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Improvements Cathode Path

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List of Acronyms and Abbreviations

Abbr.	Description	Abbr.	Description
Pt	Platinum		
RH	Relative humidity		
PITM	Platinum in the membrane		
PGS	Power Generation System		

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1. Executive Public Summary

- This report contains high level results of the activities performed during the first phase of the WP6.
- The aim of this phase was to evaluate the potential options to the cathode path.
- The proposal was focused on evaluating the benefits of cathode recirculation to prevent high cell voltages at idle power. Next to that two alternatives for humidification of the membrane were researched.
- The cathode recirculation concept has been abandoned due to the difficulty of implementation as well as limited benefits.
- Alternative architectures and controls have been proposed for each problem.
- For the idle voltage the concept of low lambda operation has been investigated.
- For the issue of humidification, the concept of dry operation has been looked at.
- The two alternative concepts provide an attractive solution to improve the cathode path.

2. Introduction

In this report potential alternatives to improve the performance of the cathode path are discussed. The cathode path currently is built according to the drawing below

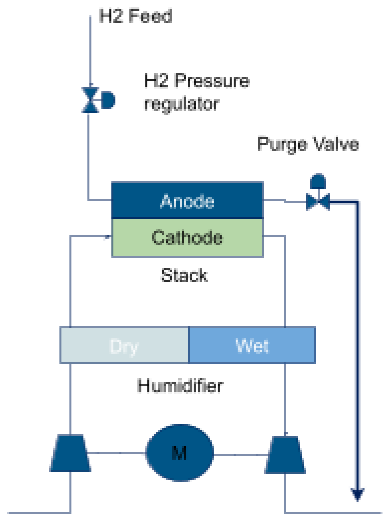

Fig 2.1 - Cathode Path of a fuel cell system

The cathode path optimization leaves little space for optimization. The two major components: compressor and humidifier add weight and complexity. The air flow cannot be deleted or merged. Therefore the compressor can't be removed, only weight reduction is feasible. Thus, more potential for optimization might be found with the humidifier. The humidifier takes on humidity from the exhaust of the fuel cell and brings it to the flow going into the fuel cell inlet. It accomplishes that by use of membranes that have high water exchange rates. This component is very common in fuel cell systems and the industry has converged to what is called a flat sheet membrane humidifier. Other variants are called tube and shell which make use of different polymers but in an extruded construction of several small tubes. An alternative to solve this issue is to use cathode recirculation (as suggested in the proposal). This is done with an active pump that recirculates part of the exhaust flow back into the fuel cell. A back up solution, called Dry Operation, has been investigated in this report as well. In this concept the idea is to remove the humidifier from the system and reoptimize the system around the limitations of the stack.

Another issue faced by the system is the high stack voltages seen at idle power. Considering the fuel cell has a higher efficiency at low power and given the number of cells typically used in aviation, it can lead to voltages. These voltages reach above some thresholds that can damage the power electronics. One of the ways to solve this problem is to use cathode recirculation, which has depleted oxygen in its exhaust stream and feed it back to the inlet of the stack. This leads then to lower cell voltages due to the lower oxygen concentration. The team has also evaluated another option to solve this problem, called low lambda operation.

3. Humidification

The humidifier aims to ensure that the air feeding the stack is sufficiently humidified so that the fuel cell membranes operate properly. To do so, the humidifier performs a transfer of water (mostly as vapor) from the air coming out of the fuel cell stack to the air going to the fuel cell stack inlet. This function is done using a so-called flat sheet humidifier.

The humidifier has some drawbacks such as introducing pressure drops, being bulky and heavy with low durability (loss of water exchange capacity overtime).

One of the solutions to this problem is to recirculate the exhaust cathode gas back to the inlet. This would lead to an increase in water content at the inlet which would then humidify the membrane. The aim of the cathode recirculation remains the same, ensure at least RH=20% at the stack inlet to protect the membranes (as specified in the WP2 requirements).

The pros and cons of the technology are summarized in the table below

Advantages	Disadvantages
• Removal of humidifier ○ Less dp ○ Less weight ○ Less volume ○ better MTBF	• Less oxygen after mixing leads to an increase of dry flow demand to obtain the right O2 molar flow at FC inlet • Pol curve eff slightly impacted by lower o2 concentration • Compressor second stage will experience liquid water • Controllability / Complexity

Table 3.1 Advantages and disadvantages of the cathode recirculation concept for humidification

With this in mind, the team has run different experiments and simulations to support the trade off analysis on this technology. The values are shown in the table below.

Parameter			Unit	Delta to Baseline
Performance	Power Required	MTO CP 120%	kW	+8
		TOC CP	kW	+9
Volume	Motorized Machine	Turbomach. (Ø)	mm	+6
		Turbomach. (L)	mm	+8
	Overall System	Components Volume	L	-52
Weight		Turbomachinery	kg	+2
		MCUs	kg	+4
		Air System Piping	kg	-3
		IHX & LHX	kg	+15
		Humidifiers	kg	-38
		Total Air System	kg	-20

Table 3.2 - Summary of cathode recirculation evaluation for humidification

As one can see by the results in table 3.2 the power required to run the new air supply system would increase, as well as its size. However, the total volume and weight of the system would be reduced due to the deletion of the humidifier. Therefore one could claim that the introduction of the cathode recirculation system should be encouraged.

However, other topics that need to be taken in consideration make the alternative not the most attractive, namely the difficult in controlling the recirculation flow, dealing with potential surge events and the overall lower performance of the stack due to the recirculation flow are qualitative assessments that lead the team to believe that, in the end, the gains shown here would be equivalent to the perceived disadvantages. The team will continue to evaluate the cathode recirculation option until the freeze of the technology that will be adopted in the PGS.

Another alternative that has shown promise is the complete elimination of the humidifier. On one hand, completely eliminating the humidifier would bring the elimination of quite heavy and bulky component. On the other hand, a lower performance at higher temperatures is to be expected, as well as some impact to the durability of the stack.

To support the evaluation, the team has commissioned a test of a short stack and looked at the stack performance loss for operation under dry conditions vs humidified conditions. The results of the test are shown below in fig. 3.1

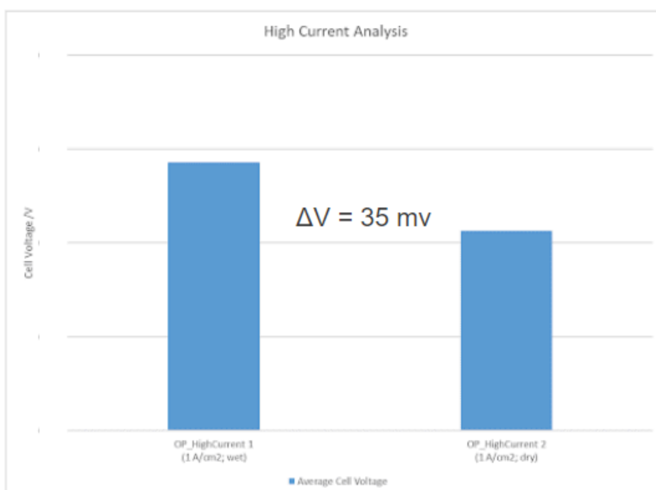

Fig. 3.1 : Performance difference between a humidified vs non-humidified stack

As one can see from the graph, the performance difference between the two options is 35mv. That means that the stack would need to pack more active area to reach the same targeted power levels. On the other hand, the elimination of the humidifier weight would require less power from the system. The volume of the humidifier also means a lower wetted area of the propulsion system, which will reduce drag. Lastly, the elimination of the humidifier reduces the pressure drop of the system, which will require less pressure increase by the compressor and therefore less power from the stack. With all these considerations at hand the team has assessed what the final system size would be, this is shown in the table below

Parameter	**Non-Humidified system**
Cell Voltage difference	-35 mv
Stack weight	+2.5 kg
Stack dimension (stacking)	+35mm

Table 3.3 - Difference in performance of a non-humidified system

As it is possible to see, the non humidifier system will yield a heavier and larger stack, however, this needs to be traded-off against the deletion of the humidifier. This study will be performed again in the future when the tasks related to system integration continue. At that specific point in time the team hopes to finalize the trade off as more information becomes available to decide between the two alternatives presented in this part of the report. Additional test data that will be available by then is the durability tests of the stack.

4. Idle Voltage Control

As explained in the introduction of this report, due to electrical requirements the power generation system is required to maintain the voltage at the interface below 850V. This is particularly hard given that the polarization curve will have higher cell voltages at idle. One of the solutions to solve this issue is to work on a solution called low lambda operation.

A fuel cell has typically an optimal efficiency at a given air flow. That air flow is generally higher than the minimum required for the reaction, because air needs to distribute evenly between the multiple cells in a stack. Therefore, one of the ways to reduce the cell voltage of the cell is to reduce the amount of air fed to the fuel cell.

To accomplish that, a controller needs to be implemented which constantly seeks to achieve a target stack voltage and then it adjusts the air flow to reach that target.

The basic advantage of this strategy is the ease of implementation as it is mostly a controls development, not requiring the use of new hardware nor adaptation to existing hardware (like cathode recirculation option). Therefore the low lambda implementation has become the preferred solution to address this issue.

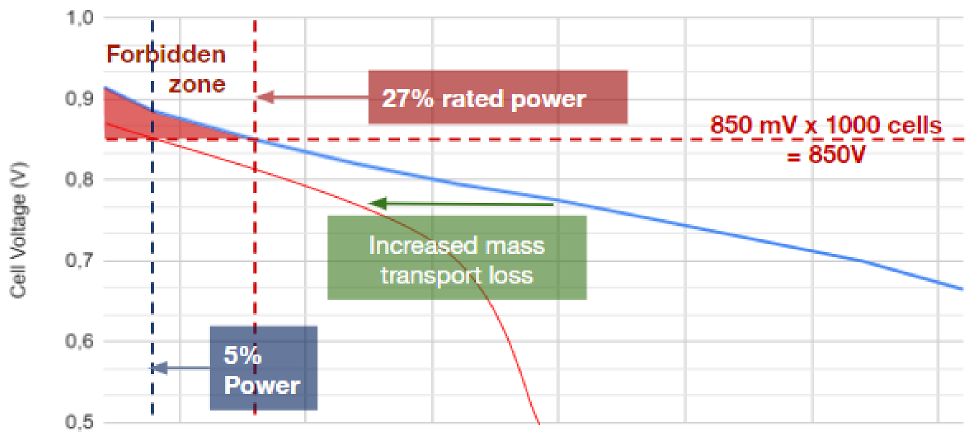

Fig 4.1 - Schematics of low lambda operation

As it is possible to note in Fig. 4.1, the polarization curve of the fuel cell, if operated at regular conditions and if the stacks have a certain number of cells (in the picture here it is depicted as 1.000 cells), then the stack voltage will certainly cross the 850V limit set by the electrical requirements (blue curve). Typically at idle the system consumes about 5 to 10% of the power of the stack, therefore the blue curve needs to shift towards teh lefthandside, reducing in efficiency. The red curve is the one representing the targeted polarization curve when operating in low lambda mode.

The next step in developing this strategy is to characterize a fuel cell stack with regards to its sensitivity to air lambda and cell voltage. This has been done and it is shown in Fig. 4.2 below.

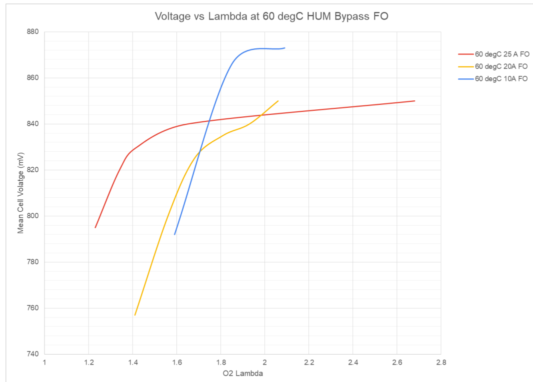

Fig 4.2 - Characterization data of a stack running at low lambda

The graph shows 3 different curves. Each curve was made of a specific current of the stack, but all the same temperature. This is required to calibrate the control as depending on the power level, a different current might be required and therefore the lambda where the power level can be reached will change. The important information from the graph is to spot at which lambda a cell voltage of 850 mv can be achieved (because 850 mV X 1.000 cells = 850V). That lambda as one can see, can range from 1.6 to 2.5 depending on the current.

With this information the control logic is then created following a simple closed loop architecture, in which the targeted voltage is your control variable. The difficulty arises because power is also a targeted variable so the limitation so there are two competing control variables determining the lambda at which the stack needs to run. But, this is not so critical as the team believes that this can be solved with basic controls laws.

With that information, the team has carried out several other tests to demonstrate the concept under different conditions, use cases (acceleration) to determine if the strategy would be robust and reliable. The data so far show promise and no show stoppers have been found. Therefore the team believes that this is a better solution than the cathode recirculation, which would require additional hardware and integration work.

5. Conclusions

In this workpackage 6 activity, the goal to find improvements to the cathode has been achieved. The problem to be solved was boiled down to humidification and durability related to the voltage limits of the system.

For both issues, cathode recirculation has been proposed as one of the solutions, however, due to the complexity of the solution and hardware the team believes that two alternative solutions would be a better fit to the overall integration goals. The non-humidfication coupled with low lambda therefore remains as our alternative and the remaining tests and analysis that will be performed until the end of the integration work, will determine if the final system will stay with these two solutions.

6. Acknowledgments

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Project partners:

#	Partner short name	Partner Full Name
1	A-D	AIRBUS OPERATIONS GMBH
2	A-E	AIRBUS OPERATIONS SL
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