model that enables IRD to easily design a custom specified stack.

- Cost efficient production methods for small scale stack manufacturing. Automatized MEA and cell manufacturing and assembly has been obtained in the TailorPEM project. However, further adjustments are needed to enable these modules and mass production methods for further cost efficiency and small scale manufacturing. This will be addressed and demonstrated in Phase II.

- The project is concluded in validation of the stack model at small-prototype stack level. The productions methods has been evaluated from an industrial point of view. The partners have assessed the project and decided on completion of Phase II.

The present project has not only enabled IRD to adjust their stack portfolio to the niche marked that presently dominates, but also enabled IRD and Denmark to fulfill the near future demand for cheap mass produced FC stacks. The outcome of the project Phase 2 will bring IRD and Denmark in a advanced position worldwide and open new sales possibilities for custom made and affordable large and small scale production. With a potential of entering a huge international market with cost reductions on large scale

Overall completion of milestones

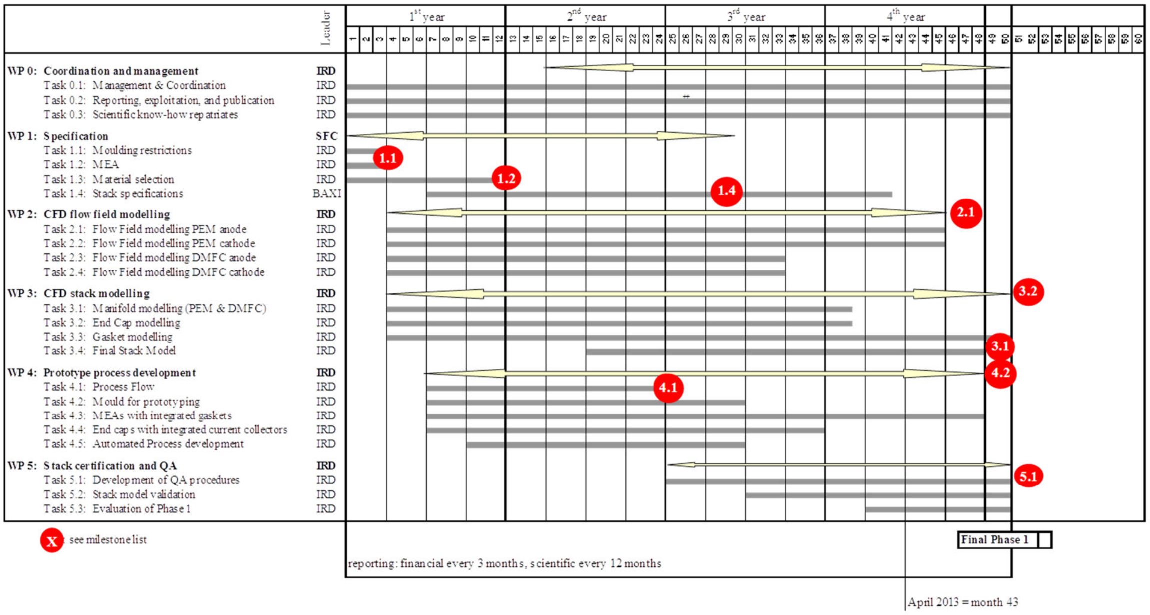


Table 1 List of Milestones

	Project month	WP	Description	Responsible partner	Nature of milestone
1.1	3	1	Report on Moulding restrictions and MEA fabrication methods	IRD	Report
1.2	12	1	Report on stack component materials	IRD	Report
1.4	29	1	Report on PEM FC & DMFC stack specification ranges	BAXI	Report
2.1	45	2	Flow field model completed and validated	IRD	Component
3.1	48	3	CFD model for manifold, end-cap & gasket model developed.	IRD	Component
3.2	50	3	Final stack model validated	IRD	Report
4.1	24	4	Automated process flow evaluation completed	IRD	Report
4.2	48	4	Process for fabrication of prototype stacks identified and verified. Feasibility of automated process evaluated	IRD	Component
5.1	50	5	Evaluation of the established stack model and manufacture methods.	IRD	Report

All 9 milestones have all been met, and as milestones the expectations are even somewhat exceeded. See the individual work packages for an elaboration.

2.5 VALUE PROPOSITION

The project value lies in being able to manufacture what customers are demanding. Because the biggest obstacle for the fuel cell market penetration in most applications is the manufacturing price the development of modular scaleable components has given access to a much larger market. Both for components such as MEAs and flow plates as well as fuel cell stacks. Based on the developed modular products system manufacturers are able to produce competitive systems with:

- Scalable power output in the range 0.5 kW to 10 kW (PEM FC) and 0.1 kW to 2 kW (DMFC) and
- Flexibility in durability/lifetime (1,000 hours – 40,000 hours)
- Flexible manufacturing processes: (10 units – 10,000 units)
- Low production costs,
- Easy assembly
- Limited use of critical raw materials

Given the technology level at the current market, this project has enabled IRD and partners to be among in the front of the fuel cell market. Given the market size and growth potential, this is a fine opportunity for the consortium and Danish industry.

3. WP1 : SPECIFICATION

The objectives of this WP is to identify, analyze and specify the materials- and processing technology. Both for cost efficient pilot production and for proper mass production of the key stack components. Furthermore, the end-users have in this WP identified the window of stack specifications of interest.

Description of work:

The starting point of this work was the state of the art at IRD, knowledge and equipment, e.g. the press for moulding-in-shape graphite composite plates and the IRD MEA spray coating process.

TASK 1.1: MOLDING RESTRICTIONS

All moulds are very expensive as they are made of polished hardened steel. This type of mould is aimed for true mass production and too expensive for small scale production series The goal of this task has therefore been to identify new cheap mould materials and identify design and process guidelines and tools for cost efficient small scale production series.

TASK 1.2: MEA:

IRD has in this task focused on further development of its “spray coating technique”. A technique which is very well suited for low cost production of both small and large series. The aim has also been to minimize the content of precious materials based on a multi-layer coating process.

TASK 1.3: MATERIAL SELECTION:

The modelling in WP2-WP3 is depended on a limited choice of materials and their mechanical properties e.g. gasket and end-cap material. The goal within this task was to select relevant materials for the various stack components, and compile the necessary properties. Shaping possibilities and cost of the components

TASK 1.3: STACK SPECIFICATIONS:

The concept of establishing a flexible stack pilot production process has been tested for several different applications (WP5-WP6). The objective of this Task is for the participating end-users to define the range of interest of stack specifications for the different applications. The stack specification for the final test (WP5-WP6) was within the specified range.

3.1 SPECIFICATION FOR PEM FC STACKS

GENERAL DEMANDS FOR A 1 KW TO 10KW STAK.

1. Target price < 2000€/kW at series of >4500 kW/år .

- Life time > 20 000 hours
- MEAs must be main cost >90%.
- Weight requirement: < 8 kg/kW.
- Surrounding temperature 0-50 deg.C
- Stack temperature 0 -100 deg.C
- Fuel pressure < 1 bar
- stack must have direct flow in and out of manifold.
- MEA must be well protected and robust

- Few components
- Easy integration in systems
- Possibility for centermanifolding for large stacks with no flow problems

1. Resistant to methanol

DEMANDS FOR SEALING

- Automatic sealing process
- Material price less than 1€
- Handling price less than 0.2€

DEMANDS FOR FLOW PLATES

- Price < 3€
- Flow plate design for flat sealing with solid or floating seal to minimize flow plate thickness and price. And give max conductivity.
- Sealing area to be minimized for max active MEA area
- “Fool proof” design for easy assembly

DEMANDS FOR END PLATES

- Low price
- Low weight

1. Must be an integrated design which includes fuel manifolding, current collection and mechanical structure for stack assembly

To fulfill the demands for a PEM FC range of 0.5-10kW and a DMFC range of 0.1-2 kW the MEA area is decided to be in the range 150 - 200 cm sq

3.2 STACK SPECIFICATIONS FROM IRD AND PARTNERS

Five potential PEM fuel cells market segments have been identified to fit the Taylor PEM strategy. Characteristics of the applications in the segments, some example markets, and potential advantages that PEM fuel cells may offer in these applications are described below:

- **Combined heat and power** - This application is already on its way to commercial products in Denmark, Germany and Japan. All countries where wind energy and therefore energy storage becomes more and more important. To obtain advantage of mass production and redundancy all countries have focused on small decentralized micro heat and power systems.
- **Backup Power -** PEM fuel cells can provide standby or emergency power to ensure uninterrupted service. PEM fuel cells could be used to provide electricity that meets standard backup requirements.

- **Grid Independent Power -** PEM fuel cells can provide continuous, stand-alone power to operations that are not connected to the grid.
- **Portable Power -** PEM fuel cells can provide continuous power to meet the complete energy needs of small electronic products. PEM fuel cells may provide a substitute for conventional batteries in products such as portable phones, cameras, computers, and security devices.
- **Auxiliary Power -** PEM fuel cells can provide an alternate source of power serving specific requirements in portable, mobile on-road transportation, and off-road transportation applications. For example, they can provide electrical power to trucks, locomotives, airplanes, boats, or military vehicles and equipment when the main power source is not operating, enabling cooling, lighting, or other auxiliary power needs to be met.

All segments fit well in Taylor PEM. This is due to the involved partners SENER, SCF and BAXI who operates in these segments. Portable Power is already a very competitive market with very large players.

IRD has through the TailorPEM project targeted all relevant application suppliers in their respective market segments. The expected decrease in production price of fuel cells due to the flexible design has also been addressed. Therefore the number of applications where fuel cells have a competitive advantage will increase.

SPECIFICATIONS

IRD Fuel Cells (DK)

has developed PEM CHP fuel cell systems and DMFC generator fuel cell systems, The specification for the PEM FC stack is:

Environmental Conditions	
Application	Stationary combined heat and power
Location	Indoor
Area classification	Non-hazardous
Atmospheric pressure	101 kPa
Ambient temperature	10 – 40°C
Ambient relative humidity	30 – 80%

Stack specifications	
Number of cells	47
Active electrode area	Active electrode area: 152 cm^2
Max. stack voltage	47 V_{dc}
Degradation per 1,000 h:	Pure H_2 fuelled: 3.0%
	Reformat fuelled: 3.6%
Size (ex. connections)	200*400*560 mm^3
Weight inc. humidifyer	16.6 kg

Output	
Nominal operation	62 A & 32 V_{dc} (BoL)
Nominal FC efficiency (LHV)	55%
Nominal power	2000 W_{dc}
Max. power	+2600 W_{dc}
Product water (nominal operation)	1.0 kg H_2O per hour
Supply	
Fuel	H_2 or Reformat (with <5 ppm CO)
Oxidant	Air (or pure O_2)
Cooling media	DI water (<5 µS/cm)

The specification for the DMFC stack is:

IRD specifications	
Application	stand-alone power backup
Location	Indoor
Area classification	Non-hazardous
Atmospheric pressure	101 kPa
Ambient temperature	4 – 60°C
Ambient relative humidity	30 – 80%

Stack specifications	
Number of cells	35
Active electrode area	Active electrode area: 180 cm^2
Max. stack voltage	30 V_{dc}

Output	
Nominal operation	13.4 V @ 45 A
Nominal FC efficiency (LHV)	31%
Nominal power	600 W_{dc}
Max. power	+800 W_{dc}
Product water (nominal operation)	1.0 kg H_2O per hour
Supply	
Fuel	1 M Methanol in H2O
Oxidant	Air
Cooling media	N/A

BAXI INNOTECH (DE)

has developed a prototype of combined heat and power (CHP)- system and want to get access to cheap reliable fuel cell stacks for that application.

The specification is:

Specifications	
Type	Baxi Innotech GAMMA 1.0
Fuel cell type	Low temperature PEMFC
Capacity	1 kW_e, 1.7 kW_{th}
Fuel	Natural gas
Electrical efficiency	32%
CHP efficiency	85%
Operating mode	>100 start-stop cycles p/a
System Dimensions	600mm x 600mm x 1600mm
Operating hours p/a	4000 - 6000 p/a

SFC ENERGY (DE)

has developed their EFOY Fuel Cell system based on DMFC with the following data:

Specifications	
Type	EFOY Pro
Fuel cell type	Low temperature DMFC
Caoacity	25W - 65W - 90W
Fuel	Methanol
Nominel consumption	0.9 l/kWh
Operating temperature	- 20 °C to +45 °C
Operating mode	640 Wh/Day - 1560 Wh/Day - 2160 Wh/day
System Dimensions	433 x 188 x 278 mm

Production rate is 10.000 units/year but further expansion is limited by high MEA and flow plate cost

SENER (ES)

has established a new project for Auxiliary Power Units for aeronautical applications based on the expected results from Taylor PEM.

The goal of this development is to design, build and test an Auxiliary Power Unit (APU) demonstrator based on the Taylor PEM fuel cells (PEMFC) specification, modelling and manufacturing processes targeting to a technology readiness level (TRL) 7.

To achieve this goal, the project is divided into two different phases:

1. Phase 1: Design, development and testing of a prototype with similar characteristics and performance to the final demonstrator with TRL 5/6.
2. Phase 2: Design, development and testing of the demonstrator prototype with TRL 7.

Phase 1 targets to a prototype demonstrated in a relevant environment, in which the main objective is to count with flight-like elements (stack included). Phase 2 targets to a prototype demonstrated in an operational environment; only qualification through test and demonstration would prevent the unit to be on board the aircraft (TRL 8).

This development is an excellent opportunity within the fuel cell and aeronautical sector since, on one side, it will count with the momentum boosted by CASSIDIAN, a large defense and security European company and, on the other side, it will make use of the particular interest of one of the world largest aircraft integrators, AIRBUS .

AIRBUS has in parallel expressed quite lively the interest to have one of the proposed FC based devices on board their aircrafts.

In this context, SENER, from the system architect standpoint, understands that IRD's contribution is of paramount importance for the successful development of the project and, in consequence, has invited IRD to join the common development of the Aeronautical APU based on IRDs Taylor PEM Fuel Cell project.

SPECIFICATION

The following matrix summarizes the main requirements for the product (APPA):

Requirement	Phase 1	Phase 2
Power	14 kW (1)	14 kW (1)
Mass	Minimum (2)	TBD (3)
Volume	Minimum (2)	TBD (3)
TRL	5/6 (4)	7 (4)

The following considerations should be taken into account when reading the above table:

(1) AIRBUS requirement points to 14 kW. Since they will be a final user, APPA power should target those 14 kws in Phase 2. For Phase 1, power requirement will be led by the state-of-the-art hardware having a module size of 3.5 kW.
(2) Mass and volume requirement for Phase 2 will be obtain during Phase 1. In particular, design and manufacturing optimization (material, shape, etc.) should be taken into account when producing a stack to be on board an aircraft. APPA mass should be less than 100 kg — including all subsystems.

Summary of specifications for the different applications:

Segment	Requirements	Application	Partner
Backup Power	High reliability (99.99%) Frequent start/stops Lifetime: 1,000 hours	UPS	APC
Auxiliary Power	Scalable power range Mobile application/Easy fuel handling (Methanol) Frequent start/stops Lifetime: 5,000 hours	APU	SFC
Grid Independent Power	Low manufacturing cost 1.5 kW Lifetime: 40,000 hours	µCHP	BAXI
Auxiliary Power for aeronautical	Low weight and volume 3.5 kW modules Lifetime: 40,000 hours	APU	SENER

4. WP2: CFD FLOW FIELD MODELING

4.1 INTRODUCTION

The main target within this WP was to establish a flexible CDF model for flow field designs. The model includes the active MEA areas as defined in Task 1.3.
The starting point of this work was the modelling of a PEM FC stack under operational conditions by applying the COMSOL Multiphysics program:

Task 2.1: Flow Field modelling PEM anode (IRD): The model has to include flow fields aimed for dry pure hydrogen dead-end operation, where higher discharge pressure is accepted as well as open-end reformate operation where pressure drop as well as water management is key issues to success.
Task 2.2: Flow Field modelling PEM cathode (IRD): The main challenge at the PEM FC cathode is to establish a proper model that take water management under different operation conditions into account without sacrificing the aimed low discharge pressure. Furthermore, the model shall be capable of handling both liquid cooled and air cooled stack designs.
Task 2.3: Flow Field modelling DMFC anode (IRD): The challenge in the DMFC anode flow field modelling is related to the two-phase flow.
Task 2.4: Flow Field modelling DMFC cathode (IRD): The DMFC cathode challenge has many resembles with the PEM FC cathode (Task 2.2). The major difference is that the model has to take the methanol cross-over into account.

The model developed are using the COMSOL Multiphysics program making it possible to incorporate the required physics of the fuel cell (Navier-Stokes equations, Butler-Volmer equations etc.) together with IRDs fuel cell MEA parameters and cell and stack specifications. Based on this it is possible to calculate the performance of the fuel cell under different operations. The model is basically a 3D, one-phase model, but the two-phase behavior of the methanol fuel flow have also been incorporated to the extent possible within the COMSOL Multiphysics program.
The model takes into account the following sub-components; the active layers at the anode and at the cathode, the gas diffusion layers, the gas channels, and the membrane as shown in Figure 1.

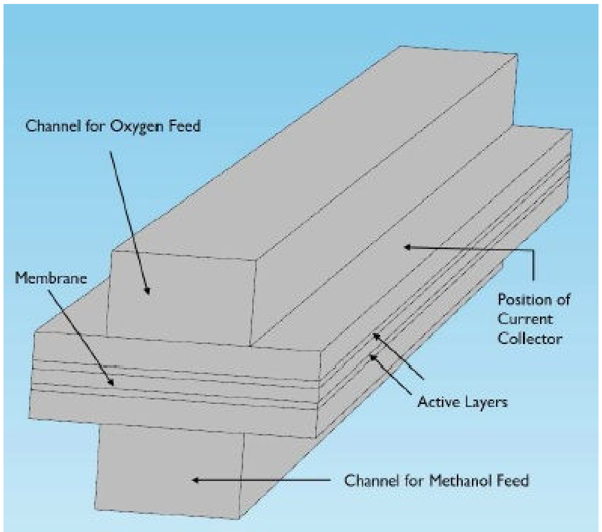
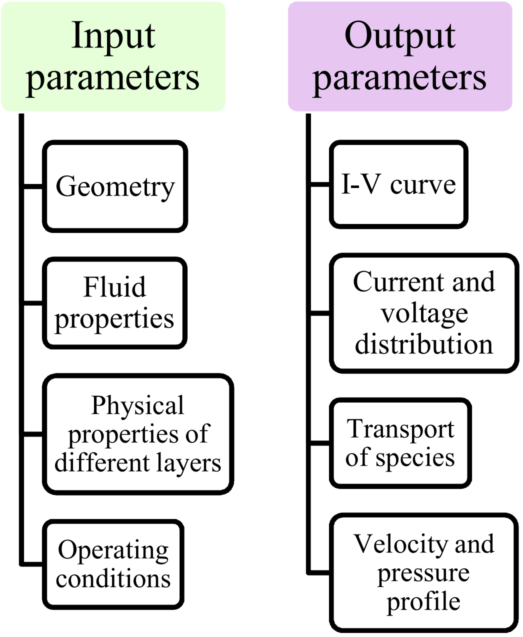


Figure 1. The sub-components included in the model.

The input and output parameters of this model are as follows:



By inserting the input parameters, one can get the relevant polarization curve of the channel which is a key characteristic for validation of the model. This model allows the user to vary either the geometric dimensioning, sub-domain material or operating conditions to adjust this model in regards to any flow field channel.

In the present study the IRD DMFC parameter values are used and the model has been validated against the experimental data which is elaborated in the following sections.

The model has been validated against the experimental data. by simulated polarization curves compared with experimental data for the different fuel cells.

The results given below describe the modelling of the DMFC fuel cell using typical operational conditions.

4.2 SIMULATIONS

POLARIZATION CURVE

The simulated polarization curve for a single DMFC cell was obtained by applying the fuel cell model and the flow field design in the COMSOL interface. Anodic and cathodic exchange current densities and the symmetry factor were the parameters adjusted to fit the experimental data. The figure below shows a good agreement between the experimental data and the simulated results.

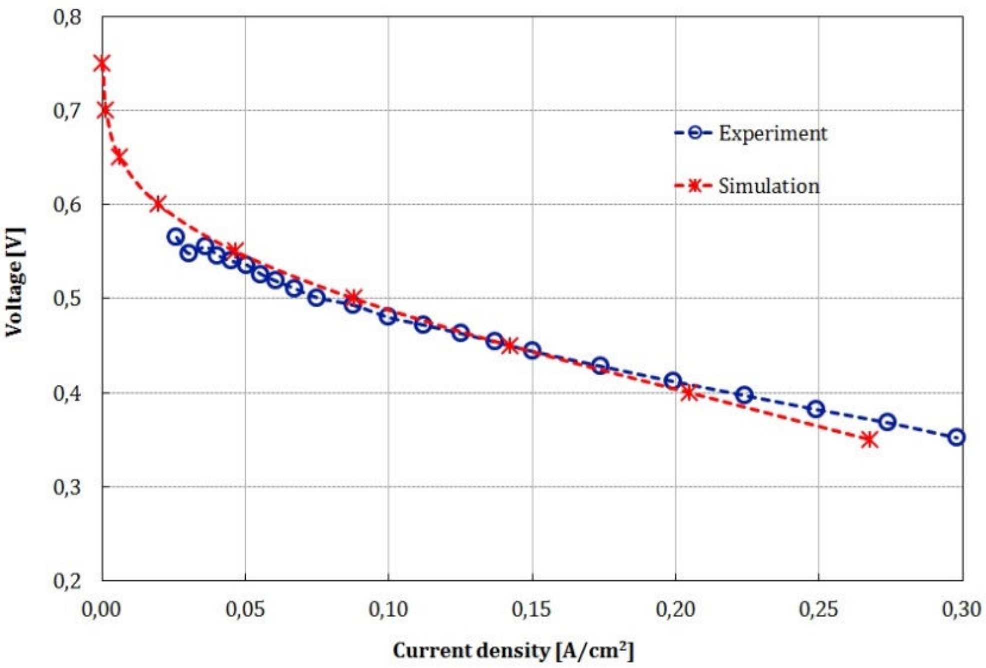


Figure 2.. A comparison between experimental and simulated polarization in the cell.

ANODE AND CATHODE CONCENTRATION FIELD

The figure 3 below shows the concentration field of methanol in the cell as calculated from the model. It can be seen from this figure that the largest contribution to the mass transport limitations is found in the porous anode, at typical operating conditions for DMFC cells with a cell voltage of 0.40 V and an average current density of 0.17 A/cm^2.

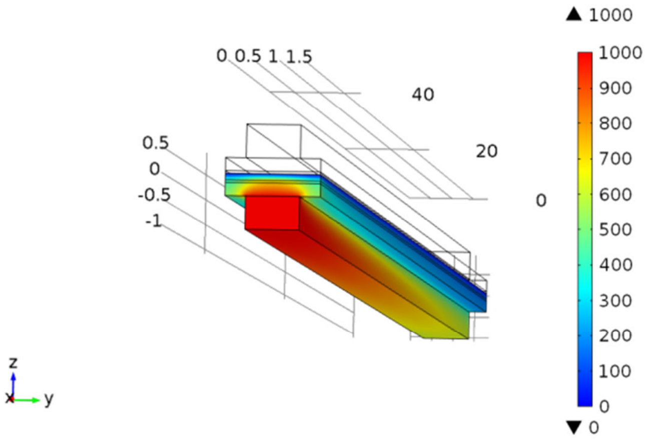


Figure 3. Concentration of methanol in the cell at a cell voltage of 0.40 V and a current density of 0.17 A/cm^2. Q_MeOH=0.008 lit/min and Q_air=1.35 lit/min are the total flow rates of the cell at the anode and the cathode side.

The concentration field of produced CO_2 is shown in Figure 4. It can be seen that at the beginning of the channel CO_2 concentration is zero and it eventually increases along the channel.

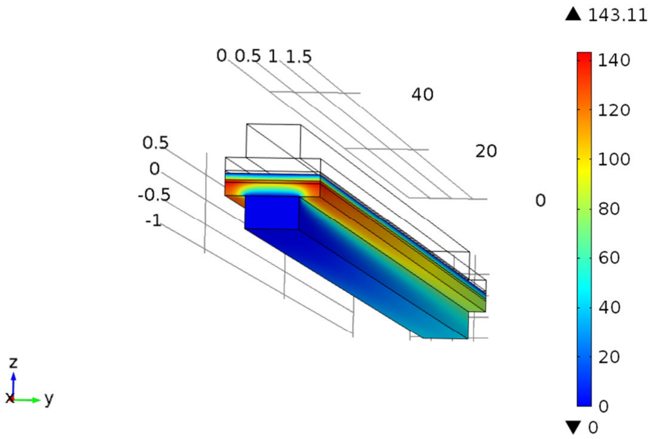


Figure 4. Concentration of CO2 in the cell at a cell voltage of 0.40 V and a current density of 0.17 A/cm^2. Q_MeOH=0.008 lit/min and Q_air=1.35 lit/min are the total flow rates of the cell at the anode and the cathode side.

The corresponding concentration profile for oxygen at the cathode side is shown below. In Figure 5. The variations in concentration are substantially smaller compared to the methanol side at the given operating conditions. These variations in a cross sections perpendicular to the direction of the flow are also smaller than those along the direction of the flow. This indicates that the mass transport limitations at the cathode side give a smaller contribution to the overpotential compared to the anode side at the operating conditions.

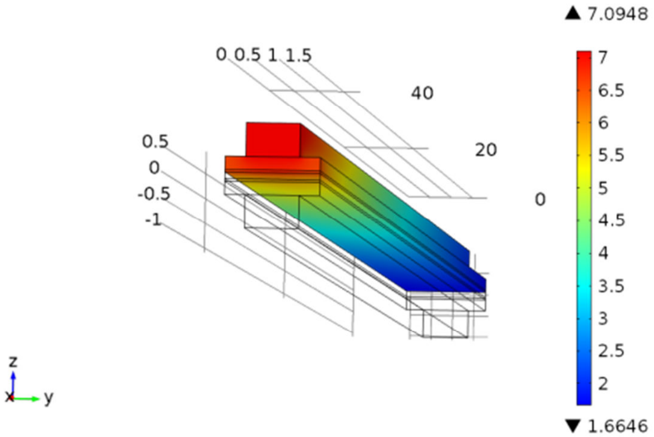


Figure 5. Concentration of oxygen in the cell at a cell voltage of 0.40 V and a current density of 0.17 A/cm^2. Q_MeOH=0.008 lit/min and Q_air=1.35 lit/min are the total flow rates of the cell at the anode and the cathode side.

CURRENT DENSITY DISTRIBUTION

The distribution of methanol and oxygen has a direct impact on the current distribution in the cell. The figure 6 below shows the z-component of the current density in the electrolyte perpendicular at 0.40 V and 0.17 A/cm^2, which represents the current density that is conducted from the anode to the cathode. The variations are clearly related to the variations of the methanol concentration in the cell.

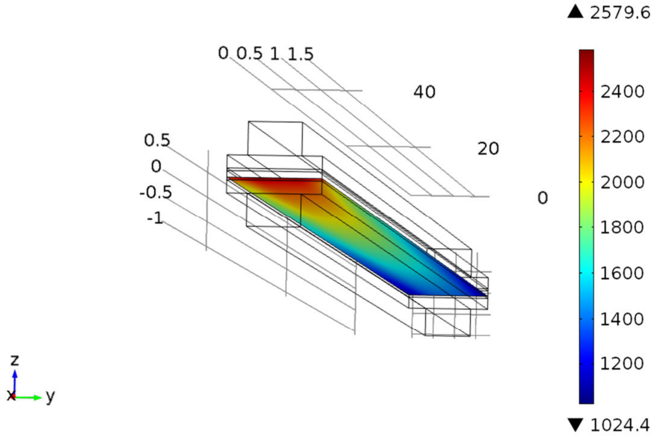


Figure 6. Current density distribution between the anode and cathode at a cell voltage of 0.40 V and an average current density of 0.17 A/cm2. Q_MeOH=0.008 lit/min and Q_air=1.35 lit/min are the total flow rates of the cell at the anode and the cathode side.

4.3 THE INFLUENCE OF THE CHANNEL GEOMETRY

By keeping fixed the cell dimension, i.e. the sum of channels and ribs width, the effect of open ratio as well as number of channels in a cell has been investigated on the cell performance. It should be noted that the operating conditions in all the case studies are the same. Open ratio of a channel is defined as

$$\mathbf{OR} = \frac{\mathbf{W_{ch}}}{\mathbf{W_{ch}} + \mathbf{W_{rib}}}$$

Figure 7 shows that the cell performance increases with the open ratio, ranging from 0.3 to 0.8, particularly at high current densities. The improved cell performance as the result of increasing the open ratio can be primarily attributed to the enhanced mass transfer rates of both methanol and oxygen.

The reasons leading to the increased mass transfer rates are as follows. Firstly, the specific area of mass transfer increases with the open ratio, yielding higher mass transfer rates of both methanol and oxygen. Secondly, the rib width decreases with the open ratio, providing a shorter distance of mass transfer from the channel region to the rib region in the GDL and thereby resulting in the higher methanol and oxygen concentration under the ribs. Thirdly, the gas CO_2 on the anode and liquid water on the cathode are more easily to be removed from the rib region to the outside as the open ratio increases. Subsequently, more active sites can be used for the electrochemical reaction in the catalyst layer, leading to the improved cell performance. It is found that for the current case study OR = 0.7 - 0.8 is the optimum value and the cell performance slightly decreases by further increasing the *OR* from 0.8 to 0.9.

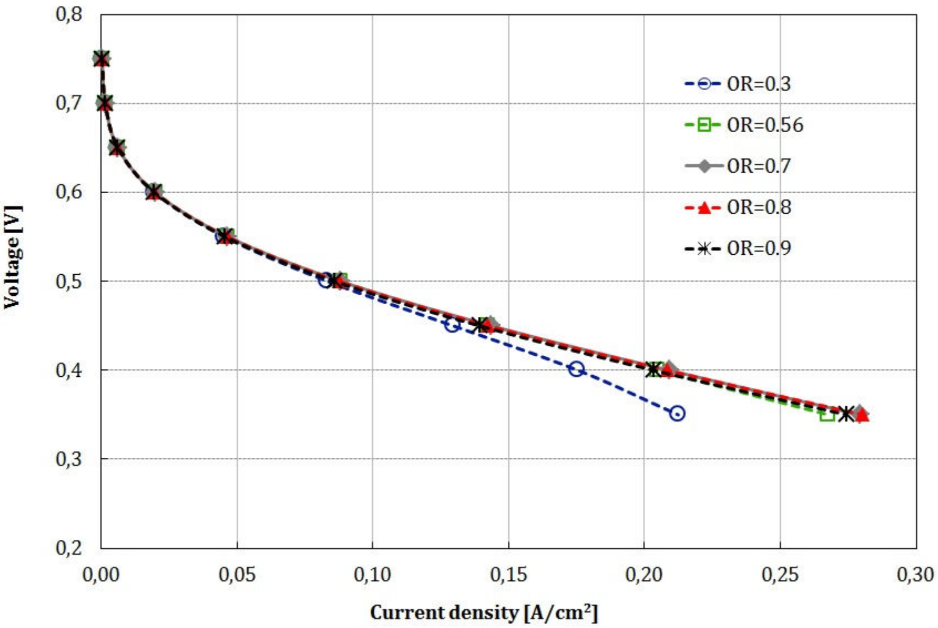


Figure 7. The polarization curve versus open ratio of the channel, Q_MeOH=0.031 lit/min and Q_air=2.7 lit/min are the total flow rates of the cell at the anode and the cathode side. N_ch=25 for all the case studies presented in this graph.

The simulation has been carried out for four different channel heights, $H_{ch} = 0.35, 0.5, 0.65\ and\ 1\ mm$. The polarization curves corresponding to these channel heights are displayed in Figure 8. The figure shows clearly that for a given methanol solution flow rate, a decrease in the anode flow channel height from 1 to 0.35 led to an improvement in the cell performance, however in the increased *OR* this effect is almost negligible. A reduction in the channel cross sectional area also leads to a higher liquid velocity. The increased liquid velocity enhances the mass transfer of methanol from the flow channel to the gas diffusion layer and hence, improves cell performance

Figure 9 shows that how the number of channels influences the cell performance. In a given cell with fixed dimensions, increased number of channels increases the fluid velocity, in consequences, an improvement in the cell performance. However this effect is more noticeable in a smaller *OR* rather than a larger one.

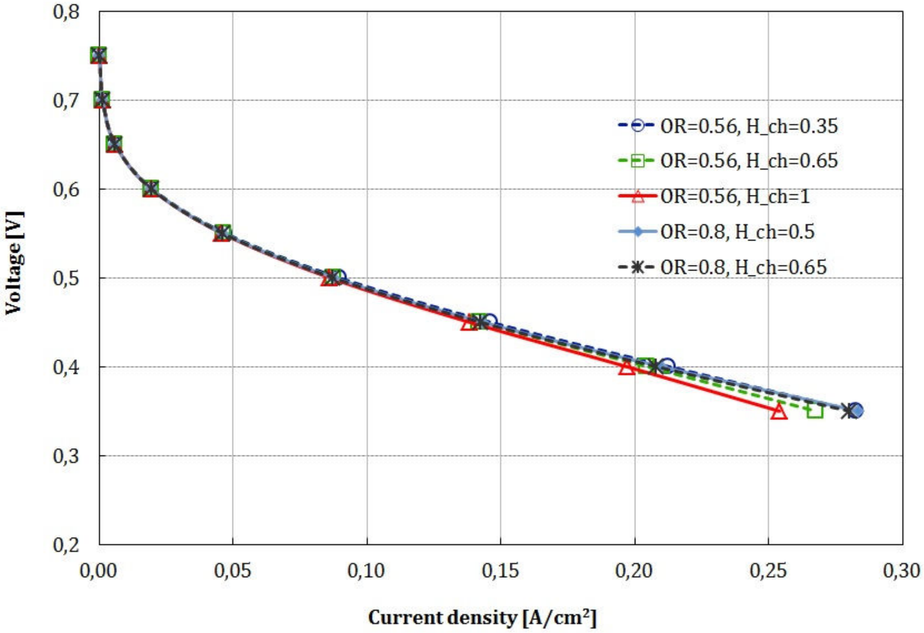


Figure 8. The effect of channel height on the cell performance, Q_MeOH=0.031 lit/min and Q_air=2.7 lit/min are the total flow rates of the cell at the anode and the cathode side. N_ch=25 for all the case studies presented in this graph.

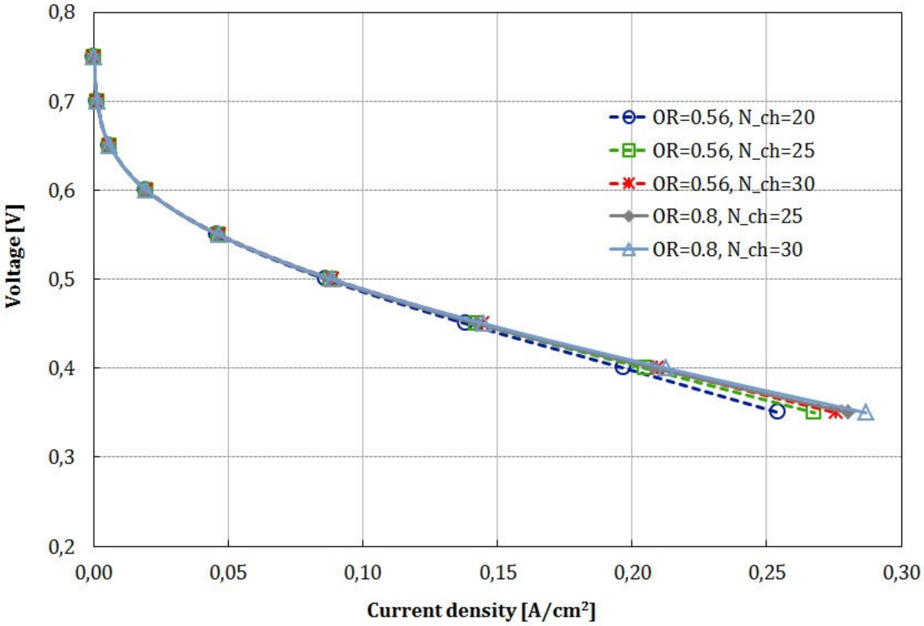


Figure 9. The effect of the number of channels on the cell performance. Q_MeOH=0.031 lit/min and Q_air=2.7 lit/min are the total flow rates of the cell at the anode and the cathode side. H_ch=0.65 for all the cases.

4.4 THE INFLUENCE OF THE OPERATING CONDITIONS

In Figure 10 the polarization curves at 1M methanol concentration are presented. In the low current density regime (<0.05 A/cm^2) the cell potential is virtually invariant with methanol flow rate. This suggests DMFC performance is relatively insensitive to mass transfer effects in this regime. In contrast, mass transfer losses in the anode reduces cell potential at higher current densities (>0.05

A/cm^2). The DMFC limiting current density generally increases with increasing inlet flow rate, as expected.

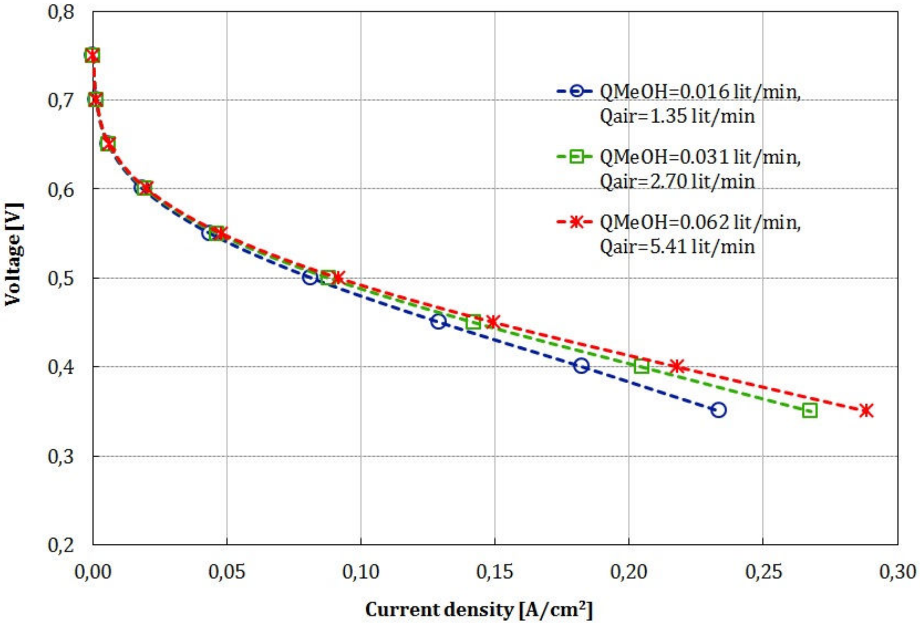


Figure 10. Polarization curves for 1 M methanol supplied at 0.016, 0.031 and 0.062 lit/min. The corresponding air flow rates are 1.35, 2.70 and 5.41 lit/min respectively.

Figure shows the effects of methanol feed concentration on the polarization curves under the following operating conditions, methanol solution flow rate of 0.031 lit/min and air flow rate of 2.70 lit/min. It can be seen that the methanol concentrations affect the cell polarization curve significantly.

At low current density, e.g., less than 0.1 A/cm^2, high methanol concentration, 1.5 M, causes a lower cell voltage and open circuit potential. This is because of the methanol crossover. In this case, methanol molecules cannot be completely consumed to produce current.

At high current density, e.g., more than 0.2 A/cm^2, high methanol concentration has better performance. This is because the methanol concentration dominates the cell performance in this region.

For the low methanol concentration, for instance 0.5 M, the polarization curve is mainly dominated by concentration (concentration polarization). The ohmic polarization curve is very short. As the current density increases, the cell potential drops very fast. Actually, when the current density increases, more methanol molecules are consumed by the electro-chemical reaction. However, since the methanol concentration is very low; there is not enough methanol molecules that can reach the catalyst layer in time. The mass transfer speed dominates the electron-chemical reaction, further affects the polarization curve. When the methanol concentration increases, the cell performance improves and the ohmic polarization region becomes longer.

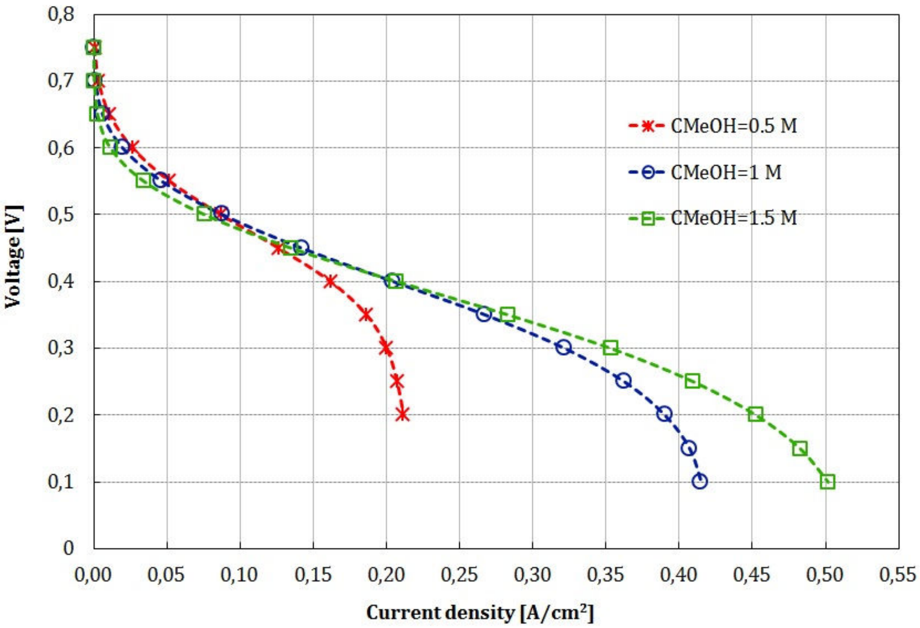


Figure 11. The effect of methanol concentration on cell performance.

4.5 INFLUENCE OF TWO-PHASE FLOW

Gas management is important in a DMFC design since the methanol electrochemical oxidation produces carbon dioxide flux on the anode side. Firstly, carbon dioxide dissolves in water and when it reaches its solubility limit, carbon dioxide gas emerges.

The main objective of gas management is to determine a DMFC design and operating conditions so as to provide uniform distribution of liquid without gas accumulation in the channels.
Channel structures are blocked by bubbles at low mass flows. An increase in inlet flow rate is beneficial to gas removal, but also led to an increased methanol cross over. Gas content and channel blocking can be reduced significantly at higher liquid flow rates. The flow geometry of the anode side has an important impact on gas evolution. Optimum flow field design is important for improving flow patterns and gas evolution in anode channels. Carbon dioxide is mostly transported out to the anode channel through the catalyst layer and the diffusion layer.

MODELING

The following model only considers laminar bubbly flow in the anode flow channel. Liquid water enters to the channel with average velocity of 0.001 m/s and CO_2 bubbles enters from channel-GDL interface, however for the sake of simplification GDL layer has not been modeled here.

Both CO_2 bubbles and liquid water leave the channel at the outlet. A time dependent simulation was carried out for investigating the liquid – gas behaviors in the channel.

ASSUMPTIONS

The bubbly flow model in COMSOL is valid for low gas volume fraction (around 10%), however at DMFC channel the gas volume fraction can be much higher than this value. But to have valid results regarding two phase flow model, CO_2 gas flux has been kept lower than its real value.

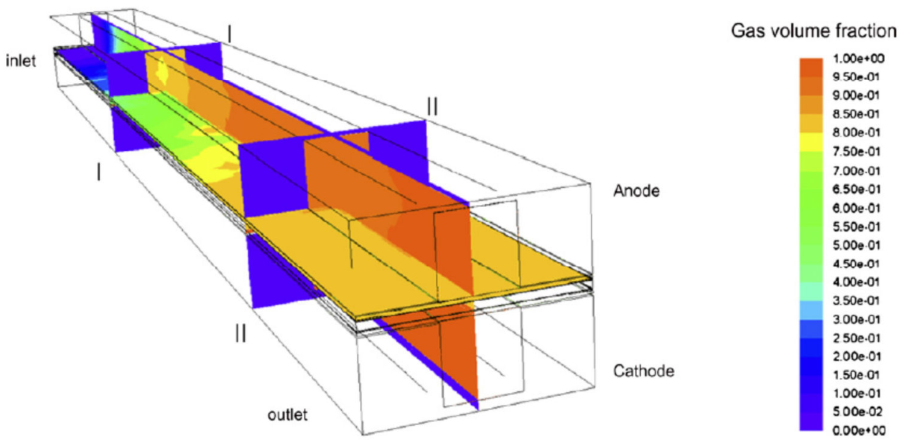


Figure 12. Average current density =

RELATION BETWEEN GAS MASS FRACTION AND VOLUME FRACTION

By assuming having and in the channel, gas mass fraction would be

$$n_m = \frac{m_{CO2}}{m_{CO2}+m_{H_2O}} \qquad (1)$$

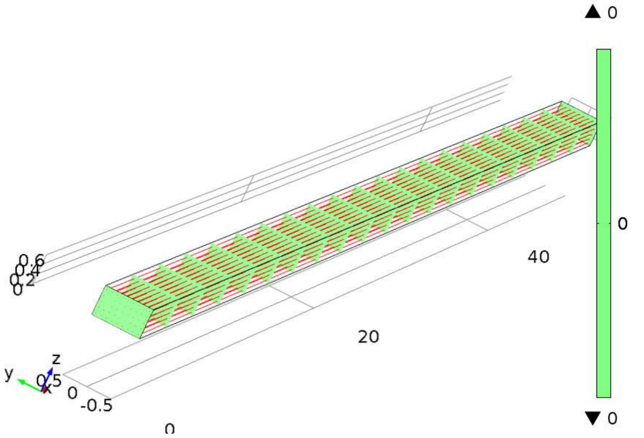
and gas volume fraction is equal to:

$$n_v = \frac{1}{1+\frac{\rho_{CO_2}}{\rho_{H_2O}}\cdot\frac{1-n_m}{n_m}} \qquad (1)$$

By having a gas mass fraction of only e.g. 0.4%, the gas volume fraction would be around 67%.

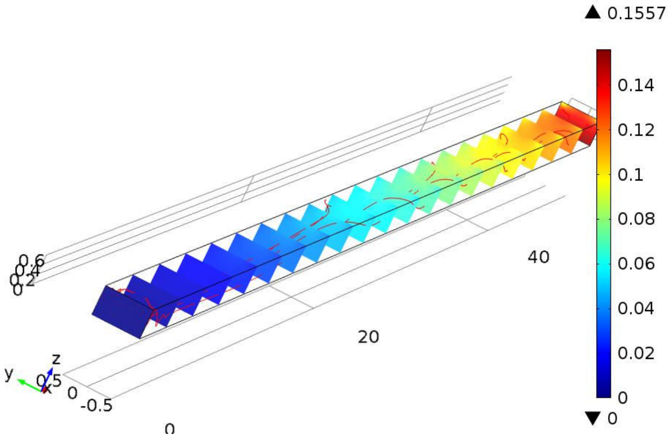
SIMULATION RESULTS:

Figure 13 shows snapshots of the gas concentration at different time steps. At the t=0 there is no gas bubble in the channel and gas volume fraction increases by time until it reaches to the steady state condition at t=5 s. The surface represents the gas volume fraction and the red lines indicating liquid streamlines.

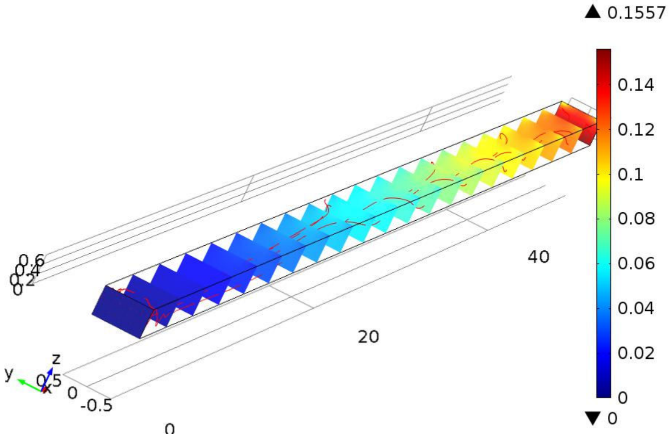


(a) t=0

(b) t=1s



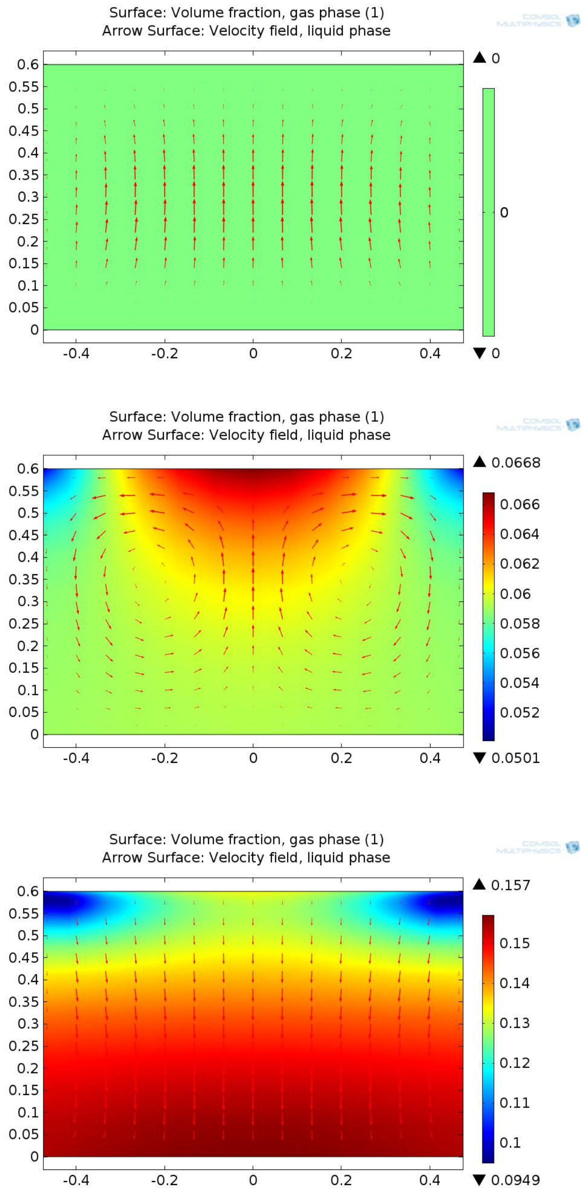
(c) t=2s



(d) t=10s

Figure 13. Gas volume fraction at different time steps.

Figure **2**14 shows snapshots of the gas concentration and streamlines of the liquid velocity. The surface shows the gas concentration and the streamlines are liquid velocity.



(a

(b)

(c)

Figure 24. Results of a time dependent simulation; at t=5 s, x=0 (a), x=25 (b), x=50 (c).

The velocity increases along the flow direction due to volume expansion of the two-phase mixture. The nearly uniform current density distribution leads to a linear increase of liquid phase velocity. At the channel outlet, the velocity reaches almost 25 times the inlet velocity,

5. WP3. CFD STACK MODELING

INTRODUCTION

The main target within this WP was to establish a flexible CDF model for the complete stack design based on specific input e.g. the flow-field modelling (WP2), stack voltage, power, and fuel (WP1).

Task 3.1: Manifold modelling (PEM & DMFC) (IRD):
CFD simulations has been done in order to evaluate different design options for a customized fuel cell stack manifolding system that combines the inlet and outlet sections of the end-caps for flexible designs easing the fuel cell integration with the end-user application.
Task 3.2: End Cap modelling (IRD):
A substantial part of this Task includes FEM analysis to ensure sufficient strength of the end-cap with a given material and an optimised design. The end-cap strength is important as insufficient strength will lead to end-cap deflection and ultimately to fuel leakages. The end-cap-modelling is also important to obtain an optimal design for further integration in a given application.
Task 3.3: Gasket modelling (IRD):
The main objective of the task is to develop a technique that can evaluate and improve the manufacturing and robustness of the sealing aimed for automated assembly. The modelling includes a non-linear, finite element analysis model with various hyperelastic material models, deformation and contact to evaluate the load-gap curves. Gasket and gasket groove configurations that enable optimum robust designs that is insensitive to variations in parameters such as manufacturing tolerances, material properties, process capabilities, tooling wear etc.
Task 3.4: Final Stack Model (IRD):
The final bipolar plate design will be made within this WP unifying the results of WP2 and Task 3.1 & 3.3. The complete stack model will finally be compiled within this Task.

The final stack model comprises flow plate model, manifold model and stack model only including simple non-flexible end cap model and simple non-compressible flat gasket model as aimed for automated assembly in WP4. Results from the the stack model of the modular and flexible flow plate, seal, endplate and stack designs are given below and demonstrated in WP4

RESULTS

The flow field in fuel cells is designed to minimize pressure drop while providing even mass distribution through the diffusion layer to the electrodes. The most common flow field designs are serpentine, parallel and inter-digitated. This section is concerned with the flow distribution in a parallel channel bipolar plate as well as a serpentine channel for a direct methanol fuel cell.

5.1 FLOW DISTRIBUTION IN A PARALLEL CHANNEL BIPOLAR PLATE

A 2D numerical simulation of the flow distribution based on the Navier-Stokes equations is performed.
The bipolar plate consists of 17 parallel channels. Inlet and outlet manifolds distribute the liquid to the channels. Channels and manifolds have a square cross-section of side length 1 mm. A typical current density of 250 $mAcm^{-2}$ is used for the given active MEA area. Using a 1 M methanol solution and operating the cell at $\lambda_{CH_3OH} = 6$ corresponds to a flow rate of 1.7 $mLmin^{-1}$As another example, a flow rate of $Q = 5\ mLmin^{-1}$ corresponds to a fuel stoichiometry of $\lambda_{CH_3OH} = 17.9$.
Numerical results corresponding to constant width and wedge shaped manifolds, respectively, are presented.

CONSTANT WIDTH MANIFOLDS

The results of the simulation are shown in Figure 15 - 20. Under the assumption that the current density is the same everywhere in the cell, i.e. 250 mAcm^{-2}, the fuel stoichiometry is plotted in Figure - 18. In the present case the lowest fuel stoichiometry is found in channel number 8. The largest fuel stoichiometry is found in channel number 1.

An enlargement of the entrance region of the three channels nearest to the fluid inlet is shown in Figure 20. This figures reveals the presence of recirculation zones (or vortex structures) at the entrance of the channels.

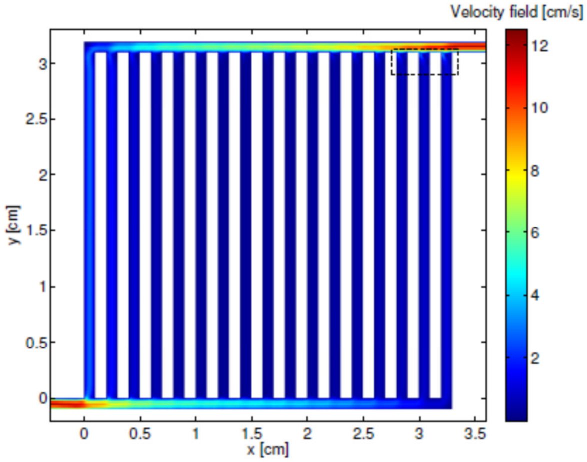


Figure 15. Velocity field. inlet manifold is at the top and outlet manifold is at the bottom.

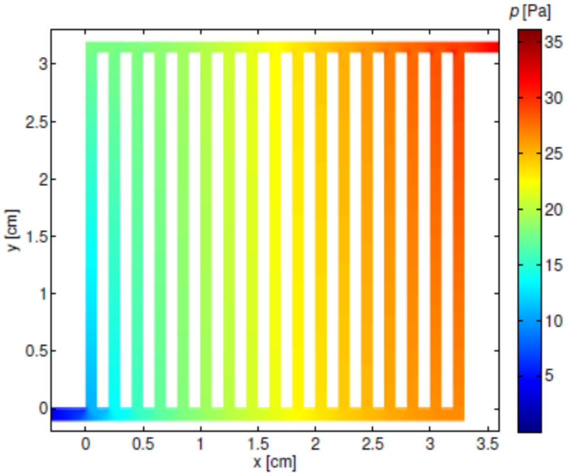


Figure16. Pressure field.

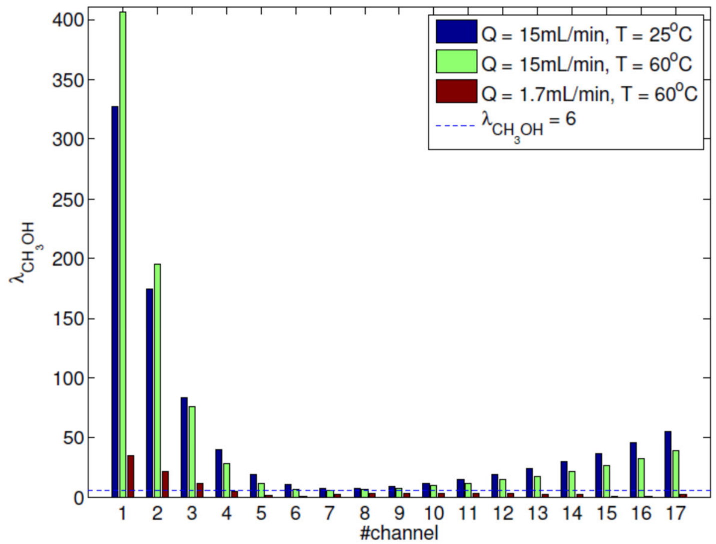


Figure 17. Stoichiometric distribution in a parallel channel flow field with constant width manifolds. The influence of the CO2 gas bubbles produced is taken into account. A flow rate of 1.7mLmin-1 corresponds to an overall stoichiometry of 6. A flow rate of $15mLmin^{-1}$ corresponds to an overall stoichiometry of 53. In the case of a flow rate of $15mLmin^{-1}$ a first approximation of the pressure drop across the flow field yields 2mbar.

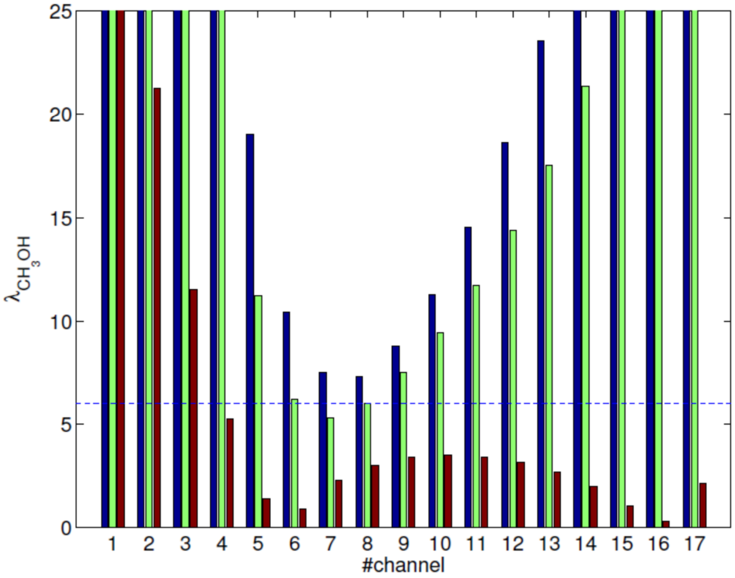


Figure 19. Zoom of figure 19.

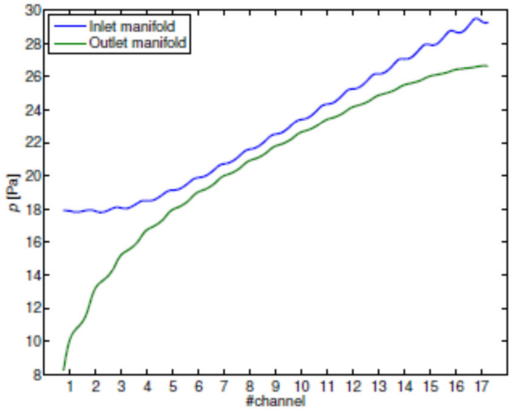


Figure 19. Pressure distribution in inlet and outlet manifolds.

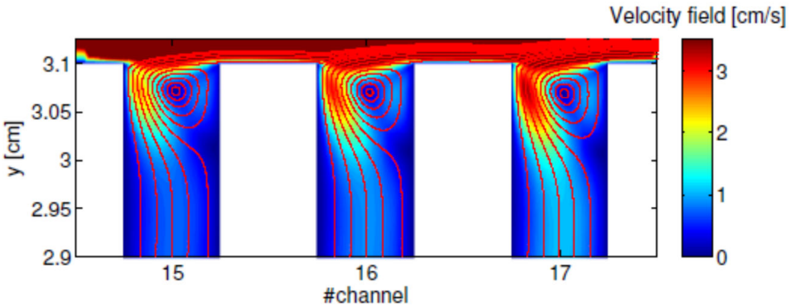


Figure 20. Velocity field and streamlines at the entrance region of the three channels nearest to the fluid inlet

WEDGE SHAPED MANIFOLDS

See Figure 21 - 25. No recirculation zones are present in the flow.

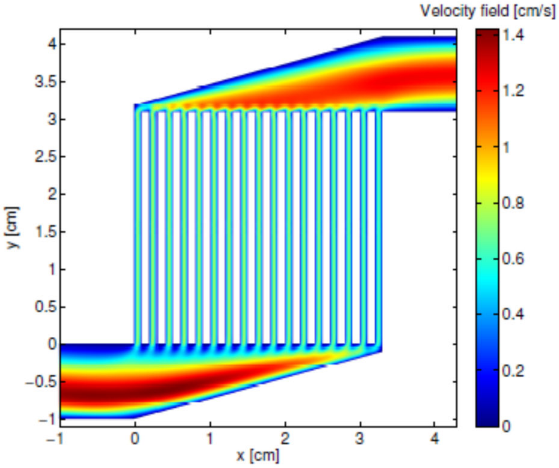


Figure 21 Velocity field.

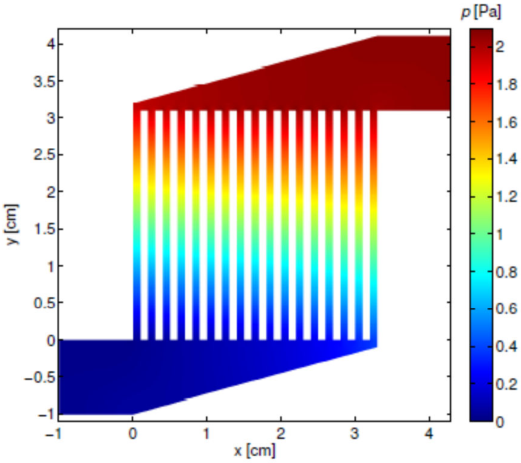


Figure 22. Pressure field.

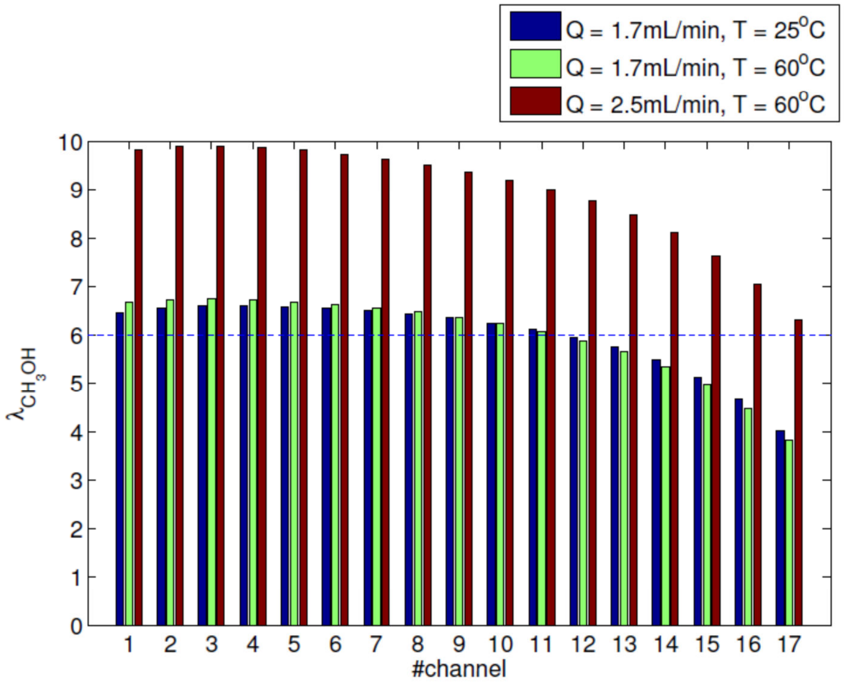


Figure 23. Stoichiometric distribution in a parallel channel flow field with wedge shaped manifolds. The influence of the CO_2 gas bubbles produced is taken into account. A flow rate of 1.7mLmin^{-1} corresponds to an overall stoichiometry of 6. A flow rate of 2.5mLmin^{-1} corresponds to an overall stoichiometry of 9. In the case of a flow rate of 2.5mLmin^{-1}, a first approximation of the pressure drop across the flow field yields 0.02mbar.

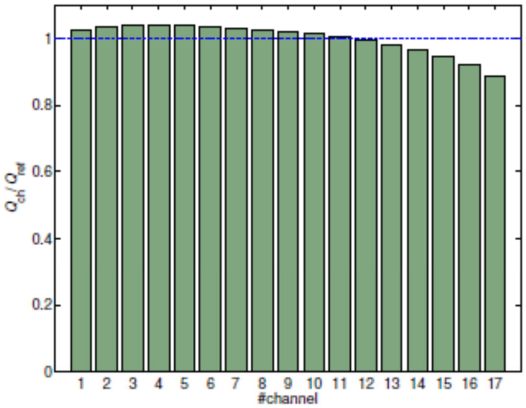


Figure 24. Flow distribution.

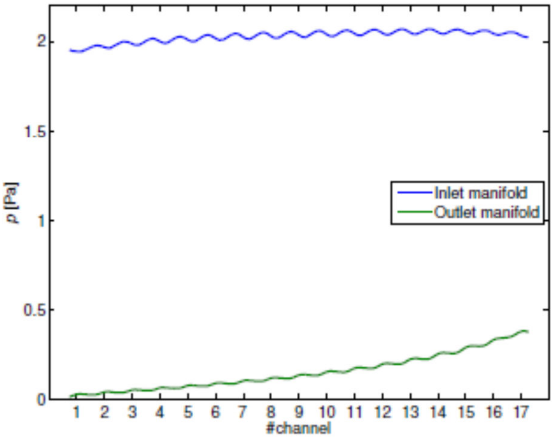


Figure 25. Pressure distribution in inlet and outlet manifolds.

5.2 SINGLE SERPENTINE CHANNEL

Changing the above parallel channel flow field into a single serpentine channel flow field, results in a single $1\times 1\text{mm}^2$ channel with a total length of 578 mm. In the case of a flow rate of 1.7 mL min^{-1} a first approximation of the pressure drop across this channel yields 5 mbar. A single serpentine channel flow field has some advantages over a parallel channel flow field:

- No risk of flow misdistribution.
- Reduced risk of channel blockage by gas bubbles or water droplets.
- Easier to obtain even flow distribution among the cells in a stack
- The cell can be supplied with a flow rate no higher than the flow rate corresponding to an overall stoichiometry of 6 (1.7 mL min^{-1}).

In conclusion the parallel channel bipolar plate with constant width manifolds gives rise to flow misdistribution among the channels. The introduction of wedge shaped manifolds results in a significantly more even flow distribution.

The parallel channel flow field with wedge shaped manifolds results in a relatively even stoichiometric distribution among the channels combined with a very low pressure drop across the flow field. Such type of flow field may be desired if low pressure drop is desired in a given application. However, the single serpentine flow field, with its advantages, may be preferred if the increased pressure drop is acceptable in a given application.

5.3 COMPARISON OF TWO FLOW FIELD DESIGNS FOR A DMFC STACK

This part is concerned with a comparison of two slightly different flow fields for a DMFC stack. Both are parallel serpentine flow fields. The first flow field, the standard design, has 30 parallel channels at the entrance and the exit. However, along the path from entrance to exit 5 of the channels split into 10 channels, and 10 other of the channels merge into 5 channels, see Figure 26.

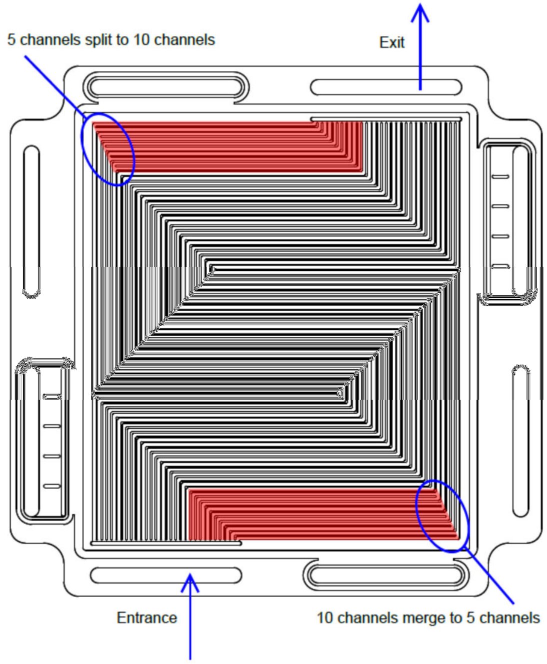


Figure 26. Fflow field for DMFC stack.

The second flow field under consideration, the new design, is covering the same area with 28 parallel channels. None of these 28 channels neither split nor merge. The cross section of the single channels in the new flow field design is almost identical to the cross section of the channels in the first design. Anode and cathode flow fields are identical in both designs.

Consider the channel segments under the areas colored in red in Figure 26. The result of the stack modelling shows that the volumetric flow rate in these channel segments is about 50% of the volumetric flow rate in the channels in the remaining part of the flow field. Thus, the volumetric flow rate in the areas colored in red may be too low in order to sustain a proper performance of the fuel cell in those areas. In particular, this may be the case at small current loads or low stoichiometric ratios. In the case of the new design, the volumetric flow rate is the same everywhere in the flow field. The main purpose of the modelling and experimental investigation described below is to investigate the difference in performance of the flow field stack design under various operating conditions.

EXPERIMENTAL SET-UP

Two stacks with 10 cells in each were constructed. One stack is equipped with bipolar plates with the standard flow field design. These plates are manufactured by compression moulding. The other stack is equipped with bipolar plates with the new flow field design. These are prototype machine milled plates. For practical reasons, the start and end plates in this stack have the standard flow field design. The two stacks are connected in series electrically. Fuel and air supplies to the two stacks are connected in parallel see Figure 27.

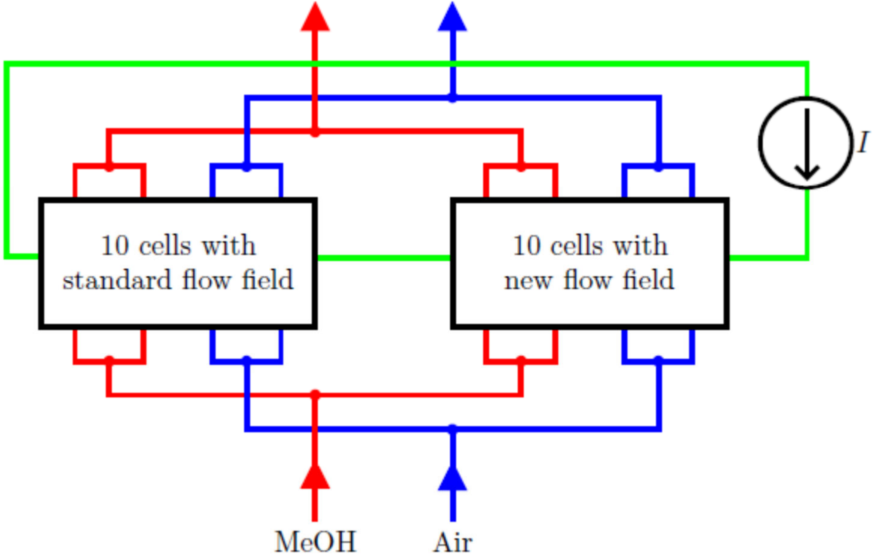


Figure 27. Schematic diagram of the experimental set-up.

This specific set-up is chosen in order to ensure that the two stacks are operated under identical operating conditions at all times. There is one major risk in connecting fuel and air supplies in parallel. If the two stacks have different hydraulic resistances, flow misdistribution among them will occur. However from the modelling, it is expected that the hydraulic resistances are very similar. This is verified during the experiments, since no signs of flow misdistribution are observed..

SPATIAL DISTRIBUTION OF CELL VOLTAGE

The cell voltage of each cell is measured at the bipolar plates in a number of positions along the edge of the cell, see Figure 28. Voltages are measured using a digital voltmeter. At zero current load the voltages measured along the edge of each cell are nearly constant. However, a significant variation in voltages is observed when the stacks are operated at I = 0.3 Acm^{-2}, see Figure . For comparison the corresponding voltages registered by the cell voltage measuring system (CVMS) are shown in Figure 29.

The stack modelling shows that the observed that this variation in cell voltages originates from the decrease in methanol concentration and oxygen concentration as the the fuel and air are consumed during the flow through the cells.

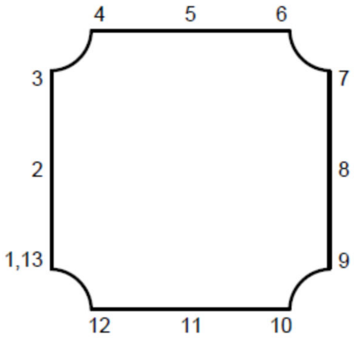
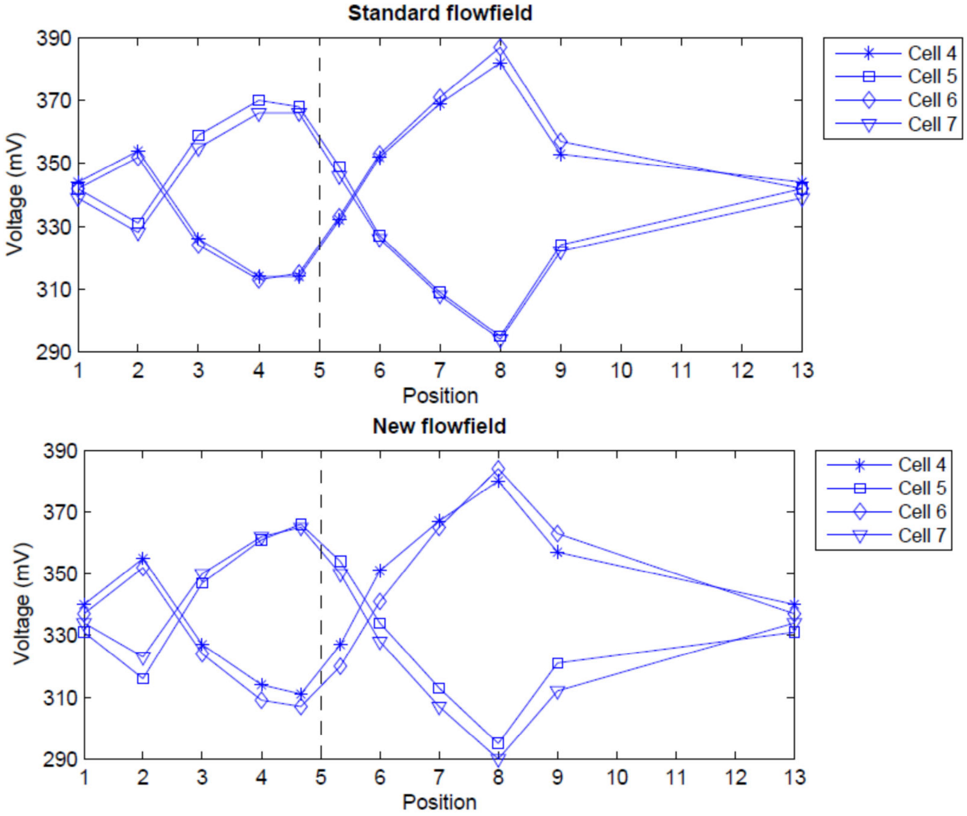


Figure 28. Positions along the edge of a cell.


Standard flowfield

New flowfield

Figure 29. Voltages measured along the edges of the cells. The stacks are operated at I = 54 A. The dashed black line indicates the position at which the CVMS is mounted.

FUEL SUPPLY CONNECTED IN SERIES

Each stack has two inlets and two outlets for fuel, and two inlets and two outlets for air, see Figure 27. One set of inlets supply even numbered cells, the other supply odd numbered cells. In the experiment described in this section the fuel supply on each stack is connected in series. On each stack the connections are such that fuel is first entered into the even numbered cells. The fuel that gets out of these cells is then entered into the odd numbered cells. Figure 30 and Figure 31, show a simplified schematic of the cells orientation in the aforementioned stack.

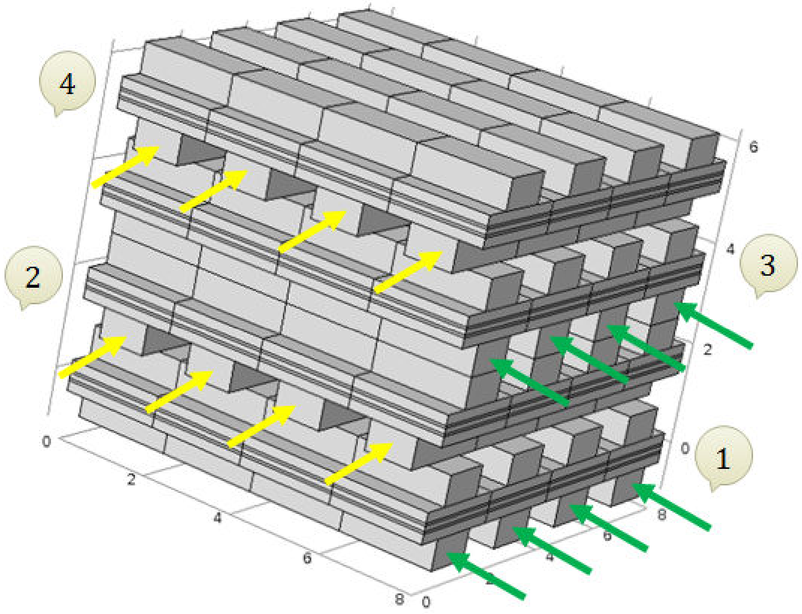


Figure 3. Schematic of a small stack in COMSOL. The inlet fuel for cells 2 and 4 is the outlet fuel from cells 1 and 3.

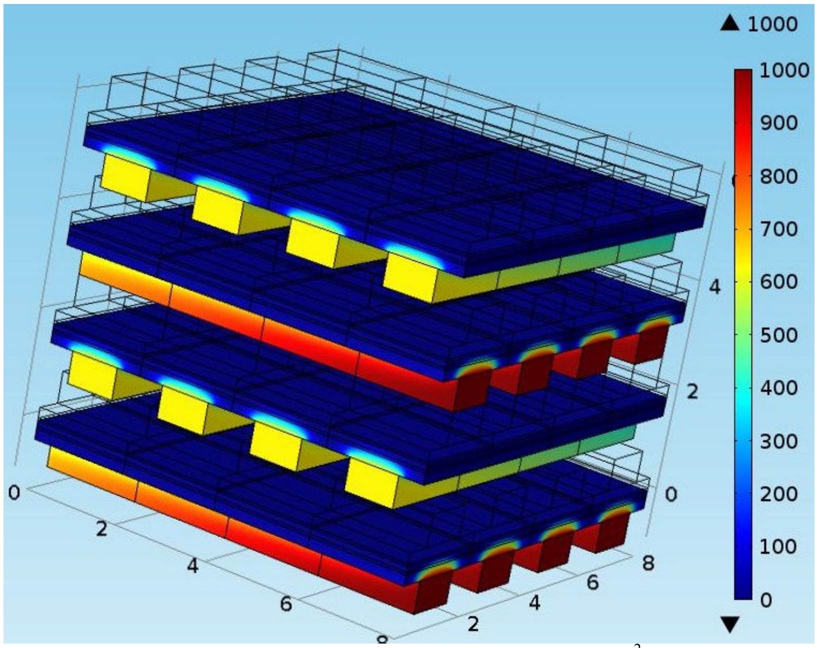


Figure 31. Methanol concentration at J=0.19 A cm^{-2}.

Cell voltages measured at I = 54A are shown in Figure 32 andFigure 33.

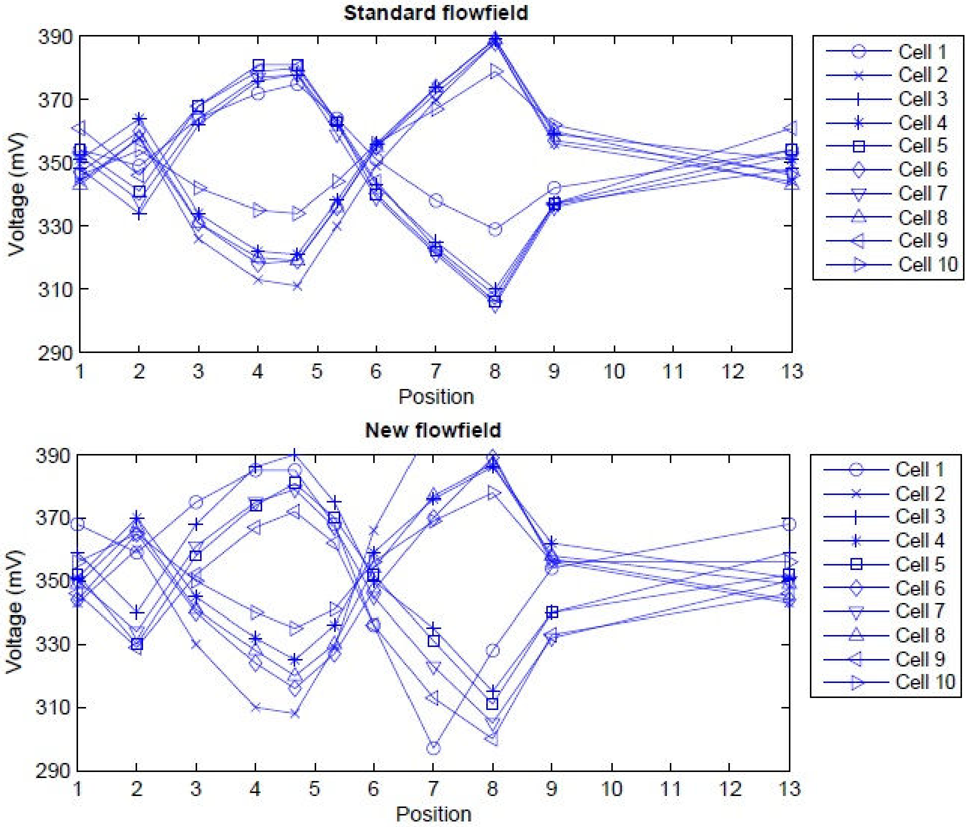


Figure 32. Voltages measured along the edges of the cells. The fuel supply on each stack is connected in series. The stacks are operated at I = 54 A. The axes are identical to those in Figure .

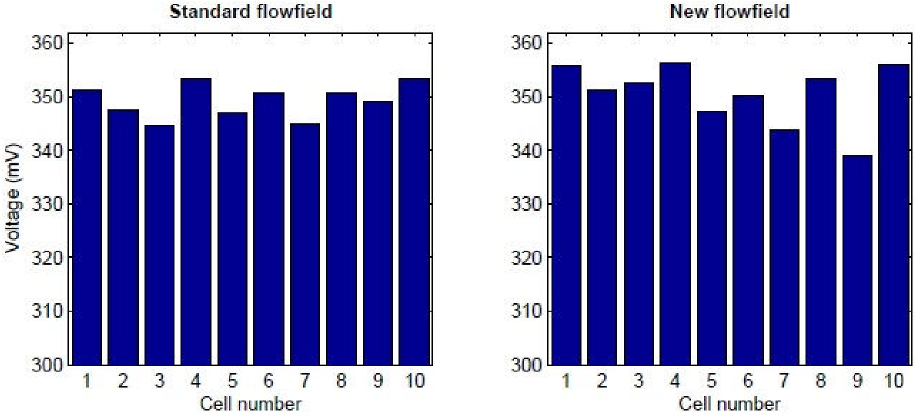


Figure 33. Mean values of the voltages shown in Figure .

POLARIZATION CURVES

Polarization curves for the two stacks are shown in 8. The minimum fuel flow rate was set to 500 mL min^{-1}, which corresponds to I = 0.25 Acm^{-2} with a fuel stoichiometric ratio of 6. The minimum air stoichiometric ratio was set to 3.

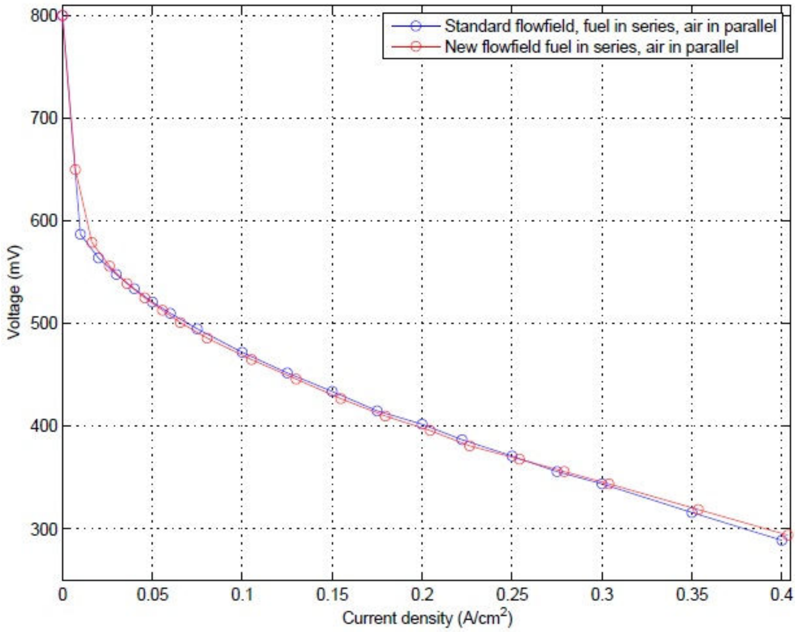


Figure 34. Polarization curves for the standard design and the new design.

Only a minor difference is observed between the polarization curves for the two stacks as seen in Figure 34. The voltage response is slightly lower for the standard design compared to the new design. The voltage response for the standard design is lower at low current and at high current. Analyzing the voltage response more detailed at low load shows that the fuel cell is starved over time with respect to both air and fuel in the last part of the flow field. The stack voltage becomes lower and lower until the system fails. The new design on the other hand keeps up the performance during the same period.

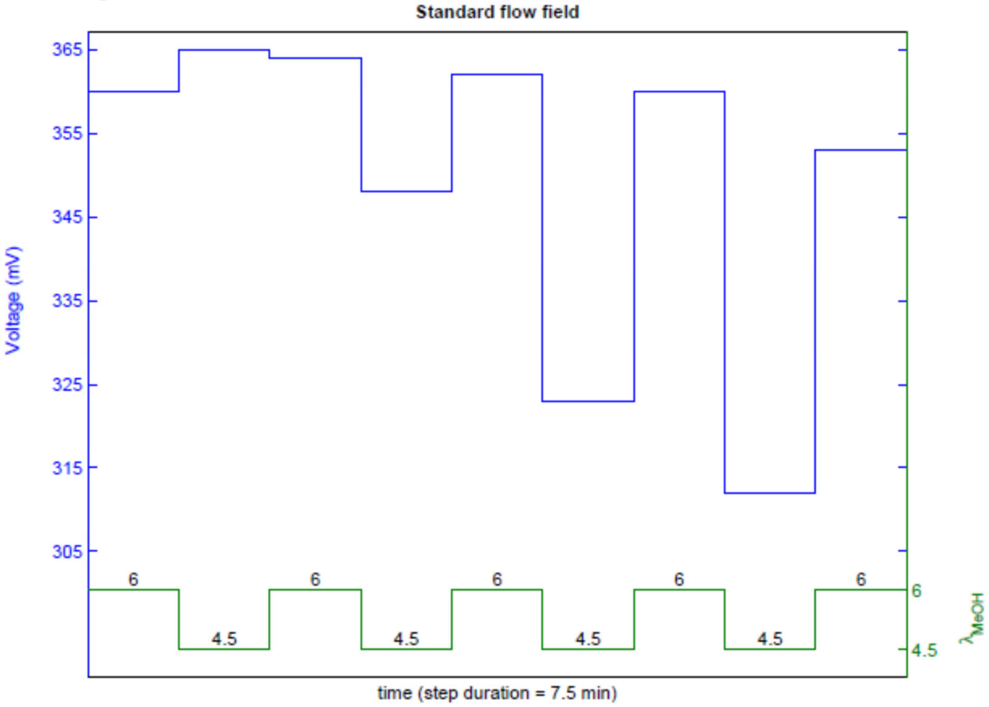


Figure 46

Figure 35. Voltage variation versus air stoichiometry.

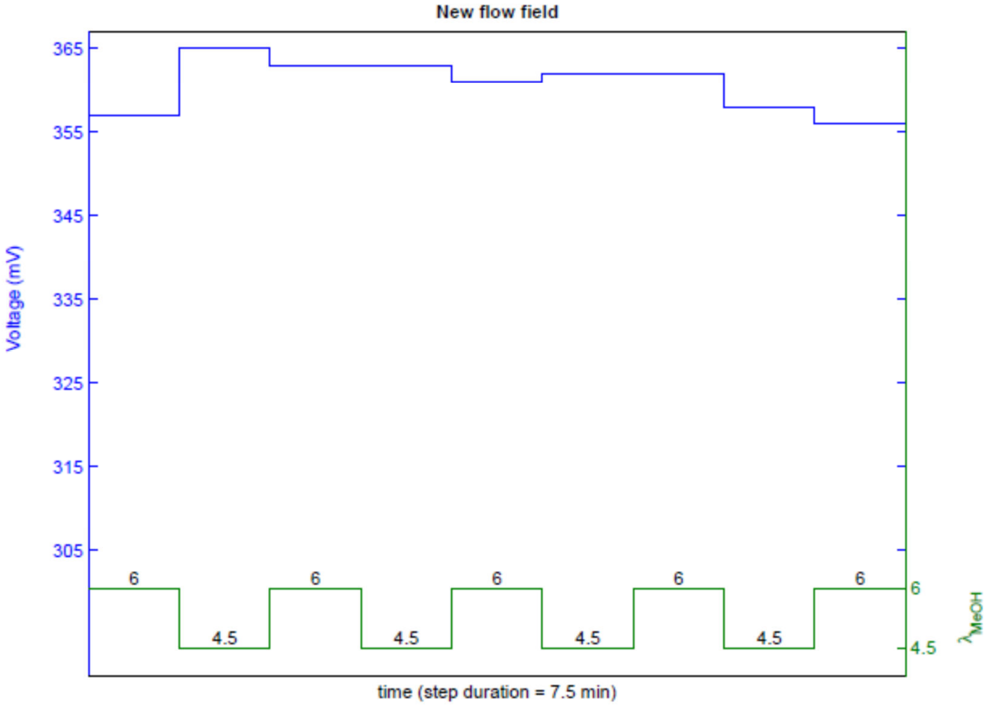


Figure 36. Voltage variation versus fuel stoichiometry.

It has been possible by using the stack model to analyze the detailed voltage response from the DMFC stack and thereby understand the stack behavior and based on this to improve and stabilise the stack performance in terms of a new flow plate design.

6. WP4: PROTOTYPE PROCESS DEVELOPMENT

The objectives of this WP is to establish cost efficient production methods aimed for mass production, but also applicable for small scale stack manufacture. The WP was divided into the following 5 tasks:

Task 4.1 Process flow:
Development of the complete process flow for automated stack manufacturing has been completed according to WP 1, WP2, WP3. Important parameters for the automated process flow have been specified. Parameters which makes the manufacturing more efficient by analyses, evaluation, optimization and carefully evaluation of each process turn around time. The outcome of this Task has been the directions to Task 4.2-4.5, and guidance to WP3 e.g. design of a bipolar plate aimed at automated stack assembly.

Task 4.2: Mould for prototyping and production_: Hardened stainless steel moulds are expensive, but proven to be cost efficient for mass fabrication of graphite composite bipolar plates. However they are not cost efficient for small scale manufacturing (Figure 37). The objective in this Task has therefore been to identify and verify materials that simultaneously allows easy processing to a small number mould and moulding for graphite plates and still keep the required tolerances. The evaluation criteria has included cost, number of possible casts, and quality.

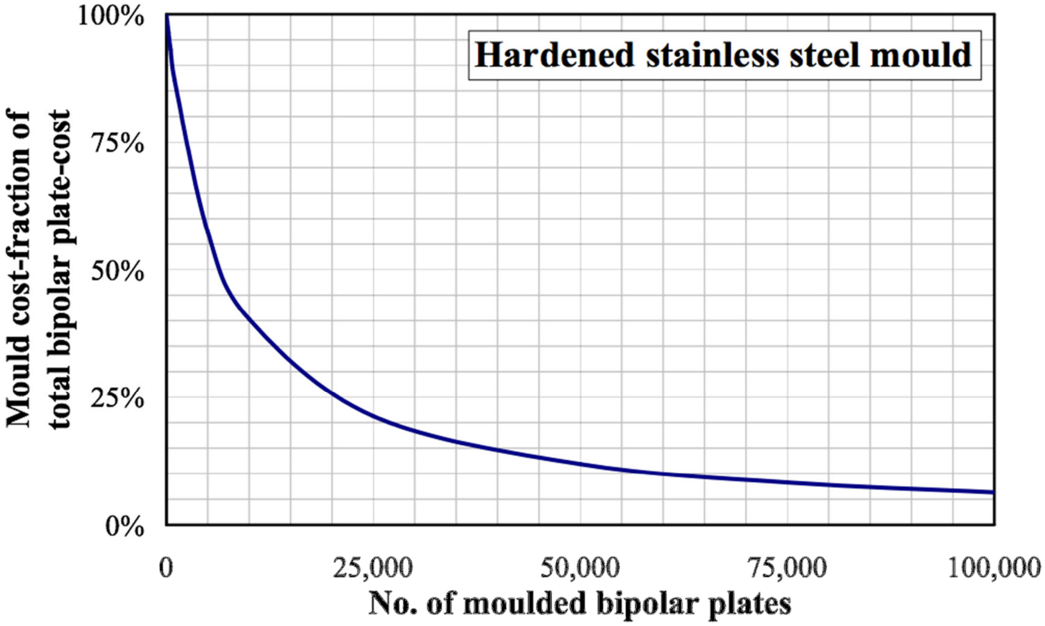


Figure 37. Fraction of mould-cost versus number of moulded plates.

Task 4.3: MEAs with integrated gaskets:
The development of low cost high performance MEAs is covered by other on-going projects and not included in TailorPEM, the same is true for gasket materials and design. However, the on-going development of the two components is not aimed for low cost automatized stack assembly, which is therefore done in this project.

Task 4.4: End caps with integrated current collectors:
The state-of-the-art current collectors at IRD are separate gold-plated cupper plates, a true cost driver. The present Task has therefore developed cost-efficient current collectors integrated in the end flow plates. Furthermore this task has developed two complete new designs and moulding processes. One based on epoxy materials reinforced with carbon fibers which can be assembled with carbon fiber rods.

This creates a light, easy to assembly, low cost end plate and assembly process.

The other based on moulding of fibre reinforced high strength concrete composite.

This creates a heavy, easy to assembly, very low cost end plate and assembly process.

Task 4.5: Automated Process development:
Based on the work in WP4.1-4.3 an automated stack assembly workflow has been specified. This is based on the new flat gaskets and the new end plate and rod design.

RESULTS

6.1 AUTOMATED PROCESS FLOW

The overall assembly line is shown below and the different steps are detailed described in Task 4.2, 4.3, 4.5.

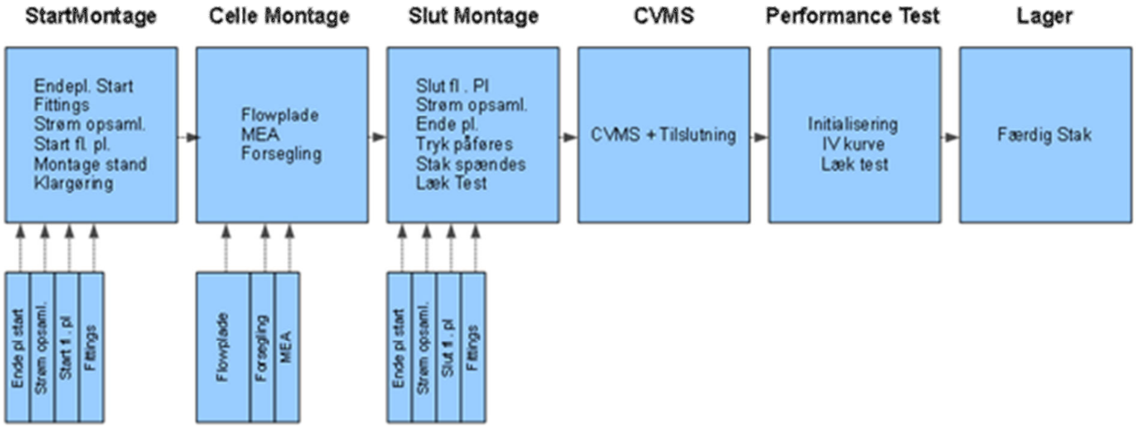


Figure 39. Layout for automated stack assembly.

6.2 MOULD FOR PROTOTYPING AND PRODUCTION

Flow plates are based on carbon or graphite. Those are the only materials able to resist the corrosive environment inside a PEM fuel cell with currents > 1Amp/cm^2 and pH=0. To give physical strenght the flow plate can be made of machined graphite. But this is a very expensive process only used for laboratory samples. The alternative used is carbon mixed with a thermal curable binder hot pressed to give the shape and physical required properties.

The problem for this process is:

- The carbon particles are very fragile. They have shapes like christmas threes, coils etc They have to be packed as dense as possible without disrupting their shape to keep high electronic conductivity.
- The required physical strength is obtained by the binder, which is a polymer able to withstand the temperature and environment. To give good electronic conductivity the binder content must be minimized. And therefore the moulding process is done under high pressure (160-700 ton) at high temperature (180-220 ^{o}C) isostatic pressure

The moulding process for the flow plates is therefore a very difficult task.

Therefore there is no easy solution except to:

- Optimize the moulding process
- Identify cheaper materials for the moulds
- Identify cheaper processes for machining the moulds

All three solutions have been executed:

- The moulding process line has been fully automatized except for the last robotic step: Feeding and emptying the mould. This is a formality when production exceeds 100.000
- Cheaper materials have been found and tested. Coated aluminum for prototypes and chromed aluminum and chromed mild steel for limited series.
- For cheaper machining process has in cooperation with moulding companies developed Electrical Discharge Machining (also known as EDM or spark erosion) for the moulds

6.3 MEAS WITH INTEGRATED GASKETS

Several methods and technologies as described have been tested and evaluated in the project.

For the DMFC the materials have been a limiting factor because liquid materials are not acceptable.

Process A

Wet in wet assembly of MEA - flow plate:

Liquid sealing is placed by automated dispenser on both sides of the flow plates(Figure 40). After stack assembly the whole stack is cured in an owen. The stack cannot be dismantled

Process B

Only the MEA has sealing material dispensed both sides followed by curing before the stack is assembled. The stack can be dismantled.

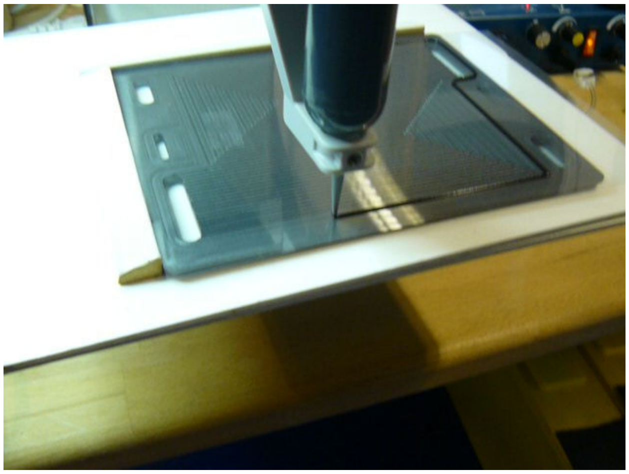


Figure 40. Automated liquid sealing of MEA/flow plate

Process C

To obtain good control with the MEA position, only one side is sealed and cured to the flow plate. Liquid sealing is afterwards placed by a dispenser on the other side side of the flow plates and the stack is assembled. The stack cannot be dismantled.

Process D

Themoplastic elastomer

Seals in proper shape are punched out of a polymer sandwich of the correct composition for the sealing. Those are based on PIB. The punched out seals are placed sequentially on the flow plate and MEA and heated under high pressure. The process can be used both for single cells and whole stacks and gives a very good protection of the membrane and the diffusion layer interphase.

The process is well suited for automatization. The stack cannot be dismantled.

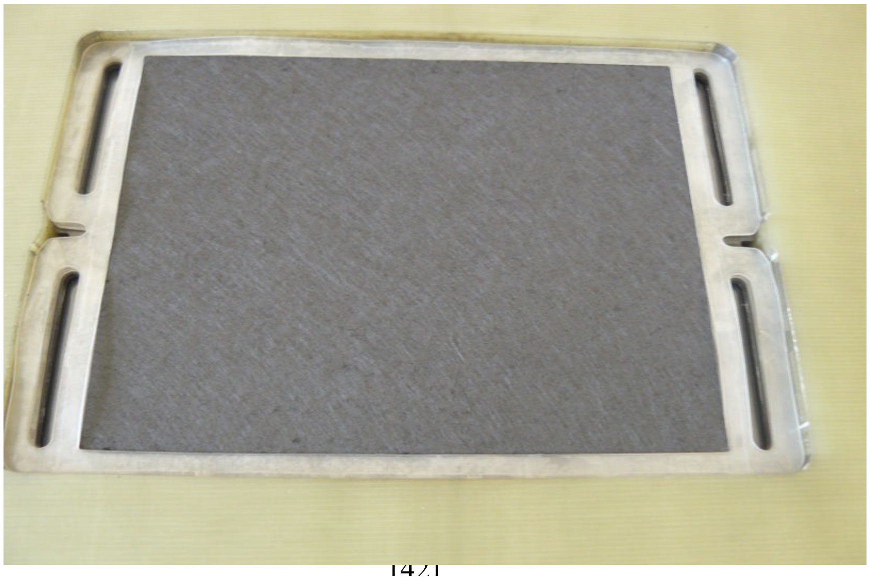


Figure 41. Thermoplastic flat sealing of MEA/flow plate

All the processes are summarized in Figure 42.

EVALUATION

Process A

Is excluded because of disfiguration of the nafion during the curing time.This is because the curing time is too long for the wet nafion. Additionally it is a difficult process to handle because the process is wet and the MEA is soft. The process is very demanding in positioning.

Process B

Has its advantage in the possibility of dismantling the stack if needed. the process is also advantageous because it is possible to destinguise between sealing and material curing. The challenge is that the process requires complicated moulding in situ and relatively long process time for each step.

Process C

The process include some of the advances and disadvances of process A and B.

The process tooling is expensive but quality can be high. Very flexible

Process D

This process has low price both in limited numbers and mass production. Because the process does not include liquid materials it is also well suited for DMFC stacks. The tooling is limited and low cost.

According to economic calculations of time and material consumption and the process flexibility the D process has been chosen and tested at stack level.

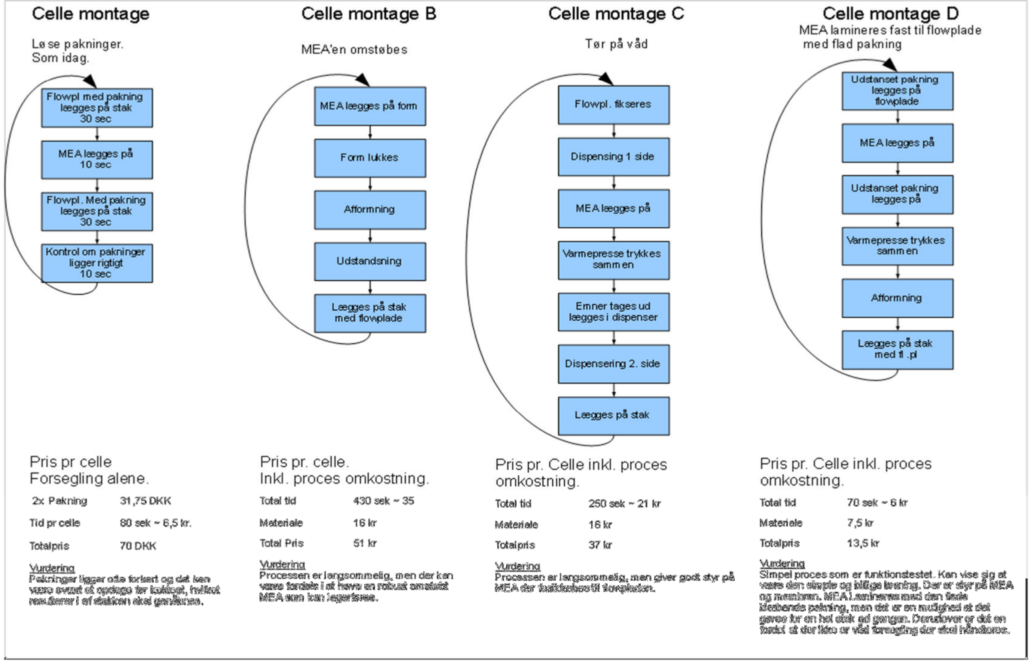


Figure 42. Cell assembly processes

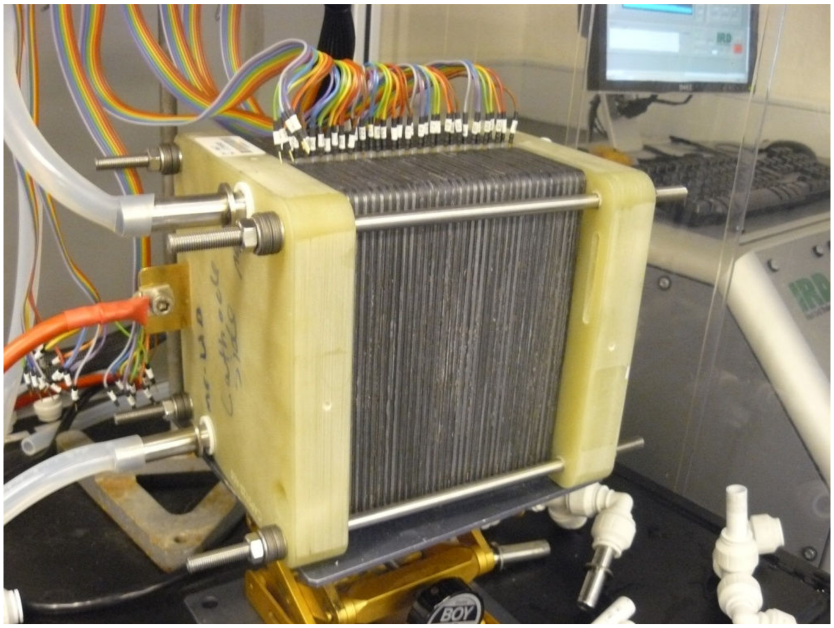


Figure 43. Test of DMFC stack flat composite seals (process D)

The flat composite seals (Process D) was verified in DMFC stacks. A 10-celle stack was tested in 1500 timer. The sealing was tight during the testing and examinations of the the sealing after testing showed no sign of degradation.
A full 31-cell stack was likewise assembled using the flat seal process seals and the stack was tested for 100 hours without any leaks or degradations of the sealing.

6.4 END CAPS WITH INTEGRATED CURRENT COLLECTORS

The task of developing new endplates with integrated current collectors has followed two lines: One line based on moulding of fibre reinforced high strength concrete composite. This line was done in a separate project in cooperation with Danish Technological Institute, EUDP project 64009-0217 .The other line was based on Carbon reinforced polyester with rods of carbon fiber.

In the projects endplates for the PEM-type fuel cells has been developed. The initial idea was to use an mouldable carbon fibre reinforced polymer to produce the endplate and thereby exploit the opportunities of great geometrical freedom to reduce weight and material consumption. Different carbon fibre compounds were produced and tested in order to use the results to optimize the results on the comput- er through FEM simulations. As it turned out, it was impossible to achieve very low cost for the endplates within the given geometrical limitations.

Material focus shifted to fibre reinforced high strength concrete composite. Test specimens were produced and tested so the results again could be used for FEM- simulations which also accounted for the technical limitations the concrete compo- site has regarding casting ability. In the process, the way the endplate is mounted was also alternated to better accommodate the properties of the concrete composite. A number of endplates were cast in specially produced moulds in order to map the optimum process parameters, and a final endplate was tested at IRD Fuel Cells A/S. The field test was successful. However, the gas sealing and the surface finish can be further improved. The weight may still be an issue for some applications,Therefore the carbon fiber reinforced solution is still an opportunity where light weight is required. This issue can be addressed innext phase. The work has resulted in a two new endplate designs, which makes the stack assembly simpler and with fewer components. The endplate fabrication involves low cost methods, which can both be used at limited production or be scaled up for mass production

Figure 44. Stack with fiber reinforced high strength concrete composite end plates

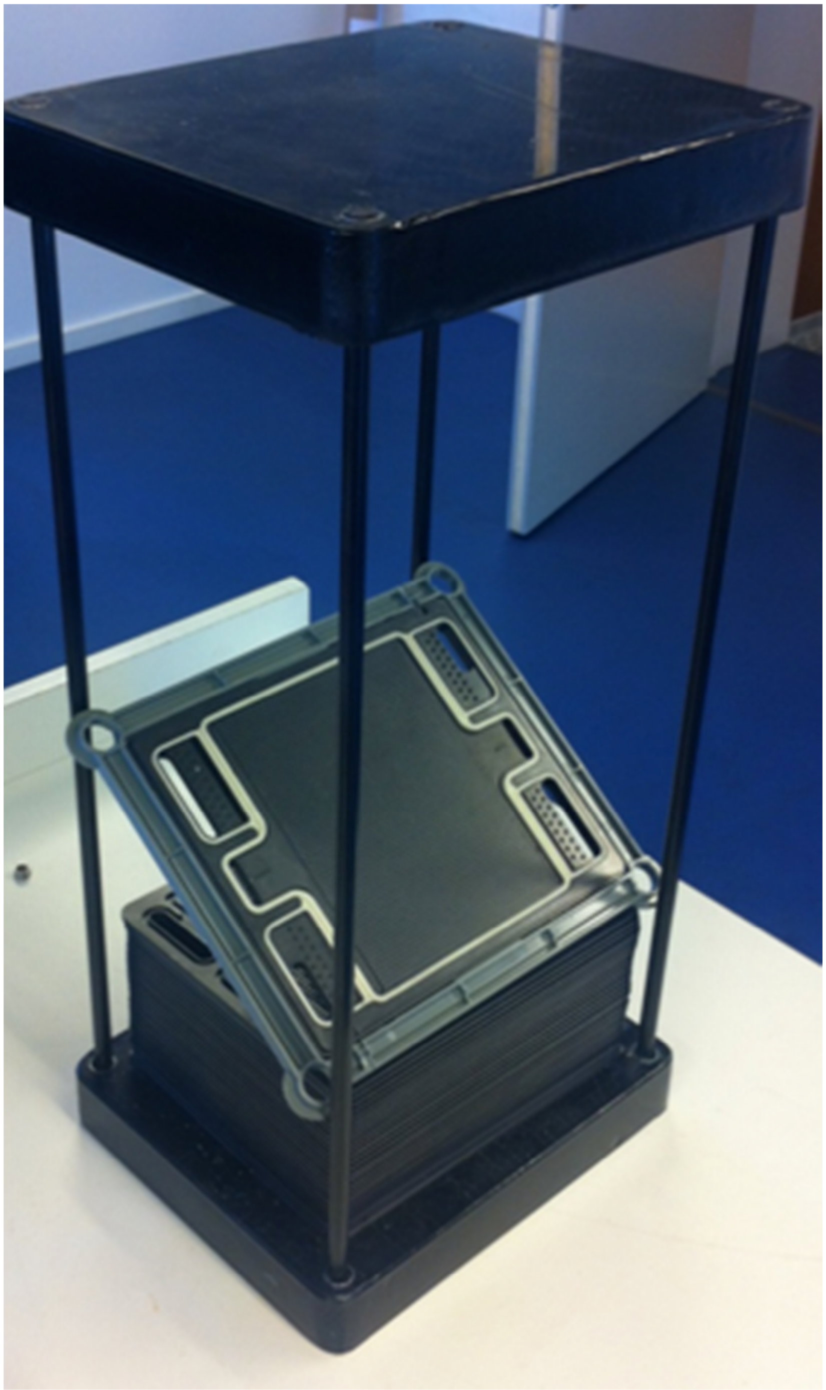


Figure 45. Stack module with carbon fiber reinforced epoxy endplates and tie rods.

7. WP5: STACK MODEL VALIDATION, QA AND EVALUATION

Task 5.1: Development of QA procedures :
Comprises the organization of the necessary activities (material entry control, component control, documentation etc.).

Task 5.2: Stack model validation (IRD):
Construction of small-scale prototype stacks 1-10 cells to validate the stack model.

Task 5.3: Evaluation (IRD):
The outcome of Phase I will be evaluated for the three end-user applications. The project Phase I will be completed with assessment and analysis. The work will conclude on recommendations and definition of Phase II headed by the end-users.

7.1 DEVELOPMENT OF QA PROCEDURES

7.1.1. SCOPE / OBJECTIVE

The objective of this WP is to provide a standardized testing and closeout handling of manufactured Fuel Cell Stacks and to verify compliance with the actual stack specification.

Stack units conforming to the System Specification are assigned an authorized stack specific *Qualification Acceptance Certificate*.

This WP describes the type of testing and performance verification to be applied to each individual fuel cell stack manufactured and ensure that all fuel cell stack deliveries comply with the quality standards specified in this document.

This work instruction is a tool to be used in the practical qualification acceptance testing of stacks, addressing the following aspects:

- Functional performance
- Workmanship standards
- Marking (Type and serial numbers)

7.1.2. CLASSIFICATION OF TEST METHODS

The PEMFC stack test and verification actions have the following classification:

INITIAL INSPECTION

An overall visual inspection of the stack components is performed during the stack assembly to ensure that no defect components are used in the stack.

LEAK TEST

Several leak tests are performed on the stack after assembly, and before and after the electrical performance test. These tests are designed to identify defect stack components and stack assembly errors as well as to ensure that the gas leak rates and gas crossover rates of the stack are within specified limits. In practical terms nonconformities can be due to missing or damaged seals, MEA's, bi-polar plates etc.

STACK INITIALIZATION

On the stack test bench an initialization is performed to prepare the stack for electrical operation including the electrical performance tests. The main purpose of this initialization is to humidify the membranes in the MEAs; to heat the stack (and pressurize if needed) to make sure that the stack components have settled mechanically at the operating conditions; to ensure that all the cells in the stack has good inter/intra cell electrical contact; as well as setting the experimental conditions for the following electrical performance test.

ELECTRICAL PERFORMANCE TEST

The electrical performance tests shall verify stack performance compliance with the system specifications, including the overall stack voltage vs. current load, and performance stability.

CLOSE-OUT

After all the tests are passed, the stack is sealed and a Qualification Acceptance Certificate documenting the stack performance capability during the test is issued.

TESTING ENVIRONMENT AND EQUIPMENT

The test facilities consist of two separate test benches. A leak test bench and an electrical performance test bench.

LEAK TEST FACILITY

The Leak test facility has been designed to be simple and flexible in use. This is important to be able to perform the various specified leak tests and, additionally, to be used for special test in the search for broken or damaged bi-polar plates. At the leak test bench Air, H_2, and N_2 gas is available. At the computer a program monitors the pressures and temperatures as function of time and stores the values in a data file for later analysis.

ELECTRICAL PERFORMANCE TEST FACILITY

The electrical performance test facility is an automatic test bench designed to test stacks under varying conditions. The electrical load, cooling water flow, stack temperature, gas pressure, anode/cathode gas stoichiometry and gas humidity, can easily be varied and the effects on the stack performance can be observed.
A computer is used for data acquisition and control of the test bench. Via the program the operator can monitor and control the hardware on the test bench.

A cell voltage monitoring (CVM) system is connected to the stack. This CVM system measures the voltages of each cell in the stack.

7.1.3. TEST PROCEDURE

INITIAL INSPECTION

The presence and validity of the stack type and serial number (stack ID) as well as labels describing the gas connections and cooling water are inspected before the testing is started. The stack ID is recorded on all relevant documents and electronic data files.

WORKMANSHIP

The overall stack workmanship of the stack is visually checked after it has been assembled and when it arrives at the test facility. The overall inspection involves:

- Presence of all inspectable stack components.
- Alignment of the cells.
- Condition of (e.g. surface damage) the bi-polar plates or other stack components
- Extra ordinary gabs between the bi-polar plates

2. General surface finish

LEAK TEST

The leak testing is performed at the assembly line and at the leak test bench. The testing at the leak test bench is performed both before and after the electrical performance test.

QUALITATIVE TEST OF OVERALL EXTERNAL LEAKAGE

At the assembly line, after a stack has been assembled, the anode, cathode, and cooling water systems are interconnected and pressurized with N_2 gas at room temperature. The stack is then lowered into a tank filled with deionised water. Leaks in the stacks are measures by the gasflow from the tank.

TEST OF GAS LEAK AND CROSSOVER FROM COOLING WATER CHANNELS

At the leak test bench, the cooling water system is pressurised with $N_{2.}$ The anode and cathode gas system are interconnected and sealed off from the surroundings at ambient pressure. A cooling water leakage is seen as a pressure drop in the cooling water system. Gas crossover is identified as an increase in pressure in the anode/cathode gas system.

TEST OF GAS LEAK FROM ANODE AND CATHODE GAS CHANNELS

The anode and cathode systems are separately pressurised and the pressure drops in both systems are monitored for at least 1 hour. The cooling water system is kept open to the atmosphere during this test. If the pressure in any of the two systems drops, the stack has failed the test

TEST OF GAS CROSSOVER FROM ANODE TO CATHODE

A constant flow of gas is applied on the anode side, and the anode pressure is kept constant . The cathode gas system is sealed at ambient pressure and the pressure is monitored for at least 1 hour. The crossover of gas from the anode to the cathode can be seen by the pressure increase on the cathode side.

STACK INITIALISATION

At the performance test bench, the stack is connected to the gas lines and cooling water system. The electrical load and the cell voltage probes system are connected.
The electrical load on the stack is increased to heat up the stack and the cooling water (and membrane humidifier if used).
At appropriate intervals the load is set "Stand By" to stop the stack water production for a while and to check the open circuit voltage of the stack (OCV).
The stack temperature and humidification temperature as well as the cooling water flow are controlled to ensure stable conditions.
The total initialization with operational stack load shall last at least 3 hours.

ELECTRICAL PERFORMANCE TEST

At the end of the stack initialization, the temperature and humidification of the stack is ready for the electrical performance test.

I/V-PERFORMANCE TEST

The electrical performance of the stack is tested by increasing the electrical load from 0 to at least max load in steps of 5 A while monitoring the stack voltage. The performance is tested under stack specified conditions i.e. Humidification temperature, Stack temperature etc.

STACK TEMPERATURE PROFILE

The surface temperature is measured during stack operation. If the temperature anywhere on the stack significantly deviates from the stack temperature (Cooling water outlet temperature), the stack has failed the test.

ELECTRICAL LOSSES

The voltage drop between each cell in the stack is measured at one position on the surface of the bi-polar plates during stack operation a If the voltage drop between any of the cells or between cells and current collectors are too high the stack fails.

CELL STABILITY AND HOMOGENEITY

During the stack initialisation and electrical performance testing the individual cell voltages are monitored by the CVM system, to reveal low performing or unstable cells. that need to be replaced.

7.1.4. CLOSE OUT

When a stack has passed all the tests a Qualification Acceptance Certificate is issued.

Based on the operator’s log and the analysis of the data file, the test results of the overall stack performance are evaluated against the actual product specifications.

Any stack failing a test or otherwise not conforming to the product specification shall be reworked and re-tested according to standard procedures described in this document.

:

7.2 STACK MODEL VALIDATION

All the described stack models and components have been evaluated and tested.

For the MEA process the ultrasonic coating process has proven to be both flexible and cost effective . In both small and large series. Additionally it gives better performance and higher utilization of the high cost catalyzer materials than any other known process.

For the flow plate the new improved and automatic process has solved a lot of problems for scaling up from prototype to mass production. One of the solutions have been to use same physical geometry of the molds but in different materials dependent on the production number

For the MEA sealing the polymer elastomer process has proven a good flexible process well suited to small and large series. Additionally it has solved the problem of same sealing material for both PEM and DMFC

For the end plate material and process the fiber reinforced high strength concrete composite process has no competition in price and flexibility. Materials are cheap and molds are cheap. However the end plates are heavy and require proper attention in the sealing process. Therefore if low weight and volume is required and a higher cost can be afforded the carbon fiber reinforced polymer endplate is the ideal choice. Furthermore it can be combined with carbon fiber rods.

Based on the above described considerations for the stack components different stacks for PEM and DMFC have been designed, constructed and tested. The stack designs are in principle similar except for the different flow patterns and the fact that DMFC has no separate cooling system. A great help for the Quality control and stack assembly has been the framing of single cells

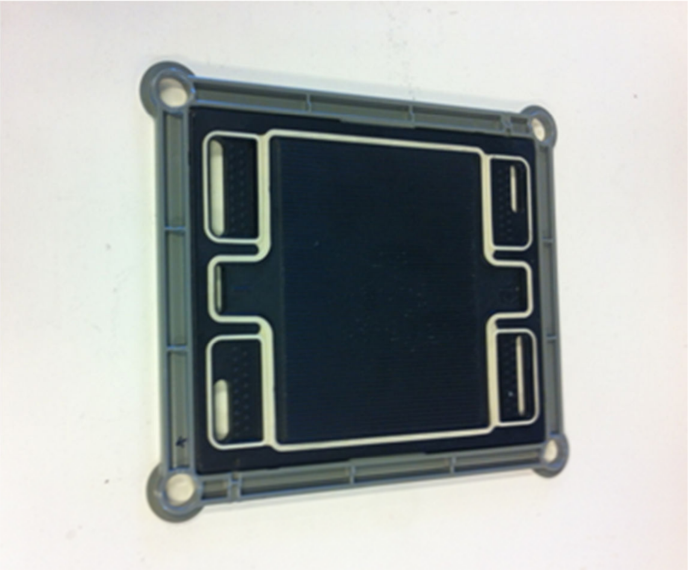


Figure 46. Frame single cell.

(Figure 46) . This gives the possibility to assembly and test the cells before stack construction.

Furthermore it creates the possibility to store tested cells and use them for a range stack powers dependent on the number of cells.

The most demanding stack design and test has been test stacks for SENER/AIRBUS.
The requirement was low weight and volume and extreme durability. Furthermore the application demanded the stack to work in any position in a rugged environment. As a result IRD and SENER designed and constructed a special test module in carbon reinforced epoxy (Figure 47.)

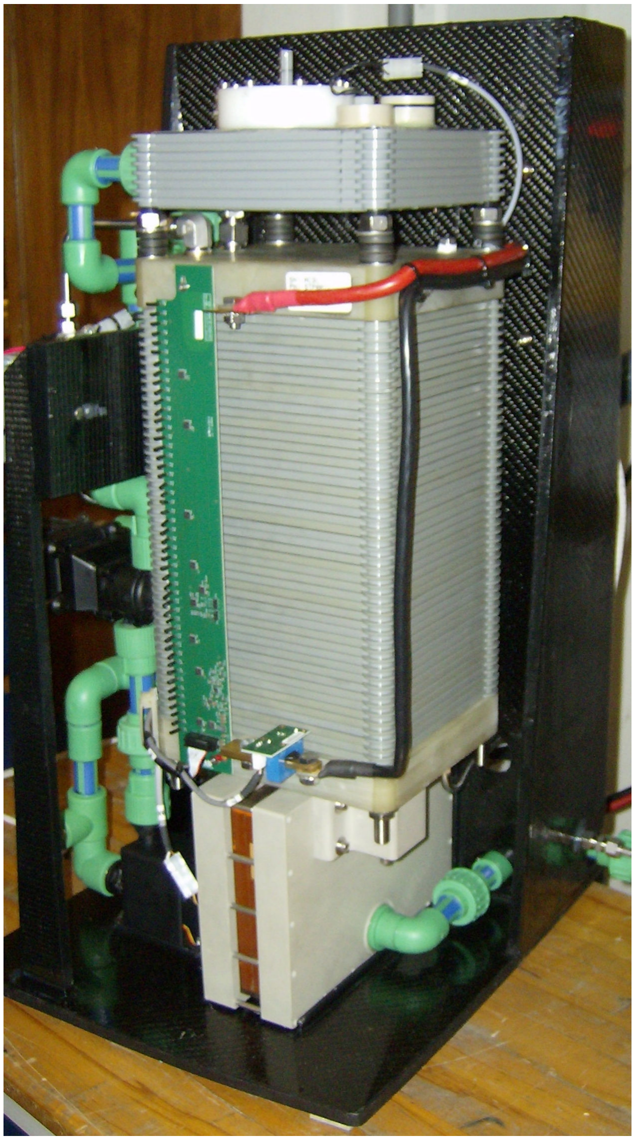


Figure 47 SENER Fuel cell test module.

This module has been tested at both SENER and AIRBUS and has passed all their tests. (Figure 48)

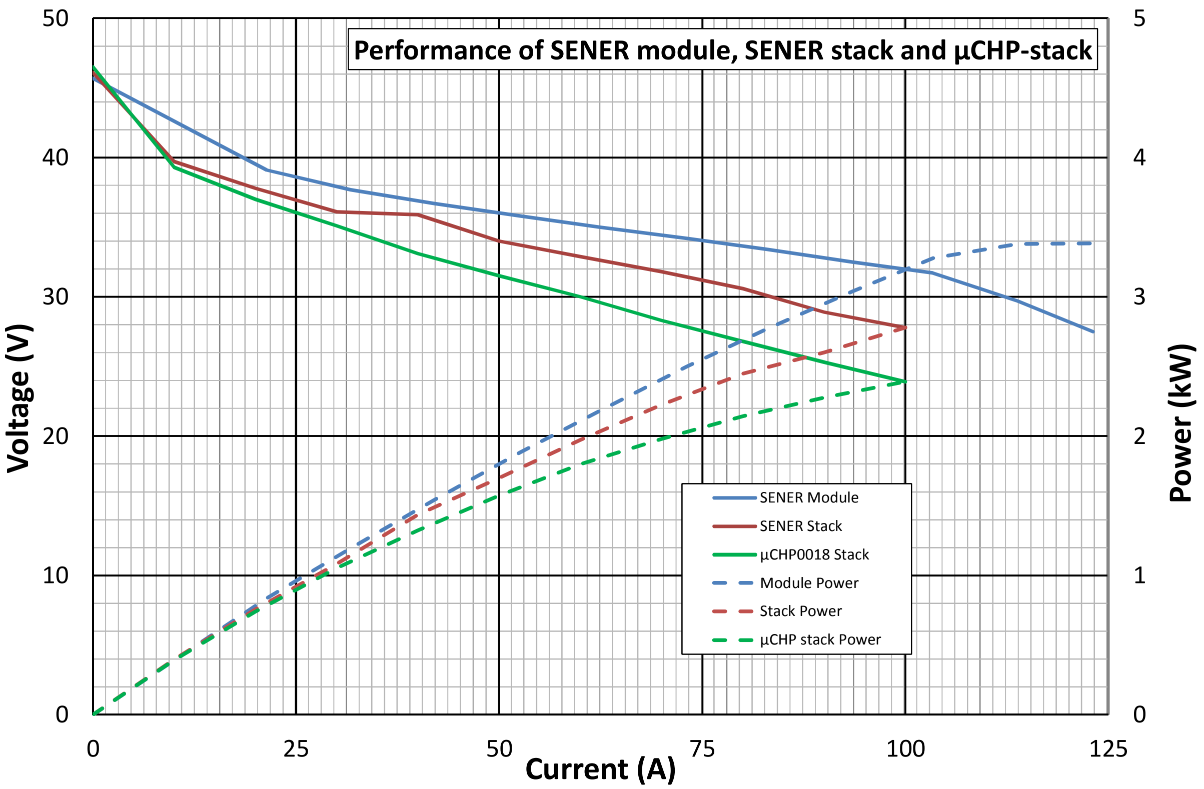


Figure 48. I-V curves for SENER test module and stack together with a standard µCHP stack

7.3 EVALUATION

The project has created a range of design tools and manufacturing processes aimed at both the project participants and future customers. As a consequence the price of stack components and stacks have been lowered considerably. The project has been so successful that the milestones of the danish road map for 2014 has been fulfilled.

Milestone 2014 PEM:

Price:	<4500€/kW
Operational life :	>6000 hours

Milestone 2014 DMFC:

Price:	<10000€/kW
Operational life :	>2000 hours

The PEM fuel cell stack market has is characterized by manufacturers offering a niche product line with limited design options due to the high cost of stack development. The adoption of PEM fuel cells is therefore confined to "component driven" applications as opposed to market requirements.

Due to the outcome of this project this problem is now circumvented. It is now possible to develop new components and stack designs with limited investments. And to manufacture cost effective in small, scalable series

IRD and the project partners has already had benefit of those new tools and production methods, i.e.:.

- IRD has obtained component contracts with partners and costumers

- IRD has obtained component contracts in competition with other manufacturers in US, Japan, Germany and China

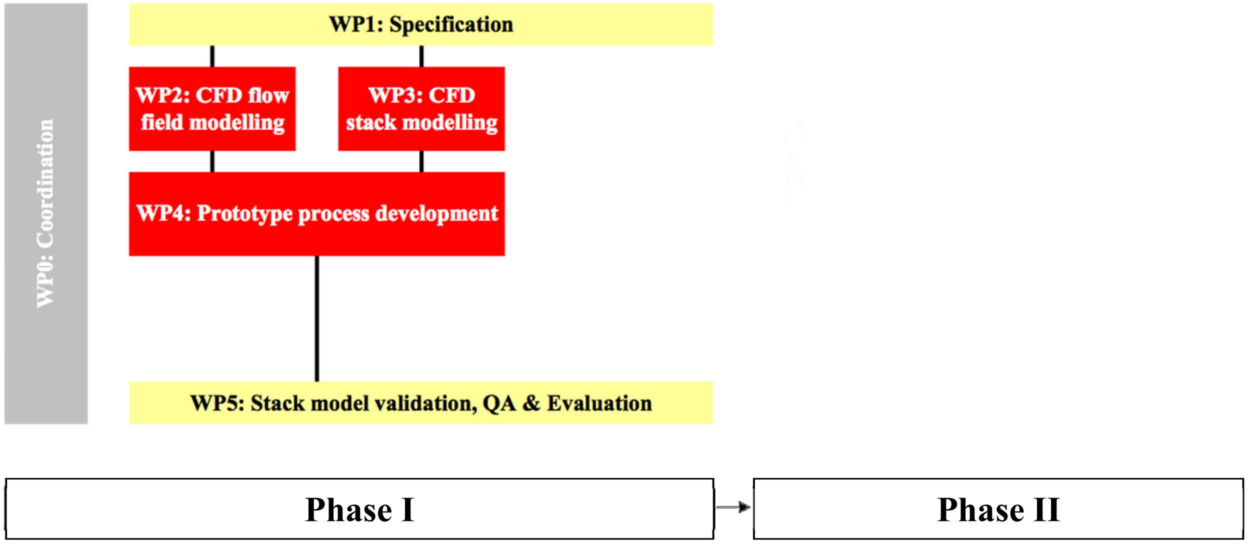
The overall objective of the TailorPEM project:

- To facilitate a marked-driven approach, where affordable PEM and DMFC stacks tailored for different applications and demands even in small scale production can be manufactured. Has been obtained.

PHASE II

Based on the successful outcome of phase I it important that phase II is executed in succession of phase I to keep the momentum both at customers and at project participants.

Given the technology level obtained in the project, the project has enabled IRD and partners to be in the forefront in the commercial fuel cell market. Given the market size and growth potential, this is an big opportunity for the consortium and Denmark.



In phase I new materials and technologies were identified and tested.

The next phase shall:

- Transform the design tools, processes and process lines from the phase I test and demonstration units into proper manufacturing units.
- Design and manufacture PEM stacks aimed for the different customer driven applications as follows:
  - Small and large (>1kW) DMFC stacks
  - Small and large (>5kW) PEM stacks
  - Light weight and low volume stacks for portable-, transport- and aircraft industry applications
- Organize a new department of design and application engineers who are in direct contact with the customers' development departments. This is for optimization of the customers system demands in the component design and manufacturing