Final report

1.1 Project details

Project title	Extreme Climate Fuel Cell Solutions - EXC-CELL
Project identification (program abbrev. and file)	EUDP 12-I, J.nr. 64012-0117
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Dantherm Power Majsmarken 1 9500 Hobro
Project partners	Aalborg University
CVR (central business register)	30804996
Date for submission	25.08.2015

1.2 Short description of project objective and results

English: The key technical challenge addressed in this project is for fuel cell systems to operate in cold and very dry conditions and hot conditions. The objectives were:

- To further develop the core technology to allow for improved startup performance by developing a better understanding of heat and water balance management and fuel cell components with enhanced performance under dry operating conditions.
- To design, develop and test a second generation climate kit with demonstrated improved performance achieved through novel system architecture and improved core components.

The objectives were met through positive collaboration and results. The new knowledge and understanding of heat and water balance management can lead to further significant improvements of the fuel cell components. The developed climate kit is implemented in the product line of Dantherm Power products for extreme climate back-up products.

Dansk: Projektet søger at løse udfordringer for brændselscellesystemer i ekstremt kolde og tørre samt ekstremt varme omgivelser. Målene i projektet er:

- At opnå en bedre forståelse for og viden omkring varmefordelingen og –styringen i brændselscellerne under de ekstremt kolde/varme driftsforhold.
- At designe, udvikle og teste en 2.generations klimaløsning med forbedret ydeevne på baggrund af nydesignet systemarkitektur og forbedrede kernekomponenter.

Målene blev nået gennem konstruktivt samarbejde og positive projektresultater. Den ny vundne viden om varmefordelingen kan bidrage til en revolutionerende ny og stærkt forbedret varmestyring gennem brændselscellerne, som vil få meget stor betydning for udvikling af brændselscellekomponenter fremadrettet. Den udviklede klimaløsning er optaget som nyt tilkøbsprodukt i Dantherm Powers sortiment af back-up power produkter til ekstreme klimatiske forhold.

1.3 Executive summary

The EXC-CELL project successfully managed to develop a second generation climate kit (CCK) to be added onto a standard back-up power system for installations in extremely cold and/or extremely hot regions. In addition, the simulation and modelling work on the fuel cells under these extreme conditions resulted in a much better understanding of the heat and water management inside the cells in general and improved the modelling tools significantly. It was concluded that thermal effects in the experiments of this project played a more dominant role which was previously unknown.

The new knowledge gained from this project revealed several opportunities for significant improvements on the fuel cell and stack design, which, going forward should/could be utilized to improve the overall fuel cell system not only for extreme climate situations but for all back-up power fuel cell systems for outdoor installations.

The climate kit design was chosen after several iterations of testing different heat exchangers in extremely cold climate, before settling on the final one. In a climate chamber at Dantherm Power the climate kit performed satisfactorily for temperatures down to -32 degreesC, which was the coldest possible temperature that the climate chamber could provide for. A 2nd and 3rd generation climate kit was developed and tested in the project. The operating principle of the 3rdG climate kit is based on bypassing the cathode air stream at low temperatures. This has several advantages over the heat exchange principle of the previous generation climate kits. The bypass module allowes to reduce the cathode air stream by 30%, which based on the measurements performed earlier in the project in the climate chamber, would be sufficient to operate the system at the specified temperatures.

With small further adjustments the climate kit is prepared for commercial introduction and is now included it in the product portfolio of Dantherm Powers back-up power line for customers in extreme climate areas.

1.4 Project objectives

The project objectives were following 2 activity tracks (one practical and one research based) with interacting links.

The practical track revolved around analyzing and specifying the needs for developing the second generation climate kit with the objective of developing a physical climate kit module to be used as add-on to the existing fuel cell system, to test it and document its performance under realistic operating conditions.

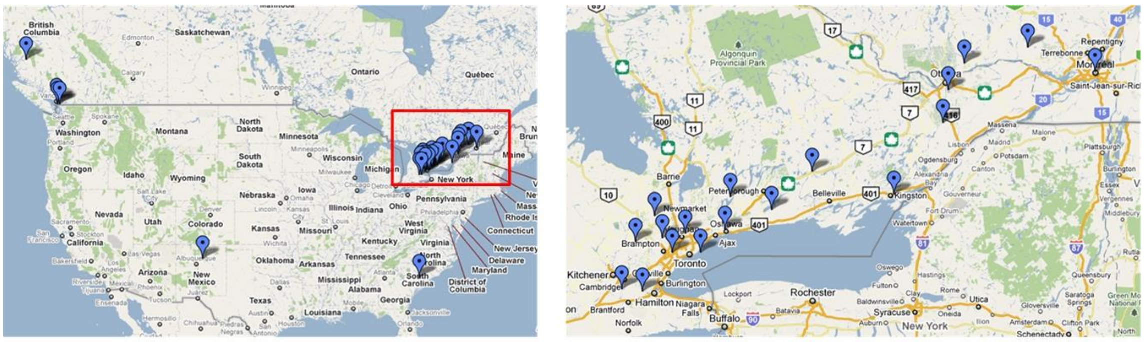
The same early analysis and specifications were the off-set for improving the fundamental insight of the link between cell, stack and system with respect to dry operating conditions with the objective to prepare for a new generation of MEAs that enable flexible use across applications and climatic conditions with a minimum of performance and lifetime loss.

The commercial objectives of the project revolved around investigating the global market and the global range of competitors in the field with the objectives to produce the necessary business plans supporting the work going forward.

1.5 Project results and dissemination of results

WP2 – System analysis and specification
The following section describes the installations and field experiences that form the basis for the climate kit development performed by Dantherm Power in the EXC-CELL project.

<u>Customer case description</u>
The starting point for the EXC-CELL project is the experiences Dantherm Power has with operating fuel cell based power backup systems in extreme climate regions. Operating the systems in extreme climates – especially cold climates, is impossible without an add-on to the systems known as a cold climate kit (CCK). For the initial customer sites located in Canada, a first generation climate kit was developed. The main experience operating power backup systems together with a CCK was gathered on a total of fifteen temporary power sites installed in the area around Montreal and Toronto in Canada during a three year period from 2012 to 2014. The telecom sites for the installations were off-grid sites that needed continuous power supply in that period, while the utility company installed the permanent power grid in the area. Six of the systems were installed on permanent sites during the period, and nine of the systems were moved from site to site as the power grid was being installed in the area. On Figure 1, a map showing the installation sites is illustrated.

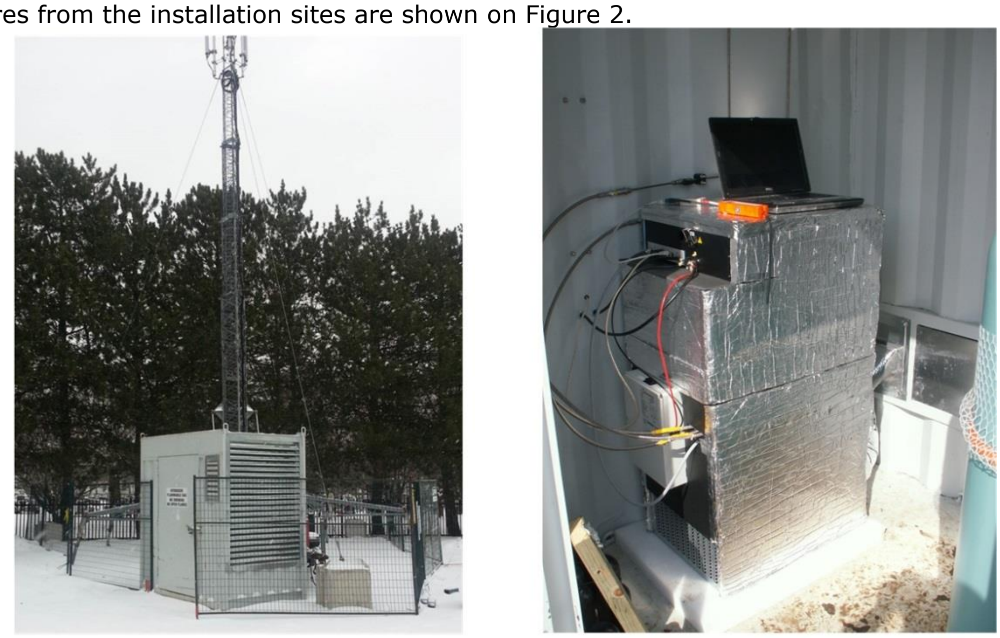


(a) (b)

Figure 1: The installation sites for Dantherm Power backup sites in North America and Canada as of 2013: (a) Overview map. (b) Detailed zoom of the Wind sites located in the Area around Toronto and Montreal.

<u>Site description</u>

The customer sites for the installations were temporary sites for mobile communication that were being put into operation before the utility grid was installed on the sites. Generally, the extreme climate conditions prohibited the use of diesel generators as these were not sufficiently reliable at the low temperatures. Pictures from the installation sites are shown on Figure 2.



(a) **(b)**

Figure 2: A typical installation site. (a): Site seen from outside. (b): Inside site shelter. A Dantherm backup system is installed on top of a 1st generation climate kit.

<u>Mission profile</u>

As the power backup systems were installed on off-grid sites, the systems were operating continuously, which for both cold and hot climate can be considered as the worst case condition, and therefore forms a very good basis for gathering field experience. This is due to the fact that under hot operating conditions, the negative effects on the fuel cell stack (typically in the form of membrane dehydration issues) only reaches full potential after several hours of operation. Under cold operating conditions, the negative effects on the fuel cell stack in the same manner often take several hours to reach steady-state. The resulting effects are predominantly ice formation in the exhaust and flooding in the fuel cell stack due to low operation temperature for the stack. The mission profile for the customer case can be summarized as follows:

Operation pattern	Continuous operation 24/7
Highest temperature recorded	+45 degrees Celsius
Lowest temperature recorded	-42 degrees Celsius

Results and field experiences

The results from the deployment of the 1st generation climate kit showed an average stack life time of about 9000 hours of operation. Generally, the climate kit enabled the systems to operate from temperatures down to -42 degrees Celsius up to temperatures of +45 degrees Celsius. However, the operation of the systems was not without challenges. The major problem experienced for the installations was condensation forming caused by the low operating temperature, that lead to early degradation of the affected fuel cell stacks. The consequences of this issue are illustrated on Figure 3. The experiences from the deployment of the 1st generation climate kits showed that the water balance challenges must be resolved before the product can be considered sufficiently mature for large scale installations.

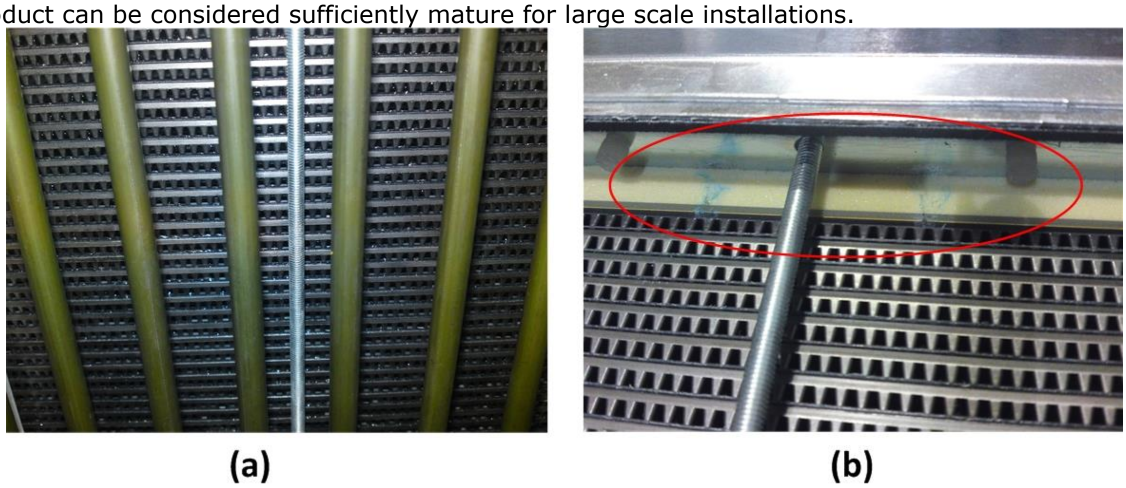


Figure 3: Illustration of stack damage caused by condensation issues. (a): Stack with cathode channels partially blocked by liquid water. (b): Cell damage caused by air starvation

Marketing study

Dantherm Power has done a marketing study based on experiences from installed systems in the field. Installations in the field include:

- fuel cell systems running continuously under extremely cold conditions in Canada during winter
- Fuel cell systems running several hours per day under extremely warm conditions in India during summer
- Fuel cell systems mostly in stand by for very infrequent backup power
    - in Norway under extremely cold conditions
    - in India under extremely warm conditions

This variety of extreme external conditions has led to a much better understanding of both performance of the fuel cell systems and requirements for the fuel cell systems.

Common for all applications has been the focus on reliability and the ability to work under different climatic conditions without compromising operation.

Specification for 2nd generation Climate Kit

The experiences from the deployment of the 1st generation climate kit led to the following set of specifications for the 2nd generation cold climate kit:

Primary requirements:

1. The CCK is to fit within a standard 19" rack. Maximum dimensions for the CCK is (W x H x D): 455 x 440 x 650 mm.
2. The CCK must be able to extend the ElectraGen-H2 1,7 kW lower operating temperature range to:
    a. constant operation at -30°C
    b. 12 hours at -40°C
3. The CCK should only operate during cold periods - to reduce power consumption plus wear and tear
4. Low electric power consumption (standby < 5 Watts and operation < 20 Watts)
5. The ElectraGen-H2 1,7kW with CCK must be able to full fill power demands in the range from 500 Watts to rated power output EOL 1,4kW continuously – meaning that additional loads can be applied to maintain the recommended stack temperature.
6. Noise and vibrations from the CCK must be avoided
7. Corrosion resistant coatings
8. Product life must be 15 years
9. Operating lifetime for the CCK in backup applications are 840 hours (24h x 7d x 5y = 840h)

10. Operating lifetime for the CCK in prime-power applications are 5000 hours (stack lifetime 10.000h)
11. Must be able to keep the EG-H2 1.7kW warm/ready for startup, if the grid fails and the site is powered by batteries for a period before the EG-H2 system starts up
12. Alarm output if the gear motor in the CCK fails
13. The CCK must be easy to couple with the Fuel Cell module and subsequently install in an Enclosure
14. Service intervals every 5 years
15. The valve block and purge system must be able to operate at the same temperatures as the CCK (constant operation at -30°C and consecutively at -40°C for an uninterrupted period of 12 hours)
16. Cost target is 850 Euro

Secondary requirements:

17. It is allowed to de-rate the power output from ElectraGen H2 1,7kW when operated > 40°C ambient temperature, to compensate extra complexity and cost to the CCK solution
18. The air intake to the CCK is located on the front for the CCK and the exhaust will exit on the backside
19. The electrical interface/connections must be on the front of the CCK
20. Operation down to -50°C for 2 hours
21. Air inlet filtering might be necessary

WP3: Fuel cell characterization and optimization

This work package focuses on developing a thorough understanding of fuel cell behavior under extreme climate conditions. A common challenge of cold and hot conditions relates to the dry operating conditions typically associated with extreme temperatures (both high and low).

Task 3.1. Detailed modeling

AAU has world-leading modeling capabilities that can shed light into water management of low temperature PEMFC as well as sophisticated multi-dimensional CFD simulations of complex geometries. The following tasks were completed:

- CFD simulations of experiments to understand the water balance in a PEMFC (T. Berning, S. K. Kær). In this task we used our world-leading computational fuel cell model to understand the water balance in a PEMFC under various operating conditions. Ballard Power System provided the experimental results for the fuel cell water balance for different types of porous media used in the fuel cell and under different operating conditions. With our multi-dimensional, multi-phase model we were able to match the experimental water balance data to a very satisfactory level. In particular, we were able to explain experimental data that were appeared to be counter-intuitive.

  It was concluded that thermal effects in those experiments played a dominant role which was previously unknown. Overall, we were able to explain qualitatively all experimental data but quantitative agreement was lacking in some cases. Because it would have taken a substantial amount of time to fully match the water balance data, we decided it is not worth the effort and concluded that we understand the experiments and can explain the results.

  One problem was that there are a large number of sensitive parameters that we need as input parameters in our model, and not all of these parameters were known in the experiments.

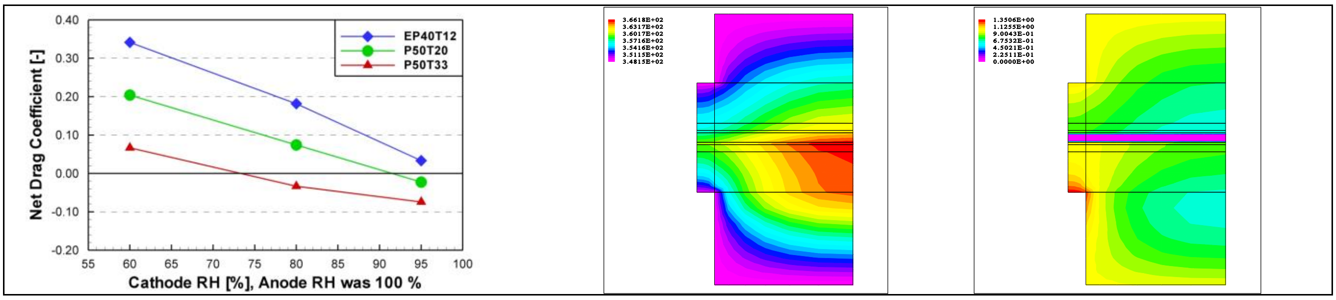


Figure 4: Water balance experimentally obtained by Ballard Power Systems (left) for different humidity levels of the cathode flow (x-axis) and different types of porous media. The porosity of the cathode side porous media played an important part in the water balance and this was qualitatively well matched by our model (not shown). However, our CFD results also indicate that there was a very substantial temperature increase inside the fuel cell and the temperature of the membrane-electrode assembly was close to 100 °C and thus very far from the nominal temperature of 75 °C (middle). This led to a very different distribution of the relative humidity inside the fuel cell (right); the values were again very far from the nominal RH values as listed in the

graph on the left. Thus, thermal effects played a very important role in those experiments, and the number of highly sensitive material parameters was accordingly high. Therefore we were satisfied with being able to explain the general trend and did not further try to exactly match the water balance data.

- A computational fluid dynamics study of the Dantherm telecom back-up unit (X. Gao, T. Berning, S. K. Kær)
  The new Dantherm unit for telecom back-up was introduced around half-way through the project. It has two Ballard fuel cell stacks arranged in V-shape and a centrally placed fan that is sucking the air through. Dantherm had removed the rotating heat exchanger that caused a lot of problems and added an electrical pre-heater. The unit also includes a by-pass to ensure a sufficient air-flow rate to satisfy safety requirements that the hydrogen has to be sufficiently diluted in case of a pipe rupture.

  Therefore, a certain amount of air flows through the fuel cell stack and there is a secondary air stream through a bypass hole in the top of the compartment behind the stacks that mixes with the fuel cell outlet air. The exact size and location of the air-bypass holes have been so far found by Dantherm by trial and error, and AAU has started to conduct three-dimensional simulations of this system using the commercial CFD solver Fluent. The detailed investigation included the role of the air filter in front of the cathode side fuel cell on the flow distribution, the three-dimensional temperature distribution inside the entire unit, the role of the flapping doors that have been added to the fuel cell system.

  Importantly, the temperature distribution over the height and width of the fuel cell stack was modeled and verified experimentally by Dantherm. It is important to understand the temperature distribution because there are restrictions concerning the temperature spread over the fuel cell given by Ballard. So far, the qualitative agreement between the experimentally measured temperature distribution at the fuel cell outlet and the calculated temperature distribution is very good, but there are still quantitative discrepancies in that the temperatures measured by Dantherm are generally a few degrees higher than the ones that were calculated with the CFD code. We have concluded for now that more work will be needed to obtain a better match. In particular, the assumption of having thermal equilibrium between the gas phase and the fuel cell stack which is modeled as a porous medium might not be accurate and may need to be revised in the future.

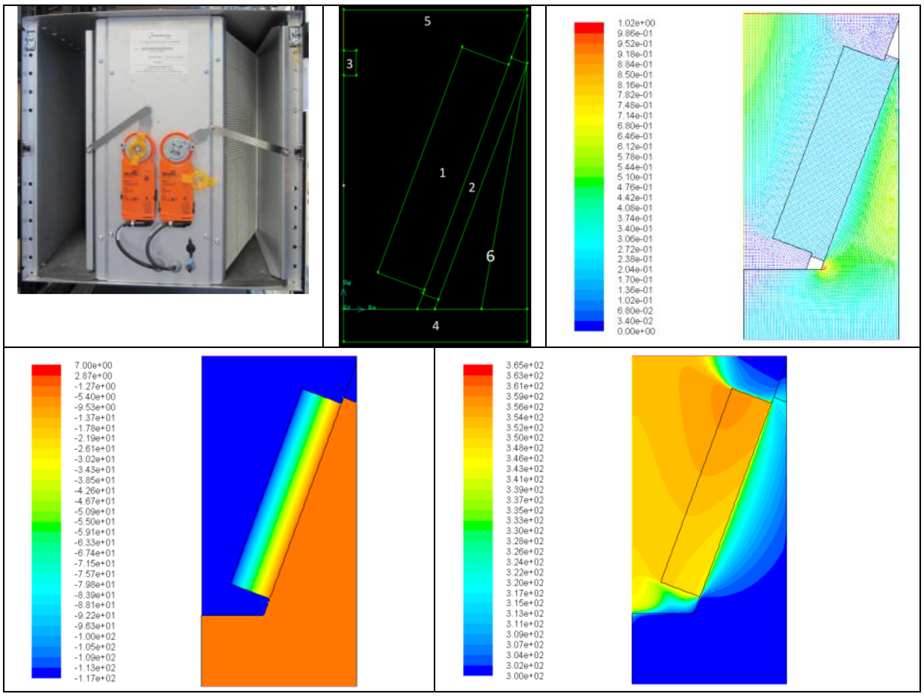


Figure 5: 3D computational modeling of air-flow through the new Dantherm telecom back-up unit (upper left). The model geometry was drawn "from scratch" (upper, middle) including the air-bypass hole in the top of the box and the flapping doors that are controlled by a step motor. Due to symmetry, only half the domain needed to be simulated. The calculated flow distribution (upper, right), pressure distribution (lower, left) and in particular the temperature distribution (lower, right) give very important insight into the module design. The goal is to use such a CFD model as a predictive tool, but currently there is still a mismatch between the calculated temperature distribution and the experimentally measure temperature distribution at the stack outlet. This might be caused by the assumption of having a thermal equilibrium between the air and the fuel cell stack that is modeled as a porous medium.

While this activity provided a lot of insight and was considered a very useful contribution to the project, more work is needed to use this CFD model as a predictive tool. We considered it a “stretch target” to obtain a full 3D model of the Dantherm unit including the flapping door and the bypass hole, and the model development and numerical behavior was very satisfactory. However, more work would be needed to obtain a better match and make this model a predictive tool.

- A thermodynamic analysis of an air-cooled fuel cell under extreme climate situations (T. Berning, S. K. Kær).
  A first-law analysis of an air-cooled fuel cell was developed in order to study whether it is feasible to operate a PEMFC under challenging conditions. Essentially, the coolant air has to absorb all the waste heat produced by the fuel cell, and this allows for the calculation of the adiabatic outlet temperature of the fuel cell. Originally, we believed that this relates closely to the fuel cell operating temperature, but the CFD analysis described below suggested differently. The figures below (figure 6) show the dependency of the temperature of the outlet gases, the operating cell voltage and the cathode stoichiometric flow ratio which in practice is adjusted by the fan speed under different operating conditions. The following findings were made:
  i. By carefully adjusting the fan speed, there should be a working point for any type of ambient conditions, i.e. the fuel cell should work, in principle, in any climate region, see Figure 6. At a standard ambient temperature of 20 °C the stoichiometry should be around 50 to obtain a reasonable cathode outlet temperature of 50 °C whereas when the outside air is -20 °C the stoichiometry should be adjusted to around 20 to reach the same air outlet temperature. These values depend on the cell operating voltage and experients are required to fine tune these values. However, these values give no insight of the internal temperature distribution or water distribution of a fuel cell.
  ii. From a thermodynamic perspective there is no reason why a fuel cell should not work at either very cold or very hot conditions (dry or humid). Even at an outside temperature of 40 °C reasonable working points can be found if the stoichiometric flow ratio is sufficiently high (60-70). This, however, is not in agreement by observationd made by Dantherm who state that the fuel cell does not work under hot and dry conditions. This can suggest that the problem is related to fuel cell start-up under extreme conditions, not steady fuel cell operation.

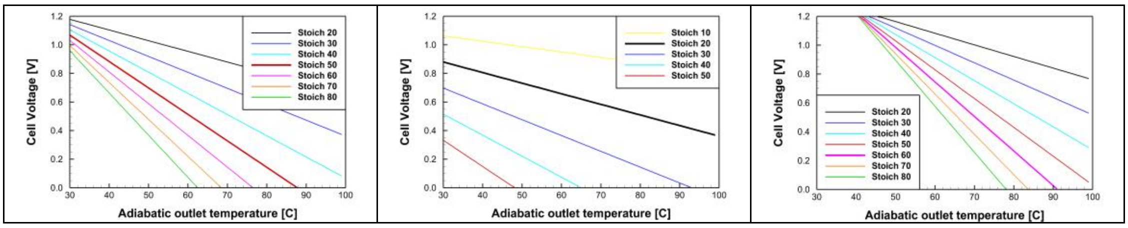


Figure 6: Thermodynamic diagrams resulting out of a first-law analysis. The adiabatic outlet temperature of the reactant gases can be adjusted by the stoichiometric flow ratio and by knowledge of the cell voltage. At standard operating conditions of Tin = 20 °C and an RH value of 30%, a cathode side stoichiometric flow ratio of 50 yields a reasonable outlet temperature (left). When the incoming air is at -20 °C and 0% RH (middle), the fuel cell may still operate but the stoichiometry has to be very carefully adjusted at a value of around 20-30. If the incoming air is at 40 °C and at only 20% RH (right), the stoichiometry has to be very high, but still from a thermodynamic perspective there is a reasonable working point.

While this thermodynamic analysis gives very useful insights into the ability of operating an air-cooled fuel cell stack in extreme climate regions, it does not provide information about the exact temperature distribution and e.g. the membrane hydration. Therefore, a CFD analysis of the air-cooled fuel cell was conducted as well.

- A three-dimensional, multi-phase computational analysis of an air-cooled fuel cell (T. Berning, S. K. Kær)

After suitable operating conditions of an air-colled fuel cell for different climate regions were identified using the thermodynamic analysis described above, a computational fluid dynamics analysis of the fuel cell operating under such conditions was conducted. It should be stated again that the ET-AAU computational fluid dynamics model based on CFX-4 has several world-leading features including the description of multi-phase flow through the different porous layers (including the catalyst layer, the micro-porous layer and the gas diffusion layer). Morever, our code accounts for the water transport through the membrane in a unique (and correct) way. Therefore, it is the world-leading tool to model the fuel cell water balance. While this study was conducted at the very end of the project, it has shed valuable insights into air-cooled fuel cell operation, including:

i. The fuel cell membrane is predicted to be almost perfectly hydrated under all conditions investigated. There is no need for an external humidifier. Even for the high ambient temperature of 40 °C and at very low inlet RH the membrane was predicted to be very well hydrated.

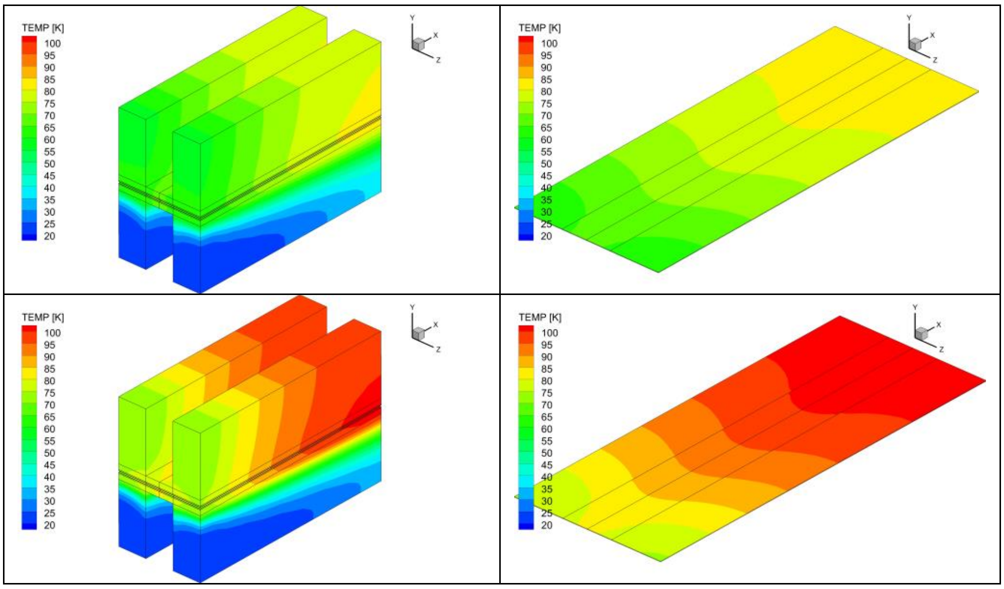
ii. The anode side of the air-cooled fuel cell was predicted to be at a nearly constant level of full saturation, i.e. the relative humidity was very close to 100%, but no liquid water was predicted at the anode side. This is very important for the understanding of the fuel cell water balance, as the results suggest that the anode leaves at 100% RH at the local anode outlet temperature, and this essentially says how much water escapes from the anode.

iii. The cathode side is predicted to be “wet”, i.e. there is liquid water predicted to leave the cell through the cathode channels. This is in agreement with experimental observations made by Dantherm. In addition, the cathode side porous media are predicted to be uniformly filled with liquid water up to the level of the irreducible saturation. In practice, the irreducible saturation depends on the TFPL (Teflon) loading.

iv. Under all conditons investigated, there is a very strong temperature increase with increasing current density. Already at a current density as low as 0.3 A/cm2 the local temperature of inside the membrane-electrode-assembly is predicted to exceed 100 °C. It is in good agreement with experiments that the maximum current density that can be drawn from the current Ballard stack is only around 0.3 A/cm2 (around 60 A stack current), and a question is, what is limiting this current. While the membrane was predicted fully hydrated, and there is still sufficient oxygen in the cathode catalyst layer at this low current, it appears that it is in fact this very high temperature in the MEA that is limiting the maximum current. If we would find ways to avoid this peak temperature, we might be able to go to much higher fuel cell currents and consequently obtain a higher power density. Currently the power density is only around 0.25 W/cm2 (which results in 40 W per single cell or 2 kW for a 50-cell-stack). This very low power density means that the catalyst utilization is very low. It should be a goal to substantially increase the maximum current density from this stack and thereby the power density to at least 0.5 W/cm2. This would mean that the stack size could be cut in half. Therefore, it is very important to understand the physical mechanisms that are limiting this current density, and from the CFD calculations the biggest problem is the very high predicted local temperature which will have to be addressed in the future. Dr. Berning has submitted an AAU internal Invention Disclosure which may lead to a potentially important patent application which can currently not be disclosed.

After the invention has been disclosed and potential patenting has been brought on the way, it would be very useful and even required to conduct experimental work to prove that the maximum cell current and thereby the cell power density can be very substantially increased.

A final note of caution is that these results were obtained for the steady-state case, i.e. the start-up procedure can currently not be modeled. Therefore, for cold conditions an electrical pre-heater may be required to warm up the fuel cell stack before steady-state is reached.



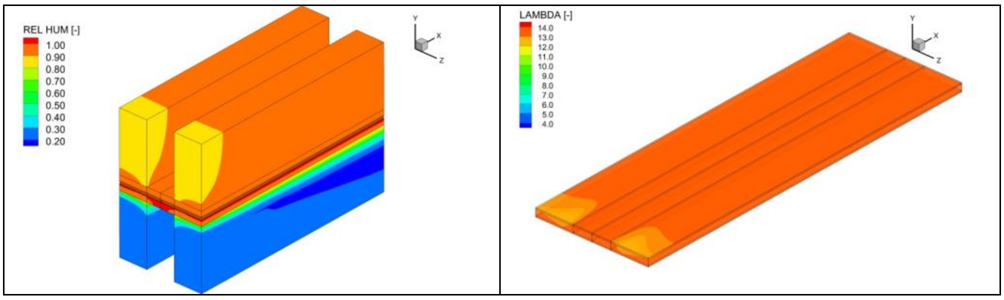


Figure 7: Sample results for an air-cooled fuel cell stack operating at standard conditions (20 °C inlet temperature, 30% inlet RH, cathode stoich 50, anode stoich 1.1, open-ended). Upper: Predicted temperature distribution at a current density of 0.2 A/cm2 in the entire cell (left) and in the cathode catalyst layer only (right). The lower part of the cell is the cathode and the upper part is the anode. Middle: Predicted temperature distribution at a current density of 0.3 A/cm2 in the entire cell (left) and in the cathode catalyst layer only (right). It can be seen that already at such a low current density the local temperature is expected to exceed 100 °C which will drastically reduce the cell performance. Lower: Predicted relative humidity distribution at a current density of 0.3 A/cm2 in the entire cell (left) and calculated membrane water content (right). The RH is predicted to be very uniform and at a very high level at the anode side of the cell while the cathode side shows a very strong gradient. The membrane is predicted to be nearly perfectly hydrated at a level of Lambda = 14. This is important because it means that no external humidifier is required, and it was observed under any conditions investigated.

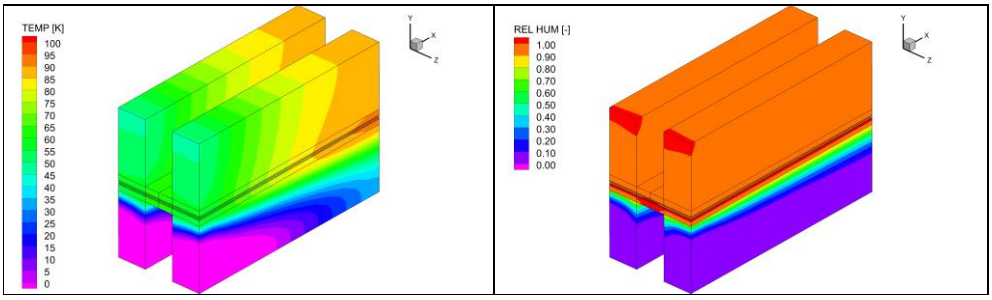


Figure 8: Predicted temperature distribution (left) and RH distribution (right) inside the air-cooled fuel cell for an inlet temperature of -20 °C and an inlet RH of 0%.The cathode side stoichiometry was set to 20, taken from the thermodynamic diagrams shown above. The current density is 0.2 A/cm2. There is a very strong temperature gradient predicted inside the fuel cell. The channel length is 70 mm and it is questionable whether that high temperature gradient over such a small distance may lead to mechanical issues. The relative humidity is predicted high in the MEA and the membrane is fully hydrated.

- Additional modeling activities (T. Berning)

In addition to the above-mentioned activities, work was carried out earlier in the project to improve the convergence behavior and demonstrate the capabilities of our computational fuel cell model.

- Link to PSO project PEMCFD (P.nr. 12041): Development of a model for PEM Fuel Cells (T. Berning)

A separate research grant was obtained by Dr. Berning from Energinet.dk to further develop and validate the existing computational fuel cell model. The nature of that project was more research oriented, and a post-doc was employed to conduct experiments. Already in November 2011 Dr. Berning had submitted an invention disclosure at AAU that describes a new method to measure the fuel cell water balance by placing a hot wire sensor into the anode outlet. Until then, the preferred method to measure the fuel cell water balance was to condense the water in the gas stream that exit the cells and weigh the amount of water after a sufficient amount of time has elapsed. This method is thus time consuming and is lacking accuracy. By placing a hot wire sensor in the anode outlet, the water balance can be detected ad-hoc and almost in real time, thus saving valuable time on expensive fuel cell test stations.

During course of the Energinet project it became desirable to measure water balance data on an operating fuel cell stack. We obtained two Ballard fuel cell stacks from Dantherm and we defined it a stretch target in the PEMCFD project to obtain water balance data of the Dantherm/Ballard fuel cell stacks.

<u>Task 3.2. Experimental characterization</u>

Early in the project, Ballard provided AAU with water balance data obtained under different fuel cell operating conditions using different types of porous media. These porous media were very thoroughly characterized, and we needed the material properties as input parameters for our numerical model.

Task 3.3. Manufacturing of improved cells
Unfortunately, Ballard Power Systems was quite inactive during the remainder of the project and while they developed new and improved cells, this was done without our valuable input. Moreover, we have made the very important CFD simulations of the air-cooled fuel cell only very late in the project phase (they were not required according to the project specification).

Once AAU has started the patenting process (if our invention is patentable) we will contact Ballard and Dantherm about a potential proof of concept that our invention works. We believe that our invention has the potential to substantially increase the fuel cell power density and thereby allow for smaller stacks with according savings.

WP4: Development of a 2nd generation climate kit

This work package concerns the core activity of the EXC-CELL project, the development of a second generation climate kit and fuel cell system.

Task 4.1: System level simulations
- A thermodynamic system analysis of the previous Dantherm telecom back-up unit (X. Gao, T. Berning, S. K. Kær).
  Early in the project we had a meeting where Dantherm presented the major problems of their (previous) telecom back-up unit which showed that under cold operation there is ice/snow building up in the rotating heat exchanger which caused system shut-down after only 20 min. The role of the heat exchanger was to pre-heat and pre-humidify the incoming air ("enthalpy wheel"). We decided to add man-power to the project in person of Dr. X. Gao, and he started to develop a thermodynamic system model using the Engineering Equation Solver (EES) software. A schematic of the system is shown below.

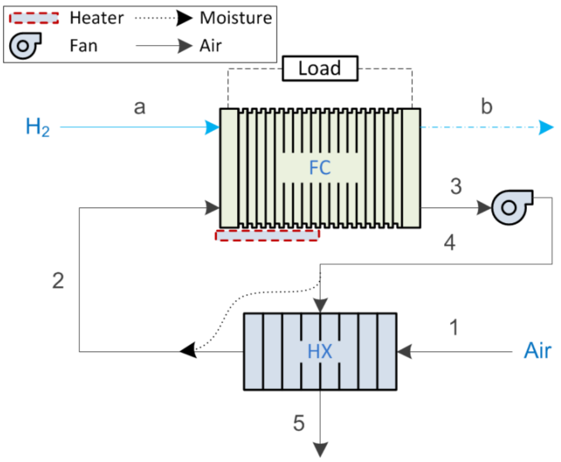


Figure 9: Schematic of the thermodynamic system model.

  The major finding of this study was in accord with Dantherm's believe that the amount of water vapour transferred from the air that is leaving the fuel cell to the incoming air is very small in cold climate. The zero-dimensional, thermodynamic model that was built by Dr. Gao was very complex and he managed to reproduce and predict the results obtained by Dantherm to a very good degree. However, mid-way through the project Dantherm changed the system design and removed the rotating heat exchanger, partly due to the finding that it did not contribute to humidify the cell.

  Note also that towards the end of the project we conducted a detailed CFD study of the air-cooled fuel cell, described below. The results suggest that ideally, there is neither a need for an external humidifier, nor a need for a pre-heater after the fuel cell has started up. However, during the start-up phase under cold conditions a pre-heater is most likely required.

Task 4.2. Control and diagnostics
This task was about estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by impedance measurement and impedance measurement circuit. It dealt with correlation between the impedance and the relative humidity of the fuel cell membrane in determining the fuel cell's start-up time

Fuel cell-based backup units are characterized by long standby periods but they must be ready to start at any instant in the shortest possible time. In the case of low temperature proton exchange membrane fuel cells, the estimation of the hydration status of the fuel cell's membrane during standby is important for determining the cell's ability to perform a fast and safe start-up. In work package a non-conventional electrochemical impedance spectroscopy (EIS) was suggested and investigated as a method to estimate the membrane's hydration status. The proposed technique differs from standard EIS in that the current through the fuel cell cannot contain a DC component, since hydrogen is absent.

In brief the idea was to symmetrically feed with air a fuel cell stack, whose temperature and relative humidity are controlled, and its complex impedance is measured at different frequencies and for different values of relative humidity at constant temperature. Power regression models can be applied to the data, and the relationships between complex impedance and relative humidity can be found.

The results show how the proposed technique is a viable way for estimating the membrane hydration status of a fuel cell stack during standby. Moreover, the most suitable frequency values at which the measurements should be performed can be defined.

<u>Impedance Measurement Circuit for offline measurements</u>
The focus of this work was to build a cheap, fast and accurate device to estimate the impedance of a fuel cell stack. The setup consists of the fuel cell or the Fuel Cell Emulator (FCE), the Impedance Measurement Circuit (IMC) as shown in Figure 10 and a PC with a graphical user interface (GUI) to observe and collect data. A block diagram of the setup is shown in Figure 11.

The IMC was designed and built to be able to represent the sinusoidal voltages of interest as DC voltages which can be read by the microcontroller. This is done using as few components as possible in order to keep the price low. In order to test the device, a fuel cell stack emulator was required, as the actual fuel cell stack was not available at all times. For this purpose, a FCE is designed and built. The FCE is able to achieve up to 128 different impedances ranging from 0.09 to 2.62 Ω. The main circuit consists of a voltage supply, the fuel cell or fuel cell emulator and a reference resistor (Figure 12).

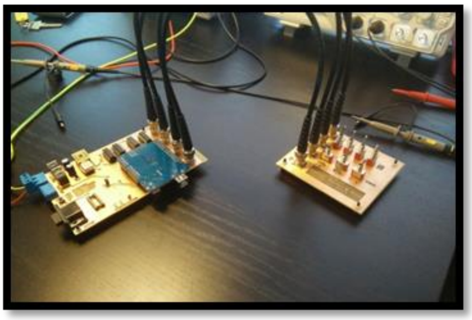


Figure 10: Impedance Measurement Circuit (IMC) board with the Fuel Cell Emulator (FCE)

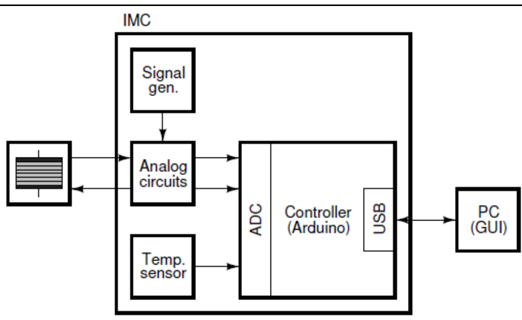


Figure 11: Block diagram of the impedance measurement circuit (IMC) connected to a fuel cell stack and a personal computer (PC) running a custom-made graphical user interface (GUI).

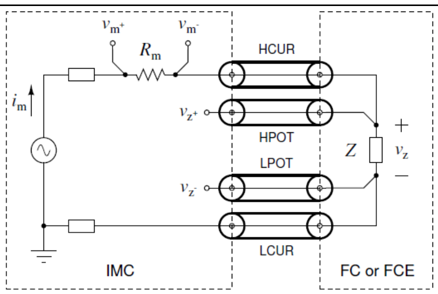


Figure 12: Basic measurement circuit.

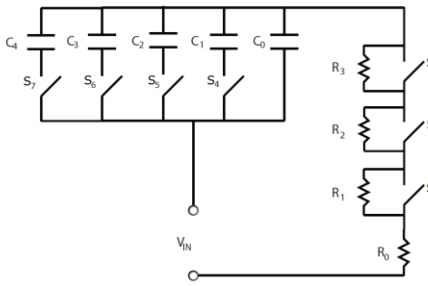


Figure 13: The FCE board

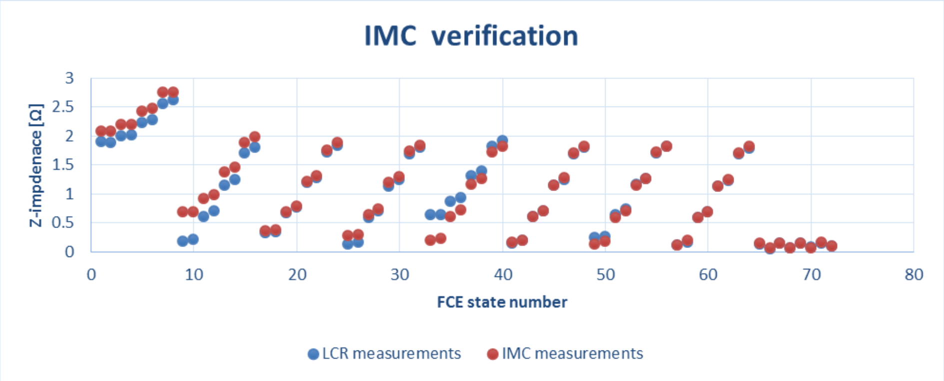


Figure 14: Comparison between IMC and LCR measurements on FCE

It should be noted that the C and R parameters of the FCE (Figure 13) are old and drifting can occur since the beginning of measurements. The FCE impedance should decrease with state number, but it is not the case for the LCR measurements. Therefore the current measurement points cannot be used to determine the accuracy of the IMC, but proves the performance improvement of the auto ranging feature of the IMC compared to previous versions (this is actually the version number 3).

The IMC measurements show that it is able to measure impedances below 100mΩ with decent accuracy as well as impedances in the 2-3Ω range. The measurements made with IMC are compared to the ones done by the LCR-meter (Figure 14). In the low impedance range, the comparison yields positive results and the relative error is below 25 %. However, at higher impedances, some of the IMC-measurements vary from the LCR-measurements to a degree that is considered unacceptable.

Future work possibilities

- Build up a setup and measure the start-up time with similar climatic conditions of an on-line fuel cell stack (with H2)
- Derive a mathematical correlation between the offline measurement results (impedance, RH and T) and the online measured start-up time with the same environmental conditions.

Task 4.3: System construction

Based on the findings in WP2, a specification for the 2nd generation climate kit was developed. Based on this specification, development of the 2nd generation of climate kits was initiated.

Identification of components and climatic characterization

The experience gathered in WP2, lead to the conclusion, that the system in order to operate reliably at low temperature required a heat exchange to take place from the warm system exhaust to the cold air intake to the system. Managing this heat exchange, however, turned out not to be a trivial task as the warm exhaust contains a large amount of water coming from the recombination of hydrogen and oxygen into water taking place in the fuel cell. This led to a number of tests conducted in order to identify the optimal type of heat exchanger for the climate kit. Initially either a cross flow or counter flow heat exchanger was considered to be the optimal choice of heat exchanger, but the testing showed that both counter and cross flow exchangers were impossible to use because of ice formation plugging up the heat exchanger. A picture taken during the testing performed is illustrated on Figure 15.

Figure 15: Both cross and counter flow heat exchangers turned out to have icing problems because of the water content in the cathode exhaust stream.

The testing of different means of exchanging heat from exhaust to intake ended up with the selection of a rotary heat exchanger, which is the type of heat exchanger that can tolerate the highest amount of moisture content without suffering from icing problems. Even the rotary heat exchanger could not handle the moisture content without problems, though, as the initial testing seemed to rule out even this type of heat exchanger because of icing problems. This is illustrated on Figure 16.

Figure 16: Even a rotary heat exchanger proved to be prone to icing issues when operated in a conventional manner.

The problems with heat exchanger icing led to the development of a control method, in which the rotational speed of the heat exchanger, and thus the efficiency of the heat exchange could be controlled via a control algorithm developed during testing of the system. This is described in more detail in Appendix 1 along with the printed circuit board that was developed in order to control the climate kit. The hydrogen supply manifold for the system also had to be adapted for extreme climates, and was tested and a key component on the manifold was changed in order for the manifold to function in extreme climates. The manifold was tested in the range from -50 degrees to +70 degrees at the test facilities at Aalborg University.

<u>Construction of prototype</u>
Following the component identification and climatic characterization, the prototype was constructed. The operating principle of the constructed climate kit is illustrated on Figure 17. The climate kit has the following advantages:

- The efficiency of the heat exchange between inlet and outlet can be controlled to counter the formation of ice in the heat exchanger (see Appendix 1 for more details)
- For hot climates, the heat exchanger can be disengaged in a simple manner by stopping the rotation of the thermal wheel

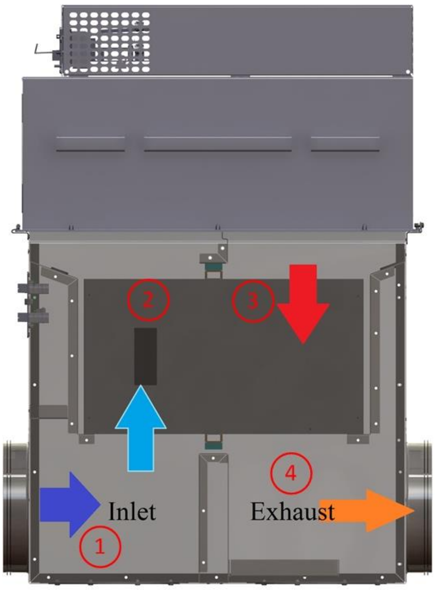


Figure 17: The operation principle of the developed 2nd gen climate kit. 1: cold intake air enters system. 2: Intake air is preheated by the rotating mass of the heat exchanger. 3: hot exhaust air is transferring heat to the thermal mass of the rotary heat exchanger. 4: cooled exhaust air is exhausted out of the system.

After completing the 3D construction of the prototype, the prototype was built up and prepared for testing. The prototype is illustrated on Figure 18.

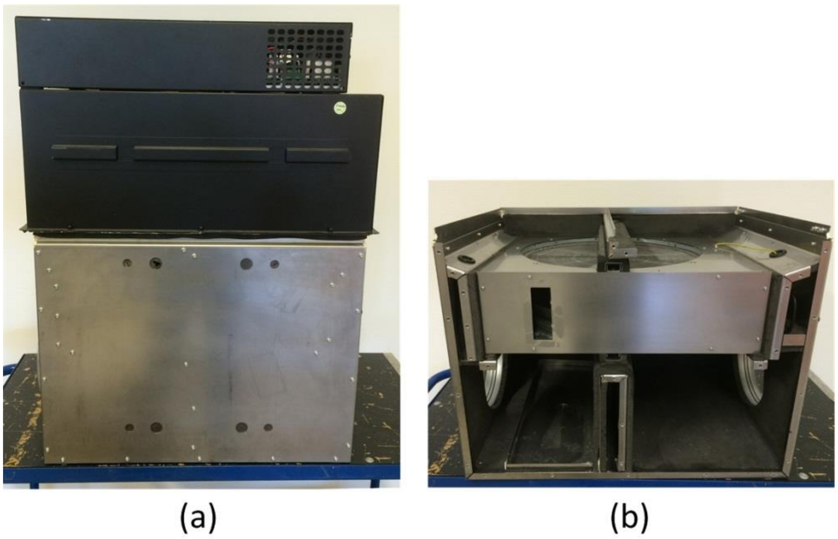


Figure 18: Picture of the 2nd generation climate kit constructed. A: Climate kit with backup power system mounted on top. b: Climate kit shown stand-alone without cover plates, exposing the rotary heat exchanger.

<u>WP5: Testing of the 2nd generation climate kit</u>

In order to verify that the climate kit was working according to the specification, the system was installed in the testing facilities at Cemtec. In order to make the test as realistic as possible, the system was installed in an environment with an ambient temperature of about 10 degrees Celsius, simulating a typical winter temperature in a telecom shelter. The system was set to receive the intake air from a cooling container making it possible to supply a stable temperature at about -32 degrees Celsius. The test setup is illustrated on Figure 19.

Figure 19: Illustration of the climate kit installed in the climate chamber. The system is installed in a temperature of about 10 degrees Celsius, drawing intake air from the cooling container at about -32 degrees Celsius.

The result of the testing is that the system operated stably during a 32 hours test period without any build-up of ice or condensation water in the heat exchanger. A plot showing the stack temperature vs. inlet air temperature during the test is illustrated on Figure 20. The temperature spikes on the inlet temperature come from a 10 hour deicing cycle from the cooling container.

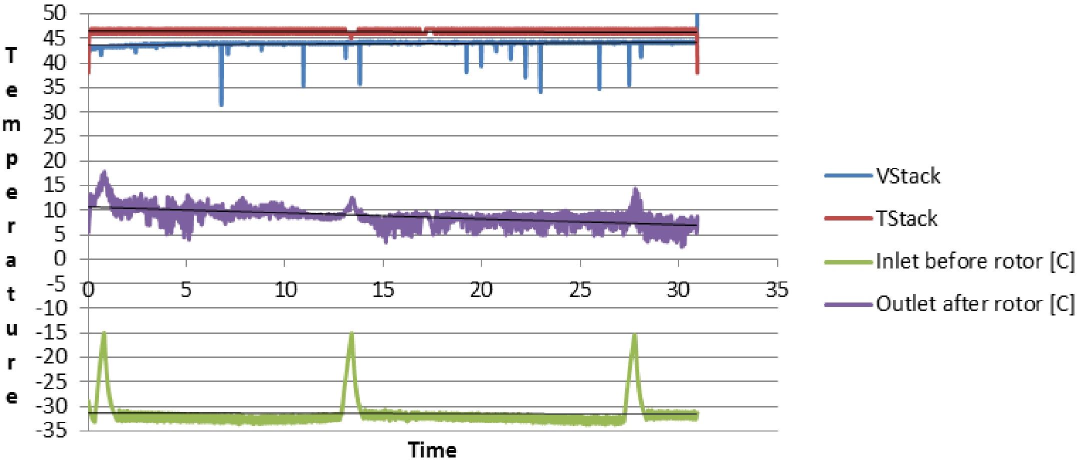


Figure 20: Plot of stack temperature versus inlet temperature from a 32 hours continuous test.

In order to verify the other end of the temperature spectrum, the system was tested in hot climate as well. The test results from these tests are presented on Figure 21. The test showed that it was possible to keep the optimal temperature for the fuel cell stack while operating at a load of 1500W with an inlet temperature of 42 degrees Celsius.

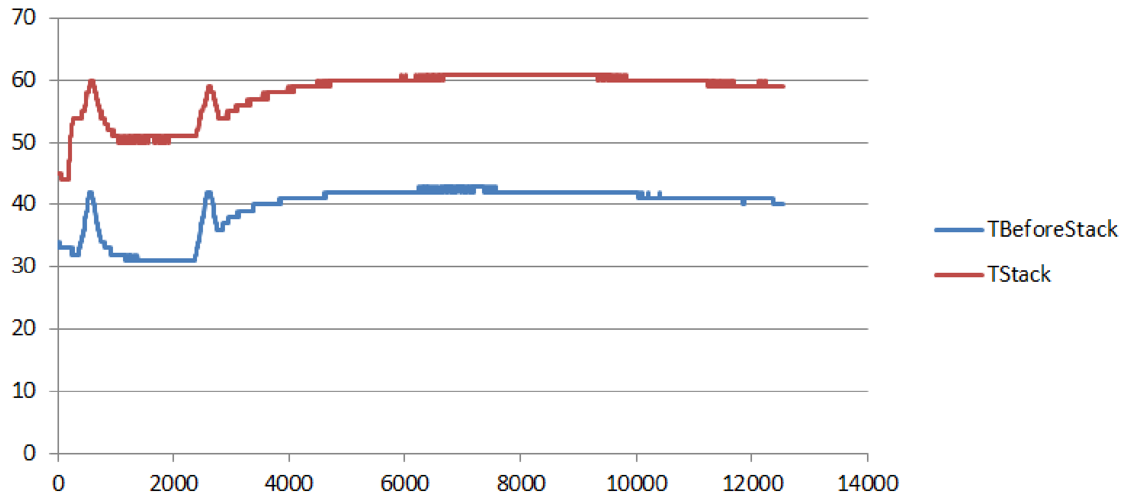


Figure 21: Plot of stack temperature versus inlet temperature from a test with high inlet temperature

The conclusion of the testing is that the climate kit is able to handle both high as well as low temperatures well.

WP6: Commercial activities

Task 6a.1: Preparation of market introduction
In order to prepare the market introduction of the climate kit, the climate kit was included into the product documentation for the hydrogen backup products. This documentation is enclosed as deliverable D6.3.

Task 6b.1: Market and competitor investigation
The potential market has been explored by help of available GSMA market data. It has been corrected by specific analysis in several markets and condensed into a total market segment of:
Total number of telecom sites globally: 3.800.000 sites

The total market size for base station towers has been corrected for number of towers with low requirements on backup power and towers where fuel cells with current cost of fuel cell systems and current cost of hydrogen, will not be competitive.
Total number of sites where fuel cells on bottled hydrogen are competitive: 190.000 sites
With increasing requirements on backup time on base stations, lower costs of fuel cells and increasing availability of hydrogen with lower cost, the total market size where fuel cells are competitive is increasing fast.

The competitive landscape of fuel cell solutions for telecom backup has been analyzed.
Current competitors on the market for hydrogen based backup power fuel cell systems for telecom have been identified. Products from each competitor have been evaluated on a number of important parameters in order to assess the competitive situation and also evaluate priorities on the different competitors.
The result of the product offering analysis shows a large variation on each parameter. This can be related to either uncertainty of where to focus on product offerings or it can reflect in some cases lack of ability to meet the offerings that the market needs.

Task 6b.2: Business plan
Business plan has been developed based on the findings in this project and findings in parallel in other projects and commercial activities.

WP 7: Construction of 3rd generation climate kit

Task 7.1: system construction
In order to further improve the performance of the climate kit – both at low and high ambient temperatures, a 3rd generation climate kit was developed. The operating principle of the climate kit is based on bypassing the cathode air stream at low temperatures. This has several advantages over the heat exchange principle of the previous generation climate kits, the main advantages being:

- Better performance at high temperatures

- More simple principle – lower cost
- Potential icing issues with heat exchangers can be entirely avoided

The cold climate kit that was developed and built is illustrated on Figure 22. From the figure, it can be seen that the climate kit consists of a bypass module and an optional preheater module for extreme low temperatures.

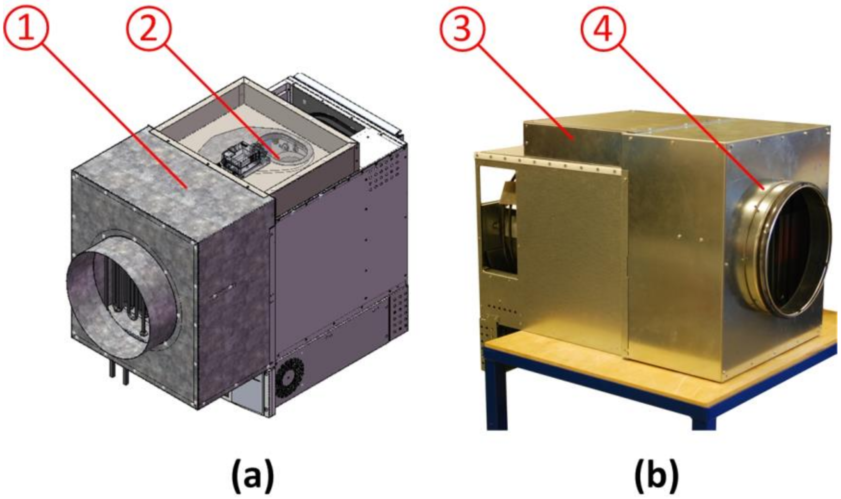


Figure 22: (a) 3D representation of the climate kit. (b) Picture of the constructed prototype. (a)1, (b)4: preheater module. (a)2, (b)3: bypass module

The internal air flow of the climate kit is illustrated on Figure 23. On this figure, it can be seen, that the bypass module allows part of the cathode fan air to be bypassed around the fuel cell stack, thereby lowering the cooling of the stack without reducing the overall air flow. In the event that bypassing the cooling air is insufficient to operate the stack at extremely low temperatures, the CCK has an additional option of preheating the inlet air to the fuel cell stacks using resistive heaters. At high temperatures, the climate kit has the advantage, that it (unlike a heat exchanger based solution) does not restrict the cooling air at all, thereby providing better performance at high ambient temperatures.

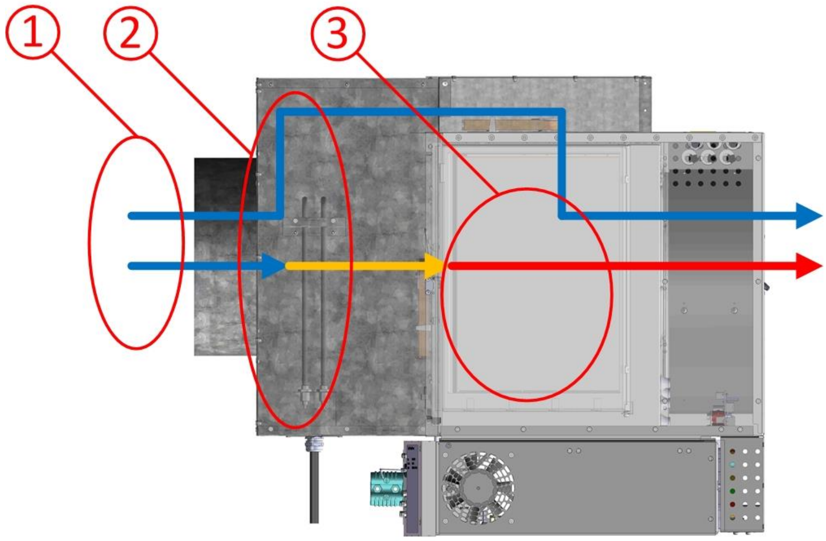


Figure 23: Illustration of the air flow inside the climate kit, explaining how the kit helps the system to operate at low ambient temperatures. 1: intake of cold process air. 2: Bypass of part of the process air and pre-heating of the air going through the fuel cell stack. 3: The fuel cell stack is now able to reach nominal operation temperature.

Task 7.2: Testing of the 3rd generation climate kit
In order to assess the performance of the climate kit developed, it was tested at Dantherm Power's laboratory facilities at Cemtec. The testing consisted of a measurement of the bypass module's ability to bypass the cathode air stream.

Air flow without bypass	Air flow with bypass
182 m3/h	127 m3/h

As can be seen from the table above, the bypass module allowed to reduce the cathode air stream by 30%, which based on the measurements performed earlier in the project in the climate chamber, would be sufficient to operate the system at the specified temperatures. A picture from the testing of the climate kit is illustrated on Figure 24.

Figure 24: Picture from the bypass testing performed on the 3rd generation climate kit at Cemtec

Dissemination of results

The following dissemination activities have been carried out in the project.

- Publications
- Conference Papers & Presentations
- Patents

Publications:
- T. Berning, S. Al Shakhshir: "Applying hot wire anemometry to directly measure the water balance in a proton exchange membrane fuel cell – Part 1: Theory", status: accepted, to appear in the Int. J. Hydrogen Energy.
- S. Al Shakhshir, T. Berning: "Applying hot wire anemometry to directly measure the water balance in a proton exchange membrane fuel cell – Part 2: Experimental", status: in preparation, to be submitted to the Int. J. Hydrogen Energy.
- S. Al Shakhshir, N. Hussain, T. Berning: "Employing hot wire anemometry to directly measure the water balance in a proton exchange membrane fuel cell", HEFAT 2015, 11th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, July 20-23, 2015, Kruger National Park, South Africa.
- B. Bidoggia and S. K. Kær, "Estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by complex impedance measurement: Constant temperature stack characterization," International Journal of Hydrogen Energy, vol. 38, pp. 4054-4066, 4/1/ 2013.
- B. Bidoggia and S. K. Kaer, "Estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by impedance measurement: First results on variable temperature stack characterization," in Ecological Vehicles and Renewable Energies (EVER), 2013 8th International Conference and Exhibition on, 2013, pp. 1-10.
- B. Bidoggia, M. Rugholt, M. Busk, M. Jensen, and S. K. Kaer, "Estimation of membrane hydration status for standby proton exchange membrane fuel cell systems by impedance measurement: First im-

pedance measurement circuit," in Ecological Vehicles and Renewable Energies (EVER), 2014 Ninth International Conference on, 2014, pp. 1-7.

Conference papers and presentations:

- T. Berning: "Multiphase simulations and design of validation experiments for proton exchange membrane fuel cells", Proceedings of the ASME 2013 Fluids Division Summer Meeting, FEDSM2013, July 7-11, 2013, Incline Village, Nevada, USA.
- T. Berning: "The effect of micro-channels in the MPL on the predicted membrane water content in a PEMFC – A modeling study", HEFAT 2014, 10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, July 14-16, 2014, Orlando, Florida, USA.
- T. Berning: "A study of thermal effects in a proton exchange membrane fuel cell with a two-fluid model", HEFAT 2015, 11th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, July 20-23, 2015, Kruger National Park, South Africa.

Patents:
Aalborg University is in the process to take out a patent for their findings and their solution to improve the heat management through the fuel cells.

1.6 Utilization of project results

The project has generally led to a better understanding of the importance of proper heat management in fuel cells and fuel cell systems. It has generated a lot of new knowledge and pointed out where to focus on further development and research activities going forward. Aalborg University is in the process to take out a patent for their findings and their solution to improve the heat management through the fuel cells.

The development and iterations of improvement on the climate kit have been proven commercially mature enough to be implemented in Dantherm Powers product portfolio for back-up power products and is being offered to customers.

1.7 Project conclusion and perspective

The project EXC-CELL successfully managed to develop and successfully test a second and third generation climate kit (CCK) to be added onto a standard back-up power system for installations in extremely cold and/or extremely hot regions. In addition, the simulation and modelling work on the fuel cells under these extreme conditions resulted in a much better understanding of the heat and water balance management inside the cells in general and improved the modelling tools significantly.

The new knowledge gained from this project revealed several opportunities for significant improvements on the fuel cell and stack design, which, going forward should/could be utilized to improve the overall fuel cell system not only for extreme climate situations but for all back-up power fuel cell systems for outdoor installations.

The climate kit design was chosen after several iterations of testing different heat exchangers in extremely cold climate, before settling on the final one. In a climate chamber at Dantherm Power the climate kit performed satisfactorily for temperatures down to -32 degreesC, which was the coldest possible temperature that the climate chamber could provide for.With small further adjustments the climate kit is prepared for commercial introduction by including it in the product portfolio of Dantherm Powers back-up power line for customers in extreme climate areas.

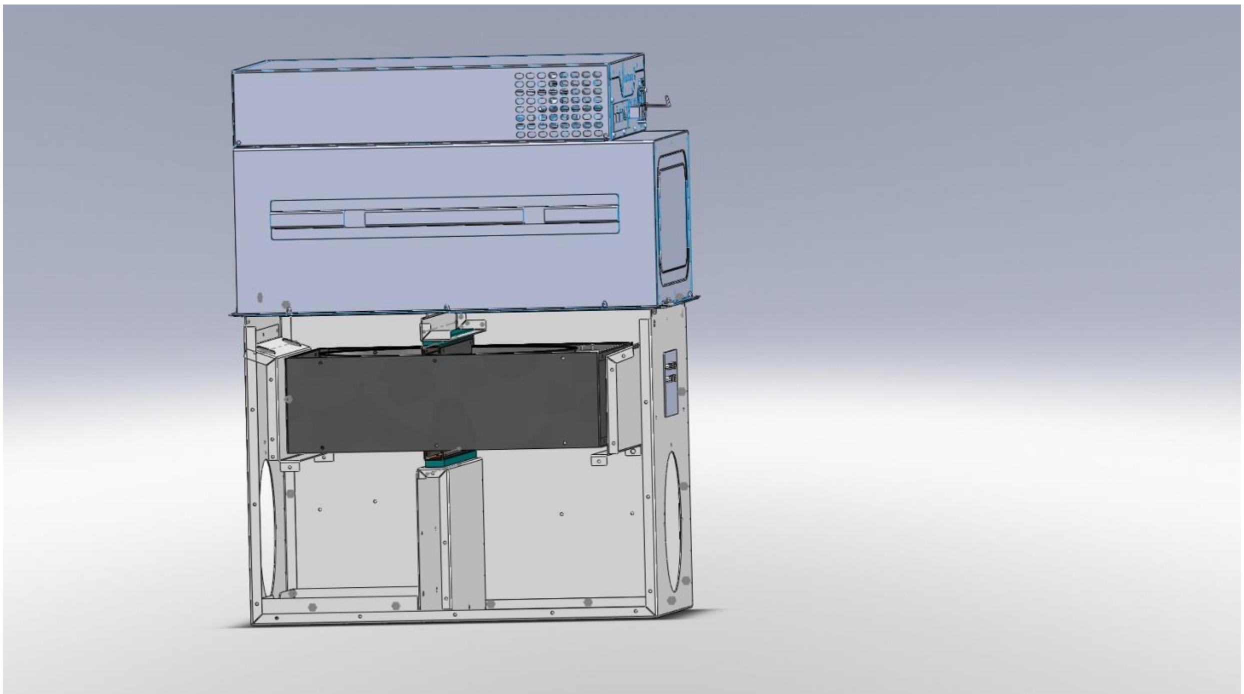
The results of this project made it very clear that further development and further focus on the challenges generated by the extreme climate conditions produce solutions and innovations that contribute significantly to the improvement of efficiency, lifetime, size (=cost) and overall performance in fuel cell systems operating under normal conditions. The results therefore have positive impact on the entire fuel cell industry and product improvement to better meet market expectations going forward.

The immediate next steps are related to continuing along the newly identified path of improving the modelling and simulation tool for better heat management with the objective to increase the overall stack and system performance, lifetime and cost for fuel cell systems operating not only in extreme climate conditions , but apply the knowledge and gain the full benefit for fuel cells operating in all "normal" conditions.

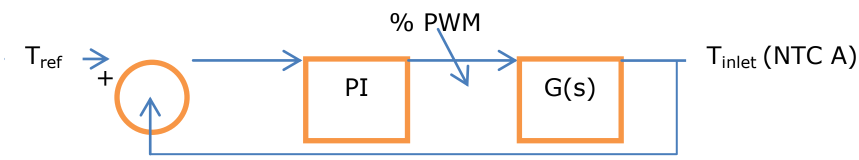
Appendix

Appendix 1: Cold climate kit control loop specification

In order for the DBX2000 and DBX5000 to be able to function reliably in cold ambient temperatures, the systems must be equipped with a cold climate kit (abbreviated CCK). The CCK consists of a rotary heat exchanger that transfers heat from the hot exhaust air to the cold inlet air. The reason for choosing a rotary heat exchanger is that the inlet temperature to the fuel cell system can be controlled by varying the rotation speed of the heat exchanger. On the below figure, a DBX2000 mounted on a CCK is illustrated.



In order to make the CCK backwards compatible, the rotation of the heat exchanger must be controlled by a dry contact output from the DBX2000 and DBX5000 systems. The idea is to control the rotation speed of the rotor by a PWM signal with a frequency of 0.1 Hz (1 s period). The thermal mass of the rotary heat exchanger will even out the intermittent rotation resulting from the slow PWM speed control, making it possible to precisely control the inlet temperature to the system.
The closed loop control to be implemented in the FCC is illustrated below:



The reference temperature is determined by the stack power draw according to the following equation:

$$Tref = 0{,}0014 \cdot Pstack + 24$$

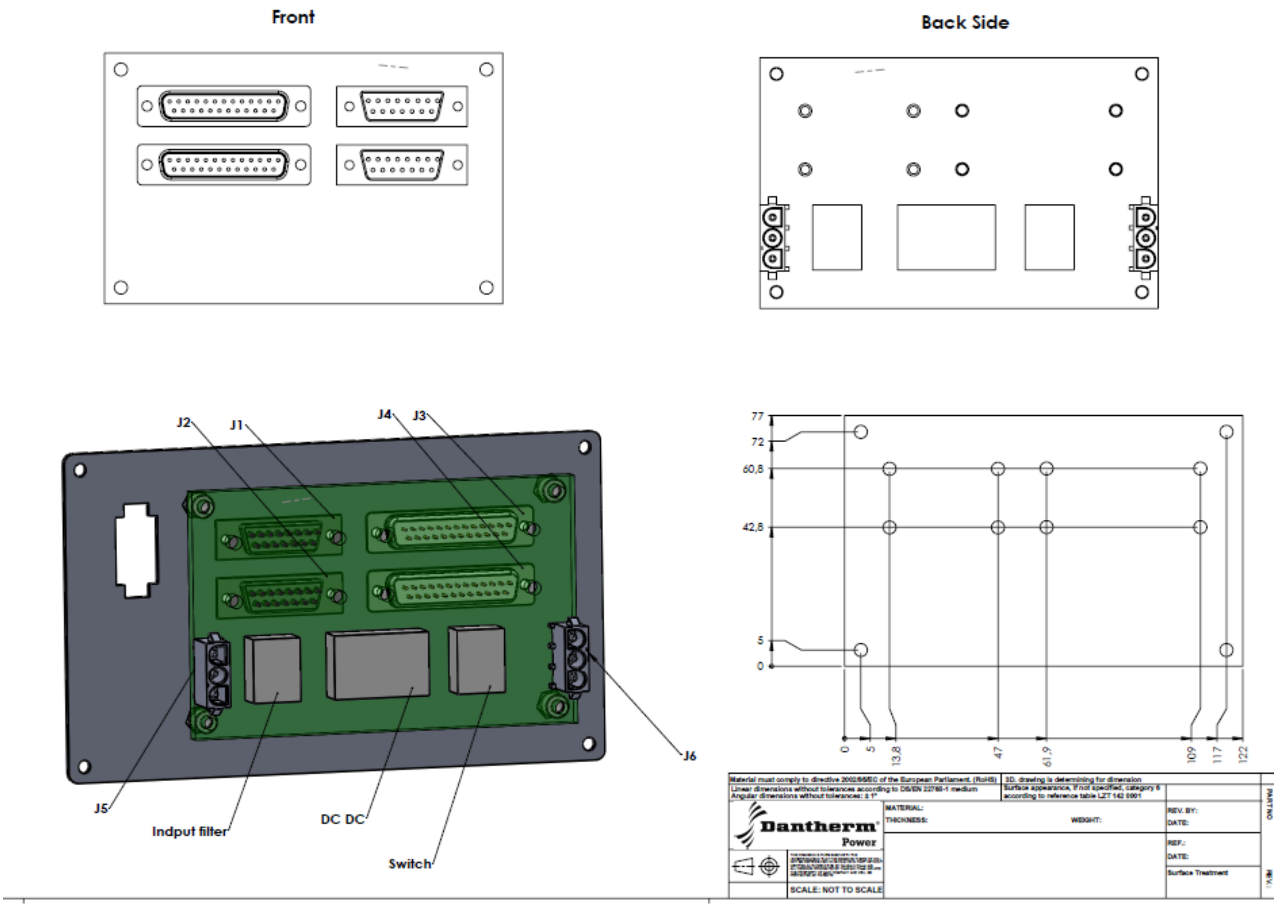
The proportional gain and integral time must be:

Kp = 1,0
Ti = 0,01

In order to precisely fine tune the control algorithm, Kp, Ti and the slope and offset of the Tref equation must be set via the config file. Also the the dry output to be used for the PWM signal must be settable, enabling the user to choose between output 1, 2, 3 and 4.

Control PCB specification

On the below figure, a mechanical drawing of the CCK PCB is illustrated. J1 is for connection to the alarm outputs on the DBX2000. J1 must be connected directly to J2 (pin 1 to pin 1, pin 2 to pin 2, etc.), making the remaining alarm inputs and outputs available to the customer. In the same manner, J3 is for connection to the alarm outputs on the DBX5000 and J3 is connected directly to J4.



On the back side of the PCB, the board is supplied by line voltage (40 - 60VDC) at J5. The DCDC converter is supplied through the input filter described in the application note for the converter. The 24V output from the DCDC converter must be PWM modulated via either dry contact output 1 from DBX2000 or from dry output 1 from the DBX5000. The switch should be realized through a simple solution like a transistor and free wheel diode. The PWM modulated 24V output for the motor supply is connected to J6.

Notes:

- Alarm outputs on DBX2000 and DBX5000 are not electrically identical - this will maybe affect the control of the MOSFET motor switch
- Safety distances to chassis: 2mm air gap, 4mm creepage
- PCB either 2 or 4 layer, 35mu Cu (number of layers depending on possible routing of signals)
- It must be checked that alarm outputs (dry contacts) on both DBX2000 and DBX5000 can be updated at a speed of 1 Hz. This update frequency is chosen in order to have good resolution on the 0,1 Hz PWM control of motor