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Executive Summary

This report aims to provide concrete plans and designs to improve the performance fuel cell based gensets developed within the project. The work is focused on the MS-20 fuel cell system, to be integrated as part of the 25 kW genset.

The report starts with a short evaluation of the current status of the MS-20, based on “D1.3 Gensets Enabling technologies (FC and H2 Storage) Assessment Report”. Improvements of the design of the MS-20 fuel cell system are targeted in terms of system efficiency, durability, operation characteristics and costs (CAPEX), also referring to FC genset performance targets set in the Grant Agreement.

Based on the evaluation, the main task to be carried out within the project is implementation of an ejector based hydrogen supply system for the 25 kW fuel cell power module. This would allow reduction of component costs, improved efficiency and durability, which is well in line with the project goals. Furthermore, freeze testing of the 25 kW module should give more input to optimize the system for increased freeze tolerance and improved low temperature operation. Instead of improving only the efficiency and durability, this task would allow the system to be applied to completely new markets. Yet another option is to improve the performance of the compressor and membrane humidifier by using a water spray before the air compressor, which improves the performance of both the compressor and humidification system.

The above three improvement approaches are the ones that may be implemented to the fuel cell power module within the framework of the EVERYWH2ERE project Task 2.1.

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Abbreviations and acronyms

BoP	Balance of Plant
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
DC	Direct Current
PEMFC	Proton Exchange Membrane Fuel Cell

1. Introduction

This report was prepared within the framework of Work Package 1: FC Gensets Specifications, and contains evaluation and initial plans for improving the EVERYWH2ERE genset efficiency, durability, operation characteristics and costs structure (CAPEX).

This work has been realized under the responsibility of VTT with the supervision of RINA-C as WP1 leader and collaboration with PCS. The improvements proposed in this report will be evaluated for the MS-20 fuel cell power module within the framework of the EVERYWH2ERE project Task 2.1.

It is important to highlight that the improvements suggested in this deliverable are only a minor possible increment on reaching the performance targets set for the FC gensets as a whole. The proposed enhancements here suggested are mostly related to activities to be performed by VTT and are such that VTT can test and implement to increase performances of the FC subsystem: the “engine” of EVERYWH2ERE gensets.

The main quantitative targets referred also in D1.3 are presented as follows:

- Lifetime up to 20 000 hours and durability of the stack up to 10000 hours
- Efficiency above 50% (55% as set in D1.3 for the stack)
- Start in sub-zero down to -20°C
- CAPEX up to 5500 €/kW (CAPEX for the FC Stack of 2000€/kW)

These targets cannot be met by a single modification or component within the fuel cell system, but require a lot of small increments. Easiest ways to improve the overall efficiency, durability and CAPEX is through sourcing components that better suit this purpose. Another way to achieve this is through more elegant design of the overall Balance of Plant system. These opportunities are evaluated in detail in “D1.3 Gensets Enabling technologies (FC and H2 Storage) Assessment Report”.

In this report we seek solutions that are not available commercially off the shelf, allowing us to potentially go beyond the project targets. Three solutions were identified, which have a potential to be realized within the MS-20 system, and which could also be validated in collaboration with VTT and PCS.

Based on the facilities and personnel resources available at VTT, hydrogen storage, power electronics and the 100 kW genset was not included in the scope of this work. However, lessons learnt from system optimization for low temperature operation, and the use of mist injection for intercooling could possibly be implemented for the 100 kW system. However, these are left out of the scope of this deliverable.

Driver of the project	Specific Objective	Key Performance Indicator

Demonstrate reliability of FC gensets	Enlarge lifetime, guarantee power in harsh environment and partial load, good efficiency and low degradation	- Lifetime up to 20000 hours (10000 hours of the stack) - Efficiency above 50% (55% of the stack) - Start in sub-zero down to a -20°C
Demonstrate adequate CAPEX and OPEX	Reduce CAPEX using already on the market solutions also from other sectors (i.e.RES power electronics)	- CAPEX up to 5500 €/kW - 6h installation time to reduce installation costs - Reduced Maintenance & H2 costs, higher efficiency (OPEX - 10%)

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2. Proposed Improvements

To review the current design and components shortly, the MS-20 will be based on a liquid cooled 264-cell S2 stack. The anode subsystem, employs a Busch MA0018 hydrogen recirculation pump. The cathode subsystem is based around a FISCHER EMTC-150k Air turbo compressor and a Fumatech Ecomate® H20 membrane humidifier. The coolant circuit uses a AVID Technology WP29 pump, and a 3-way valve to regulate the portion of flow running through the radiator. Figure 1 illustrates the MS-20 design, with more details given in “D1.3 Gensets Enabling technologies (FC and H2 Storage) Assessment Report”.

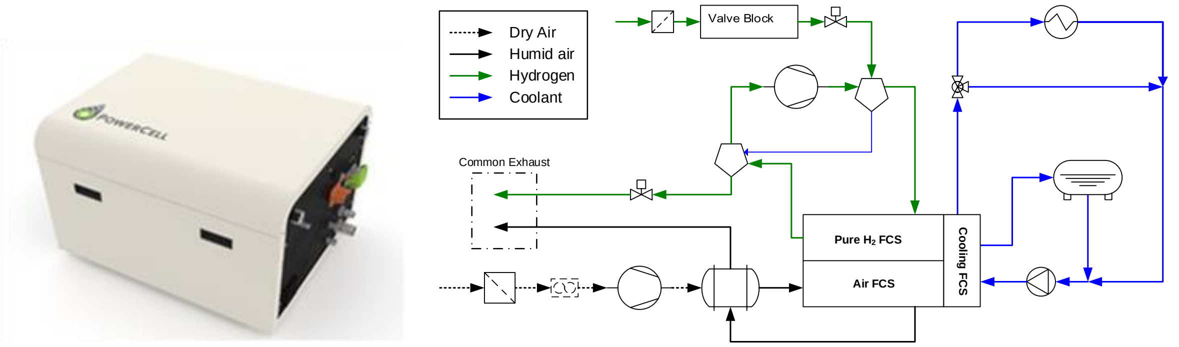

Figure 1: Picture of the current MS-20 packaging and a simplified piping and instrumentation diagram.

Based on the initial evaluation, one of the most straightforward improvements in the design would be to replace the mechanical recirculation pump with an ejector based hydrogen recirculation system. VTT has previous experience in ejector sizing and control system development, and facilities to test the solutions experimentally for fast prototyping.

Another path to improve the commercial viability of the system is through making it more flexible for operating in harsh conditions. Especially operation in freezing conditions was seen as major advantage, and this is something VTT and PCS have been working on previously. VTT has suitable experience and laboratory facilities for fuel cell system freeze testing, so this was chosen as the second concrete route to improvements within the project.

Yet another option is to improve the performance of the compressor and membrane humidifier by using a water spray before the air compressor, which improves the performance of both the compressor and humidifier.

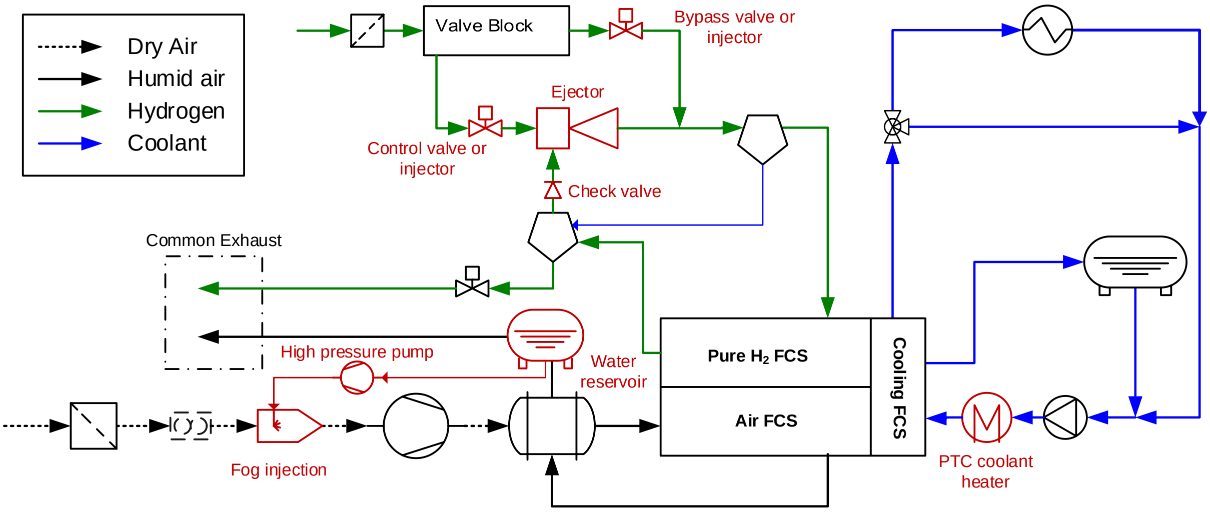

Figure 2: MS-20 simplified diagram, with example realization of the suggested modifications shown in red. The fuel supply side modifications reflect to the possibility of using an ejector, air supply side modifications show a simple fog injection loop, and the coolant loop shows an additional heater for increased freeze start-up capability.

Figure 2 shows one embodiment of these improvements laid out in the original MS-20 system piping and instrumentation diagram. More details on these specific approaches are given in the following chapters.

2.1 Ejector based fuel supply

Replacing the currently used mechanical recirculation pump with an ejector brings several benefits. First, an ejector improves durability and requires less maintenance since it has no motive parts and has a lower probability of failure. Second, the use of an ejector reduces PEMFC system power consumption and improves system efficiency since the energy for the ejector comes from high-pressure hydrogen storage. Third, the ejector manufacturing cost is a fraction of that of a mechanical pump's.

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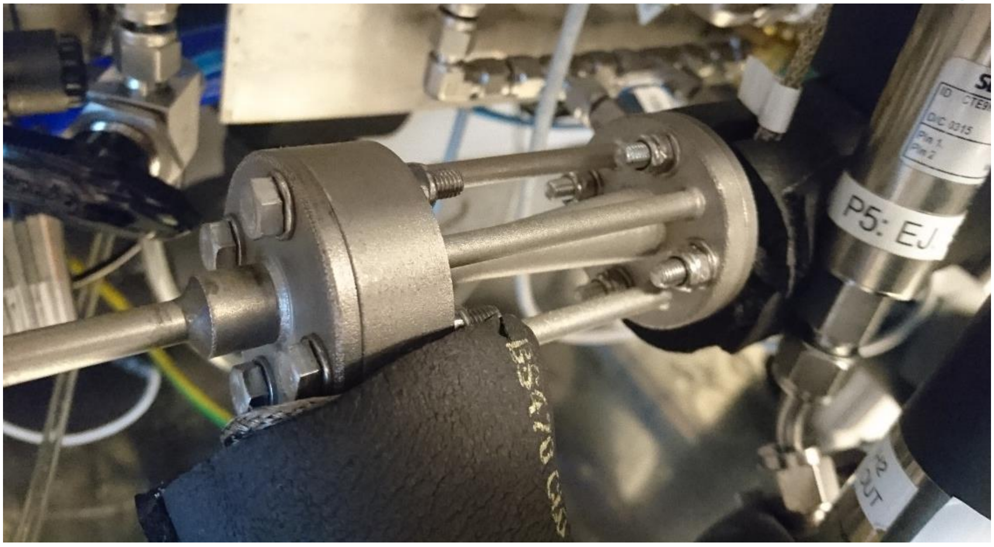

Figure 3: 3D-printed ejector installed within a 5 kW PEM fuel cell system.

The challenges associated with replacing a mechanical recirculation pump with an ejector are two-fold. Firstly, an ejector has a narrow turn-down ratio (i.e. operating window where it achieves sufficient recirculation rate). Therefore, the ejector should be carefully sized for each specific application. Secondly, the fuel gas supply rate through the ejector must be actively controlled to match it with fuel consumption rate by varying the fuel supply pressure since the ejector is a passive device. The requirement of controlling the fuel supply pressure adds system complexity.

The challenge of the ejector's limited turn-down ratio can be resolved in a number of ways. In a hybrid system, a mechanical pump and an ejector are placed in parallel and the pump is employed only at ejector's off-design conditions. However, this approach does not do away with the need of an expensive mechanical pump. Another approach is to trigger the anode purge more frequently at ejector's off-design conditions, thereby alleviating problems associated with insufficient anode gas recirculation. Yet another approach is to use a variable geometry ejector with a higher turn-down ratio (but also higher price) than a fixed geometry ejector. Further, several fixed geometry ejectors, each optimized for a specific operating point, can be placed in parallel. In case of very low flow resistance in the anode system, sufficient recirculation rate can possibly be achieved with a single fixed geometry ejector and minimum acquisition costs.

The ejector requires careful sizing in spite of the method employed to resolve the ejector's limited turn-down ratio. Ejector sizing is a relatively complex task because of the many dimensions and operating parameters affecting ejector performance. The easiest and most accurate method to size an ejector is employing computational fluid dynamics (CFD). VTT has experience as well as the hardware and software needed for this purpose.

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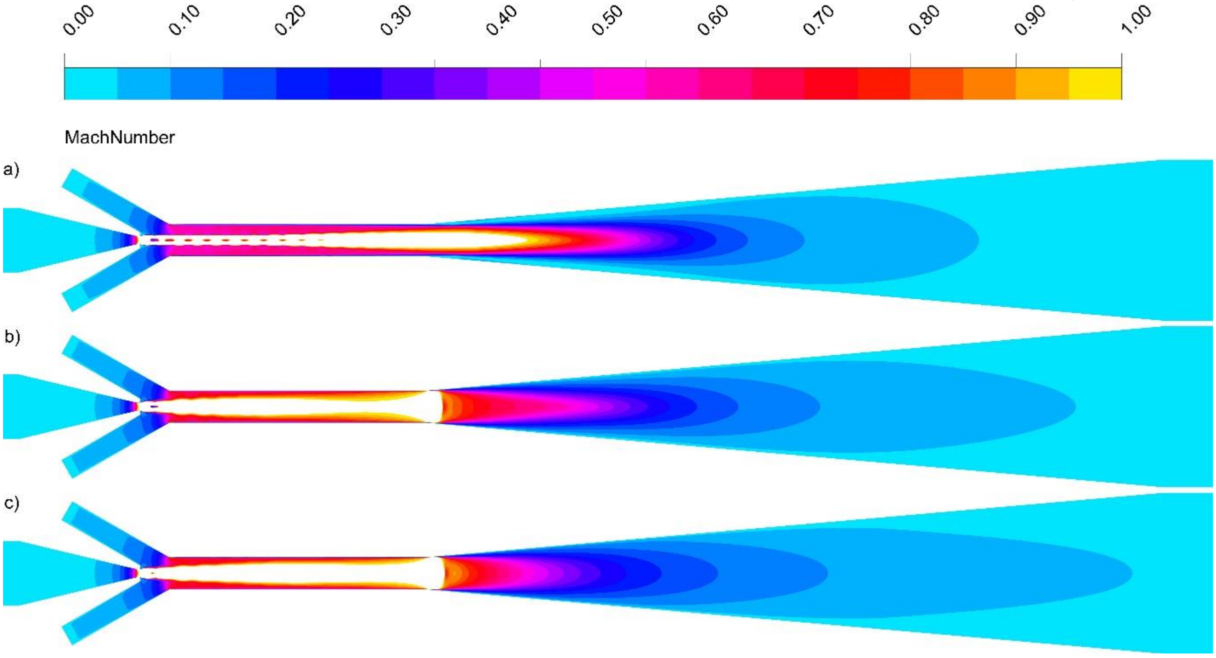

Figure 4: Mach number contours predicted by axisymmetric 2D CFD model with a) SST k-ω, b) RNG k-ε, and c) Realizable k-ε turbulence models. [1]

The ejector design must ultimately be verified experimentally. VTT has test rig dedicated for ejector characterization (see Figure 5). The test rig allows automated testing of ejectors up to flow rates corresponding to ca 20 kW PEMFC electric power with gas mixtures containing hydrogen, nitrogen, and water and up to flow rates corresponding to ca 80 kW PEMFC electric power with gas mixtures containing air and water. Also, tailor-made testing, for example of fuel supply control, is possible at VTT.

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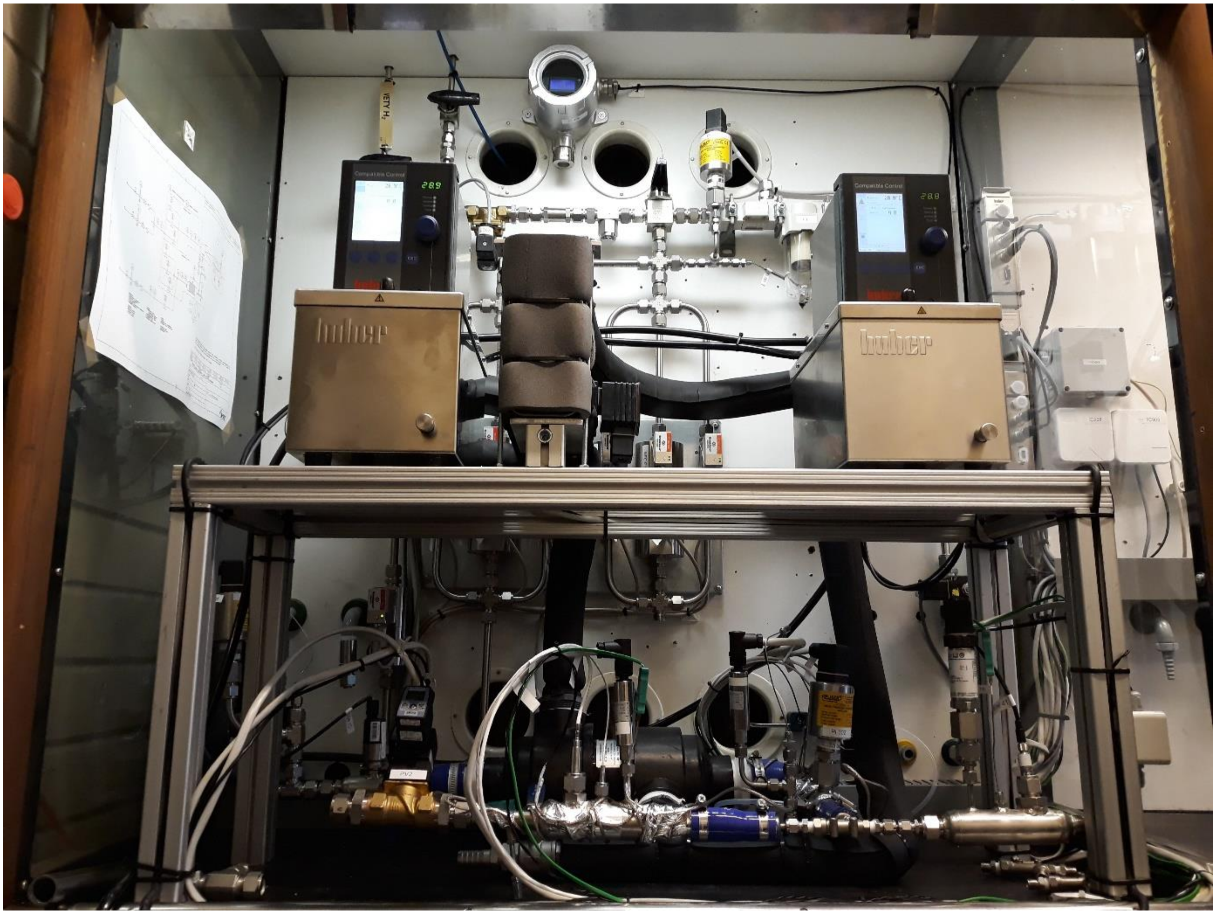

Figure 5: Ejector test rig at VTT.

The MS-20 system that is based on the S2 stack has very low flow resistance on the anode side. Consequently, it might be possible to achieve the target recirculation rate (specified by stack manufacturer) with a single fixed geometry ejector. The use of a single ejector for anode gas recirculation results in least expensive and most durable system. Therefore, the anode gas recirculation setup based on a single fixed geometry ejector will be evaluated.

The anode gas recirculation setup based on a single fixed geometry ejector might not achieve sufficient recirculation rate. Two other approaches will be evaluated if this happens: 1) the hybrid setup containing a mechanical pump and an ejector in parallel and 2) two ejectors in parallel, each optimized for different operating points. The hybrid anode gas recirculation setup makes sense in this particular case since the mechanical pump is already available. The setup with two differently sized ejectors would enable low fuel supply pressure, which translates into more complete use of fuel storage. Table 1 sums up the main opportunities and possible drawbacks of using ejector based anode fuel supply system.

Table 1: Opportunities and risks of an ejector based anode fuel supply system.

Durability	Efficiency	Flexibility	CAPEX	OPEX

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✓ **Higher** durability compared to mechanical pumps	✓ Higher fuel supply efficiency	✗ Partial load operation capabilities reduced	✓ Lower component costs	✓ Lower maintenance needs

2.2 Low temperature operation

Ensuring that the fuel cell system is able to start from sub-zero allows the system to be used in a wider variety of applications, especially in the northern climates. Although several automotive manufacturers have reported freeze start-up capability from -30 °C, successful unassisted cold starts from -20 °C have not been reported in the literature, although failed start-up attempts from -20 °C have been shown to induced severe stack degradation [3].

Capability of the S2 stack to handle freeze start-ups has been previously verified at VTT and PCS, showing that the stack may be freeze started from -25 °C (Figure 6). The next logical step is to design the BoP system around the stack to facilitate freeze start-ups and low temperature operation.

Within the project, the MS-20 will be tested at VTT battery lab climate chamber, shown in Figure 6.

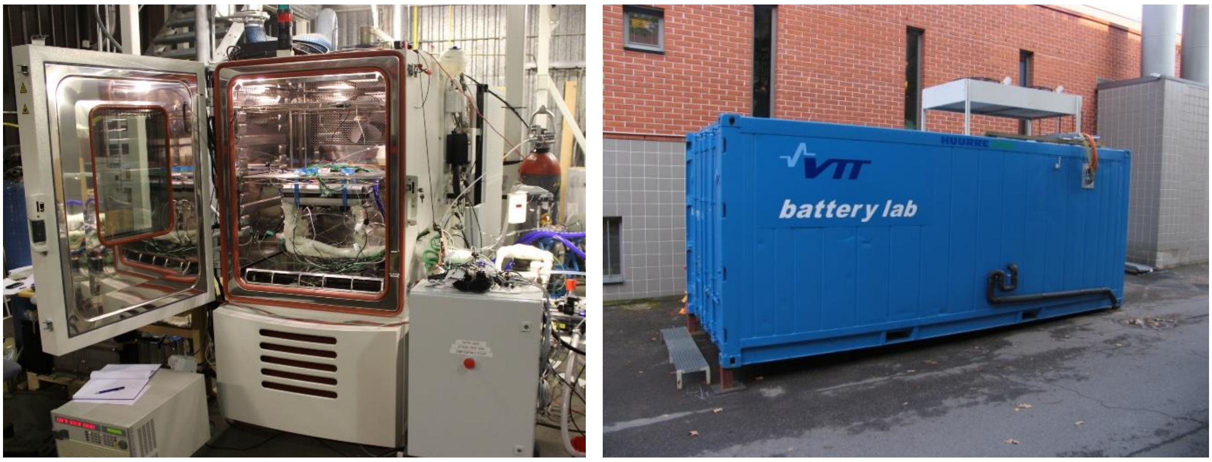

Figure 6: Left: 1 kW S2 stack during freeze testing in a climate chamber. Right: VTT climate chamber suited for testing larger systems.

Based on the freeze testing results, modifications may be implemented to the system. The improvements are mainly related to the operation procedures, but may include modifications to the piping, mechanical and electrical design, placement of heaters and heat exchangers, insulation and thermal coupling of certain components.

If the hardware design is seen fit, more effort can be focused on optimizing the operation routines. Special attention should be focused on the shutdown procedure optimization. The procedure should leave the stack and system is sufficiently dry for safe freezing, while allowing the catalyst to recover from any reversible contamination. Moreover, the procedure should be quick and not pose any safety risks regarding mixing of hydrogen and oxygen.

Tweaking the operation procedures hopefully allows the system to reach nominal power faster after start-up as well as reduce the time and power needed during the shutdown. Another thing to consider is also the stack durability regarding freeze/thaw cycles.

The downside of the modifications are that this may increase the system cost and complexity. In essence, freeze start capability may be achieved with little additional components, with a trade-off of lower stack durability. The main opportunities and possible drawbacks are summed up in Table 2.

Table 2: Opportunities and risks of system optimization for low temperature operation.

Durability	Efficiency	Flexibility	CAPEX	OPEX
✓ Lower stack degradation per freeze start-up	✓ Faster start-up to nominal power ✓ Faster shut-down procedure	✓ Wider low temperature operation window ✗ Possibly reduced operation capability at high temperatures	✗ Additional heaters and thermal integration adds costs	✓ Lower maintenance need in cold temperatures

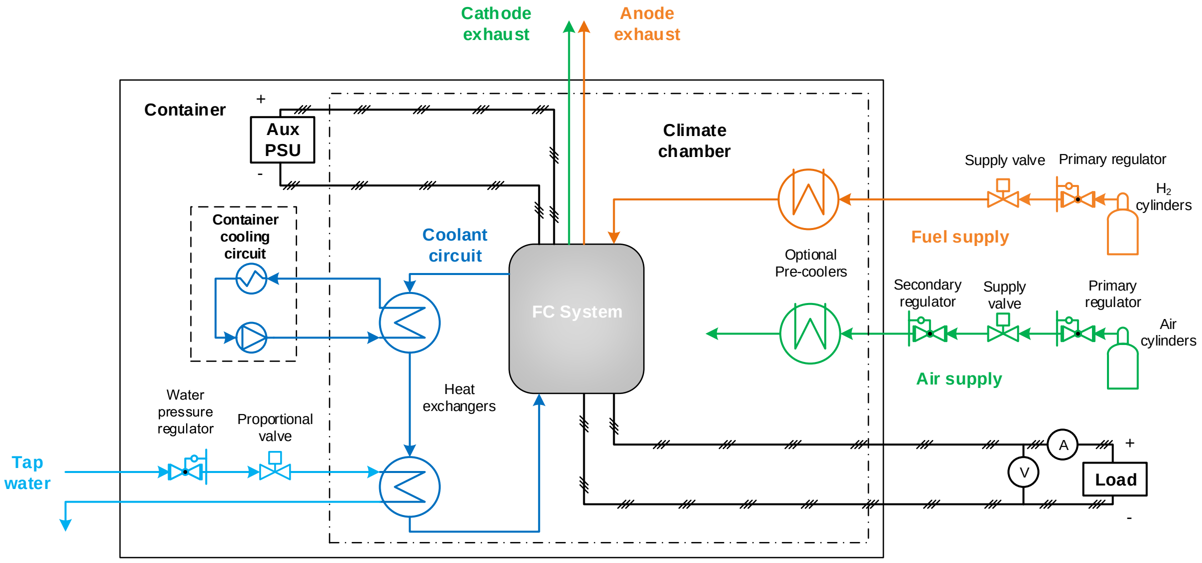

Figure 7: Simplified piping and instrumentation diagram of the freeze test set-up for MS-20.

The proposed test set-up for cold testing of the MS-20 is depicted in Figure 7. As the test chamber has been originally designed with battery testing in mind, the container does not have an active ventilation system which could supply fresh air in, while removing the fuel cell exhaust consisting of water vapour and oxygen depleted air.

Supplying in ambient air, which typically has much higher dew point than the temperature inside the test chamber, would result in catastrophic condensation and icing problems. Drying sufficient amount of air to match the need would require large cooling capacity. To keep the system simple enough we have decided to use pressurized technical air cylinder batteries to supply sufficient amount of dry air to the container. The gas will be bought from AGA, and contains less than 20 ppm of water, corresponding dew point of approximately -60 °C.

The pressure of the air supply is controlled with two regulators. The first regulator reduces the pressure from the 200 barg to c.a. 16 barg, and the secondary regulator delivers 100 - 200 mbarg overpressure. The air supply is initiated by opening an air supply valve controlled by the MS-20.

The hydrogen is supplied from the buildings gas distribution system. Both cathode exhaust and the anode exhaust gases are led directly out of the container, and the piping is heated to avoid condensation and freezing of the humid exhaust. Both the air supply and hydrogen supply may need to be pre-cooled.

The cooling system of the container should be able to regulate the container temperature between -30...+50 C, with approximately 10 kW heat removal capacity. This should be sufficient for a freeze start-up, where most of the heat produced in the MS-20 is used to bring up the system thermal mass to nominal operation temperature.

In addition, the container coolant circuit may be cooled down to -20 C, with 5-10 kW power and heated to +50 C with 3 kW power. The exact details of the cooling circuit are still under consideration, but Figure 7 shows the main design principles. The containers own coolant circuit is used to allow faster equilibration of the MS-20 to the desired test temperature. In addition, another larger heat exchanger and cold tap water is employed to allow full power operation tests at ambient temperature.

The battery test container is connected with an AVL bidirectional power supply (20…1000 V, +- 600 A, +- 320 kW) that is used to sink the power produced by the fuel cell stack. In addition, 2.4 kW 24 VDC and 12 kW 380 VDC power supplies are installed to feed the MS-20 BoP.

2.3 Water spray injection before air compressor

The use of water spray before air compression can increase PEMFC performance in two different ways. Firstly, evaporation of water inside compressor improves compressor efficiency. Secondly, performance of membrane humidifier is improved when dry air inlet temperature is reduced. The feasibility of this potential enhancement will be studied by VTT also with PCS support, to benchmark it with ejector solution and, considering partners' budget, to make a feasibility analysis and maybe preliminary validation tests.

Mendoza et al. showed that water injection increases the isothermal efficiency of a scroll compressor [3]. Wang et al. could clearly increase volumetric efficiency of oil free water-lubricated twin-screw air compressor by water injection [4]. In the work of Tian et al. performance of a twin-screw water vapour compressor was increased by water-injection [5]. Based on both simulations and some experimental work the water injection could increase the volumetric efficiency 5% and adiabatic indication efficiency 6%. In their early work, Zhao et al. studied water injection in a scroll compressor intended for an automotive fuel cell system [6]. The results of their simulation and experiment show that the scroll compressor has nearly isothermal compression with water injection.

In the work of Li et al. the effect of water-injection on performance of a twin screw compressor was studied [7]. They also observed that with increasing water injection flow rates, the isothermal indicated that efficiency and volumetric efficiency will improve and the discharge temperature will decrease. Based on the literature the reduction in power consumption of the compressor and following improvement in the efficiency of the PEMFC system is dependent on the compressor type and operation point of the compressor. There is additional power consumption for water injection but it is usually small compared to the power consumption of the compressor.

Evaporation of water inside compressor cools down the gas and decreases the discharge temperature of the air, which is fed in the humidifier. The decrease in discharge temperature can be several tens of degrees. In PEMFC systems air intercooler is often applied between compressor and humidifier to prevent damaging the membrane humidifier. This is an additional component and increases pressure drop in the system.

The performance of the membrane humidifier is dependent on the dry air inlet temperature [8], as seen in Figure 8. The lower the inlet temperature the better the performance. Therefore, reducing the inlet temperature by water injection in the compressor improves the performance of the humidifier and enables use of smaller humidifier.

VTT has sufficient experimental equipment and facilities to measure the improvement in compressor efficiency and humidifier performance if water injection in the air compressor is applied.

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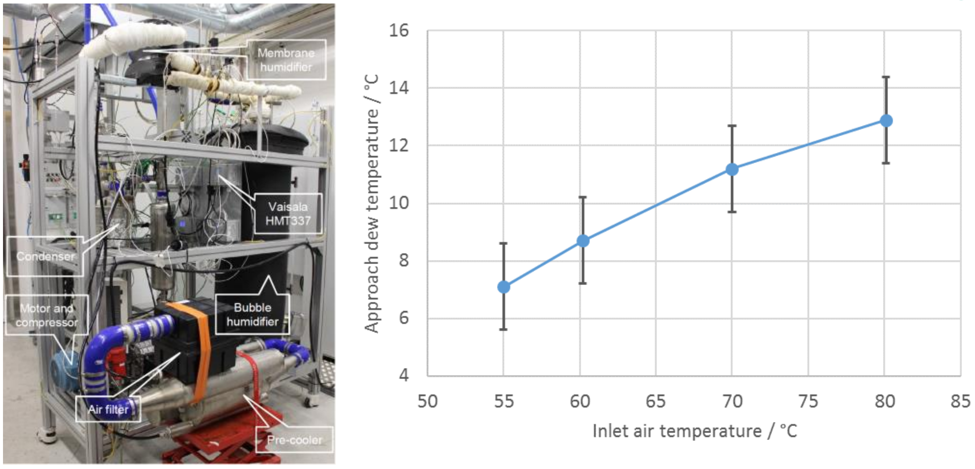

Figure 8: Photo of the constructed test bench with a commercial membrane humidifier installed and commercial humidifier's approach dew temperature at different inlet dry air temperatures. [8]

As a summary, water spray injection in the air compressor has a potential to improve the system efficiency. Due to the complexity of water injection, this may not be viable option in automotive application. However, it has high potential in stationary application, especially in the larger scale. Table 3 sums up the main opportunities and possible drawbacks of using this approach.

Table 3: Opportunities and risks of mist injection to air compressor.

Durability	Efficiency	Flexibility	CAPEX	OPEX
	✓ Higher compressor efficiency		✓ Possibility to use smaller humidifier ✗ Additional components needed	

3. Conclusion and Future Plans

This report provides a description of the three concrete approaches to improve the EVERYWH2RE gensets and particularly the 25 kW, where according to the GA, some innovations at BoP level are foreseen. The first one relies on evaluating an ejector-based solution to fully or partially replace the current mechanical hydrogen recirculation pump in the MS-20 fuel cell system. The second approach focuses on improving the operating flexibility of the MS-20 through a set of freeze testing trial, giving experience on how the system behaves on freezing conditions, and giving input for more suitable hardware design or operation procedures. In addition, experimental investigation of water spray injection is considered as an additional task, if this is seen viable on a commercial system.

These approaches will be investigated within the framework of the EVERYWH2ERE project Task 2.1, depending on their feasibility for the MS-20. Currently, the main focus is given for developing an ejector based recirculation solution for the MS-20, which will and verified at VTT ejector test bench. Second priority is given for the freeze testing trials, which can be performed at VTT battery test container. However, the exact results, needs and demands for achieving project targets are still unknown, until the experimental data is available for basis of actual design improvements.

In addition to the proposed main activities, also other improvements are taken into account during the development process. These may also include improvements for the 100 kW system design, such as ejector optimization for the given hydrogen storage approach. Different hybridization concepts for the power electronics side of the genset may also be investigated.

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