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High Differential Pressure PEMWE System Laboratory

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Abstract

Direct electrochemical compression of hydrogen offers several advantages over mechanical compressors which are prone to high maintenance, low efficiency, noise, and vibrations. Since the capital- and operational costs of hydrogen compressors make up a significant share of the hydrogen costs in hydrogen refueling systems [1], high-pressure electrolyzers delivering hydrogen at 350 bars may become a viable option for a more cost-efficient supply of hydrogen for various transport applications. The standard output pressure of commercial proton exchange membrane water electrolysis (PEMWE) systems is today around 30 bar. This is considered the techno-economic optimum due to reduced Faradaic efficiency (caused by hydrogen crossover), losses associated with reinforced membranes, and other necessary safety measures when going to even higher pressures [2]. Small-scale high-pressure PEMWE-stacks operating at 350 and 700 bars have been demonstrated [3], but more R&D on such high-pressure systems is required before this technology can be deployed commercially.

Institute for Energy Technology (IFE) has designed and built a flexible PEMWE-system laboratory for testing of PEM water electrolyzers up to 33 kW, as part of a new national research infrastructure in Norway (*The Norwegian Fuel Cell and Hydrogen Centre*). A state-of-the-art prototype high pressure (350 bar) PEM water electrolyzer stack with a production capacity of 2 Nm^3/h is used as the reference technology for commissioning of the test facility. The test rig is designed for differential pressure operation, where the anodic circulation loop can take up to 10 bar and the cathodic loop up to 350 bar. The water electrolyzer and a 20 kW Li-ion battery module is connected to the same DC-bus via dedicated DC/DC converters. The DC-bus is connected to the local grid via an AC/DC-converter, which can be programmed to emulate different operational load profiles.

The high-pressure PEM water electrolyzer laboratory system at IFE can be used to emulate duty cycles (e.g. grid load profiles, solar and/or wind generation), test hybrid system configurations of water electrolyzers and batteries, investigate the performance of differential pressure systems at different startup/shutdown regimes and partial load operation, and to perform R&D on the key components of the balance of plant (BoP).

Introduction

Hydrogen produced by Water Electrolysis (WE) is considered a viable means of storing excess energy coming from variable renewable energy (RE) power sources. Water electrolysis technology is therefore expected to play a major role in future RE-based energy systems. However, regardless of the further use of the hydrogen – storage, direct injection into the natural gas grid, or as a fuel for transport – it needs to be compressed. Hydrogen compression can be realized either with a mechanical compressor connected downstream from the electrolyser, or by pressurizing the electrolyser itself. In the latter case, there are two main system configurations: (1) Balanced pressure electrolysis (entailing pressurization of the feed water) [4-6] and (2) Differential pressure electrolysis (i.e. electrochemical compression), also referred to as asymmetric systems [4, 6-9].

Balanced pressure electrolysis is technically possible in both alkaline and proton exchange membrane-based systems, whereas differential pressure operation can only be realized in systems with PEM-based electrolytes. In this case neither a water pressurisation pump nor a mechanical hydrogen compressor is necessary, which again yields hydrogen production systems with less noise and fewer moving parts [9]. From a practical point-of-view, differential pressure operation appears favourable as it reduces the technical work required for the compression, as well as the number of devices [10]. Furthermore, differential pressure systems allow for the use of ambient pressure oxygen in the oxygen loop, which has significant safety advantages and reduces the capital costs (expensive high-pressure piping in the oxygen loop is redundant) [8].

Hydrogen produced by water electrolysis contains a significant amount of humidity due to water permeation through the membrane from the anode to the cathode during operation. This water flux is controlled by several mechanisms, including electro-osmotic drag, diffusion drag and hydraulic transport [7, 11]. For refuelling purposes, hydrogen cannot contain more than 5 ppm moisture (ISO 14687), and dehumidification therefore adds to the energy required for gas conditioning. By enforcing higher hydrogen delivery pressures, the water content in the gas stream is significantly reduced [12]. This has been demonstrated by for example Honda [3], who reported that the water content in electrochemically compressed hydrogen at 350 bar is reduced by 30% compared to ambient pressures. *Differential* pressure operation furthermore has a counteracting effect because an opposing pressure gradient is established. Reduced water crossover under differential pressure operation was demonstrated by Medina et al. [7].

The major drawback of asymmetric pressurized PEMWE-systems is the high hydrogen back-diffusion through the membrane from the cathode to the anode side, decreasing the Faradaic efficiency of the system. Furthermore, at lower loads the hydrogen crossover may exceed the critical limit of 4 vol% of hydrogen in oxygen; hence, the lower load range needs to be limited to a specific current density. As a consequence heavy-duty thick, reinforced membranes are required to guarantee the mechanical support in differential pressure electrolysis cells, which results in larger ohmic resistances [9]. These losses imply that there is a trade-off with respect to energy efficiency.

Previous studies on modelling of PEMWE-systems suggests that electrochemical compression outperforms the other two pathways for hydrogen delivery pressures up to 20-40 bar [10, 13]. However, there may exist some niche markets for high-pressure water electrolysis. Alternative options may for example be required in smaller start-up markets where it is relatively costly to install large systems. In the build-up of nationwide hydrogen refuelling infrastructure, it will be most cost-effective to install large stations (>1000 kg/day) at key locations to provide hydrogen to end-users with a high hydrogen demand (e.g. captive fleets of trucks or buses). However, to serve a small number of vehicles operating in remote locations (e.g. tractors on farms) it may be an option to establish small single-user systems (<10 kg/day). In some special cases high-pressure PEMWE may also be an option for home refuelling concepts for early adopters (ref. Honda). High-pressure production systems can eliminate mechanical compression entirely and minimize the storage at output pressures > 350 bar and are therefore characterized by small footprints. This will allow for fuelling of FCEVs overnight with hydrogen generated on-site [8].

If high-pressure water electrolyzer systems are to be deployed it is crucial to have in-depth knowledge on design, construction and operation of such system. Institute for Energy Technology (IFE) in Norway has designed and built a flexible PEMWE-system laboratory for testing of water electrolyzers up to 33 kW with hydrogen output pressures of a maximum of 350 bar. This system testing platform can be used to emulate duty cycles (e.g. grid load profiles, solar and/or wind generation), test hybrid system configurations of water electrolyzers and batteries, investigate the performance of differential pressure water electrolyzers at startup, shutdown and partial load operation, and to validate system models. The system laboratory will be commissioned during 2019. Below is a detailed description of the design and safety of the IFE water electrolyzer test rig.

1. PEMWE System Overview

A sketch of the PEMWE-system (also referred to as the Balance of Plant, or simply BoP) with all the peripherical equipment required for operating a differential pressure PEMWE is presented in Figure 1. The BoP includes a low-pressure water/oxygen loop (anode side) and a high-pressure hydrogen system (cathode side), which is built around a 12 kW prototype PEMWE-stack that can operate at a differential pressure up to 350 bar. The stack (photo in Figure 1) has a hydrogen production capacity of 2 Nm^3/h, but the test rig is dimensioned for production rates up to 6 Nm^3/h.

The key function of the BoP is to provide a continuous supply of high-purity water to the anode side of the stack, to ensure a proper electrochemical reaction (hydrogen production) and provide thermal management of the stack (which has an electrical efficiency of about 70%). Deionized water is continuously circulated on the anode by a main circulation pump, and consumed water is automatically replenished by a make-up water pump. The BoP also ensures separation of the produced gases from the process water. On the cathode side the water separated from hydrogen is sent to drain. The test system is currently designed for direct release of oxygen and hydrogen through dedicated exhaust pipes but can easily be modified for further conditioning (drying) of the hydrogen.

A drawing and a photo of the PEMWE-system test rig is shown in Figure 2. Most of the key hardware components have been designed and built by IFE, except for the smaller components related to inputs and controls (I&C). This system includes pressure vessels/tanks, coolers/dryers, filters/mix-beds etc. The test rig is currently being installed in a 15 feet container, which originally was used for an alkaline water electrolysis system (10 bar, 10 Nm^3/h) in the so-called Hynor Lillestrøm hydrogen station (part of a larger national demonstration project from 2010-2015).

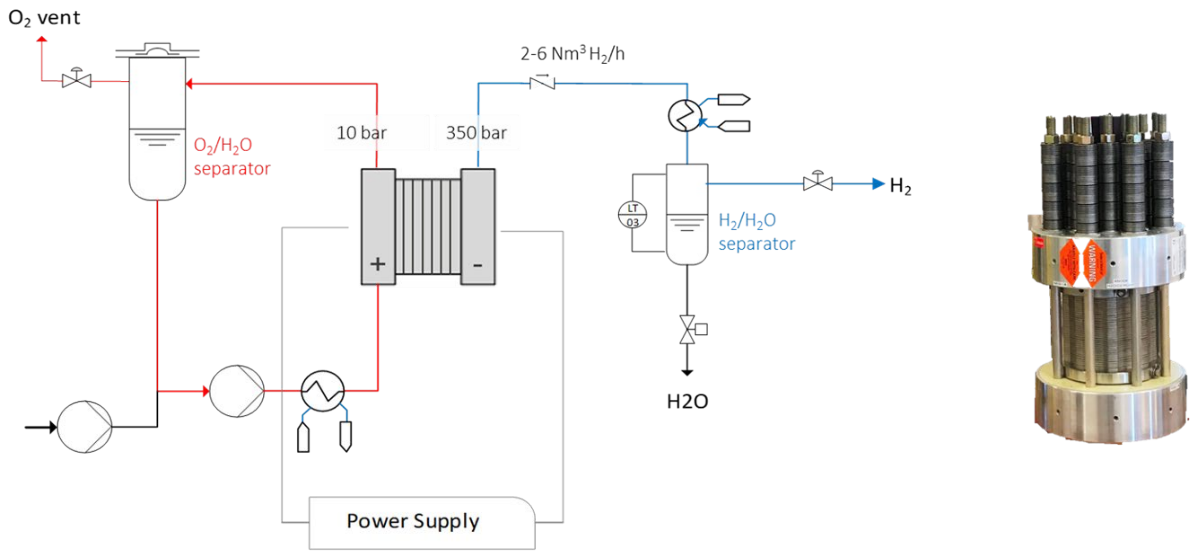

Figure 1: Sketch of WE system test rig (left) and prototype PEMWE stack operable at differential pressures up to 350 bar (right).

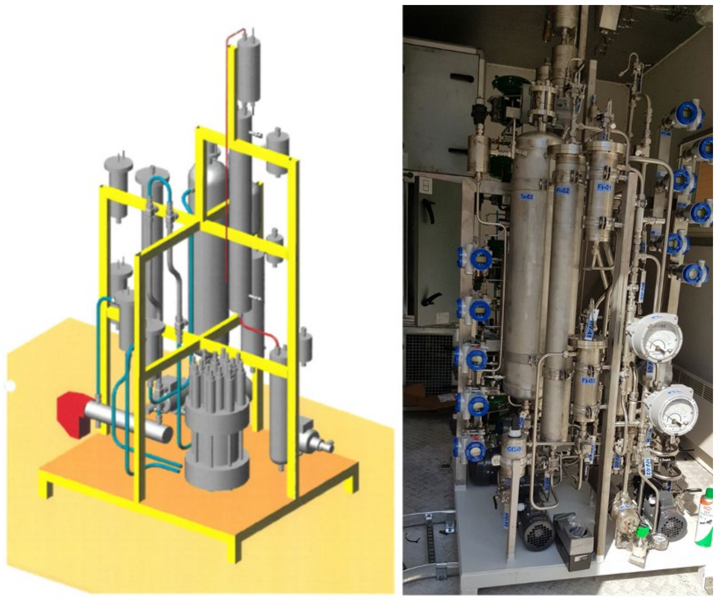

Figure 2: Mechanical design and photo of the PEMWE system test rig.

The layout of the electrical system and the power converters for the water electrolysis and fuel cell systems laboratory established at IFE is shown in Figure 3. The laboratory currently includes a 13 kW PEM fuel cell reference stack (Power Cell), a 20 kWh battery module and the above described 12 kW PEMWE stack (Nel/Proton Onsite). Each of these key components have their own dedicated DC/DC-converter (Hot Platinum), which all are coupled to the same DC-bus. The DC-bus is connected to the local grid via an AC/DC converter (Bitrode), which can be programmed to emulate different kinds of loads and power profiles. It will for example be possible to use the heavy-duty li-ion battery to test different hybrid electric topologies for the water electrolyser system. This is important since PEMWE-stacks operating at high pressures (e.g. 200-350 bar) cannot operate in load-following mode (due to the risk of gas crossover) in the same manner as more conventional PEMWE-stacks designed for operation at lower pressures (e.g. 15-30 bar).

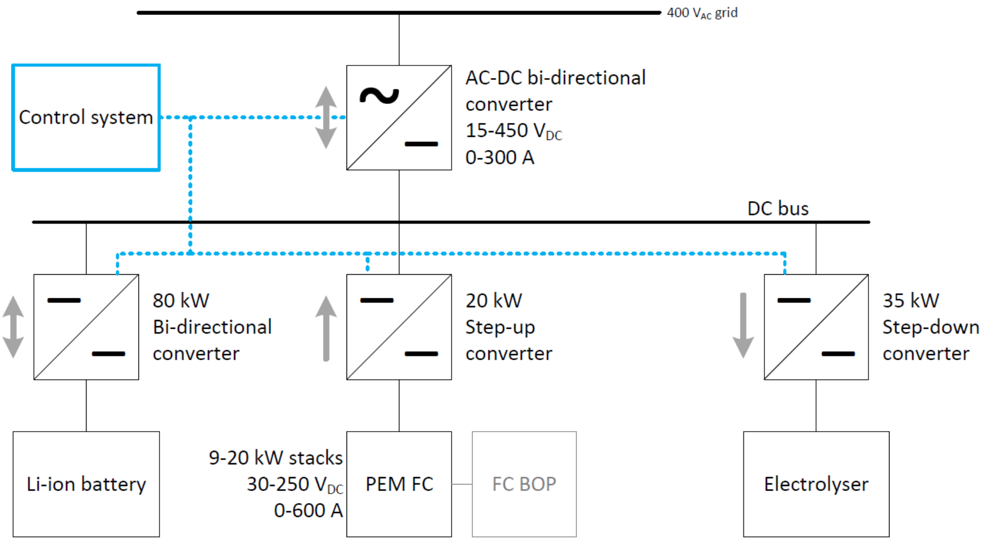

Figure 3: Electrical system and power converters of the systems laboratory at IFE.

The DC/DC step-down converter for the water electrolyser has been designed to operate over a wide range of voltage and current outputs (0-150 V_{DC} and 0-410 A), making it possible to test stacks with different cell electrode areas. The rated power of the step-down converter is however only 33 kW, which is significantly less than the 61.5 kW it can deliver at the rated current and voltage, respectively 410 A and 150 V_{DC}. The controls in the converter ensures a maximum power limit on the converter and reduces automatically the converter output current draw to limit the maximum output power drawn by the electrolyser. The output characteristics of the converter is shown in Figure 4 below.

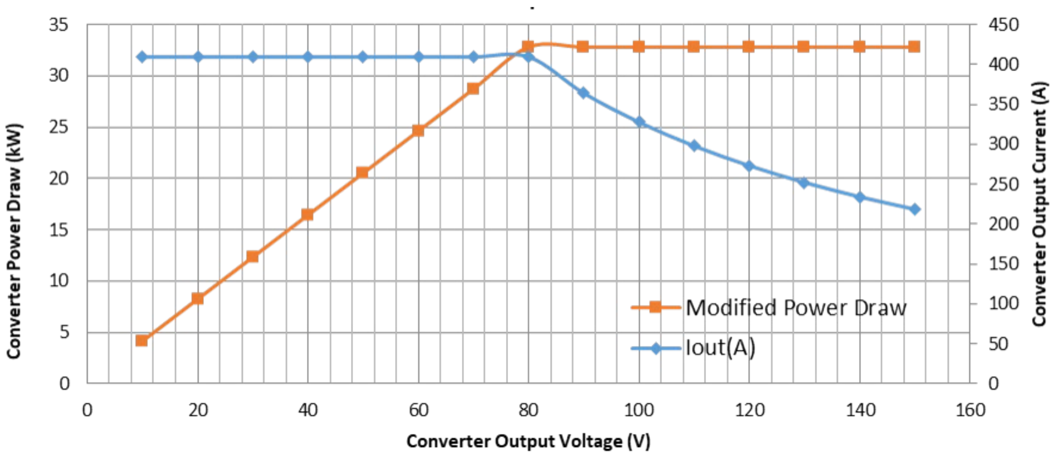

Figure 4: Output characteristics of DC/DC converter for water electrolyser system.

The PEMWE-system test rig includes a programmable controller (PLC) with a dedicated Human-Machine Interface (HMI) terminal installed in an in-house control room located adjacent to the WE-system container (which is located outdoors). The key component for controlling and collecting the signal data from the PEMWE-test rig is a cRIO-controller from National Instruments. The controller is situated in an electronics rack inside the PEMWE-system container and is designed to collect all signal data from the experiment and to control the experimental conditions of the system.

2. Detailed Balance of Plant Design

The Process and Instrument Diagram (P&ID) developed by IFE is shown in Figure 5. The BoP design was developed in collaboration with Politecnico di Torino (Italy) and FZ Jülich (Germany), who both have experience in constructing high pressure PEMWE test rigs [7].

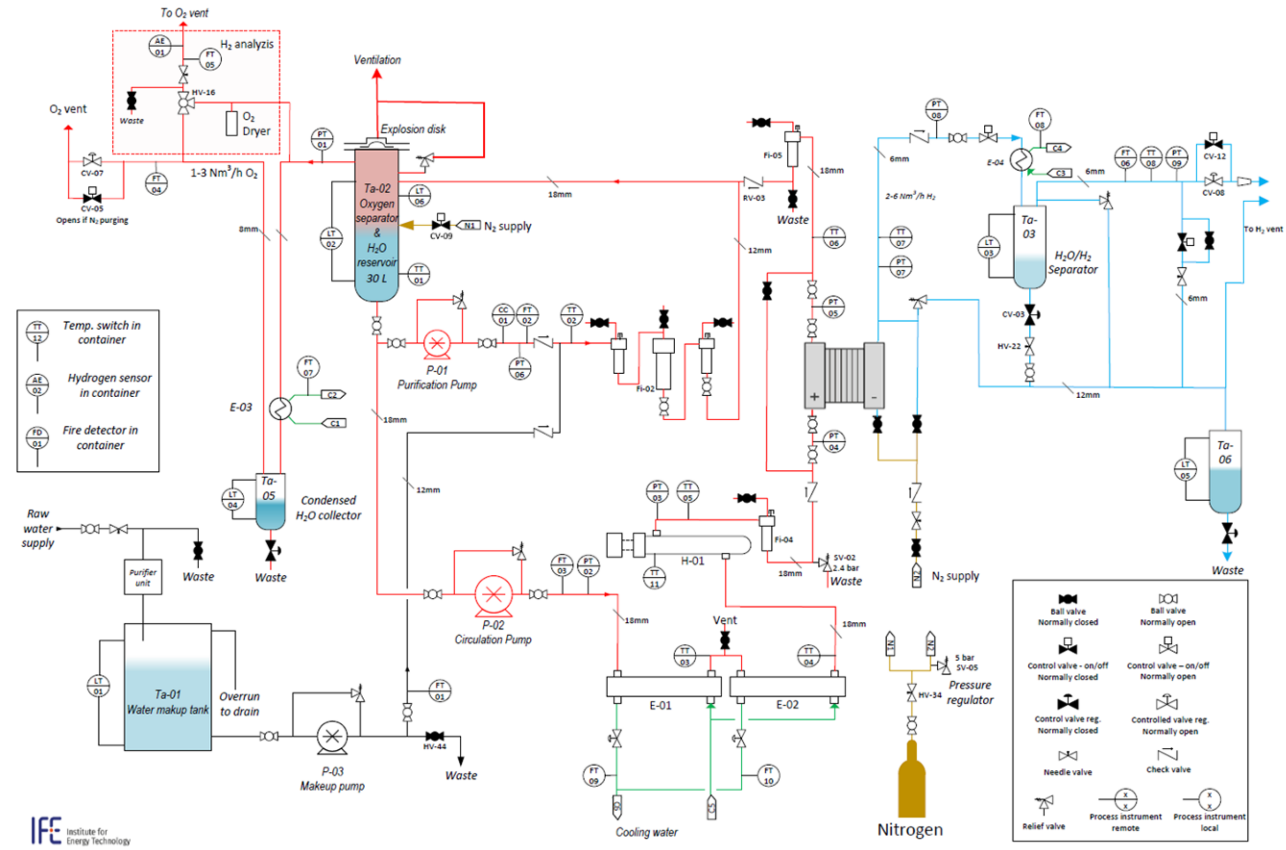

Figure 5: P&ID of PEMWE system

The anodic loop consists of a circulation pump (P-02) which continuously supplies the stack with water at a certain purity (ensured by mixed bed Fi-2) and a certain temperature (regulated by heat exchanger E-01 and E-02 and electrical heater H-01). The water/oxygen separator vessel (Ta-02) is used for a first separation of the residual liquid water in the O_2 outlet stream (separated by gravity and residence time), and a second water-oxygen separation takes place (Ta-05) after the O_2 outlet stream have passed through a condenser (E-03).

The process uses deionized water which is produced by a reverse osmosis production unit (Merck Millipore) and fed to a makeup water tank (Ta-01). From the makeup water tank a small pump (P-03) feeds the loop system through the purification filters on signal from the level sensor in in the oxygen/water separator (Ta-02). The control system aims to keep a constant level in this separator, but when the water consumption is below the minimum capacity of the pump it will be necessary to switch to dead band (on/off) control. The parallel purification loop (controlled by pump P-01) has been installed to maintain an adequate water quality (<0.5 µS/cm) which is important for preventing contamination of the stack and premature cell failure. This loop continuously bleeds off water from the main loop through a pre-filter (screen type), an ion exchanger (Fi-02) and a back filter (screen type). The ion resin is of high temperature type and withstands at least 90°C. The water quality is monitored using a conductivity measurement instrument (Jumo).

As the PEMWE-stack generates heat, two heat exchangers with a heat removal capacity of 2 and 6 kW are installed in series (enabling a total of 8 kW heat removal) in the main circulation loop. The coolers are of a cross-flow coaxial type, which is widely used at IFE and has a simple and reliable design (Figure 6). The cooling water is supplied by use of an air/water cooling system, and the heat removal rate is controlled by adjusting the cool water flow rate. An electrical heater is installed to heat the loop water to the desired temperature during startup, as well as to maintain the operating temperature at partial load operation (the system is uninsulated and will have significant heat losses). It is possible to regulate the heater power from 0->100% (PWM control), and it has a high-temperature switch (independent of the control system) that switches off the power to the heater if the temperature exceeds a pre-defined limit.

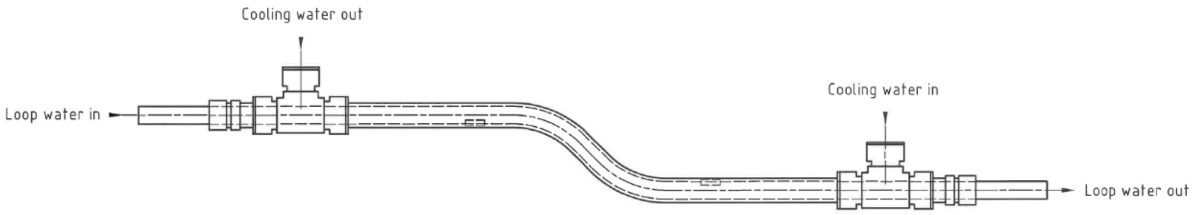

Figure 6: Heat exchanger design for E-01 and E-02.

The hydrogen pressure is controlled by a back-pressure regulator (CV-08, Emerson) with the use of a pressure transmitter (PT-09). To enhance water removal from the hydrogen gas stream, a heat exchanger (E-04) is mounted upstream of the water/hydrogen separator vessel (Ta-03). The separator is drained via a control valve (CV-03) upon a signal from a point level transmitter, and the separated water is collected in a second tank at ambient pressure (Ta-06). The water crossover during steady state operation will be followed by logging the water level in Ta-06 and keeping track of the batch-wise release of water. The mechanical drawing of the high-pressure separator vessel (Ta-03) is presented in Figure 7.

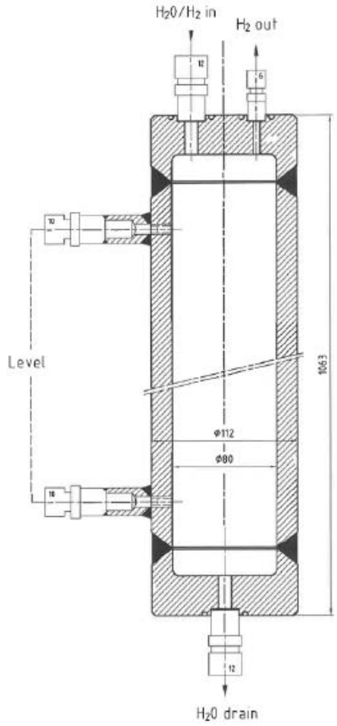

Figure 7: Water/hydrogen separator vessel (Ta-03), designed for pressures up to 350 bar.

3. Safety Considerations

In the event of a reverse flow of hydrogen into the anodic circulation loop (e.g. membrane rupture) a check valve is placed directly downstream from the stack to ensure that only a limited volume enters the oxygen subsystem. A differential pressure sensor (PT-08) over the check valve will trigger the Emergency Shut Down (ESD) procedure if the stack outlet pressure becomes lower than the hydrogen/water separator pressure. A safety valve on the oxygen/water separator tank Ta-02 opens and releases gas to the vent system if the pressure build-up is too high, and if the hydrogen/oxygen gas mixture combusts, a rupture disc on top of the tank goes off.

Since high differential pressure systems are particularly susceptible to hydrogen crossover, critically high hydrogen concentrations in the anode subsystem (> 4%) may arise also without a complete membrane rupture (and the accompanying instantaneous pressure build-up). An on-line hydrogen sensor (AE-01, Pemac) is therefore installed to continuously monitor the hydrogen content in the oxygen off-stream. In case the hydrogen concentration approaches the critical level, the stack is immediately shutdown and nitrogen will be purged through the oxygen subsystem (via CV-09).

Self-ignition via friction/adiabatic pressurization in highly oxygen enriched atmospheres is another risk associated with PEMWE-systems. This can be caused by pressure build-up (e.g. due to failure of the pressure control system) or stray particles entering the system. To mitigate this risk a particle filter has been placed downstream from the stack, and the control valve on the O_2-side is programmed to be “fail open”. The tube diameter in the anodic loop is furthermore selected to ensure an oxygen flow rate below 12 m/s (in accordance with industry gas standard).

The container in which the PEMWE system test rig is installed has fire walls and a ventilation system with a capacity of 1000 m^3/h, corresponding to approximately 35 air changes per hour (ACH). The ventilation system ensures a high degree of ventilation until the system is completely depressurized (a pressure switch situated in the hydrogen pipe is directly coupled to the ventilation system). A flow guard furthermore blocks for start-up of the electrolyzer in case the required air flow is not present. If hydrogen enters the room a hydrogen detector will trigger the Emergency Shut Down (ESD), if the concentration reaches 10 % of Lower Flammability Limit (LFL).

In order to evaluate the risk associated with severe hydrogen leakages, calculations assuming a 1.9 mm hole (10 % hole size) in a 6L hydrogen segment at 200 bar and 35 ACH have been performed. The results are shown in Figure 8 where the transient release rate, the accumulated released mass and the average concentration in the room are plotted. In this scenario, the average hydrogen concentration reaches a maximum of 3.2 %, and all the gas in the system is released within 10 seconds. Under normal operation there may be a "secondary grade" releases from leaky-seals and similar (ref. IEC60079-10-1). It is therefore necessary to define an ATEX Zone 2 within a LFL-distance corresponding to a hole of 0.1 mm^2, which in our system implies a release rate of 1.06 g/s and a LFL-distance of 1.4 m from the leak point.

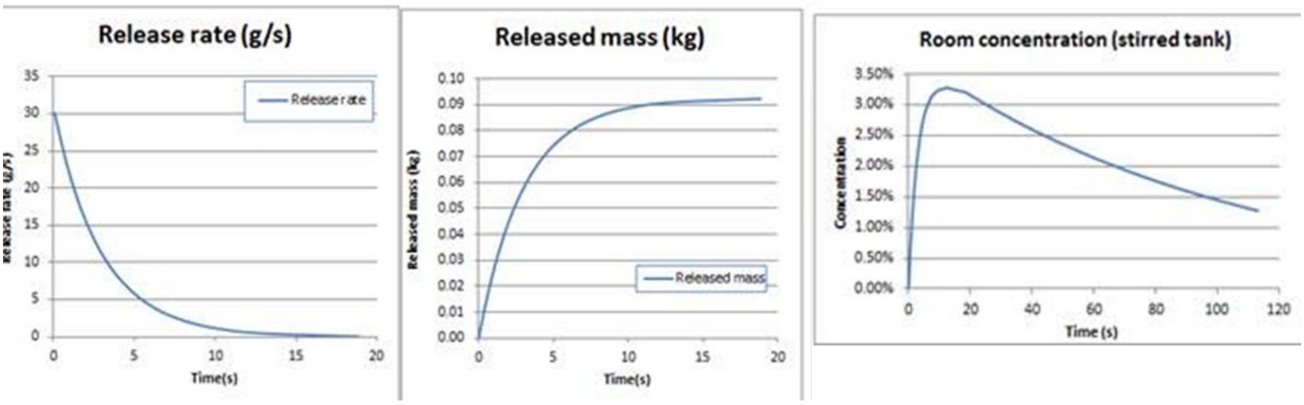

Figure 8: Transients associated with a severe hydrogen release (1.9 mm hole in 6 L hydrogen tank at 200 bar) in the PEMWE system container at IFE.

Conclusions and Future Work

A small-scale PEM water electrolyzer system test rig (6 Nm3/h, 60 kW) has been designed and built at IFE, and is soon ready to be installed at the *IFE Hynor Hydrogen Technology Center* (IFE Hynor), as part of a new national research infrastructure in Norway (*The Norwegian Fuel Cell and Hydrogen Centre*). The main purpose of the water electrolyzer system test rig is to test and characterize the performance of new designs of PEMWE-stacks capable of operating at high-pressures (>200 bar). The information provided above, including process diagrams and mechanical drawings of some of the key component, show that it will be possible to operate this high-pressure PEMWE-system test rig in a flexible and safe manner. The PEMWE-test rig is currently being installed in a dedicated water electrolyzer system container and will be commissioned in the second half of 2019. The functionality and operability of the PEMWE-rig will be tested thoroughly during the first half of 2020, using the reference PEMWE-stack technology described in this paper. From the second half of 2020 the test rig will be available for testing other high-pressure PEMWE-stacks designs.

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