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Testing Platform for SOFC Stack Modules Utilising Marine Fuels

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Abstract

To characterise and validate ammonia and methanol as alternative fuels for SOFC stack modules, a comprehensive testing platform has been developed. This platform accommodates SOFC stack modules up to 15 kW and operates alongside expanded infrastructures for ammonia storage and methanol distribution. The integrated BoP components have been designed and selected based on the compatibility of materials with marine fuels. Special attention has been devoted to safety measures, particularly regarding ammonia detection and the implementation of safety protocols. This developed platform will be utilised in two separate projects, focusing on stack module performance with marine fuels.

Introduction

Methanol and ammonia have been widely recognized as promising fuels for marine based SOFC applications due to their superior storage capabilities compared to hydrogen. VTT is actively participating in two European Union-funded projects, AMON and FuelSOME, in which the VTT's expertise in stack module testing is utilized for the characterization of SOFC systems operating alongside fuel processing units. To fulfil the testing requirements of these projects and ensure adaptability for future stack module testing needs, a comprehensive upgrade of a testing platform was planned, along with an expansion of the fuel storage capacity.

This abstract succinctly represents the strategic upgrades implemented to accommodate increased methanol and ammonia usage within the testing platform.

1. Basis for upgrade process

Prior to the upgrade process for the testing platform, objectives and requirements were thoroughly discussed. The decision-making process took into account the capabilities available in the VTT's hydrogen laboratory, the specific needs outlined in the project scopes of AMON and FuelSOME, as well as a forward-looking approach to support future characterization and validation projects for stack modules. An initial simplified process flow diagram was defined, as shown in Figure 1.

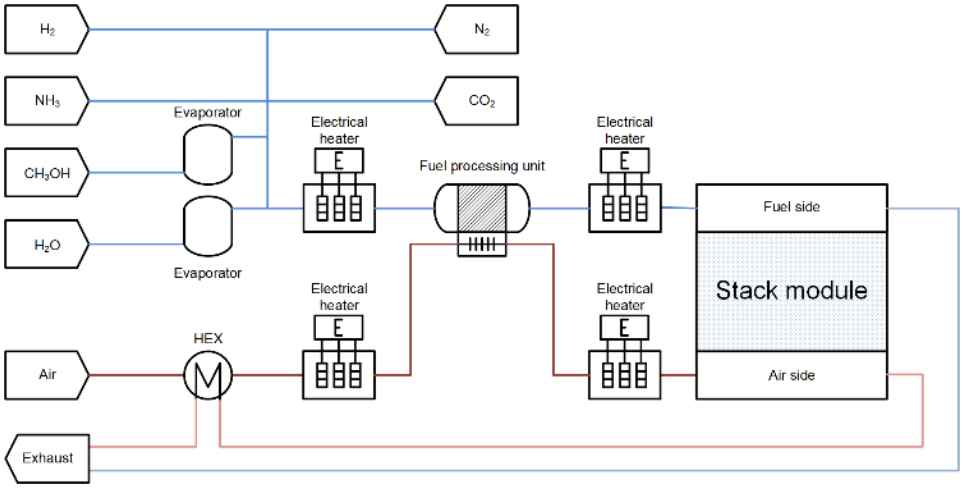

Figure 1. Initial process flow diagram for the testing platform.

The following objectives and requirements were established for the upgrade process:

- Enlarge ammonia and methanol storage and supply systems to stack modules up to 15 kW.
- Reassess and enhance safety measures to align with the upgraded testing platform.
- Ensure the platform's compatibility with marine fuel handling, particularly ammonia.
- Optimize component placement to facilitate modifications, required for testing different stack modules and fuel processing unit designs.
- Select components that also support steam electrolysis and co-electrolysis testing for potential future projects.

Subsequent sections will detail the upgrade process, focusing on safety considerations and introducing the final design and layout of the enhanced testing platform.

2. Safety measures for ammonia and methanol usage

To enhance the safety of the testing platform and its environment, comprehensive safety measures were implemented. The process that guided these implementations, along with the specific safety measures enacted, are detailed in this section. This ensures that all operations conducted on the platform adhere to the highest safety standards, mitigating any potential risks associated with the handling and testing of fuels.

2.1. Enlargement of methanol and ammonia storages

For testing a 15 kW scale stack module, it was determined that a full storage capacity should last for one week. This required, based on energy density estimations of the fuels and conservative fuel utilization for the tested modules, storages of 1000 kg for both fuels to be considered during the upgrade process.

Under Finnish law regarding the handling and storage of hazardous materials, an end-user storing over 1000 kg of methanol or 100 kg of ammonia must submit a chemical usage declaration to the local fire and rescue department for any substance exceeding these limits. This declaration includes details about storage location, formal safety plans, and risk assessments. Following a review of these documents and an official inspection of the storage site, the fire and rescue department may grant permission for chemical usage, potentially with additional mandatory safety measures.

Considering the initial upgrade plans for methanol storage was 1000 kg, a storage concept for 1000 dm^3 of methanol, equivalent to 791 kg at 20 °C and 1 bar(a), was designed. This effectively meant choosing an intermediate bulk container as the primary storage solution. From a legislative standpoint, this size negated the need for a chemical usage declaration. Nevertheless, stringent safety measures were implemented to enhance safety comprehensively. The main methanol storage was placed into an existing chemical storage area, complete with a drainage system, ventilation, and sensors to monitor room air methanol levels. Additionally, clear guidelines for safe methanol handling were established. Methanol was transferred from the main storage to an intermediate tank located at the developed testing platform through a secure supply line designed to prevent leaks. The safety enhancements specific to the testing platform are detailed in the subsequent subsection.

For the upgraded ammonia storage, bypassing the chemical usage declaration process was not feasible. A storage solution was thus developed in collaboration with the industrial gas distributor Linde, consisting of two tanks with a combined capacity of 950 kg of ammonia, each tank having a volume of 900 litres. Linde was responsible for tank distribution for the storage. The tanks were placed in a container outside the laboratory building housing the upgraded testing platform. To mitigate risks, several safety measures were implemented, with key measures highlighted as follows: continuous ammonia concentration monitoring within the container, defined safety logics for the container's control system, and multiple pressure relief valves for controlled venting of ammonia through safety lines to a secure location in case of emergency. For regular operation, the supply line pressure was capped at 2.5 bar(g), and the maximum flow rate was limited to 2 g/s using an orifice plate. Similar to methanol, the ammonia supply line to the testing platform was solid and fitting-free. An

extra casing pipe was installed around the supply line for added safety. Comprehensive protocols were established for tank changes and supply line flushing with nitrogen after any interruption exceeding five days.

2.2. Safety measures for the testing platform

For the testing platform constructed in VTT's hydrogen testing laboratory, numerous upgrades were implemented to ensure safe and efficient operation with ammonia and methanol. This subsection will focus on upgrades relevant to marine fuel usage. Standard safety measures, such as rigorous monitoring, setting safety limits for process parameters, and equipping the lab with hydrogen, carbon dioxide, and carbon monoxide sensors, are in place. The testing platform also features a ventilation hood and is surrounded by protective curtains, although these are not the primary focus of this discussion.

A significant consideration when utilizing marine fuels is material compatibility, particularly with ammonia due to its high toxicity. Therefore, all materials were thoroughly evaluated for potential risks. For the fuel side of the testing platform, all check valves were upgraded to feature EPDM seals instead of the typical FKM used in hydrogen applications [1]. Additionally, to minimize challenges related to ammonia-induced nitridation in conventional steel grades at high temperatures, Alloy 600 was chosen for the electrical superheaters that preheat fuel entering the fuel processing unit and stack module. Alloy 600, a nickel-chromium-iron alloy, is noted in literature for its resistance to nitridation from ammonia compared to some other typical high-temperature steels [2]. The use of Alloy 600 enhances the durability of testing platform components, ensuring a high-quality testing environment for stack modules. This selection of a more reliable material also improves the testing platform's reliability and safety.

To ensure the safe handling of methanol within the testing platform, several precautions have been implemented. A 50-litre intermediate tank is utilized to mitigate the need for a constant supply from the main storage. The methanol level within this tank is closely monitored through a system that combines level switches and pressure measurement. Methanol detectors, set with a warning threshold of 50 ppm and an alarm threshold of 100 ppm, are strategically placed above key components such as the intermediate tank, methanol evaporator, and the fuel processing unit. An additional detector is installed in the environment of the testing platform to ensure comprehensive coverage. In the event of a leak, these detectors trigger safety protocols that shut down the system in a controlled manner. Furthermore, a dedicated drain tank is positioned below all components that handle liquid methanol, including the intermediate tank, methanol pump, and evaporator, to manage any potential liquid spillage effectively.

To enhance the safety measures for ammonia handling in the testing platform, a comprehensive approach was adopted. The ammonia supply is connected to an ammonia supply control unit, which includes a pressure reducer, valves, a pressure measurement, a mass flow controller, and a check valve, all placed inside a casing that is continuously flushed with nitrogen. The concentration of ammonia within this casing is constantly monitored to detect any leaks, with the AEGL1 limit for ammonia set at 30 ppm serving as the alarm threshold [3].

Similar to the methanol safety measures, ammonia concentration is also monitored with detectors placed near all critical components, including the superheaters, fuel processing unit, and stack module. In addition to external monitoring, inline concentration

measurements are taken continuously from several locations, such as post-fuel processing unit line and the exhaust line after the stack module. These measurements, along with monitored temperature changes, are utilized to assess the degradation and performance of the catalyst surfaces within the fuel processing unit.

A layers of protection analysis was conducted to determine the appropriate level of ammonia protection. Based on this analysis, a safety PLC was integrated into the testing platform alongside the industrial PLC, which manages the monitoring and control functions. This integration allows for the execution of safety measures, such as closing the ammonia inlet valve and initiating enhanced dilution, even in the event of an industrial PLC malfunction. The coupling of critical ammonia measurements with the safety PLC constitutes the most significant enhancement to the overall safety concerning the hazardous nature of ammonia.

3. Final design of the testing platform

The process of expanding the storage capabilities for both ammonia and methanol, coupled with establishing best practices for their safe handling, paved the way for the final design phase of the testing platform. A detailed piping and instrumentation diagram (P&ID) was essential, but the placement of components was deemed equally important. Leveraging the advantage of VTT's easily modifiable testing platforms, which result from in-house construction and design, the component placement was strategized to facilitate effortless replacement and maintenance. This approach inevitably led to some heat loss between high-temperature Balance of Plant components, a trade-off for a more compact component arrangement. However, since temperature integration was not the primary focus of the test rig design, the goal was to prioritize practical use and a flexible design that could meet various testing requirements. Ultimately, the upgrades to the testing platform were executed to enable effective stack module testing, emphasizing practicality and adaptability over compactness.

The major design parameter for the testing platform was its capability to test various stack modules from different suppliers. Therefore, the space allocated for the stack module was designed to be as flexible and spacious as possible. The stand for the stack module was engineered to easily integrate modules with their own insulation systems, as well as to accommodate custom insulation setups for stack modules that require them.

While heat integration was not the primary focus of the testing platform's design, an air-air heat exchanger was incorporated into the system to recover heat from the exhaust air of the stack module. This design choice also reduced the heating demand for the in-house built superheaters, each with a maximum power of 8 kW.

Regarding the fuel processing unit, although the system was initially designed for heat exchanger type fuel processing units, replacing these with an electrically heated packed bed reactor is feasible. The space reservation in the testing platform was intended to be flexible enough to accommodate more space-demanding designs. For the air side piping, this change would result in a minor simplification, allowing for a direct pipeline from the first air superheater to the second. This placement also enables the removal of such a unit for tests that do not require it.

To facilitate operation in electrolysis mode, a bidirectional load capable of acting both as a load and a power source was integrated into the testing platform. The electrical circuit design allows for easy switching between fuel cell and electrolysis modes. Additionally, the steam

production capabilities were already dimensioned to match the operational scenarios required for stack module scale electrolysis operation.

The initial process flow diagram, as presented in Figure 1, underwent a meticulous design process to become the detailed piping and instrumentation diagram presented in Figure 2. The culmination of this design process is the strategic component placement, presented in Figure 3. This progression ensures that the testing platform's layout is not only functional but also meets the requirements set forth for various testing scenarios.

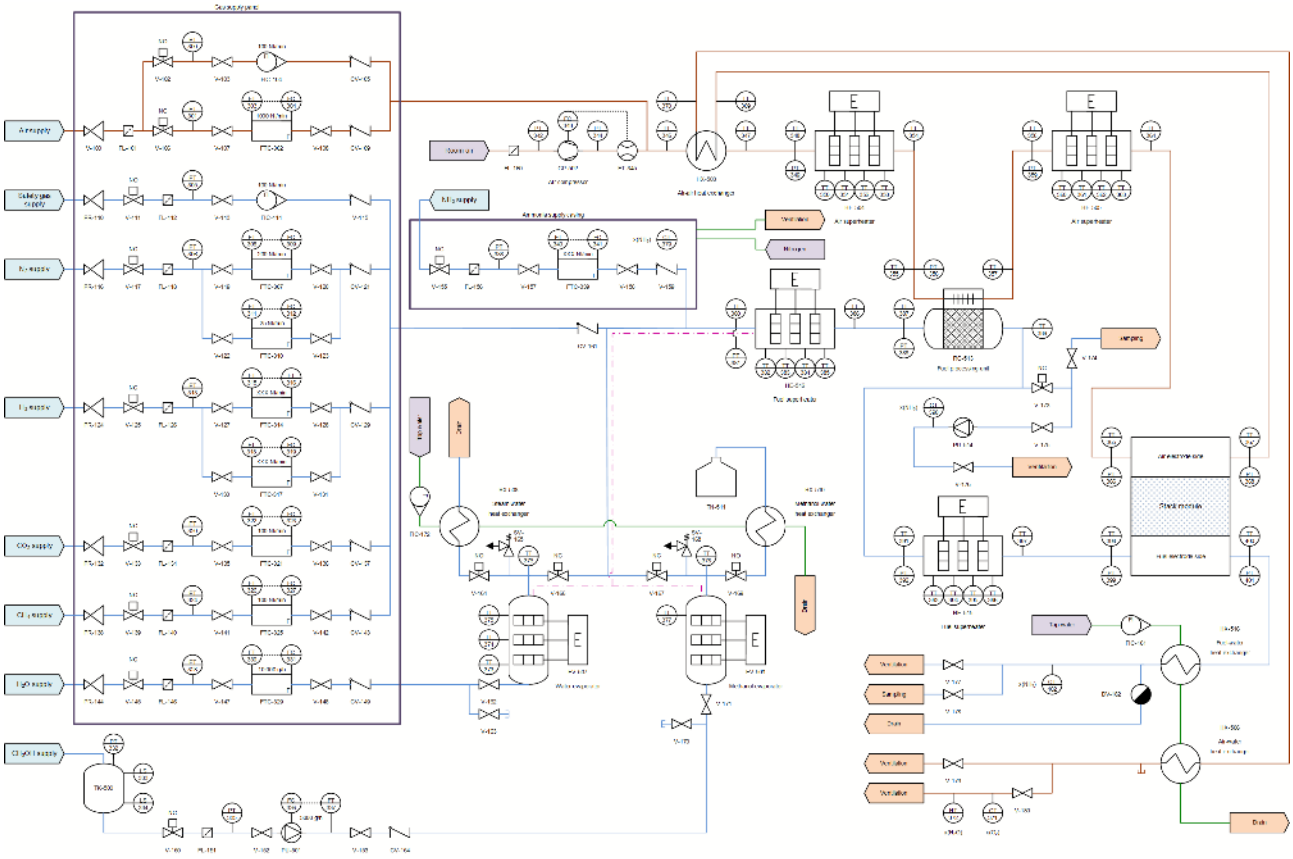

Figure 2. The P&I diagram for the testing platform.

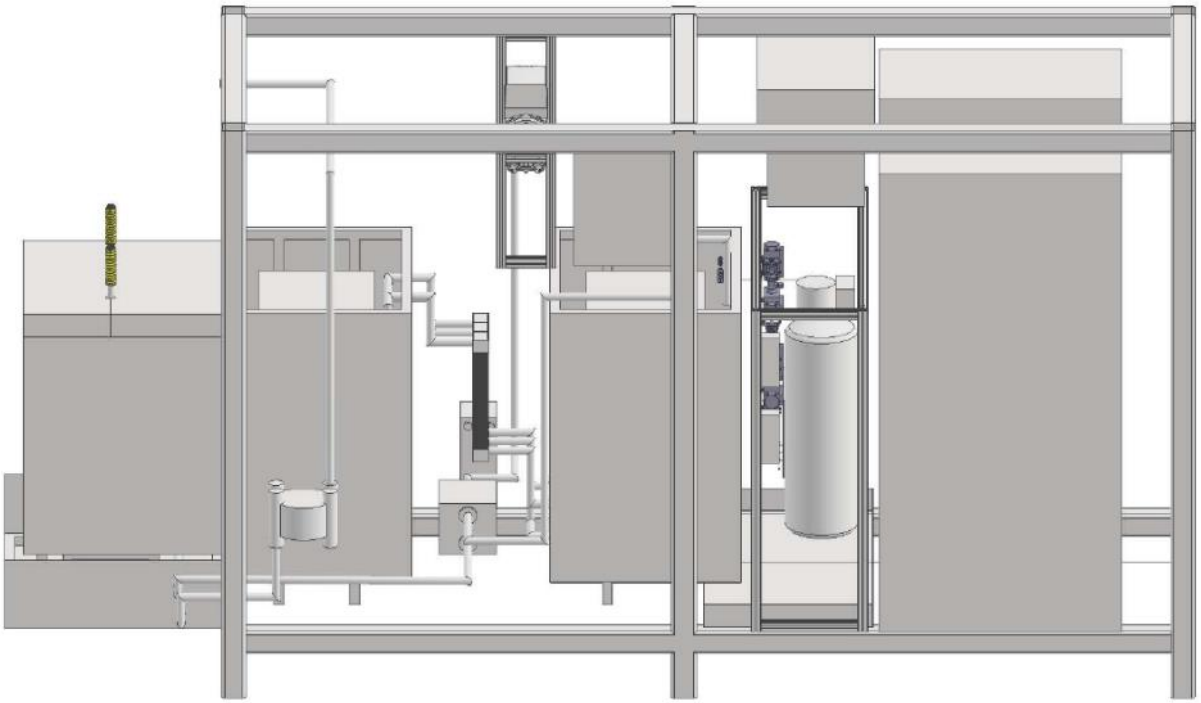

Figure 3. The placement of the major components in the testing platform.

4. Outlook

The developed testing platform is scheduled for use in late 2024 and early 2025 for two specific projects focused on marine fuel utilization. In the FuelSOME project, a 6 kW Elcogen stack module will undergo testing alongside VTT's in-house developed coated plate heat exchanger reactor, which is adept at handling both ammonia cracking and methanol steam reforming. In the FuelSOME project, the Elcogen stack module's performance will be evaluated during continuous operation with both marine fuels. Shortly thereafter, the platform will be employed in the AMON project. Here, the performance of an 8 kW SolydEra stack module will be characterized in conjunction with an optimized heat exchanger-based ammonia cracker, a product of the same project developed by Alfa Laval.

The design choices, such as incorporating a bidirectional load and an electric steam generator, facilitate the platform's adaptability for future projects. Consequently, the platform is versatile enough to support various operations including SOFC with multiple fuels, rSOC, SOE, and co-SOE. Moreover, the in-house design and build-up, coupled with the judicious selection of components, ensure that the platform can be upgraded or modified as needed without a complete overhaul.

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