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A fuel cell power unit and hydrogen storage for the research vessel Aranda

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Abstract

The development and technical aspects of a hydrogen fuel cell power system and accompanying hydrogen fuel storage intended for maritime applications is presented. The fuel cells are proton exchange membrane (PEM) type and the power unit has a nominal net AC power output of 165 kW. The hydrogen storage capacity is ca. 80 kg, at a designed 300 bar maximum storage working pressure. For development, testing and safety reasons the fuel cell power system, the related electrical equipment and the hydrogen storage are constructed in a modular fashion, into two modified sea containers with dedicated compartments for each of these three functions. The system is tested both on land as well as on-board the research vessel Aranda, while operating on the Baltic Sea.

Keywords: maritime fuel cell applications; hydrogen; fuel cells; zero-emission shipping; low-noise energy source;

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1. Introduction and background

Striving to meet the IMO (International Maritime Organization) targets for 50% CO_2 emission reduction by 2050 (Talanoa dialogue, 2018), the shipping industry is looking towards zero-emission propulsion technologies. Power production based on fuel cells (FCs) and hydrogen (H_2) is considered to offer a viable technology for this purpose.

The research project MARANDA - Marine application of a new fuel cell powertrain validated in demanding arctic conditions - was launched in 2017 to evaluate the feasibility of hydrogen-based production of power and heat on-board a sea-going vessel (MARANDA (2017)). In this project, a 165 kW (AC net) fuel cell system and an accompanying hydrogen storage of 80 kg capacity are installed on-board the marine research Aranda, which operates regularly on the Baltic Sea. At the time of writing in October 2019, system build has started and the approval process is on-going with the Finnish flag state authority Traficom. The system will be deployed on-board Aranda during May 2020, after build and testing on-land.

This paper reports the technical design and selected features of the system. The purpose of the paper is to illustrate the challenges related to deploying a hydrogen-carrying fuel cell power system, which is subject to strict safety requirements and is sensitive to particular ambient conditions such as saline marine air, and to present potential technical solutions to them.

As the scope of this paper is restricted to the case in question, readers looking to investigate the general status of hydrogen and fuel cells in waterborne and maritime applications are requested to see recent reviews by e.g. EMSA (2017), DNV-GL (2019), LR (2019), SANDIA (2017), IEA (2019) and MCT (2019).

2. Technical system overview

The rated net output power of the fuel cell (FC) power plant is 165 kW. The FC output power is supplied to the Aranda vessel as 660 V three-phase AC electricity and is used to power auxiliary devices, when considered appropriate by the ship operating crew. The hydrogen (H_2) fuel is stored as compressed gas, in a storage pressure up to 300 bar under normal conditions. The maximal capacity of the hydrogen storage system is 80 kg of hydrogen, which enables operating the fuel cell plant on maximum power for ca. eight hours. Thus, the continuous operation of the plant per re-fill is limited to only several hours at a time due to the system structure.

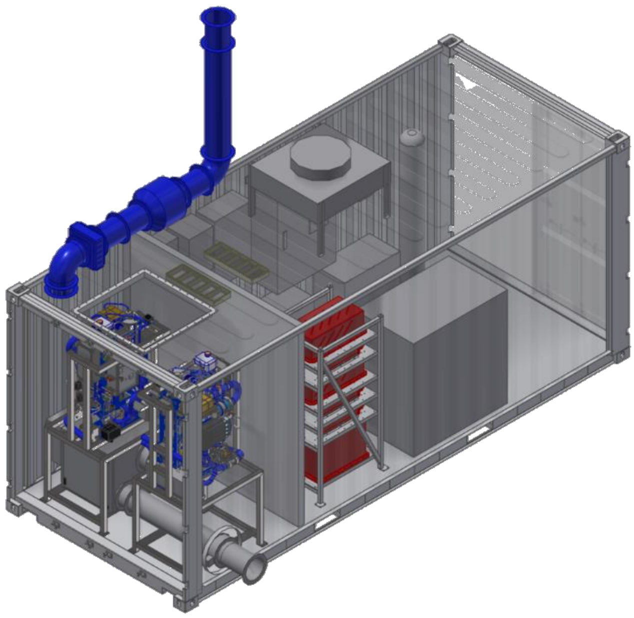

Fig. 1 - A CAD illustration of the fuel cell container. A gas-tight wall is between the fuel cell space and the equipment space compartments.

2.1. Fuel cell power system

The FC system is built into a 20-foot modified container. However, a gas-tight wall splits the container into two compartments with the FC system occupying only one compartment (denoted *FC space*). The other part of the FC container holds the equipment space (*EQ space*), described further in Section 2.3, below. This compartment arrangement is made due to reasons of gas safety (discussed in Section 3). An illustration of the FC system container is shown in Fig. 1.

The FC space contains the fuel cell stacks and the process equipment immediately required to support the power production in the stacks. In addition, there are the relevant ventilation and safety systems (Sect. 3). The FC power equipment are constructed into two identical fuel cell power modules (FCPMs), which each contain one fuel cell stack, an air compressor and humidifier, the primary cooling subsystems, the instrumentation and actuators. Each

FCPM is mounted on a dedicated support frame. The fuel cell space has an explosion relief panel in its roof and the container floor is made of steel.

2.2. Hydrogen storage

The hydrogen storage container is a modified 10-foot container. This container, illustrated in Fig. 2 forms a single compartment, which holds the high-pressure storage cylinders for storing the hydrogen fuel. In addition, there are the hydrogen supply system as well as the fully redundant ventilation and safety systems relevant for this container. Electrical devices in the container which are intended to remain operable at all times (e.g. ventilation blowers, solenoid valves, pressure sensors, hydrogen detectors) are EX-rated. The hydrogen pipeline running from the H2 storage container to the FC space is routed via the ambient (through the roofs of both containers). The H2 container has an A60-grade fire insulation in its walls and roof and the container floor is made of steel. Explosion relief panels are installed on the roof of the container.

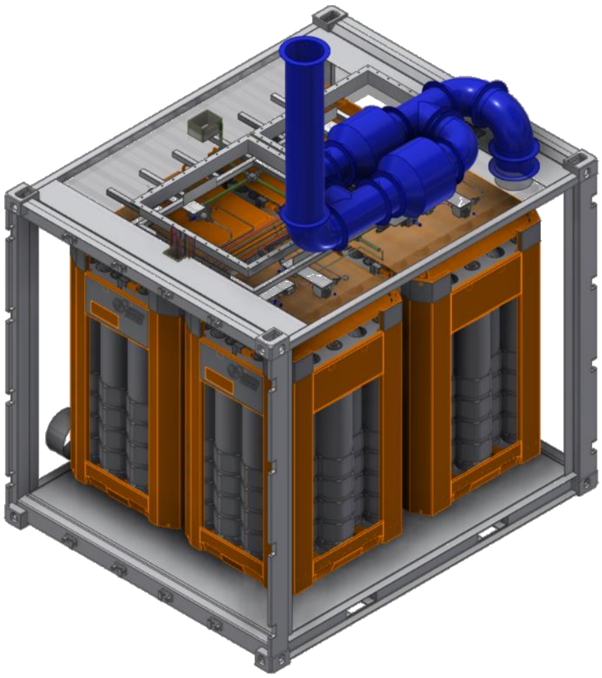

Fig. 2 - A CAD illustration of the H2 storage container. Four gas cylinder bundles ("bottle packs") can be seen inside the container.

2.3. Power electronic and control equipment

The EQ space (illustrated in Fig. 1) holds the automation and control devices, the signal input/output interface devices, FC power converters and filters, the auxiliary power supply distribution and a cooling unit for the power electronics. Under normal conditions, no hydrogen enters the EQ space.

All cables and pipes, which run between the FC space and the EQ space, are led via the ambient and thus no direct through-holes between the two spaces exist. This approach is taken to ensure that the high-voltage equipment located in the equipment space may be operated safely as thorough EX-proofing of all devices in the EQ space is not possible for the time being.

2.4. Interfacing with Aranda

The fuel cell relies on the Aranda vessel in terms of auxiliary power, cooling, as well as the fire alarm system. In addition, the power produced by the fuel cells is fed from the system to the Aranda power network, and to this end, the fuel cell system power production and the Aranda power management system (PMS) communicate via a data link. The location of the containers on the deck of Aranda is illustrated in Fig. 3. All cooling, power and data connection points are located towards the rear of the vessel from the containers where a dedicated site for gas-tight lead-through of cables and pipes below deck is prepared.

3. Technical details of main subsystems

3.1. Fuel cell power modules

The purpose of the fuel cell power module (FCPM) is to convert hydrogen fuel and oxygen in the air into electricity. To this end, the module contains a fuel cell stack and an array of auxiliary (so-called balance-of-plant, BoP) components. The fuel cell stack in the module consists of 455 proton exchange membrane fuel cells separated from each other by metallic bi-polar plates. Hydrogen fuel is supplied to each cell in the stack by pressure gradient-driven flow, from the H2 storage. Air is supplied to the stack by an air compressor, driven by an electric motor.

To maintain suitable operating conditions in the stack, the air fed to the stack is humidified in a pre-humidifier and the air pressure is adjusted by a back-pressure valve. Additionally, to adjust the stack temperature a cooling system, circulating a coolant inside the stack exists in the module. Heat from the stack is extracted by this cooling system to a heat exchanger, through which the heat is further transferred to the Aranda main space heating circuit.

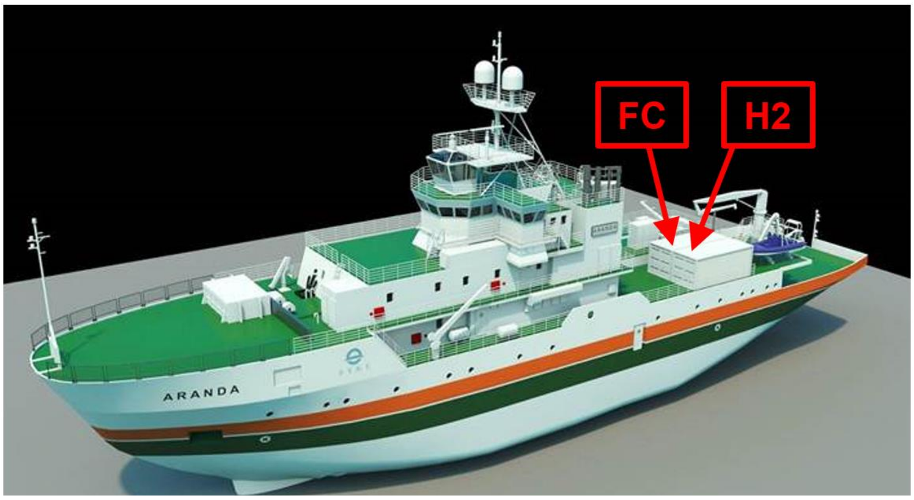

Fig. 3 - An illustration of the Aranda vessel and the FC and H2 containers' site on its deck. (N.B., in this illustration both containers are generic 20-foot containers.)

Power from the stack is extracted by leads connected to the very first and last cells in the stack. The net power output produced by the FC power module may be adjusted between 15-100% of its nominal power, which in this case is ca. 100 kW. As the nominal parasitic power consumption of the BoP components in the module is ca. 15 kW, this equals ca. 85 kW net power output from the module. As the power drawn from the FCPM is adjusted, the internal control equipment of the module manipulate the fuel feed, air feed, cooling and other process parameters to maintain the module in good operating conditions.

In the Aranda FC system there are two identical FCPMs. Each FCPM can be operated independently of the other, which adds redundancy of the system and enable studying various operating profiles. The FC power modules were delivered by Swiss Hydrogen SA / Plastic Omnium, Switzerland and they are based on the S3 stack by PowerCell Sweden (PowerCell S3, 2019).

3.2. H2 storage

The function of the H2 storage is to hold the gaseous hydrogen fuel. In order to facilitate a sufficient fuel storage capacity, the H2 storage is designed to support a nominal gas storage pressure of 300 bar. With this rating, the Aranda H2 storage system capacity amounts up to ca. 80 kg of hydrogen gas.

The Aranda H2 storage consists of 72 composite cylinders (Type IV) split into four 18-cylinder bundles. In each bundle, the cylinders are connected in parallel by a collector line. Each bundle has a manual valve for closing the line to the bundle external connector (VTI Ventil Technic, K50-1.0-S12, stainless-steel body diaphragm valve). A H2 cylinder bundle weighs ca. 640 kg when empty (+20 kg when full), resulting in a total weight of ca. 2700 kg for the four full gas storage bundles. The cylinder bundles to the Aranda H2 storage are provided by Carbotainer S.L., Spain (Carbotainer, (2019)).

The cylinders and the bundles both are TPED-approved (EU TPED, 2010) and the bundle structure as well as functions abide to standard multi-element gas container (UNMEGC) characterization according to the regulations in ADR (2017). This enables either transferring the cylinder bundles to a re-fill site by truck or simply exchanging the bundles for a compatible replacement delivered at the port. Swapping of the empty cylinder bundles to filled ones may be carried out by the ship crew on the deck of Aranda, and lifting bundles to/from ground can be done by the crane installed on Aranda.

3.2.1. Take-aways from the H2 storage development effort

During the early stages of the work, also other arrangements than modestly-sized, detachable TPED-approved cylinder bundles were investigated for implementing the hydrogen storage system. Due to lack of a hydrogen bunkering site at Aranda's home harbor, Helsinki, the direct re-filling of a fixed hydrogen storage by a hose from a land-side re-fill system was quickly considered infeasible. However, as an alternative, a movable mid-size hydrogen storage module option was designed during the project but eventually also found infeasible for reasons discussed below.

For compatibility with the land-side hydrogen infrastructure, it would have been beneficial to be able to fill the hydrogen storage from automotive hydrogen re-fill stations (HRSs). To this end, the hydrogen storage module was designed to consist of multiple EC79-approved (EC79 (2009)) automotive fuel cylinders with EC79-approved functional components for hydrogen supply and re-fill.

For operating on the Baltic Sea under potentially icing conditions, the hydrogen storage was designed to be housed in a modified container, which is otherwise gas-tight except for the motorized ventilation. Furthermore, such a containerized module could be transported with a standard logistics truck from the Aranda vessel to the re-fill site and back.

In the course of the work it became clear that such a containerized hydrogen storage module consisting of *ad-hoc* componentry could be assessed for safety and approved for use at sea on-board the Aranda vessel. However, in order to receive approval for use on road in Europe according to the ADR regulation or the TPED directive, the module design and construction would not benefit from an on-sea approval but would also have to undergo significant destructive test programs particular to on-road transport. Subsequently, the mismatch between application-specific on-sea requirements and the general on-road freight and automotive requirements was highlighted in many ways, for instance:

- Whereas a gas-tight, ventilated compartment is required for on-sea use under icing conditions, on the road a naturally ventilated, open or tarpaulin-covered frame structure is preferred for flammable gas freight
- While the EC79 automotive hydrogen storage cylinders are certified to a working pressure of 350 or 700 bar, the TPED pressure ratings are usually lower or higher, thus mandating either an interim pressure-regulator for re-fill or an over-dimensioned storage vessel, respectively
    - Additionally, the temperature range for TPED approval may be narrower (e.g. -20…+65°C) than that for EC79 (e.g. -40…+85°C). The EC79 temperature range reaches lower due to generally less controllable operating conditions of automotive solutions, but it goes higher due to the requirements of re-filling at HRS's. Thus utilizing TPED cylinders with land-side HRS infrastructure is again complicated
- Whereas low weight is beneficial in movable hydrogen storages, and thus composite material storage cylinders are preferred for this purpose, the TPED (and ADR) are principally intended for application only to metallic vessels (although recently exceptions are becoming common)

Because of such technical and regulatory complications, the hydrogen storage and re-fill solution was designed and built so that the on-sea and on-land operation can essentially be separated on the deck of the vessel, and the regulations relevant to the two modes of transport may be abided to.

3.3. H2 supply subsystem

The hydrogen supply system ensures that hydrogen is provided to the fuel cell in the correct pressure. Furthermore, several components, which are elementary structural parts of the H2 supply system, include safety features aiming to guarantee that hydrogen flows only where intended to and only when intended to.

The hydrogen supply system consists of four identical hydrogen pre-conditioning and safety units ("units") where each unit is independently connected to one of the four H2 storage bundles. Each unit contains a filter, two pressure sensors (high and low pressure side), a two-stage pressure reduction by pressure regulating devices, a thermally activated pressure relief device (TPRD) and an overpressure relief valve at both regulated pressure levels as well as two solenoid-operated hydrogen feed shut-off valves. A collector line for hydrogen feed from the H2 storage container to the fuel cell container exists only after each pre-conditioning unit.

In the collector line, there are manual valves for the manual shut-off of the H2 supply system in case of maintenance or other decommissioning, requiring separation of the H2 container and the FC container. A solenoid-operated shut-off valve (normally open) for enabling bleed of the H2 supply line to a controlled location in case of malfunction of the H2 supply shut-off valves is positioned after the two shut-off valves in the H2 supply unit. Additionally, there is a hydrogen feed line shut-off valve on the receiving side. This valve arrangement constitutes a so-called double-block-and-bleed set-up in the H2 feed line, as required by safety regulations. The H2 supply subsystem components are designed and manufactured for marine use particularly, and delivered by OMB Saleri, Italy.

3.4. Power electronics and control

The main elements of the power electronics subsystem are the FCPM-specific DC/DC converters, the DC/AC inverter and the filters on both input and output sides of the converter train, illustrated in Fig. 4. In the direction of power flow, first a remote-operated, mid-voltage (~500 VDC) contactor separates the power electronics from the voltage source (the fuel cell stack). Then, a choke-type filter is used to protect the fuel cell stack from the possible current ripple caused by the DC/DC converter next in line. The DC/DC converter regulates the DC voltage from the stack to a constant level, which is suitable for subsequent conversion by the DC/AC inverter. Finally, after the DC/AC inverter there is a filter and an isolation transformer to reduce possible disturbances towards the vessel power system. The power is fed to the vessel system as three-phase 640 VAC power (without neutral). The power electronics subsystem is provided by ABB.

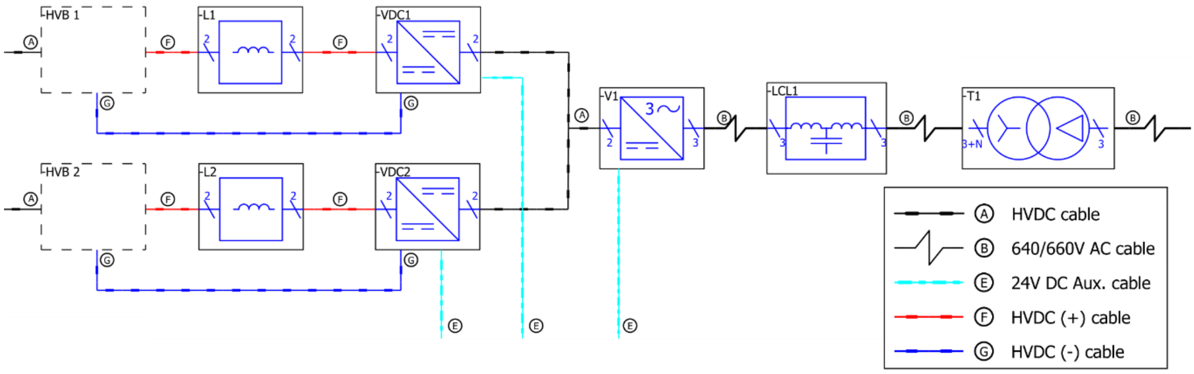

Fig. 4 - A line diagram illustrating the power electronics train of the FC power plant from the fuel cell (left) towards the vessel (right).

To ensure operability of the FC power converters, a dedicated cooling system for the power electronics devices, in particular the DC/DC converters is installed in and on the roof of the equipment space. The cooling system transfers the low-temperature heat generated in the power electronic devices to a liquid-to-air heat exchanger, from where the heat is dissipated to the ambient.

The FCPM-specific DC/DC converters are used to control the load per each FCPM, based on a power requirement from the Aranda vessel side. To administrate both the fuel cell process as well as the top-level system control, multiple controllers are deployed, each with their specific tasks as follows:

1) Process control of the FCPM is carried out by programmable logic controllers (PLCs), with one controller for each FCPM. These controllers manipulate the FCPM actuators in order to maintain suitable operating conditions for the fuel cell stack and so reach sufficient power production at each module.
2) System level control is carried out by a dedicated PLC, which communicates with the FCPM-level PLCs, the power electronics devices, the H2 storage system as well as the Aranda vessel automation system.

3.4.1. Considerations on power electronics for retrofit integration

The Aranda vessel does also have a high-capacity battery energy storage system. Thus it would be fully feasible to connect the fuel cell power to the DC bus of the vessel. This arrangement would make the DC/AC inverter, the filter after it as well as the isolation transformer, a large and heavy component, unnecessary. In addition, conversion losses (esp. when charging the battery with the fuel cell) could be smaller. However, such an integration of the FC power source with the existing vessel DC bus would require seamless integration with the battery control system, which in a retrofit case may be complicated to realize.

The power conditioning arrangement chosen in this work minimizes risks related to integrating the fuel cell power source with the Aranda on-board power system. Connecting to the power system via the main switchboard with a standard AC power connection is possible on the ship power management and integrated automation system (PMS/IAS) level, without direct integration with the battery control system or the diesel generator governors.

3.5. Nitrogen subsystem

The system includes a dedicated nitrogen gas storage and supply system to provide improved system operability and safety. The nitrogen gas is stored in a standard metallic compressed gas bottle (C-type container), at a maximum rated storage pressure of 200 bar. Nitrogen is supplied from the bottle through remote-operated solenoid valves in order to purge the fuel cell power module of hydrogen gas, when the system is not in operation. Furthermore, nitrogen is also used to purge the H2 feed line in order to minimize the components containing hydrogen gas in the system when it is not in use.

4. System safety and operability at sea

The safety of the FC and H2 system is based on several mechanisms: (i) continuous monitoring for gas leakage and fire, (ii) controlled ventilation of potentially H2-containing spaces, (iii) EX-proof installation of electrical devices potentially in contact with H2-containing atmosphere, (iv) an intrinsically safe system normal-state and (v) passive protection measures such as fire insulation and explosion relief hatches. In addition, the active safety systems, i.e. gas and fire detection, ventilation as well as fire suppression systems are equipped with continuous electronic self-monitoring to ascertain their proper functioning.

As the deployed FC technology is already validated for automotive applications, the main item considered to create a hazard for FC operability and lifetime is the saline marine environment. To counteract this, a multi-phase intake air filtering solution was developed.

4.1. Systems for hydrogen gas safety

Hydrogen safety is based on (i) continuous monitoring of hydrogen in the containers, (ii) automatic shut-off valves (iii) container ventilation mechanisms and (iv) dedicated relief devices and venting routes to prevent uncontrolled release of gas due to system overpressure. The hydrogen detection and alarm system monitors the hydrogen content in the hydrogen storage container and in the fuel cell space. The system can continuously measure the hydrogen content in air within the range of 0-4% and thus detect any hydrogen leakage in said spaces. The warning limit for hydrogen leakages is 4000 ppm corresponding to 10% of H2 LFL (Lower Flammability Limit). The alarm limit is at 8000 ppm / 20% of LFL. Detectors in the hydrogen storage container and the fuel cell space are redundant and connected to the gas detection system (GDS) control unit by redundant cabling, so that no single fault in the detection hardware installed within the H2 and FC system will render the detector system inoperable. Faults in the hydrogen detection system are monitored and a fault signal is given if the hydrogen detection system is not operating correctly. The GDS is based on Salwico products and provided by Consilium Marine, Finland.

In case of gas alarm, a safety relay mechanism is used to trigger the pre-defined safety precautions, in particular, system shut-off and de-energization of all non-EX-rated devices, close of H2 feed valves (automatically due to power-off), ventilation of spaces by using EX-rated devices, a visible and audible alarm (i.e. beacon and siren).

Ventilation of the hydrogen and fuel cell system is dimensioned to provide full space air volume change of a minimum 30 times per hour. For example, in the hydrogen storage container (10 ft container), this corresponds to ca. 480 m3/h (8000 dm3/min), which allows a very significant H2 leakage of ca. 320 dm3/min without reaching hydrogen's lower flammability limit of 4% in air.

4.2. Systems for fire safety

Fire safety is based on active and passive measures including (i) continuous fire detection and a related fire alarm system, (ii) fire suppression flaps in ventilation channels, (iii) fire insulation in H2 container. Additionally a manually triggered fire suppression system is installed in each compartment.

The fire detection and alarm system monitors the fuel cell and hydrogen container compartments for the case of fire. In particular, both smoke and heat detection is used in all sensors. The fire detectors in the H2 container and in the fuel cell space are redundant and installed in such a manner that no single component failure can lead to inoperability of fire detection system. In the equipment space, only a single detector is installed.

The fire detection system (FDS) for the FC & H2 system uses the existing FDS control unit installed on-board Aranda. The existing FDS control unit is extended with appropriate input/output communication modules, but utilizing the existing control unit enables tested and streamlined integration of the FC & H2 system fire safety with the existing Aranda fire safety system. The FDS is based on Salwico products and provided by Consilium Marine, Finland.

In case of fire detection the FDS signals the fuel cell system where a safety relay mechanism is used to trigger the pre-defined safety precautions for fire, in particular, system shut-off and de-energization, shut down of space ventilation, close fire suppression flaps (automatically, by power-off), a visible and audible alarm (i.e. beacon and siren). Additionally, the crew may initiate fire suppression inside the FC and H2 containers manually. In order to guarantee operability of the fire suppression system also in sub-zero conditions, it is based on release of high-pressure inert gas mixture (Inergen®) and not e.g. carbon dioxide or other liquid suppression media. The fire suppression system is provided by AGIS Fire & Security, Finland.

4.3. Other safety systems

In addition to automatic gas and fire safety systems, the FC & H2 system is equipped with the following safety devices and features:

- Emergency stop button for manual emergency stop of system, which enables a human operator to halt the operation of the system, leading to hydrogen feed shut-off and system power-off, at any time.
- Explosion relief panels in the H2 container roof and the FC space roof (provided by RSBP, Czech Republic).

4.4. Filtering of intake air for salinity

To insure that the intake air for the fuel cell and the ventilation is clean of salt particles or salt dissolved in micro-droplets, a three-phase air filtering arrangement was sourced, tested and verified suitable for this purpose. The filtering arrangement is illustrated in Fig. 5 (a) and consists of (i) a weather guard, (ii) a pre-filter and (iii) a main filter. The filter assembly is provided by Camfil, Sweden.

Fig. 5 (b) illustrates the filtering capacity of the filter pack at nominal air flow (1000 m3/h) before and after a salt-water loading test which was designed to correspond to operation in normal marine conditions for ca. 13 years. As seen in the picture, the filter performance is good also after the test. The pressure difference over the filter pack increases from ca. 150 Pa to 200 Pa during the loading test, indicating that as long as the filter remains clean of dust or dirt, air droplets or salt particles will not lead to filter clogging.

4.5. System approval for operation

As for any system deployed in a vessel operating at sea, also the Aranda FC and H2 system must be approved for use. A thorough description of the safety assessment and approval procedure required for the deployment of hydrogen systems on sea-going vessels is out of the scope of this paper but in general, the approach follows the IMO alternative design approval process, outlined in MSC.1/Circ.1455 (2013). The approval for the installation and operation of the FC and H2 system on-board the Aranda vessel is due to be obtained directly from the Finnish flag state authority Traficom and the approval is considered to be temporary. For the purpose of the approval, the FC and H2 system is assessed for safety by utilizing established formal safety assessment methods such as hazard and operability studies (HAZOP) and failure modes and effects analysis (FMEA), carried out by experienced specialists at VTT.

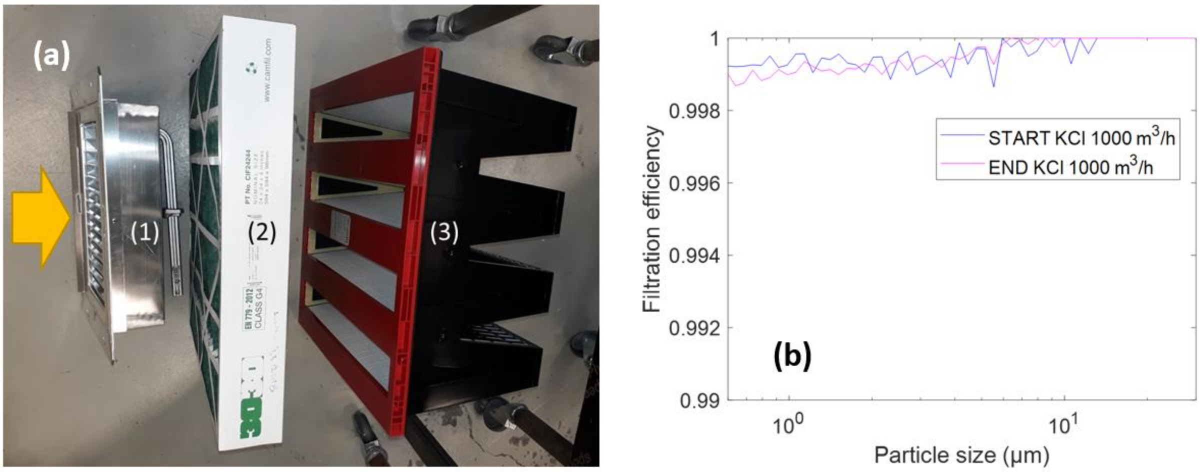

Fig. 5 - In sub-figure (a), the chosen filter pack: (1) Camfil CamVane-100 weather guard, (2) Camfil GT Aeropleat G4 preliminary purification filter, (3) Camfil CamGT H12 gas turbine filter. In sub-figure (b), the filter pack filtration efficiency before and after a salt-particle and humidity loading test.

5. Operative test program for the Aranda FC & H2 system

The system test campaign consists of two parts: tests on land and tests on-board the research vessel Aranda. The first part is due to start early 2020 at the VTT bioenergy piloting test facility Bioruukki, in Espoo, Finland. During the land tests, basic operability of the system is verified and, in particular, proper operation of safety mechanisms is confirmed. The on-land test period will also involve significant finalizing activities of system construction and in particular of the system control subsystem software.

The test program on-board the Aranda vessel, scheduled to start in May 2020, is due to last for a minimum of 18 months, with a targeted minimum 30 re-fills of the hydrogen storage (á 80 kg). During the test program, the fuel cell system is intended to operate as an auxiliary power unit for the Aranda vessel, supplying power and heat to the ship. The power will be fed to the vessel power network as alternating current through the vessel main switchboard. Fuel cell output heat will be recovered to the vessel space-heating network.

When operated, the targeted average power output of the total fuel cell system is 100 kW, leading to ca. 8-10 hours of operating time between re-fills. The targeted average output power is well below maximum system power output and thus allows for dynamic operation of the system as well as periodically running only one half-system (i.e. one fuel cell power module instead of two). During system operation process data from numerous instruments is recorded to a data repository and behavior of individual system components, such as the fuel cell module efficiency, intake air filtering performance as well as the conversion efficiency of the power electronics are monitored. The test campaign experiences are published in several publicly released deliverables of the hosting MARANDA project.

In addition to the complete system level tests, the fuel cell power module is tested in dedicated durability tests with a targeted minimum test duration of 4380 hours. These on-shore durability tests take place before system deployment on-board the Aranda vessel and are due to start November 2019.

6. Conclusions

The technical solution for a fuel cell power plant and the accompanying hydrogen fuel storage, intended for retrofit install on-board the marine research vessel Aranda, was presented. System safety, in terms of gas leakage and explosion inhibition was found to be a key determining factor for system design. In addition system operability in the marine conditions required several considerations on filtering of intake air both for the fuel cell as well as for system ventilation. The necessary modifications to the fuel cell power modules, power electronics or the hydrogen storage components were minor, which illustrates the maturity of the basic technology. During the work, several complications related to safety approval and the guiding regulation relevant for hydrogen installations in sea-going vessels were observed. Further marine applications are still necessary to establish a solid prescriptive and well-guiding rule base to simplify the deployment of zero-emission hydrogen propulsion technologies.

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