HyFlexDrive

800944F

Final report

1. Project details

Project title	**HyFlexDrive**
Project identification (program abbrev. And file)	800944F
Name of the programme which has funded the project	EUDP
Project managing company / institution (name and address)	Ballard Power Systems Europe A/S (former Dantherm Power) Majsmarken 1, 9500 Hobro, Denmark
Project partners	Aalborg University Cemtec M-Fields ApS
CVR (central business register)	30804996
Date for submission	31th December 2018

2. Short description of project objective and results

HyFlexDrive project is a consortium between Ballard Power Systems Europe (BPSE - former Dantherm Power), Aalborg University, Cemtec and M-fields ApS that aimed at developing the next generation flexible and optimized fuel cell system for material handling applications. The workplan for the HyFlexDrive project was designed to address the main technical challenges and barriers associated with getting the H2Drive fuel cell system from early demonstration to a more mature technology ready for market demonstration. The project was organized along eight work packages (WPs), which led to develop and evaluate a compact 20kW system.

3. Executive summary

The product platform developed in the HyFlexDrive project is targeting light and medium duty vehicles. 3 markets segments have been evaluated in the design phase: Material handling vehicle, airport tow trucks and mining vehicles. The works has been centred around two main groups:

I. Fuel Cell Module Re-engineering:

By re-designing, we have been able to find robust and cheaper alternatives to components. It has been achieved by combining modelling effort with sourcing of standard components from the automotive industry, where large volume production has driven prices down on proven components. We have also been able to cost reduce the hydrogen recirculation, air supply, hydrogen tank controller and standard OEM controller.

II. Vehicle integration and design verification

The integration study led to a compact lean integration prototype which was installed in one of the vehicle platforms. The platform was demonstrated by operating the unit as standalone vehicle.

BPSE and the project partners have leverage critical know-how on non-stationary system and are now in a position to enter the mobility solution market. This provide the possibility to demonstrate the technology capability to customers interested by mobile solution. Finally, many of the know-how could be used on other market segment such as maritime.

4. Work Package Objectives

4.1. WP1 - Project management

BPSE had the task of managing the project smoothly with focus on project partners and the generation of results in the project work packages, together with managing across time zones, using the knowledge from external partners (M-Field and Ballard). Transfer of expertise and knowledge to each of the consortium members, together with dissemination of technology and know-how beyond the consortium to technological and market stakeholders represented important bullet points of the work package.

A series of changes took place along the development of the project, such as withdrawal of one of the project partners, M-Fields Aps, which led to the need of applying for an extension of the original time plan, and therefore postponing the delivery for the 31st December 2018, one year from the original plan.

4.2. WP2 - System Architecture and Design (BPSE)

The WP is dedicated to defining the system design from both a safety, functionality, robustness and cost point of view. It is meant to build on the state of the art system developed by H2Logic, where the product should be taken to a next generation product, with focus on robustness, flexibility and lower cost. The design of a system fulfilling all product specifications as stated in the Product Requirement Document (PRD) represents the task of creating the system architecture. In this work, the interaction of process, safety, software and hardware, hardware in form of electronics and mechanics, design (form factor and modularity), documentation and most of all functionality and reliability should be included.
This WP is capturing the overarching system engineering activities and consolidating the sub system activities from WP3, WP4, WP5 and WP6 with the design for manufacturing activities in WP7 into a complete system design with bill of material and CAD drawings ready for manufacturing in WP7.

4.3. WP3 – Modularity (BPSE)

The focus along the WP is on generating flexibility for fitting the same basic product into diverse applications, both project partners and future markets across different applications such as materials handling, tow tractors and smaller utility vehicles. This task will ensure modularity of the core blocks of the system focusing on reusing these blocks with other system form factors and will have major interaction with the 3D design and cost reduction. By ensuring a modular design, the usability of the systems will be broadened to accommodate a wide range of platforms and users. The modular design is also an important part of the design for manufacture to enable efficient line manufacturing. This work package will as such be closely linked to the design for manufacturing part of WP7.
Based on the information collected at the project partners, modularity in the mechanical design of the sub-systems such as heat mitigation, water management system, regenerative braking and a kinetic energy recovery system as well as driver compartment climate control must be assessed and incorporated into the different design solutions of the systems. Modularity based on the different user patterns will affect the design requirements as well. Some users require a longer range/operational cycle than others.

The system is designed to provide a reliable power for the entire operational cycle of the vehicle.

4.4. WP4 - System modelling (AAU)

The WP is focusing on continuing development of a system model from previous projects describing dynamic aspects of system operation and thereby enabling optimization of system for functionality and giving a tool for the functional aspects of cost reduction initiatives. The dynamic system modelling will be validated by experiments and testing on the real stack and system.

4.5. WP5 - Heat and Water Management (AAU)

Heat and water management is identified as an essential aspect achieving optimum fuel cell stack operation. The stack electrolytes must be hydrated to a certain extent while avoiding flooding of the stack. The WP is aiming at characterizing and optimization of the heat and water management subsystems required to operate the fuel cell stack optimally with respect to the dynamic operation tasks required in the materials handling systems.

4.6. WP6 - Air system - Reactants (BPSE)

This WP is of similar importance as the water management system. Proper air quality to the fuel cell stack is essential for minimizing the degradation of the fuel cell stack. On the anode side the efficient re-circulation of anode waste gas is important for the performance of the fuel cell stack but also a potential cost-adder if not handled efficiently. This WP aims at resulting in optimized air delivery system and anode recirculation system by assessing the impact of air contaminants and designing for contaminants in a way that supports a more durable and reliable system.

4.7. WP7 - Design for manufacturing, build and testing (BPSE)

The WP contains activities that are in focus with the new consortium behind the H2Drive product where new capabilities on manufacturing are brought to the table. In this work both supply chain and manufacturing are involved – and involved from the early system architecture and component selection activities to ensure best possible design for manufacturing, lowest cost and smooth prototype builds. This WP also ties very much into to the modularity in WP3 which is important to ensure easy subassembly design for manufacturing

4.8. WP8 Demonstration Planning (CEM)

Both vehicle-user selection and demonstration planning for the demonstration in the project are the focus of the WP. It also includes a Market Report based on integrator requirements and information, end customer requirements and general market information, which will also enable a more informed decision about which end-users that are most relevant for following demonstration of larger fleets of fuel cell systems.

5. Project results and dissemination of results

5.1. WP1 - Project management

The HyFlexDrive project had a good start with a successful kick-off meeting, a productive work meeting and a steering group meeting. The group has proven to work good together and the partners in the project have established productive work relationships.

A visit at the Company STILL in Germany at the beginning of the project (the first half of year 2015) by members of the project group led to a positive feedback from STILL, stating that they are very interested in supporting and engaging in the HyFlexDrive project.

In the next period (mid 2015 – mid 2016) the project partners have been performing the work mostly on their own, which led to limitations in knowledge sharing. As a result, the project management team increased their focus on the communication between the different parties, by holding steering group meetings every three months.

In this period, it was also noticed that some partners were ahead of plan, while others were behind, which led to the project being delayed and behind with deliverables. Project management team has therefore followed up on the progress, to secure positive development of the plan.

The HyFlexDrive event from February 2016 that took place in Aalborg Harbour brought positive feedback from several companies with special vehicle needs, which showed their interest in fuel cell driven off-road vehicles, such as the fork lift or the tow tractor.

The regular steering group meetings proved to be beneficial regarding the dialogue between the group members. A technical workshop was organized, where the tasks were discussed and planned, which led to strengthened knowledge sharing and cooperation.

The uncertainties on the continuation and eventually withdrawal of M-Fields ApS from the project led to delays in the demonstration planning. Also, due to focused efforts on adjusting the project to the market demands and specific industrial customers, it was necessary to apply for extension of the project scope of target applications, such as:

- A prototype fuel cell system development targeting a medium duty underground vehicle of a specific customer based on the HyFlexDrive fuel cell system (FcVeloCity module);
- Urban utility vehicles and other types of transport vehicles that can leverage the same fuel cell module.

A 12 months extension was approved, to allow for the development of the above-mentioned target points to happen and an internal prototype testing to be performed.

The intention was for M-Fields to focus on controls development, but since they withdrew from the project, another approach was needed. An alternative controller was investigated, but since the controller supplier is a major player in the automotive industry, the development of software is standardized and must follow a rigid process. This would make the development of a software for this application difficult and time consuming, since the project is in the prototype stage where the possibility to make changes in the software is inevitable.

Therefore, the integration of the Fuel Cell Module entitled MD30 (Medium Duty 30kW) from Ballard, that includes BoP components, sensors and controller with the software to control the Fuel Cell Module and support interaction with the Main Controller of the vehicle via CAN communication, was chosen as a solution to be pursued.

5.2. WP2 - System Architecture and Design

The architecture of the system design from both a safety, functionality, robustness and cost point of view is based on the product platform developed by H2Logic. This platform was the starting point to develop the next generation of product using standard module from Ballard.

The product requirement specification led to the identification of 3 main applications in the light / medium duty market segment:

- Material handling (Still Germany and M-field)

- Tow tractor for airport (Mulag)

- Mining equipment (Sandvik)

The design of a system fulfilling all product specifications as stated in the Product Requirement Document (PRD) represents the task of creating the system architecture. In this work, the interaction of process, safety, software and hardware, hardware in form of electronics and mechanics, design (form factor and modularity), documentation and most of all functionality and reliability has been measured.

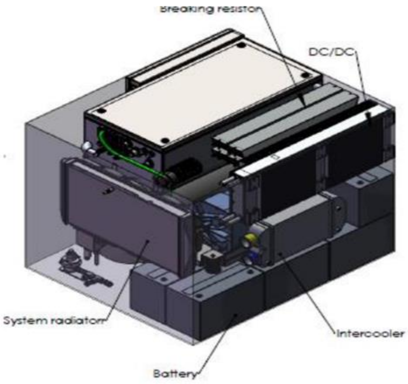
Four categories of requirements are considered in the design study. The emission, the battery replacement and low air velocity for cooling. All those requirements have been integrated into 3 concepts study using a standard fuel cell module.

	Emission	Battery replacement	Cost	Low air velocity for cooling
Material Handling	★★★	★★★	★★★	★★
Tow tractor	★★★	★★	★★★	★★★
Mining equipment	★★★	★	★★★	★★★

In the mechanical integration study, different features have been identified and integrated to fit the customer design requirement and categorized by application:

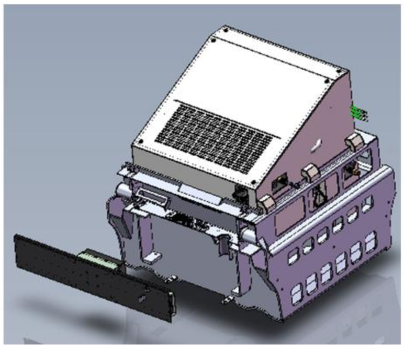
Material Handling:

- Form factor compatible with different product from Still
- Breaking resistor placed outside the compartment
- Weight management optimized to locate the gravity centre toward the rear of the module



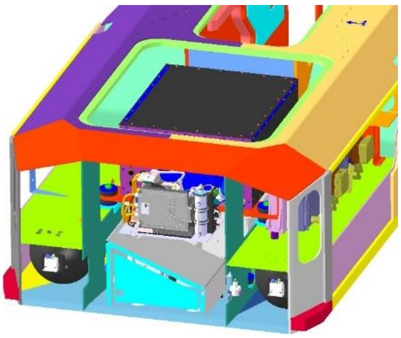
Tow truck:

- Freeze tolerant
- Evaporation of condensate to elimination risk of water spillage

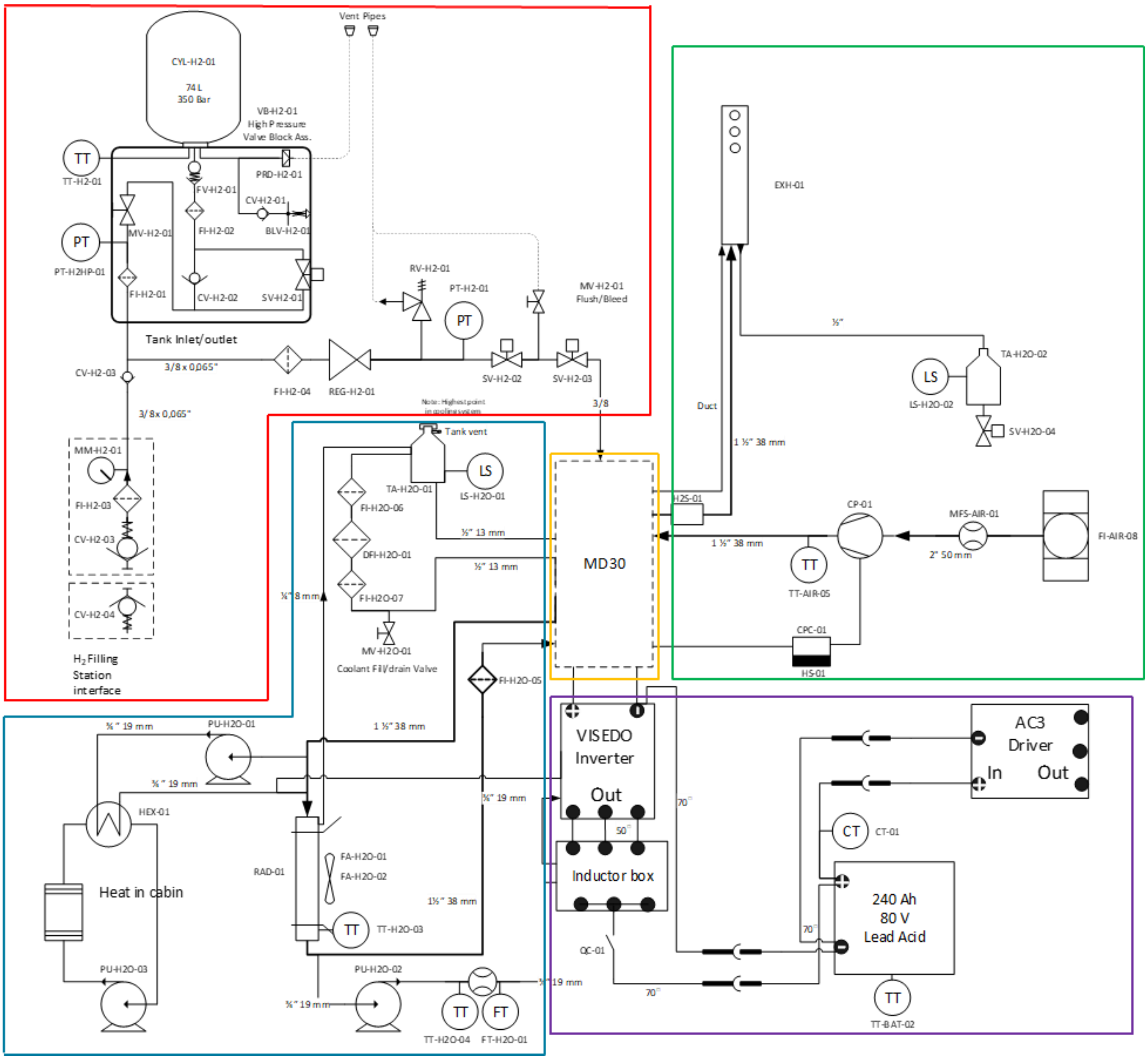


Mining Vehicles (amendment 1):

- Integration of the MD 30/MD60
- Heavy duty air filtration
- Integration of standard components (tank, controller, DC/DC converter)

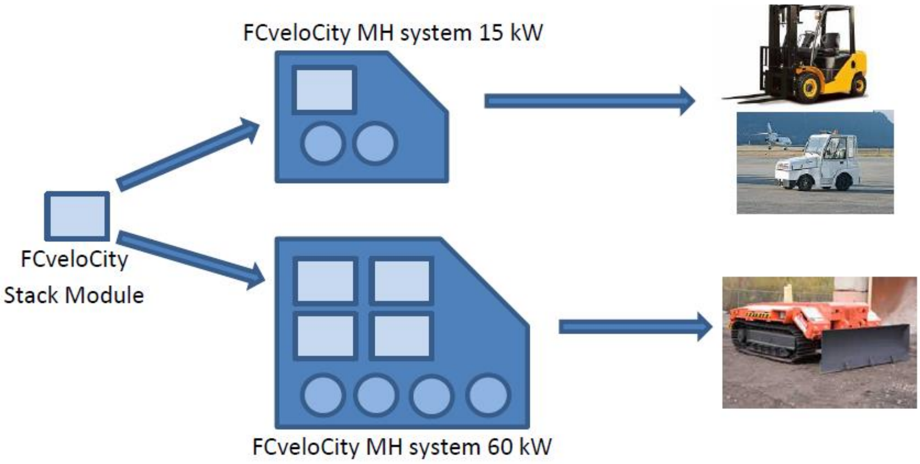


After the definition top level mechanical functions of the module, a generic design has been implemented to fit the 3 mechanical concepts. The core of the system has been declined in 4 main sub-assembly as shown in the PID below. The hydrogen sub-assembly described in red contain the high-pressure tank, the refuelling interface, the pressure regulation both high and low and the safety equipment such as pressure relief valve. The cooling functions are shown in the blue perimeter below and contain the cooling circuit, the DI water circuit, the auxiliary coolant circuit and the cabin heating circuit. The air supply and exhaust are shown in green and have the function of the unit with reactant air as well as eliminated the depleted reactant in oxygen from the system. The fuel cell module contains the fuel cell stack and the hydrogen management functions. Finally, the electrical energy is managed is the purple perimeter and contain the main DC/DC conversion, the air compressor drive and the interface to the battery bank.



5.3. WP3 – Modularity (BPSE)

From the requirements established in the WP2, a new design has been agreed upon. It did include physical differences compared to the first design, but also at a component and software level.



A series of factors were determined and incorporated all PRD for a common platform.

- Change of the climate system
- Size of the stack
- Change of the Main and Intercooler Radiators
- Sizing of the H_2 tank
- Redesign of the water recovery unit.
- Modular DI-filter cartridge
- Optimized drive voltage

In the initial design phases of the electrical architecture, an attempt to optimization the battery pack size by reducing the number of cells was followed. This would lead to a reduction of the battery bus voltage. But the consequential higher current was challenging for the converter. Consequently, this approach was parked.

In the absence of M-Field contributions, an alternative solution had to be sourced for both the main controller and the power conversion unit. The preceding futile efforts, and the subsequent tasks for sourcing and integration of new components, as well as controller programming did set the team back quite a bit.

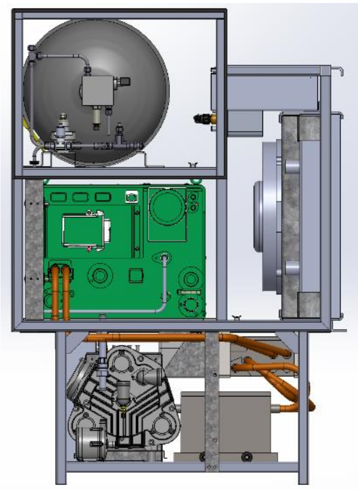
After identifying and obtaining a new controller and DC/DC, it was noticed that the basis system was functioning properly. The basis module was suitable for both the previously identified airport tow tractors as well as forklifts.

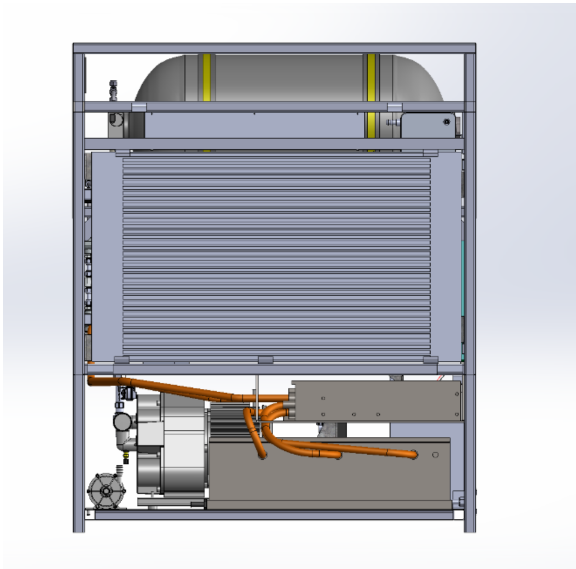
Mechanical	Electrical	Others
• *Designed for mobility, with up to 10 G vibration* • *Enclosure class IP67* • *Liquid cooled*	• *Wide voltage area. 0-850 VDC* • *Electrical Isolation resistance measurement*	• *Quality components, industry recognized.* • *Competitive prize.* • *Two-piece components*

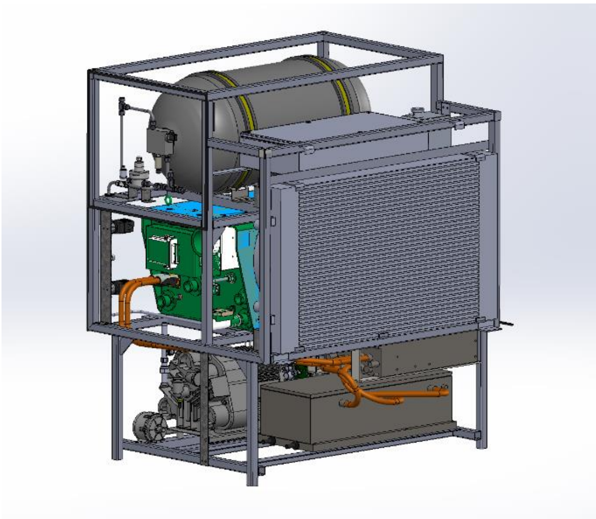
• *Elevated operating temperature*		• *65 kg*

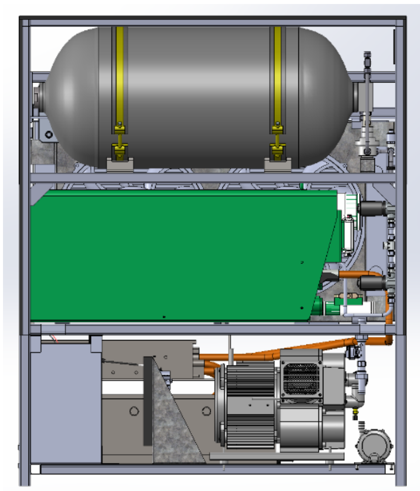
As an added benefit of having to shift the controller and DC/DC platform, BPSE had a "new module" that had a potentially much larger field of application than just forklifts, tow tractors or mining vehicles. The system is scalable in the new setup to much larger power ranges as well as smaller. The new controller platform is an industry leading automotive grade controller that allows for integration with a wide range of motive and stationary drive controllers and master controllers. This allows the potential use of the system to broaden considerably.

A complete Mechanical study was completed to redesign the module:









This task will ensure modularity of the core blocks of the system focusing on reusing these blocks with other system form factors and will have major interaction with the 3D design and cost reduction. The unit is based on main mechanical assemblies, divided into:

MD/HD standard module with a new high-pressure air management compressor based on scrolled technology.

The tank module includes a modular, standalone tank controller unit, which can be configured to different tank system setups, with varying number of On-Tank-Valves, temperature measurements and tank sizes. The controller also includes a filling station interface for a potential optimization of the filing rate.

A dedicated air cooling unit has been designed and fitted on the back of the module. This module can be detached and placed in different area depending on the vehicle architecture.

A new platform of standard OEM controller has been evaluated to fit the 3 application platforms. We have obtained good result using automotive controllers, but pricing was incompatible with the product cost target. A heavy-duty equipment and industry OEM industry controller was successfully and implemented into the system. This controller is operated with SIL 2 certified sub module which could be required for the tank controller.

5.4. WP4 - System modelling

5.5. WP5 - Heat and Water Management

The system modelling and the heat water management study has been combined into one work package. A complete model has been programmed to size the intercooler and the ejector. The model is based on 110 cells Ballard FC velocity stack.

The first part of the document will describe the procedure to size cooling system for a Ballard fuel cell 110cell stack.

Model of the cathode air inlet stream

Prior to enter the FC stack, air is compressed and cooled down in an intercooler. Humidification is provided by a humidifier.

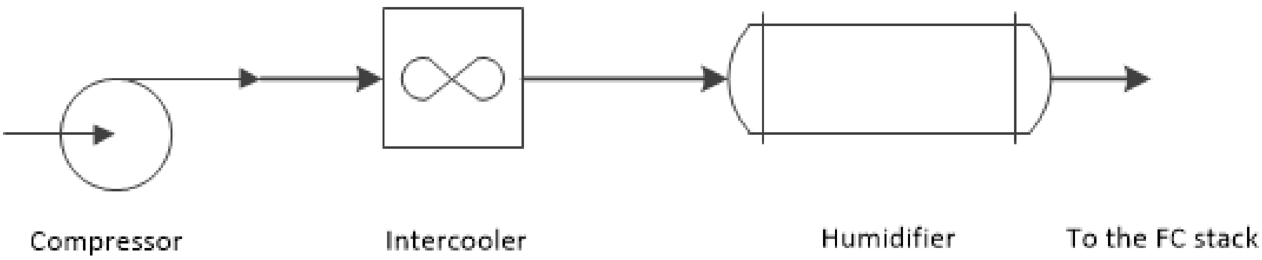


FIGURE 1CATHODE AIR INLET

Cathode air mass flow rate estimation is provided by Ballard manual [1]:

$$\dot{V}_{Air} = 2.7E-7 \cdot i \cdot n_{cell} \cdot \lambda \quad [normal\ m^3/s]$$

The relationship is function of air stoichiometry ratio λ and current i. We calculate the air volume flow rate at the highest stack load i.e. $i = 300\text{A};\ \lambda = 2$.

Temperature at the compressor outlet estimation is necessary to determine the amount of cooling in the intercooler to achieve our desired final temperature. We calculated the temperature rise across the compressor as:

$$T_{Comp,out} = T_{Air,amb} \cdot \left[1 + \frac{\left(\frac{P_{comp,out}}{P_{air,amb}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta} \right] [K]$$

We consider compressor efficiency $\eta = 0.6$ in the lower range as we assume that the compressor will operate at **high load**. In this condition the temperature at the compressor outlet will be around 85°C.

<u>Intercooler designing criteria</u>

We assume that at the intercooler inlet, temperature is equal to compressor outlet i.e. $T_{in,intercooler} = T_{out,comp}$. $\dot{m}_{air,out}$ Cathode mass flow rate is calculated using cathode air mass flow rate estimated by Ballard.

The intercooler provides air at the cathode inlet at roughly $T_{cat,in,FC} = 80°C$. This means that when the system operates at high load (i=300A), temperature must be reduced of 10°C from the compressor outlet. Hence, some heat must be dissipated. We can estimate this heat using basic relationship:

$$\dot{Q}_{cat,air} = \dot{m}_{air,hum,out} \cdot c_{p,Air} \cdot \left(T_{in,intercooler} - T_{in,cat,FC}\right)$$

The heat which must be dissipated $\dot{Q}_{cat,air}$ is roughly 500 W and can be used to size the intercooler. The overall heat transfer coefficient of each radiator is defined as:

$$U_{Rad} = \frac{Q_{rad}}{A_{norm} \Delta T_{air-coolant}}$$

The primary goal is to calculate the overall heat transfer coefficient, h_{rad} , i.e.

This type of intercooler can be classified as a cross-flow heat exchanger. In this study, experimental measurements of gas-side heat transfer coefficient and pressure drop data have been correlated by Kays and London (1984)[2]. These data are implemented in EES heat exchanger library which was used for this project.

EES library uses a specific nomenclature for heat exchanger geometry exemplification which is given in the next figure and table.

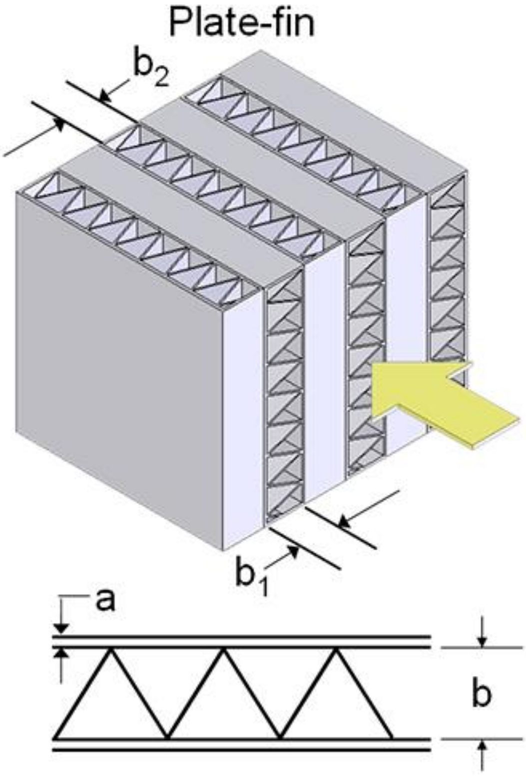


FIGURE 3 HEAT EXCHANGER EXEMPLIFICATION

The characteristic of the radiator type (e.g. plate thickness; thickness of the passages) are important to size the radiator. Model input data from EES are shown in table below.

Geometry Inputs	
Heat exchanger type and surface	Plate-Fin
a: plate thickness [m]	0.001
b_2: - thickness of passages through which the second fluid passes [m]	0.01
Frontal Area [m2]	0.06
Heat Exchanger length	0.062
Outputs	
Pressure drops	57 Pas
fin pitch – the number of fins per meter [1/m] or [1/ft]	
D_h – the hydraulic diameter [m]	
fin_thk – thickness of fins (not applicable to pin-fin) [m] of [ft]	
sigma – minimum free flow area/frontal area	
alpha – heat transfer area/total volume [m^2/m^3]	
A_fin\A – fin area/total area	

H Heat transfer coefficient	

As mentioned before at high load, around 500W must be dissipated by the intercooler. From the figure below, we can conclude that the intercooler is undersized for current performance. In fact, only 400W will be dissipated at high load.

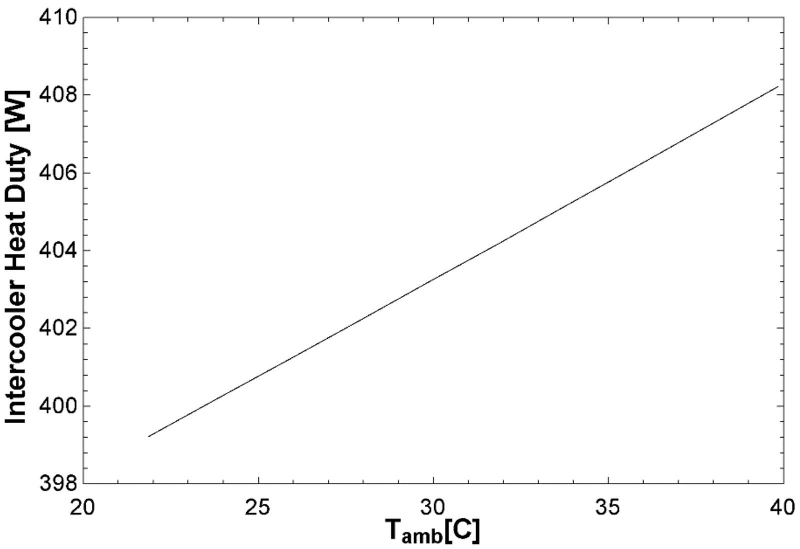


FIGURE 4 HEAT EXCHANGER EXEMPLIFICATION

Below we summarize the sizing procedure for the intercooler. First, we determine the air mass flow rate at the highest load using the equation provided in the manual, we calculate the temperature of this flow at the compressor outlet using the isentropic compression relationship. We estimate the temperature drop to bring the air to correct fuel cell inlet temperature; we can calculate the heat that which must be dissipated to reduce air stream temperature. Finally, we can correctly size the intercooler according to the heat duty.

Cathode Air Mass Flow Rate	$\dot{V}_{Air} = 2.7E-7 \cdot i \cdot n_{cell} \cdot \lambda \; [normal\ m^3/s]$
Compressor Outlet temperature	Isentropic compression $T_{Comp,out} = T_{Air,amb}\left(1 + \frac{\left(\frac{P_{comp,out}}{P_{air,amb}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta}\right) [K]$
Intercooler Cooling requirement	Fuel cell inlet temperature
Intercooler sizing	Heat exchanger type Fuel cell inlet temperature Oversizing factor

FIGURE 5 INTERCOOLER SIZING PROCEDURE

Intercooler Fan Design and Selection Criteria

A fan operates along a performance curve in which speed (i.e. revolutions per time) are constant. When head pressure increases mass flow rate through the fan will reduce. At fixed speed the head pressure will be the highest when the mass displaced by the fan is zero.

In Figure 5 we can see that when the fan is operating at fixed speed on the performance curve N1 point “A”, the flow will be Q1 against pressure of P1.

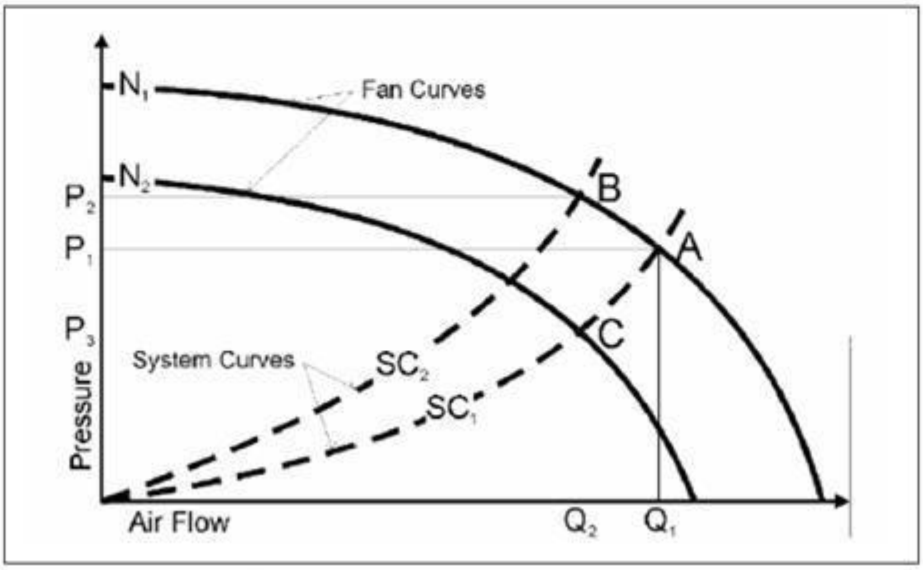


FIGURE 6 FAN CHARACTERISTIC [3]

It is ideal to cover as much as possible of the radiator area with a fan as shown in figure 7.

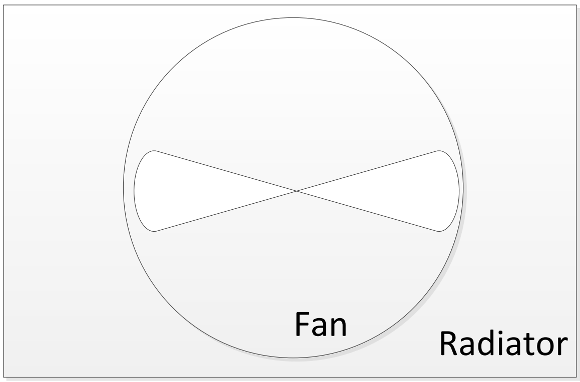
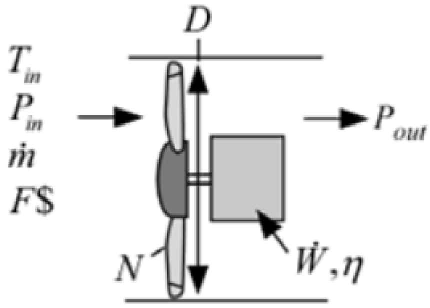


FIGURE 7 FAN AREA

The model of a vane axial fan comes from EES library and is based on curves for dimensionless pressure rise shown in figure 5 as a function of dimensionless volumetric flow rate derived by heat exchanger pressure losses and dimensionless power. These curves were generated by collapsing performance data from several manufacturers and models [4]. Intercooler fan will use around 12W electric power at high load.



Inputs:	
m_dot: mass flow rate (kg/s)	
T_in: inlet temperature (C)	
P_in: inlet pressure (kPa)	
N: rotational speed (rev/s)	
D: blade diameter (m)	Estimated based on the intercooler radiator size
Outputs:	
P_out: outlet pressure (bar)	Estimated based on Heat exchanger pressure losses
W_dot: power (W)	
T_out: outlet temperature (K)	
eta: efficiency	

FIGURE 8 FAN MODEL INPUT OUTPUT FROM EES [4]

<u>Stack Cooling System Design</u>

Stack cooling is achieved by means of a radiator/fan and a coolant pump. Radiator/fan assembly is chosen from car industry and sized according to the predicted stack heat load. The fan was designed according to the radiator size.

Radiator/fan assembly are sized so that coolant absorbs heat from the stack at the same rate it is rejected from the radiator. The radiator model tube fin type in included in EES database.

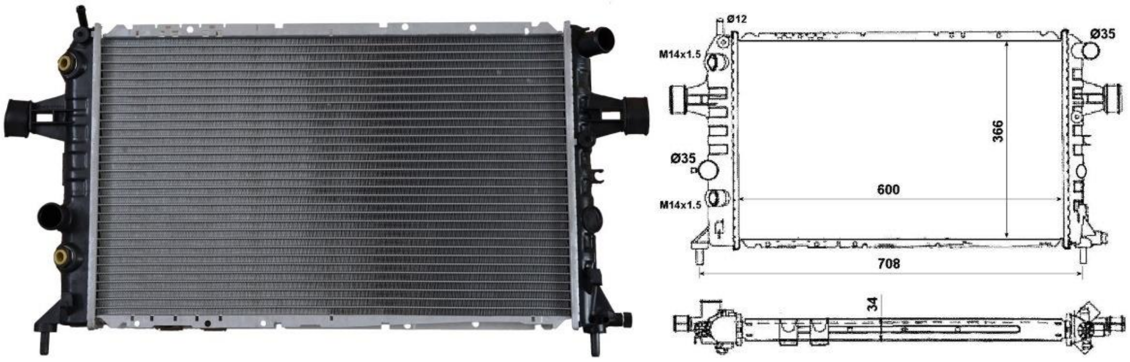


FIGURE 9 RADIATOR USED BY DANTHERM SYSTEM

<u>Selecting and Sizing a Radiator</u>

The characteristics of a radiator type are used to determine how much area is needed to cool the fuel cell stack.

The following parameters were used in these calculations:

- Overall heat transfer coefficient, U_{rad}
- Likely worst-case thermal load, Q_{rad}, which the stack thermal model predicted to be 22 kW.
- Worst-case inlet air temperature, $T_{air,in}$ = 40 °C.
- Coolant inlet temperature, $T_{coolant,in}$ = 80.0 °C.
- Coolant outlet temperature, $T_{coolant,out}$ = 74 °C.

<u>Fuel Cell Energy Balance</u>

As thermal load is considered the heat must be rejected for the fuel cell system to operate indefinitely at full power at 80 °C. Waste heat is generated by several inefficiencies inherent to PEMFC operation and by water vapor condensing in the stack.

FIGURE 10 FC ENERGY BALANCE

The heat rejects from the stack $\dot{Q}_{stack} = -\frac{n \cdot I \cdot \Delta H}{2 \cdot F} - \dot{Q}_{el} - \dot{Q}_{loss}$ with electric power at full load of $\dot{Q}_{el} = 21.2\ [\mathrm{kW}]$. Ballard manual[1] suggests relationship:

$$Q_{Stack} = \frac{(V_0 - V_{cell}) \times I \times N}{1000}$$

with $N = 110$ and $V_0 = 1.42$. In figure below the heat production for stacks depending on no. of cells is depicted.

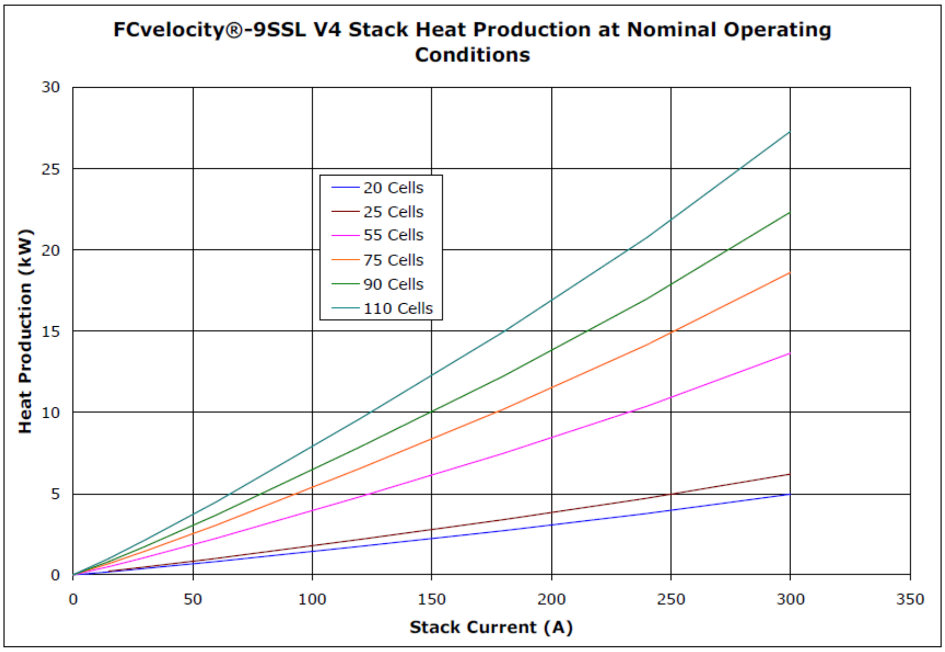


FIGURE 11 HEAT PRODCTION DEPENDING ON STACK SIZE (I.E. CELLS)[1]

Heat is removed from the stack by means of the coolant fluid the cathode flue gas and the hydrogen purge.

The heat from the stack is transferred to the coolant according to the same relationship.

$$\dot{Q}_{stack} = \rho_{coolant} \dot{V}_{coolant} c_{p,coolant} (T_{coolant,FC,in} - T_{coolant,FC,out})$$

In the figures below we show heat rejected by the air $\dot{Q}_{stack} = \dot{m}_{air} (i_{in} - i_{out})$ and its pressure drops depending on mass flow rate and we summarize the sizing procedure of the stack radiator.

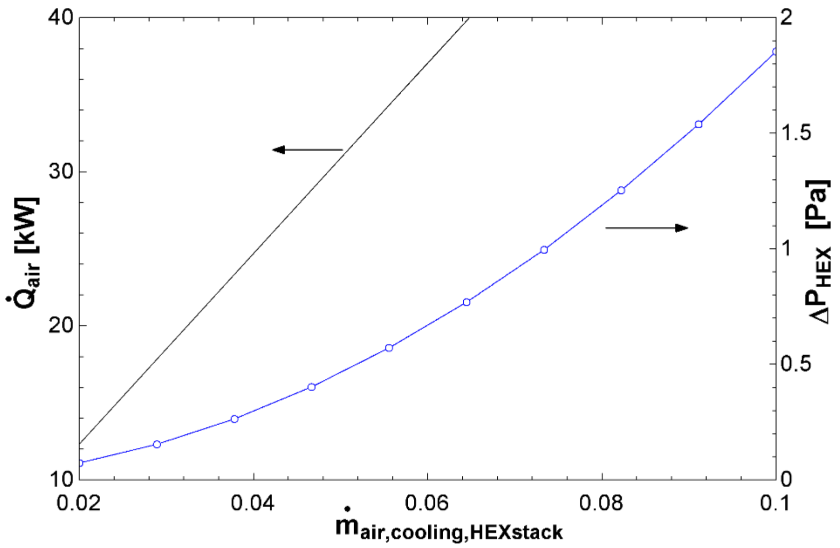


FIGURE 12 HEAT REJECTED BY THE AIR AND ITS PRESSURE DROPS DEPENDING ON MASS FLOW RATE

Highest stack load Worst ambient conditions	$\dot{Q}_{stack} = -\frac{n \cdot I \cdot \Delta H}{2 \cdot F} - \dot{Q}_{el} - \dot{Q}_{loss}$
Coolant mass flow rate	$\dot{Q}_{rad} = \dot{m}_{air}(i_{in} - i_{out}) = \rho_{coolant}\dot{V}_{coolant}c_{p,coolant}(T_{coolant,FC,in} - T_{coolant,FC,out}) = \dot{Q}_{stack}$
Heat transfer coefficient	Fuel cell inlet temperature
Radiator sizing	Heat exchanger type Oversizing factor
Fan sizing	Heat exchanger type Oversizing factor

FIGURE 13 STACK RADIATOR SIZING PROCEDURE

<u>Designing of Ejector</u>

The high-pressure pure hydrogen of the primary flow is chocked at the throat of the primary inlet and forms supersonic flow in ejector. When the primary flow expanded passing through the throat, its velocity increased, and a low-pressure zone is formed.

Then, the relatively low-pressure hydrogen at the secondary inlet is entrained by high-speed primary flow and mixed in the mixing chamber. The shock wave occurs in the ejector depending on the outlet pressure.

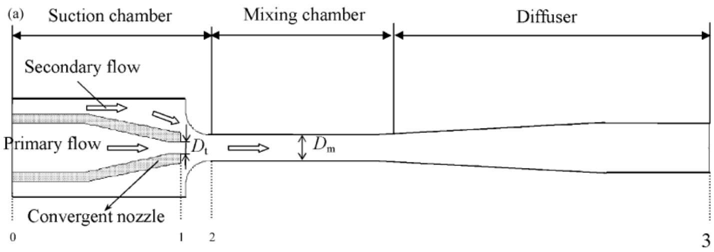


FIGURE 14 EJECTOR NOMENCLATURES [5]

Several design procedures for ejectors have been published. The majority solve the one-dimensional mass, momentum and energy conservation equations applied to the ejector control volume with the assumption that the flow is inviscid and adiabatic. In this we refer to paper: *New theoretical model for convergent nozzle ejector in the proton exchange membrane fuel cell system.* Yinhai Zhu, Yanzhong Li. Journal of Power Sources 2009 [5].

We define the following important parameters.

- i the species in the mixture i.e. H; H_2O
- n [kmol] is the number of kilomoles of the mixture $n = \sum n_i$ and $x_i = \frac{n_i}{n}$ is the molar fraction of each species
- m [kmol] is the number of kilomoles of the mixture $m = \sum m_i$ and $y_i = \frac{m_i}{m}$ is the molar fraction of each species
- $\gamma = \frac{C_P}{C_V}$
- $C_P = \sum y_i C_{P,i}$ $C_V = \sum y_i C_{V,i}$
- M is the molar mass $M = \frac{m}{n}$
- R is the specific gas constant for the fluid $R = \frac{R_u}{M}$
- The hydrogen stoichiometry is defined as the ratio between the hydrogen FC inlet and the hydrogen used in the electrochemical reaction $\lambda_{H2} = \frac{\dot{m}_{an,H2,in}}{\dot{m}_{an,H2,F}}$

As main assumption we assume velocity distribution of secondary flow at section 2 is assumed to be an exponential function along the direction of the radius as shown in the next figure.

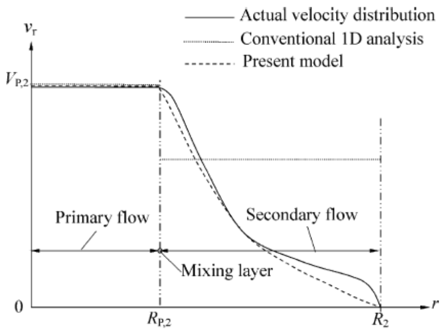


FIGURE 15 VELOCITY DISTRIBUTION

Nozzle Throat Diameter

In order to accelerate the primary ow to supersonic Mach number a convergent-divergent nozzle is used. From quasi-one-dimensional analysis it is shown that for an inviscid adiabatic flow the flow velocity and Mach number M are related to the flow cross sectional area by the area-velocity relation given acceleration at subsonic velocities requires a reduction in cross sectional ow area and at supersonic velocities an increase in cross sectional flow area. This is the principle a convergent divergent nozzle utilizes to accelerate a subsonic flow to supersonic.

The flow must however have a sufficiently high stagnation pressure to become sonic. Else the flow accelerates to a maximum subsonic velocity in the convergent nozzle section and is then decelerated in the divergent portion of the nozzle.

To determine the required nozzle diameter D_t for the primary flow to become sonic at the throat and subsequently become supersonic in the divergent nozzle section we use equation from Zhu,2009 [5]. 21

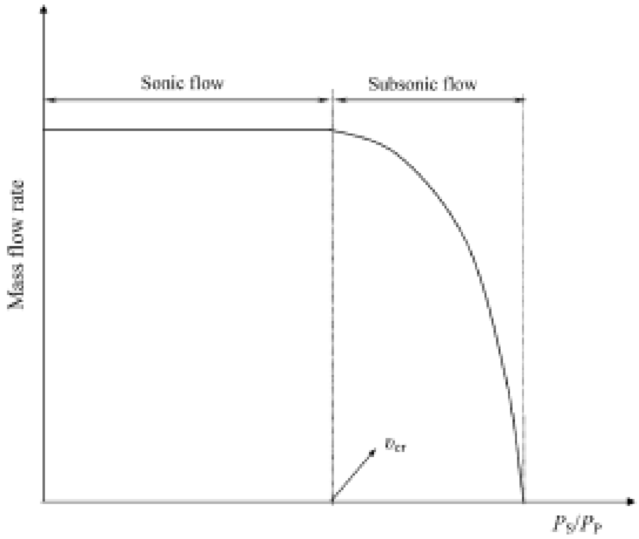
For this application, a convergent nozzle was selected. The advantage of this type of nozzle, as opposite to a convergent-divergent nozzle, is the does primary flow does not reach high Mach numbers. Throat diameter is calculated assuming isentropic flow through the nozzle as in the equation below. This is a reasonable assumption since the flow is uni-dimensional and very fast.

$$D_t = \left(\frac{4\dot{m}_{p,0}}{\pi\varphi_{p,0}}\right)^{1/2} \left(\varphi_p \gamma_p R_p T_{p,0}\right)^{-1/4} \left(\frac{2}{\gamma_p + 1}\right)^{-\frac{\gamma_p+1}{4(\gamma_p-1)}}$$

In order to determine the hydrogen velocity at the nozzle throat the critical pressure ratio, u_{cr}, was calculated. When the ratio between secondary and primary flow pressure is larger than its critical value, than the flow reached sonic conditions. For a convergent nozzle the pressure ratio is calculated as follow:

$$u_{cr} = \left(\frac{2}{k+1}\right)^{k/(k-1)}$$

This ratio is dependent on hydrogen heat capacity ratio considering the range of operation of this specific case will be around 0.52. As secondary flow pressure is slightly above atmospheric pressure, we can estimate that when primary flow is over 2 bars, hydrogen will have reached sonic condition at the nozzle throat and supersonic at the outlet.



MASS FLOW RATE AS A FUNCTION OF PS/PP [5]

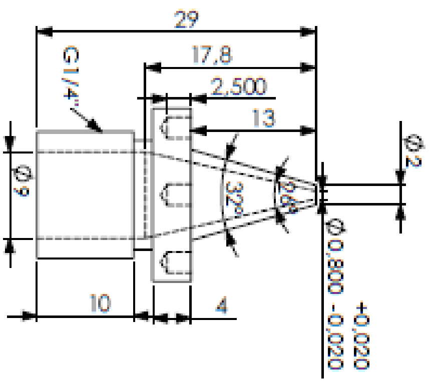
Mixing chamber diameter

The primary flow expands out of the nozzle and does not mix with the secondary flow until the mixing chamber inlet as assumed by Zhu, 2009 [5].
Zhi

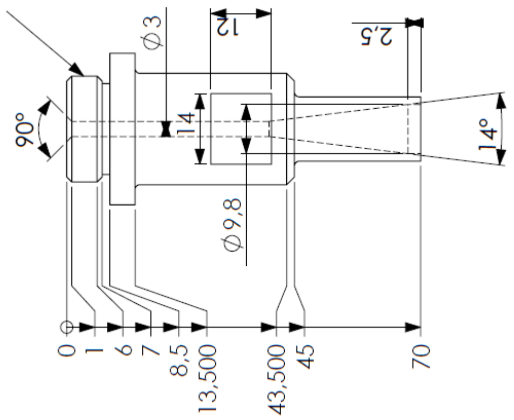
$$n_v = \left(1.393\cdot 10^{-4}\right)*exp\left(p_{s0}/p_{p0}/0.05\right)+0.456\cdot R_3\cdot 2/D_t+0.1668;$$

$$\dot{m}_{an;rec} = \frac{2\pi\rho v_{P,3}(R_2-R_{P,2})(R_2+R_{P,2}+n_v R_{P,2})}{(n_v+1)(n_v+2)}$$

The convergent nozzle is used to entrain the secondary flow in the mixing chamber as shown in the figure below. In a system with fuel recirculation, the consumption will be slightly above 1.0 stoichiometry as 1% to 2% of the flow will be required for purging. In a flow through configuration, the consumption of hydrogen will equal the recommended stoichiometry.



Nozzle



Mixing Chamber

Model Input for 120 cells stack

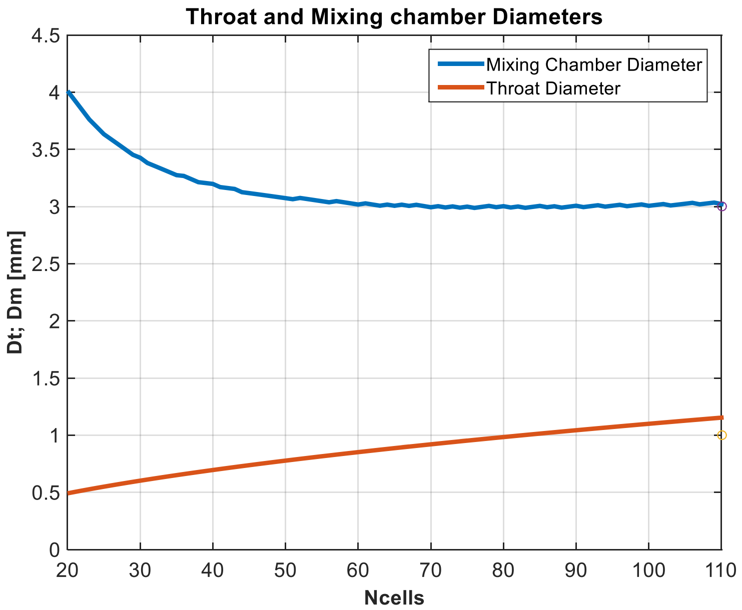
Parameter	Value	Unit
Faraday constant F	96485.3	(s A)/mol
Primary Flow Pressure p_{p0}	12	Bar
Secondary Flow Pressure p_s	1.03	Bar
Primary flow temperature T_{p0}	333 (60°C)	Kelvin
Secondary flow temperature T_{s0}	343 (70°C)	Kelvin
Current	30	A
Anode Gas Recycle Ratio	1.02	-
Hydrogen Stoich	3.4	-
Number of cells	110	

Output

Parameter	Value	Unit
Nozzle Throat diameter	0.8	mm
Mixing Chamber diameter	3	mm

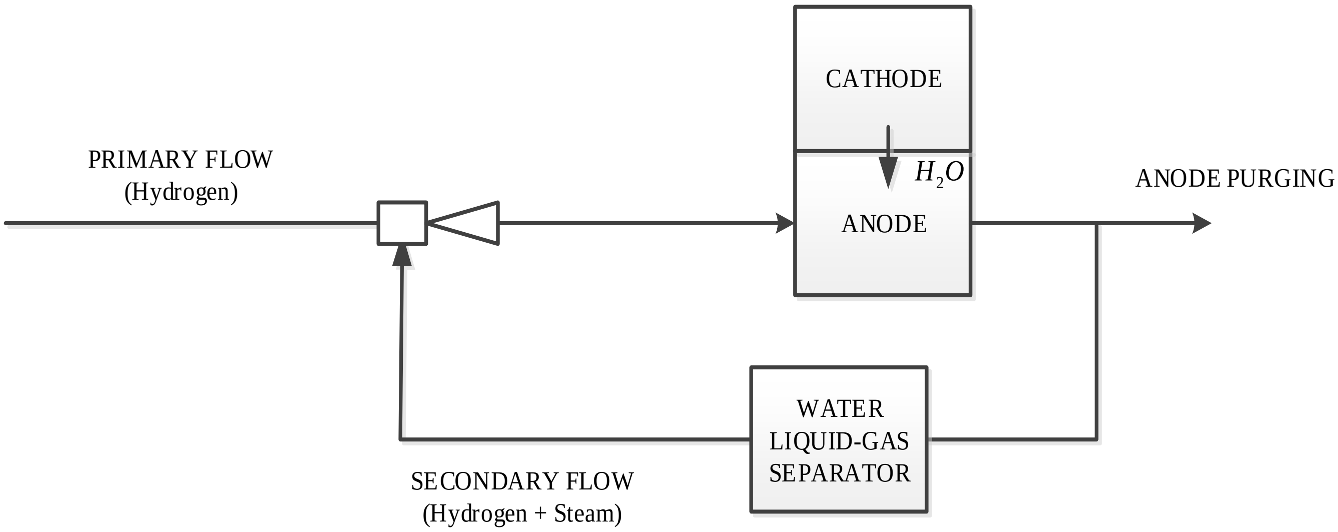
All the other measurements of the nozzle are proportional to the throat diameter. In the same way all the other mixing chamber measurements are proportional to the mixing chamber diameter. From the figure below is possible to estimate what would be the mixing chamber diameter and the throat diameter for different stack size.

Dots represent Nozzle Throat and Mixing Chamber diameters used by Dantherm fuel cell system.



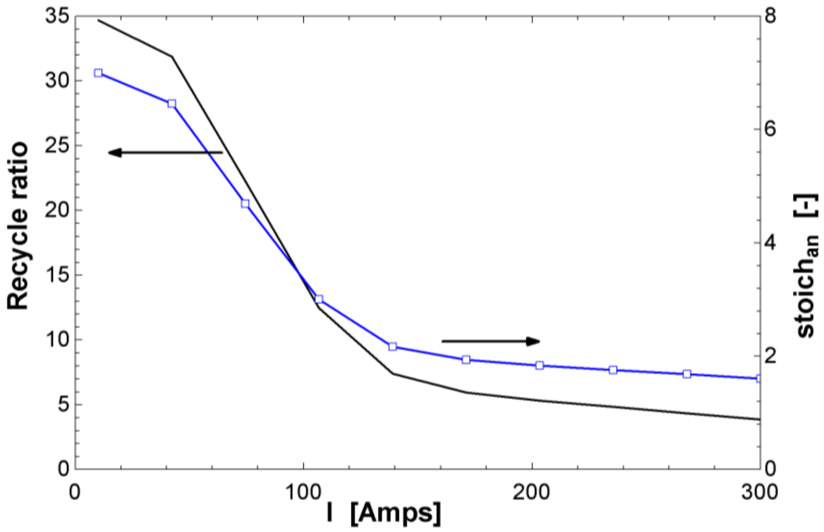
THROAT AND MIXING CHAMBER DIAMETER FOR FCVELOCITY STACK FROM 20 TO 110 CELLS.

In the figure below, we can see how the ejector operates in the contest of anode recycle for a PEM Fuel cell system. Anode depleted gas is recovered after a liquid water knock out. Depleted gas is purged depending on a pressure threshold.



THROAT AND MIXING CHAMBER DIAMETER FOR FCVELOCITY STACK FROM 20 TO 110 CELLS.

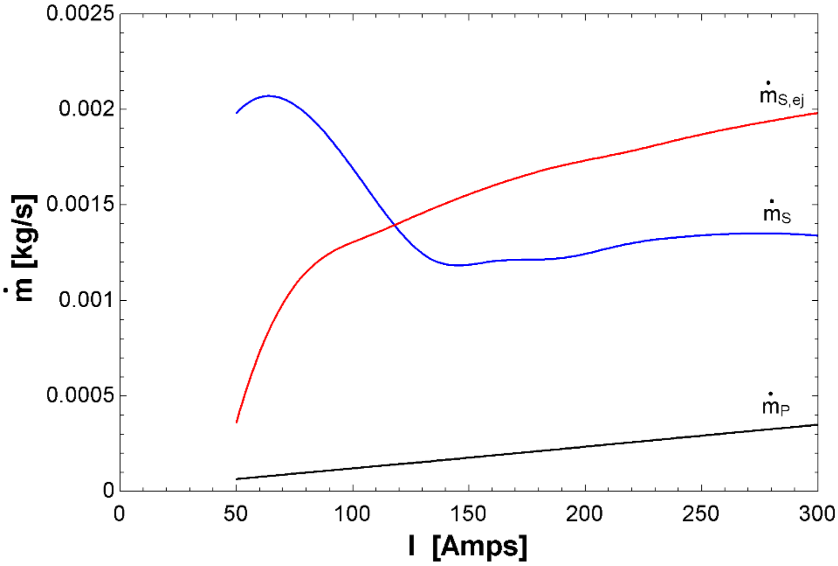
In the figure below, we can see the stoichiometric ratio and recycle ratio at the anode side. It can be noticed that the stochiometric ration at the anode side is high at low current values reaching values as high as 7. Such a high value is desired because the hydrogen mass flow will help eliminating water droplets which have accumulated in the anode side due to the water diffusion process from cathode to anode. In the figure below the recycle ratio black curve represents the mass flow rate of hydrogen and steam which must be recirculated to respect the anode stoichiometry requirements. We can see that at low loads a recycle ratio reaches value as high as 35. This is due to the high content in steam in the secondary flow at low load regimes. This observation leads to conclude that an ejector should be designed to operate in a range between 35 down to 5 recycle ratio however the small momentum of primary flow makes impossible to accelerate the secondary flow which is reach in steam.



EJECTOR RECYCLE RATIO AND ANODE STOICHIOMETRY RATIO AT DIFFERENT LOADS

From the figure below, we can see primary and secondary flow in the ejector when it is operated at different loads. We plot the secondary mass flow rate which should be kept maintaining the secondary at the desired stoics condition, $\dot{m}_s$, and the secondary mass flow rate that is recycled from the ejector, $\dot{m}_{s,ej}$.

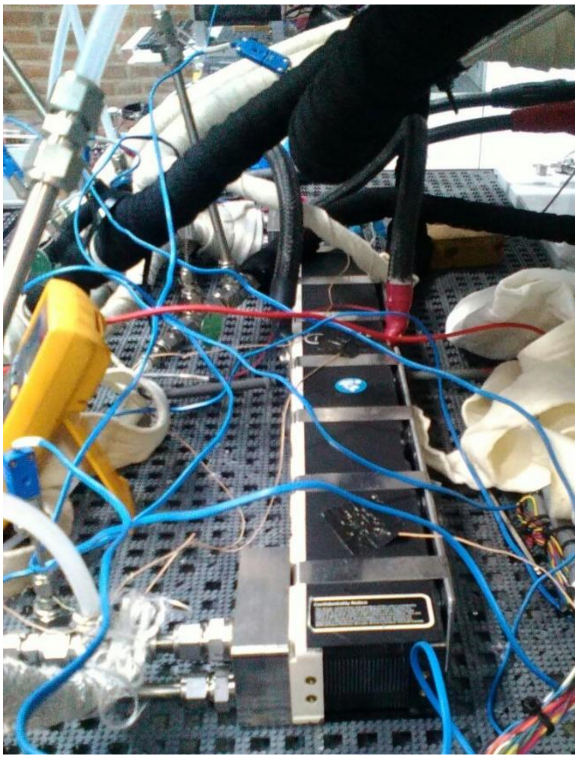
We can conclude that above 110 Amps the recycled mass flow will exceed the required hydrogen mass flow, however below 110 Amps the recycled stream will not be sufficient to provide enough steam and hydrogen. Therefore, an alternative strategy will have to be adopted at low current to provide the requested hydrogen and steam composition. A possible solution is the use of dead-end mode with increasing purging interval rate at lower range operation.



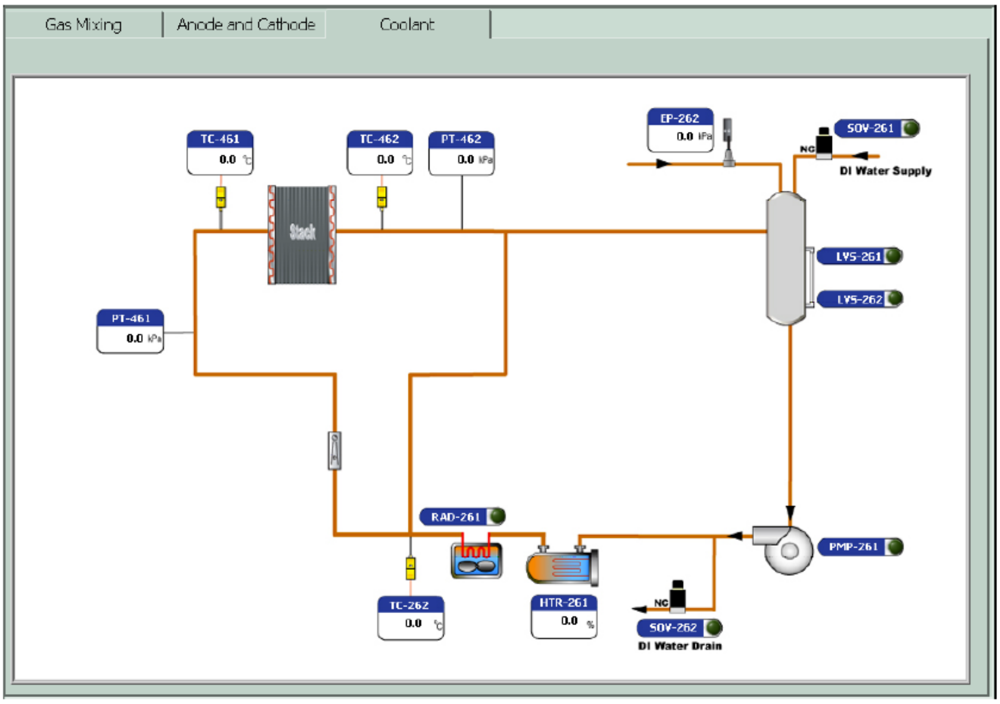
EJECTOR PRIMARY ANS SECONDARY MASS FLOW RATE WITH 0.8MM D_T AND D_m

A 20 cells fuel cell stack was tested on a greenlight test bench. The test was aimed to study the thermal behaviour of the stack in dynamic operation.

- Coolant is circulated in a plate heat exchanger
- Cooling effect is provided by public utility water
- Coolant Temperature is set at stack inlet
- Coolant LPM is set constant during the test period



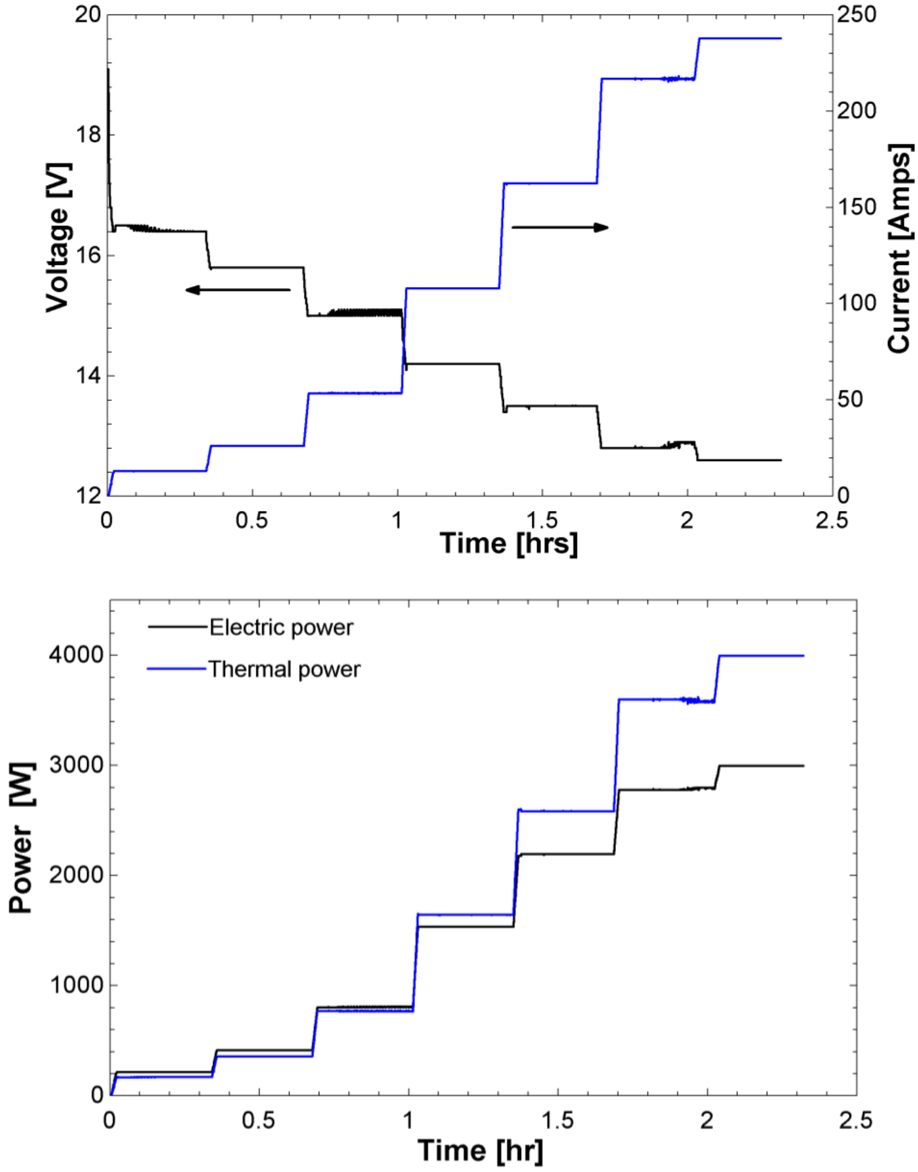
BALLARD TEST SETUP



PRINTSCREEN WATER COOLING LOOP FROM THE TESTRIG

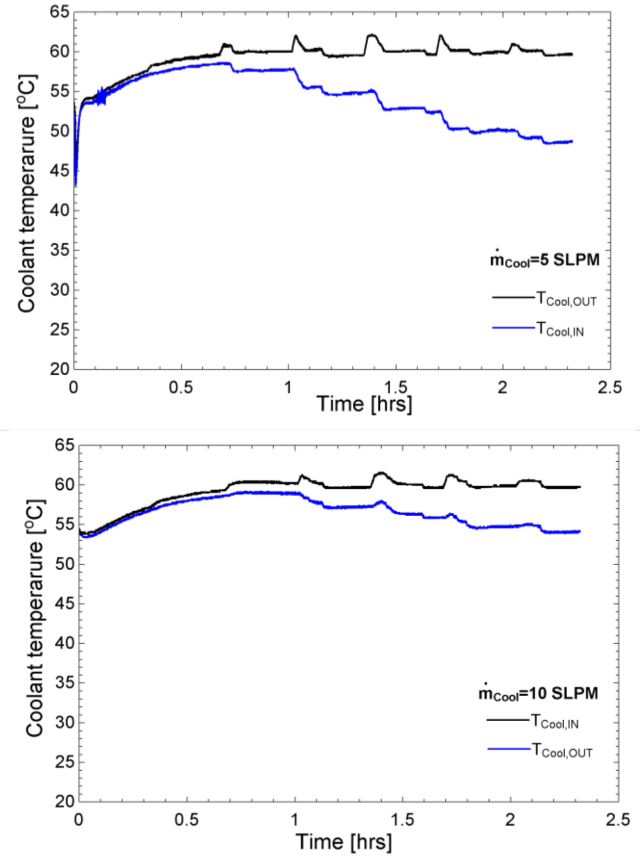
The figure below shows the electrical and thermal output of the stack. Thermal output was calculated based on equation from Ballard manual [1].

$$Q_{Stack} = (1.47 - V_{Cell})20 \times I \quad \text{[W]}$$



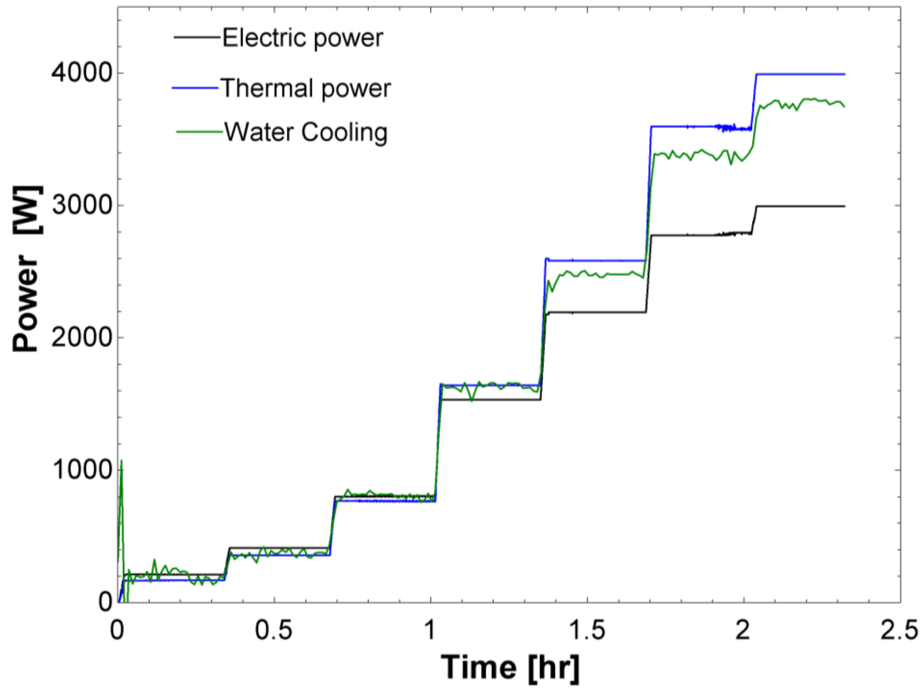
POLARIZATION CURVE TEST AND ELECTRIC AND THERMAL POWER OUTPUT OF THE BALLARD STACK

The polarization curve test was repeated twice with cooling water at two fixed values respectively of 5SLPM and 10SLPM. At high coolant flow rate ΔT between inlet and outlet will decrease. More specifically, with 10SLPM the temperature difference will be kept below 10°C. This is because the higher water mass flow rate will help removing the heat faster.



COOLANT INLET AND OUTLET TEMPERATURE

In the figure below, we can see that the cooling water will absorb most of the heat. At high loads, other effects such as air natural convections and cathode air will become more effective at removing the heat produced by the electrochemical reaction.



HEAT REMOVED BY THE COOLING LIQUID COMPARED TO HEAT PRODUCED BY THE STACK

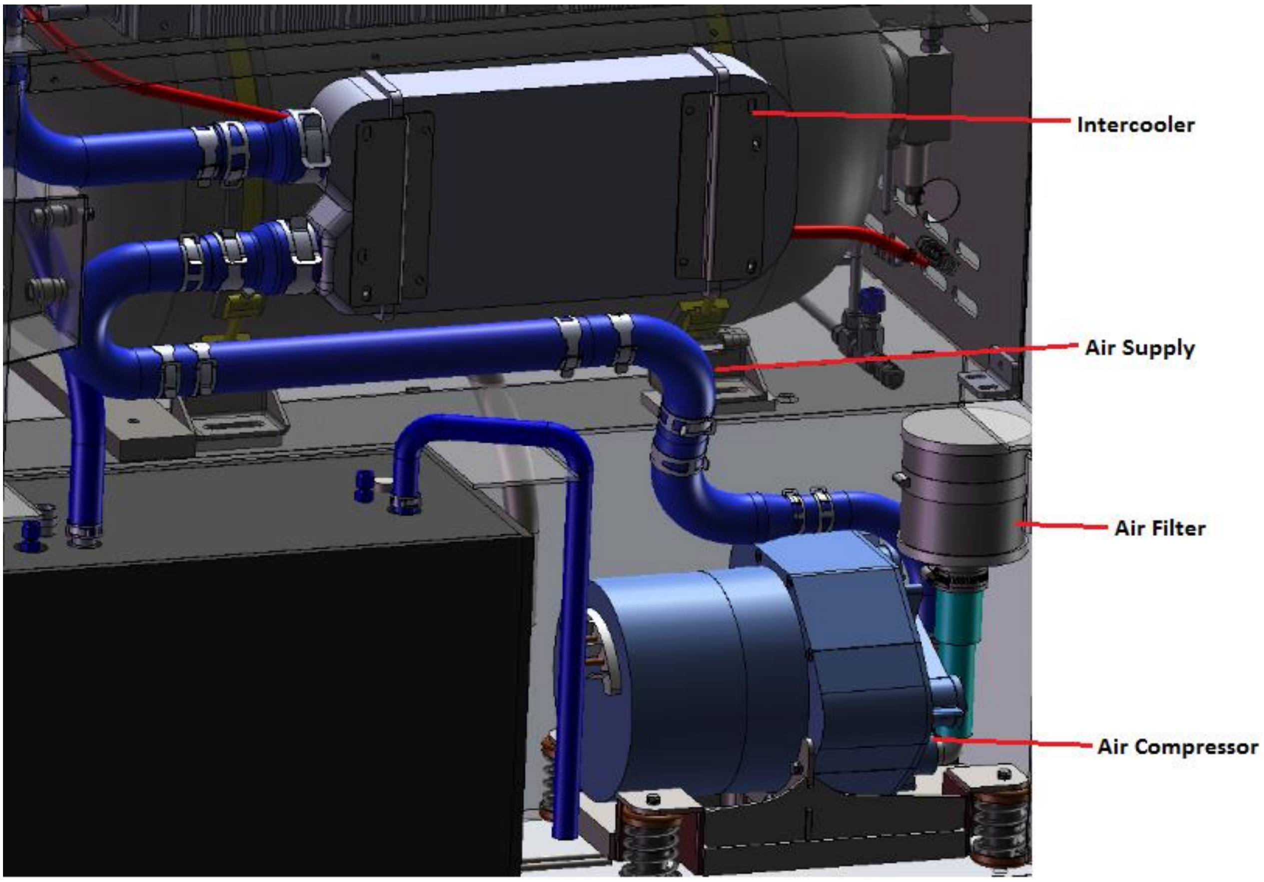
[1] Ballard. FCvelocity®-9SSL V4 Product Manual and Integration Guide. 2011.
[2] Kays WM, London AL. Compact heat exchangers. New York: McGraw Hill; 1998.
[3] http://blog.mechguru.com/machine-design/understanding-fan-curves/ n.d.
[4] FChart. EES Components Library 2016.
[5] Zhu Y, Li Y. New theoretical model for convergent nozzle ejector in the proton exchange membrane fuel cell system. Journal of Power Sources 2009;191:510–9.

5.6. WP6 – Reactant Management – Air system (BPSE)

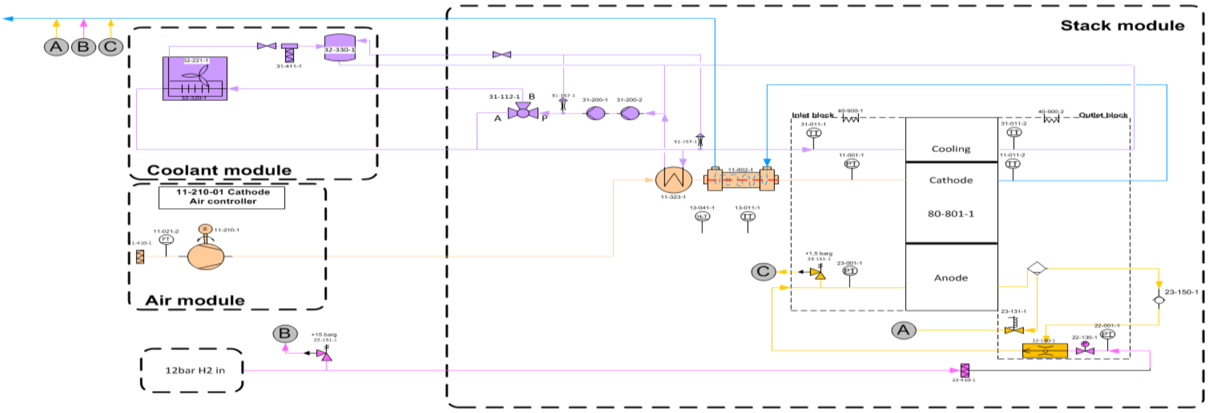
This WP is of similar importance as the water management system. Proper air quality to the fuel cell stack is essential for minimizing the degradation of the fuel cell stack. On the anode side the efficient re-circulation of anode waste gas is important for the performance of the fuel cell stack but also a potential cost-adder if not handled efficiently.

This WP aims at resulting in optimized air delivery system and anode recirculation system by assessing the impact of air contaminants and designing for contaminants in a way that supports a more durable and reliable system.

The air compressor sub-assembly is designed to deliver the fuel cell cathode air at an air stoichiometry of 1.7 to 2.0. A pressure drop system characteristic is calculated from the design study in WP 4. The air sub-assembly contains 3 components, an active carbon air filter to remove harmful contaminants from the ambient air, an oil free air compressor to compress the air to the desired set-point and an intercooler to cool the air prior to supply the humidifier and the fuel cell. The humidifier cannot tolerate high temperature operation which imply the usage of the intercooler.



A test bench has been built and all three components has been sized, integrated and evaluated according the PID shown below:

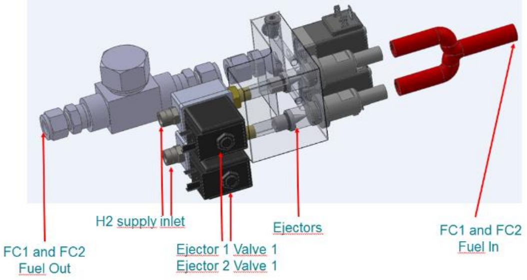


An OEM automotive intercooler, air filter has been chosen for design and an oil free scroll compressor compatible with our operating condition (15g/sec – 600mbar(g) – 15 kW)

The evaluation of hydrogen recirculation methods has been conducted. This includes the design of ejectors loop, hydrogen recirculation pumps as part of the amendment 3. Aalborg University did an extensive ejector modelling work to characterize its behaviour (Cf. WP3). 31

<table>
<tr><th>Ejectors</th><th>Recirculation pumps</th></tr>
<tr><td>

- Low BOP and compatible with tank residual pressure
- No moving parts
- Limitation of water management during shut down



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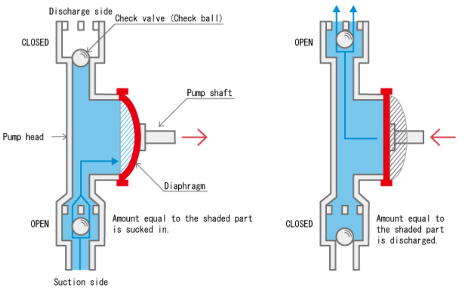
- Long-term durability test of possible candidate for Hydrogen Recirculation Blower
- Better for bottom and top load variations and anode dry out than ejectors, but also more complex design



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</table>

The design study led to choose the diaphragm pump as a primary option. A durability test performed on hydrogen recirculation pump in climate chambers with over 6000 hours of testing at 70°C/100% RH with air and over 5400 with dry H_2 at RT with air has been conducted without loss of performance. The test result was proven solid and repeatable, as it was performed on 4 identical pumps.

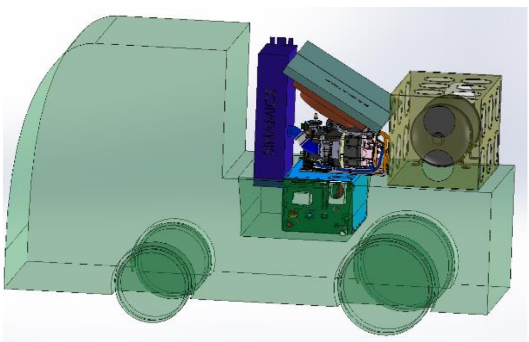
5.7. WP7 - Design for manufacturing, build and testing (BPSE)

5.7.1. Design

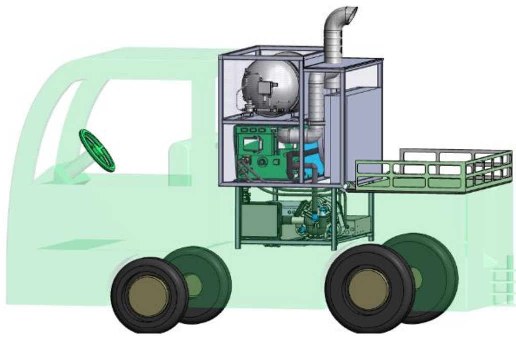
The WP contains activities that are in focus with the new consortium behind the H2Drive product where new capabilities on manufacturing are brought to the table. In this work both supply chain and manufacturing are involved – and involved from the early system architecture and component selection activities to ensure best possible design for manufacturing, lowest cost and smooth prototype build. This WP also ties very much into to the modularity in WP3 which is important to ensure easy subassembly design for manufacturing. There are 3 main objectives:

- Fabrication of a15 to 30 kW motive complete module including, FC module, Tank system, Heat exchanger and control interfaces
- Design of 60 kW module, for a mining equipment (amendment 1)
- Evaluation of standard MD 30 module including an off-the-shelf DC/DC converter (amendment 3)

The design study for the vehicle integration aim at reducing assembly time by implementing some design for manufacturing technics. This was centred around a skid mechanical approach where all components are integrated in a prefabricated chassis. The figure below shows the initial design to the final version.



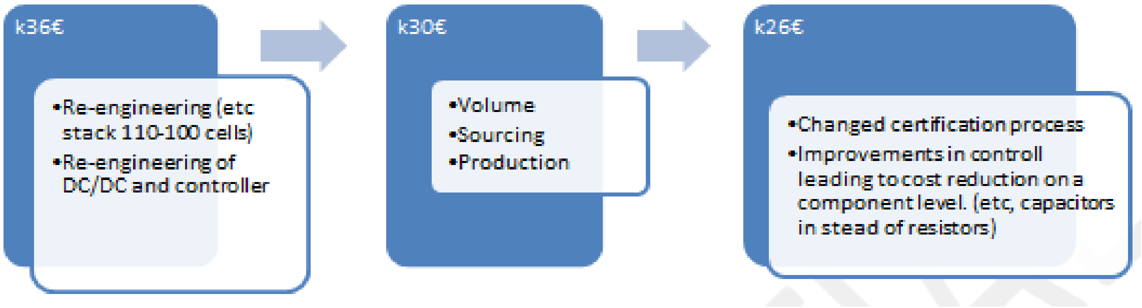
Initial design



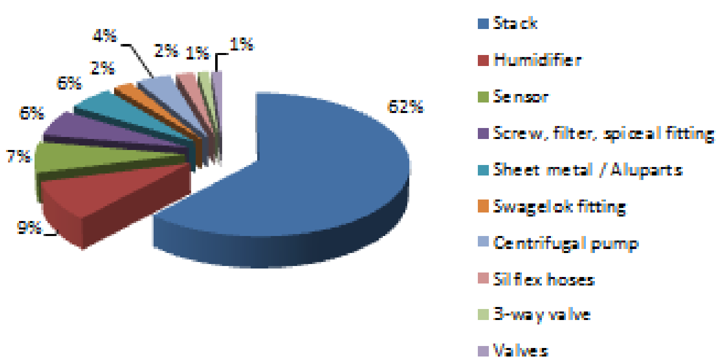
Final design

This design for manufacturing study was seconded by a volume cost study to ensure a complete cost alignment with the cost target of the system. In volume the new design could lead a 30% cost reduction which is well in line with the market cost target.

Overall cost reduction process



The module cost reduction has been by optimized by performing a bill of material cost analysis. We can observe that the Fuel cell stack along with the gas to gas humidifier has the highest share of the fuel cell module sub-assembly. Around 30% of the module cost is coming the BOP components.



5.7.2. Build

The final product was configured using all learning from each deliverable. A complete unit is shown incorporating the following features:

- Used of standard Controller
- Integration of standard DC/DC converter
- Integration of deliverables from WP 4, WP5 and WP6
- Design for manufacturing by the means of building sub-assemblies
- This includes standardized fork lift truck power module compartments and airport pull truck engine compartment
- Adaptation of the module for Amendment

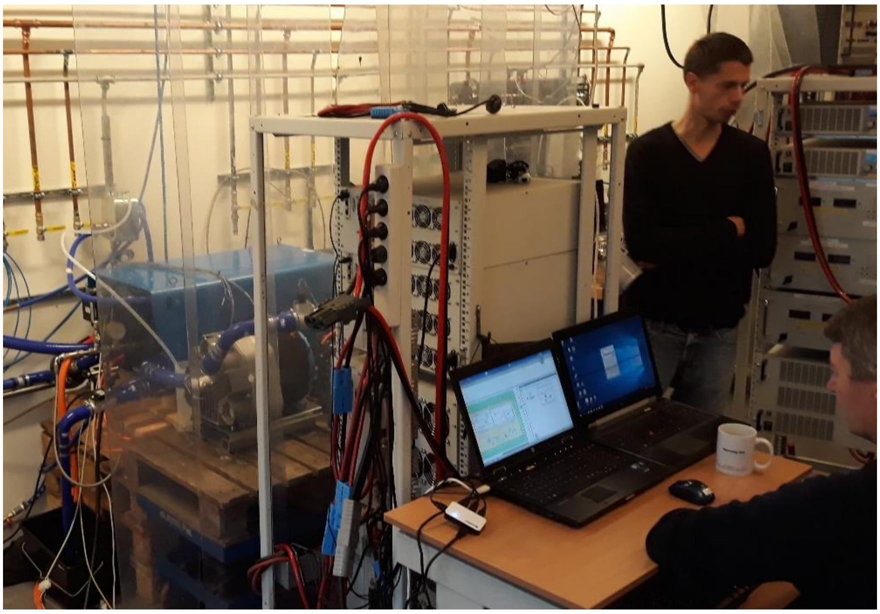
1, adaption to 30 kW module

5.7.3. Laboratory testing

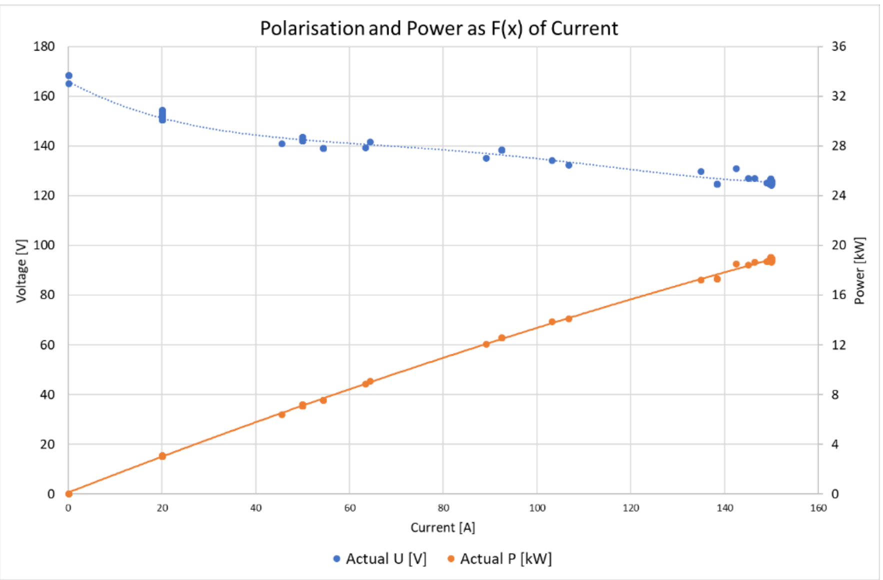
Prior to assembly the various sub systems was undergoing validation in the test facilities.

A large part of the validation was concerning the controller routines, to ensure safe and reliable operation, prior to vehicle operation and demonstration.

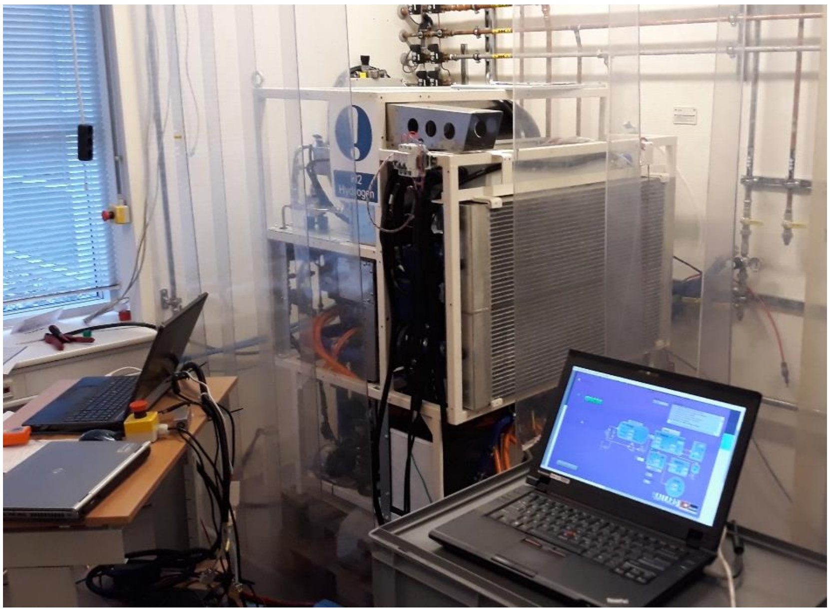
The MD 30 fuel cell module undergoing performance test, and validation control functions in the extraction cabinet.

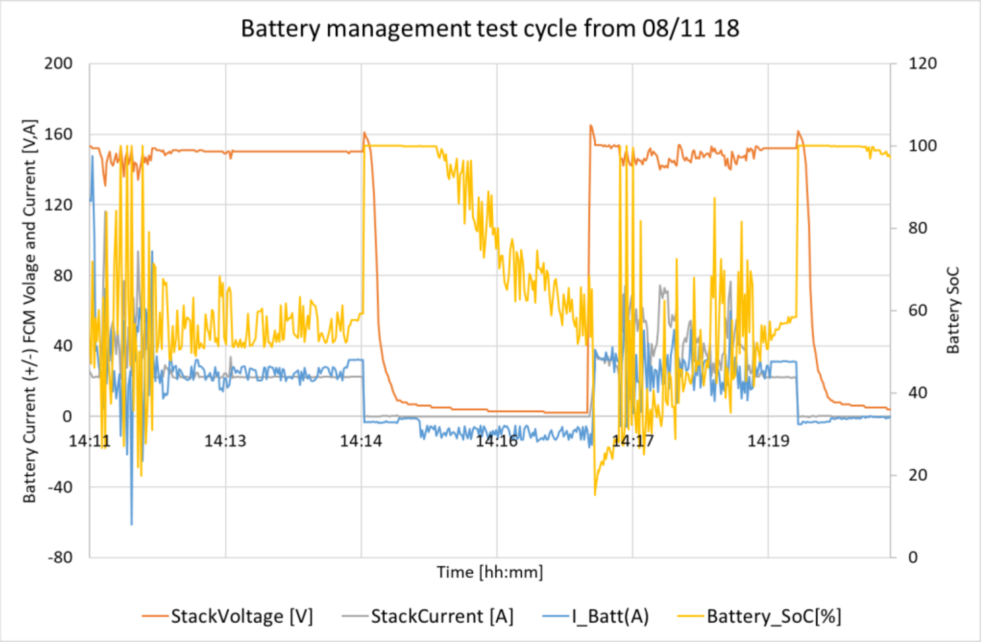


The obtained Polarization curve derived from the operational data are in line with expectations.



The assembled power unit with Tank, Fuel cell module, DCDC air compressor and Cooling placed in the extraction cabinet for extensive controller validation.





Above is an example of test sequence from the lab. Besides the incorporation of componets and controllers, a large effort was put in the ability to establish a acceptaple level of confidence in the battery management. As the fuel cell is going to effectively charge the battery, there is a responsibility not to damage and overcharge it.

The test reveales that the chosen strategy needs refinement, as the calculated battery SoC varies much as a result of varying current levels and direction. Depending on the when current varies, and dramatically jumps as the status changes from charge to discharge. This is a challenge as the intention is to have the load on the fuel cell as a inverse function of the energy availeble in the battery.

5.7.4. Test drive

FIGURE 4) TEST TRACK[1]

The designated test track is a 1.000-meter round trip, on the parking area of CEMTEC, and the low traffic public road Majsmarken.

[1]Test track at Majsmarken from google maps

Filling

To enable the test drive, the tank has to be filled. In the absence of a filling station, the vehicle was filled from a set of gas bottles batteries. The filling is done as a cascade filling, with a 1st step from a lower pressure, and 2nd step, topping up from a full battery to get the onboard reservoir as full as possible.

On Figure 3 Cascade filling3 and 4 the filling is presented as State of Charge, as derived from pressure and temperature. On 3 the entire manual filling procedure is represented, with a pause between fillings, as the filling connection was shifted from one battery to the other. This does lengthen the filling procedure.

4 is a synthesis of the 2 filling sequences, adding up the temperature increase, and removing the pause. This is not to be representative but gives an idea of the development in the tank as a one-take filling would be done.

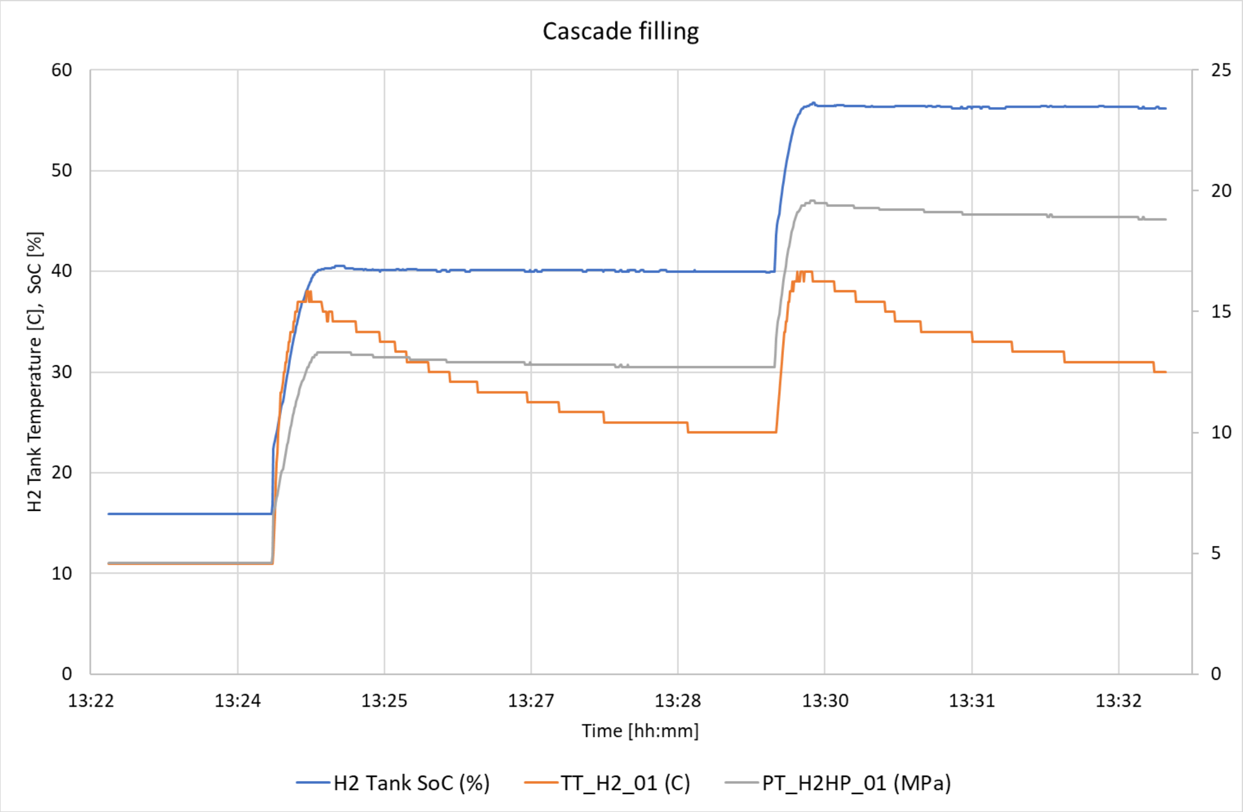


FIGURE 3 CASCADE FILLING

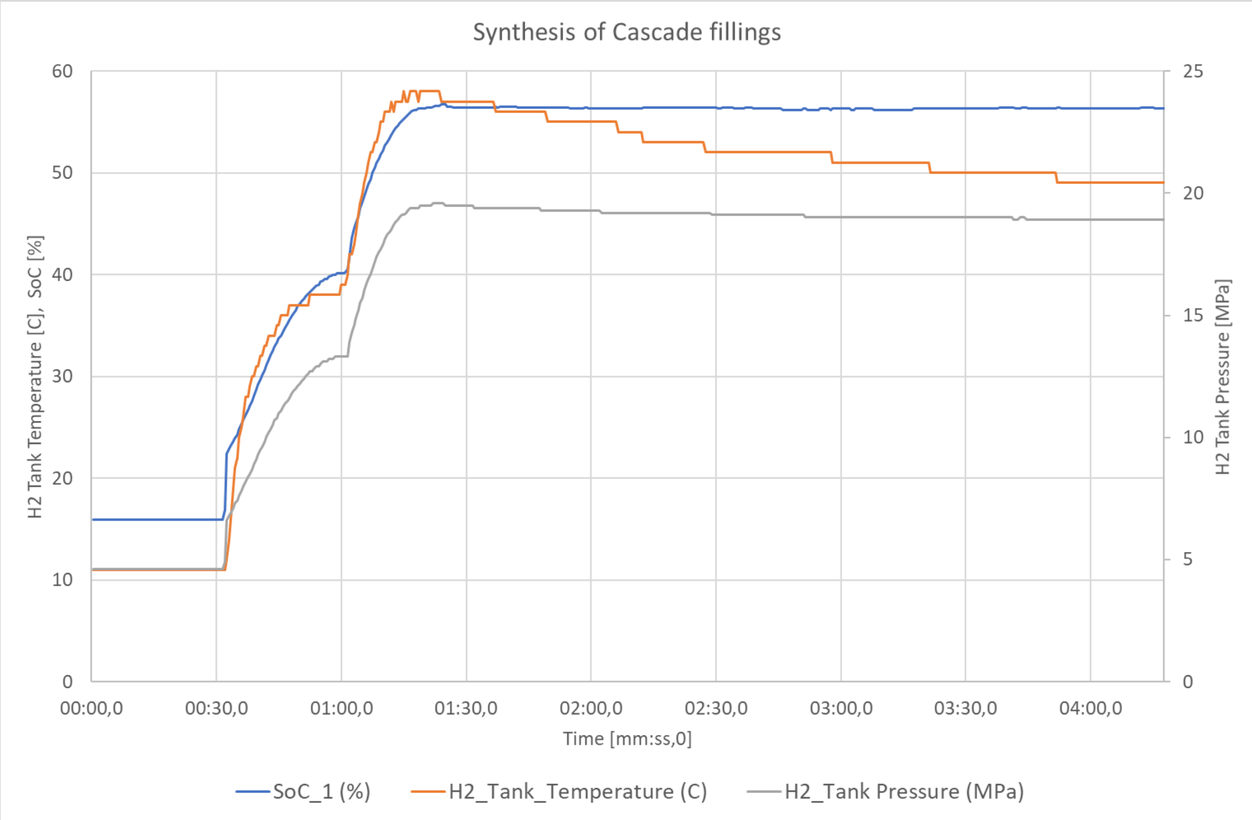


FIGURE 4 SYNTHESIS OF CASCADE FILLING

In any case the filling was concluded after 5 minutes, including Hydrogen battery change.

The net filling time was approximately 50 seconds.

The resulting filling was from 15 % to a bit above ½ full at 56% or a net filling of 41 %. On the 74-litre tank is corresponds to a mass transfer of 728 grams.

Time to complete cascade filling	5 Minutes
Net filling time (Synthesised)	50 sec.
SoC net change	40,4 %
Mass charged	728 gr.
Mass transfer rate (Synthesised)	0,86 kg/min

TABLE 1 FILLING CHARACTERISTICS

The above net filling times and SoC suggest a complete filling could be concluded within 2 minutes, provided the filling station transfer rates and pressure supply is compatible.

According to the bottle manufacturer the bottle can be filled at any rate, as long as the temperature and the corresponding pressure is not exceeded. -40°C to +85 °C,

The uncertainty here is the temperature. The Synthesized graph does only give an indication of the level of temperature rise. It has not been feasible to fill to 100% SoC.

5.7.5. Operational results

An accumulated 20 round trips on the test track within the test period gives approximately 20 kilometres travelled distance.

Test time	H2 Tank SoC	Fuel energy	Fuel Cell Energy	Drive train usage	Battery charge	Battery Discharge
13:31	56,3 %	33,3 kWh	0 kWh	0,02 kWh		
15:24	21,2 %	12,5 kWh	12,4 kWh	9,58 kWh		
01:53	35,1 %	20,7 kWh	12,4 kWh	9,56 kWh	5,22 kWh	3,31 kWh

TABLE 2 ENERGY BALANCE

5.8. WP8 Demonstration Planning (CEM)

The WP had set out to do a market report based on integrator requirements and information, end-customer requirements and general market information. Thus, along with the dissemination activities, several relevant companies for the market report were identified. A questionnaire survey was planned, to map more stakeholders for the market report. In-depth interviews with relevant agents from Rockwool, Hedegaard Food and Arla were planned to be performed, to substantiate the information.

The market report was intended to be utilized for strengthening the business plan and the project development going forward, while also clarifying the opportunities for a future demonstration of the material handling vehicles after the ending of the project.

It is important to note that due to a change in the partner composition during the project in 2017. The project shifted from focusing on the development of fuel-cell powered fork lifts to the development of fuel-cell powered tow tractors.

Although this strays away from the focus of the market report. The knowledge gained in the analysis is not wasted as Ballard Power Systems Europe former Dantherm Power is still involved in the forklift market. As such this report still provide Ballard Power Systems Europe with valuable information about the forklift market in which they are still engaged.

On February 3rd, 2016, the first Fuel cell forklift Event at the Port of Aalborg was held. The purpose with the event was to create awareness and knowledge about the fuel cell forklift, and to get a better understanding of the target group for potential fuel cell forklift users. Approximately 60 people came to the event, and the participants represented a wide target group from researchers to truck drivers. The event also resulted in a lot of media coverage.

Based on the dialogue with potential customers, the questionnaire surveys as well as data collection from secondary sources, the Market report and a deliverable was prepared, which offers a general outline of the fuel cell forklift market as it was at that time, both on a national and international level, as well as an insight into the interest in the fuel cell forklifts based on experience gained in the HyFlexDrive project so far.

The market report established that there was a great focus on hydrogen mobility and a great interest in the fuel cell forklift. The market was dominated by a roll-out in especially north America, however more projects like the HyFlexDrive were paving the way for the introduction and support of the fuel cell forklift on a European level.

However, it was noticed that there was still a long way to go for the fuel cell forklift to become commercial acceptable and available for companies. The technology was at that time quite new, and there was not that much demand for it and as the questionnaires showed there was little to no knowledge about the fuel cell forklift. Therefore, there was a need for a reach out to the bigger companies, who have the resources to both put time and money in a demonstration period and invest in the fuel cell forklifts. And preferably in addition also have a lot or some focus on CSR and/or green branding of the company.

Based on the questionnaires and the knowledge obtained through the preparation of the market report, an indication of who the potential customers could be for a future demonstration was given. Those potential customers were companies who are using the forklifts indoor and almost 24/7. Most of these companies were using forklifts which run on batteries. Nevertheless, for it to be a sustainable business case for the customers, they will need a refuelling station close by, in such way that they should not spend time on the refuelling process more than the 3-5 minutes, which takes to refuel the forklift.

New areas of use and new customers are yet to be identified when we know more about the design, tractive force and performance on the Mulag tow tractor. When this have been identified, we will move on with the demonstration planning and the identification of potential stakeholders interested in demonstrating the Mulag tow tractor.

Dissemination

Several dissemination activities were carried out, where the HyFlexDrive project was presented at various occasions.

The first press release was published on 19th October 2015, which resulted in a visit from a reporter and photographer from Nordjyske, which published an article in the newspaper and a small video interview on 24Nordjyske.

On the 25th of October 2016, a class of talent students from Mariagerfjord Gymnasium visited CEMTEC and got a presentation from both Hydrogen Valley and Ballard Europe as well as an introduction to the HyFlexDrive project. The students also got a tour around the Ballard facilities and the fork lift, which for a long time has been a part of the HyFlexDrive project.

On the 29th of November 2016, a group from IDA (the Danish society of engineers) visited CEMTEC in Hobro, and they were presented to the HyFlexDrive project through presentations from project partners Hans-Jørgen Brodersen, project manager at Hydrogen Valley/CEMTEC, Lector Mads Pagh Nielsen from Aalborg University and Kristina Fløche Juelsgaard, Business Development Director from Ballard Power Systems Europe.

The HyFlexDrive project was also presented at the Transport Fair in Herning on the 23rd - 25th of March 2017, where Ballard Europe had a stand.

On the 6th of April 2017 Mads Pagh Nielsen from Aalborg University presented the HyFlexDrive project in Sønderborg at an event arranged by IDA Syd.

On the 29th of April 2017 Hydrogen Valley/CEMTEC together with GASmuseet hosted an event within the framework of the Danish Science Festival with the focus on hydrogen in the future energy system. And again, here the HyFlexDrive project was presented to the around 70 participating children and adults.

On the 28th of November 2017 Vincenzo Lizo presented the HyFlexDrive project at the Danish Brint og Brændselscelledag in Odense at Syddansk University.

In 2017, we also planned to do a press release in both Danish and English as well as updates on social media. However, as the dissemination activities are closely connected to the demonstration period and the overall development of the project, it was put on stand-by due to the challenges the project was facing.

On the 19th of November 2018 Kristina Fløche Juelsgaard presented the HyFlexDrive project at the Danish Brint og Brændselscelledag in Odense at Syddansk University.

In December 2018 a small video about the Mulag tow tractor was produced, together with a press release marking the end of the project. The press release and video was published and shared on hydrogenvalley.dk and LinkedIn on the 11th of January 2019.

6. Utilization of project results

6.1. WP1 - Project management

N/A

6.2. WP2 - System Architecture and Design (BPSE)

New platform developed using motive module

6.3. WP3 – Modularity (BPSE)

Identification of sub-component such as DC/DC converter, air compressor

Development of Hydrogen tank controller and hybrid controller

Development of integration method

6.4. WP4 - System modelling (AAU)

Complete model of ejectors and liquid cooled system

6.5. WP5 - Heat and Water Management (AAU)

Evaluation of Ballard mark 9SSL and model verification

6.6. WP6 - Air system - Reactants (BPSE)

Evaluation of compressor and air sub assembly component for the 15-30 kW market

Validation of ejector and hydrogen recirculation pump

6.7. WP7 - Design for manufacturing, build and testing (BPSE)

Development of method of integrating complete fuel cell power module into vehicle. Method can be applied to other vehicle or liquid cooled stationary system

6.8. WP8 Demonstration Planning (CEM)

Identification of field trial partner as part of the consortium is necessary to conduct adequate field trial

7. Project conclusion and perspective

This project has allowed BPSE to develop competencies and know-how in the integration of fuel cell in light vehicle application. This platform can be used to target and support all new customer and project.

In addition, we have identified the following areas of potential improvement:

- Possibility to simplify further the system by using the new generation of the Ballard liquid cooled stack

- Evaluation of operating fuel cell stack without gas to gas humidifier to reduce pressure drop and reduce cost.

- Complete utilisation of all learning for other application such as railway or maritime

- Possibility of using the technology for high power stationary application