PREVENTION OF HYDROGEN ACCUMULATION INSIDE THE VACUUM VESSEL PRESSURE SUPPRESSION SYSTEM OF THE ITER FACILITY BY MEANS OF PASSIVE AUTO-CATALYTIC RECOMBINERS

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ABSTRACT

Hydrogen safety is a relevant topic for both nuclear fission and fusion power plants. Hydrogen generated in the course of a severe accident may endanger the integrity of safety barriers and may result in radioactive releases. In the case of the ITER fusion facility, accident scenarios with water ingress consider the release of hydrogen into the suppression tank (ST) of the vacuum vessel pressure suppression system (VVPSS). Under the assumption of additional air ingress, the formation of flammable gas mixtures may lead to explosions and safety component failure.

The installation of passive auto-catalytic recombiners (PARs) inside the ST, which are presently used as safety devices inside the containments of nuclear fission reactors, is one option under consideration to mitigate such a scenario. PARs convert hydrogen into water vapor by means of passive mechanisms and have been qualified for operation under the conditions of a nuclear power plant accident since the 1990s.

In order to support on-going hydrogen safety considerations, simulations of accident scenarios using the CFD code ANSYS-CFX are foreseen. In this context, the in-house code REKO-DIREKT is coupled to CFX to simulate PAR operation. However, the operational boundary conditions for hydrogen recombination (e.g. temperature, pressure, gas mixture) of a fusion reactor scenario differ significantly from those of a fission reactor. In order to enhance the code towards realistic PAR operation, a series of experiments has been performed in the REKO-4 facility with specific focus on ITER conditions. These specifically include operation under sub-atmospheric pressure (0.2 – 1.0 bar), gas compositions ranging from lean to rich H_2/O_2 mixtures, and superposed flow conditions.

The paper gives an overview of the experimental program, presents results achieved and describes the modeling approach towards accident scenario simulation.

1.0 INTRODUCTION

Hydrogen generated in the course of a severe accident may endanger the integrity of safety barriers and may result in radioactive releases in both nuclear fission and fusion power plants. For nuclear fission reactors, accidents in the nuclear power plants Three-Miles-Island (USA, 1979) and Fukushima (Japan, 2011) have underlined the relevance of hydrogen mitigation measures which have been retrofitted in plants since the 1990s. In the case of future nuclear fusion power plants, hydrogen mitigation measures are already considered in the design phase.

In several reference accident scenarios inside the ITER fusion facility [1] currently under construction in Cadarache, France, hydrogen generation from various steam-material reactions is considered. The possibility of air ingress may support the formation of flammable gas mixtures and explosions, which may lead to safety component failure. As a consequence, several counter measures are under discussion. One option is the installation of passive auto-catalytic recombiners (PARs), which are well known from nuclear fission reactors. PARs convert hydrogen into water vapor by means of passive mechanisms and have been qualified for operation under the conditions of nuclear power plant accidents [2].

The working principle of a PAR is illustrated in Fig. 1. Inside the catalyst section, catalyst sheets form a set of parallel vertical flow channels. On the catalyst surface, hydrogen entering the PAR is converted with oxygen to water. Due to the exothermal reaction, a buoyancy-driven flow is induced inside the chimney on top of the catalyst section. The chimney ensures an upward directed gaseous flow through the PAR which inherently feeds the surrounding hydrogen/air mixture into the catalyst section.

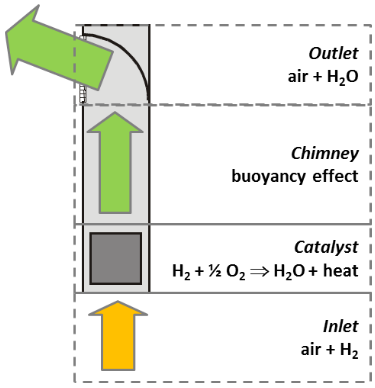

Figure 1. Principle of passive auto-catalytic recombiners (PAR)

In cooperation between IRSN (France), Forschungszentrum Jülich (Germany) and RWTH Aachen University (Germany), the efficiency and robustness of PARs for hydrogen mitigation in ITER is being assessed. In order to simulate relevant accident scenarios with ANSYS CFX, enhanced numerical models are required which take into account the specific boundary conditions of a fusion reactor accident compared to a fission reactor accident. For this purpose, an experimental program has been performed in the REKO-4 facility at Jülich to study PAR operation under sub-atmospheric pressure, oxygen starvation, and superposed flow conditions. The codes SPARK (IRSN) and REKO-DIREKT (Jülich), which describe the operational behavior of PARs [3], will be enhanced and validated according to the experimental results.

2.0 ACCIDENT SCENARIO AND BOUNDARY CONDITIONS

The analysis of severe accident scenarios plays a key role in the licensing of ITER in order to demonstrate the low risk of the operation to the public. The Generic Site Safety Report (GSSR) [4] defines different event categories and reference events according to the probability, namely normal operation, incidents and accidents. Furthermore, release guidelines are defined for elemental tritium (HT), tritium oxide (HTO), divertor or first wall activation products (AP) and activated corrosion products (ACP). Besides these release guidelines, further acceptance criteria are defined which include the prevention of flammable mixtures of hydrogen and air.

Up to now, loss of coolant accident (LOCA) and loss of vacuum accident (LOVA) represent reference scenarios for which hydrogen risk is considered [5]. LOCAs can be divided into two different scenarios with a failure inside the VV or an ex-vessel failure. In the case of an in-vessel LOCA, water enters the vacuum vessel and raises the plasma impurity level which leads to plasma shutdown by disruptions. These disruptions generate locally high heat loads and can entail electromagnetic loads to plasma-facing structures and pipework. The cooling system gets depressurized and the flow conditions change, which reduces the heat removal from the plasma-facing components (PFC). Simultaneously, the leaked water into the VV will react with the hot surfaces producing steam and by this pressurizing the VV. Further reactions of the PFC with the steam generate hydrogen, lead to higher pressures and cause hazards of explosion, if air ingress occurs additionally. In the case of an ex-vessel LOCA, a pipe or component outside of the VV fails and leads to a fast depressurization of the cooling system. The heat removal is significantly reduced and leads to fast temperature transients. Coolant tubes may start melting and can lead to an in-vessel LOCA with above-mentioned consequences. In a LOVA scenario, some equipment attached to the VV fails and leads to plasma disruption, temperature transients, pressurization of the VV, chemical reactions and radioactivity mobilization. In such a scenario a further failure of water piping is very likely, which can lead to hydrogen production and to explosion hazards [5, 6].

First theoretical analyses for the short-term hydrogen production due to oxidation reactions between beryllium and steam were published by Gaeta et al. in 1997 [7]. The calculations were performed with the MELCOR code based on an ex-vessel LOCA scenario. The resulting hydrogen mass for the first-wall/shield-blanket (FW/SB) design amounts to approx. 67 kg. Similar simulations for the divertor section only predict 0.3 kg of hydrogen due to additional cooling. Experimental investigations on the steam oxidation of PFC materials have been performed by Anderl et al. [8]. Figure 2 shows the hydrogen generation rates for tungsten and beryllium. Hydrogen generation for both materials is strongly dependent on the temperature and reaches significant rates especially above 800 °C for beryllium and above 900 to 1000 °C for tungsten.

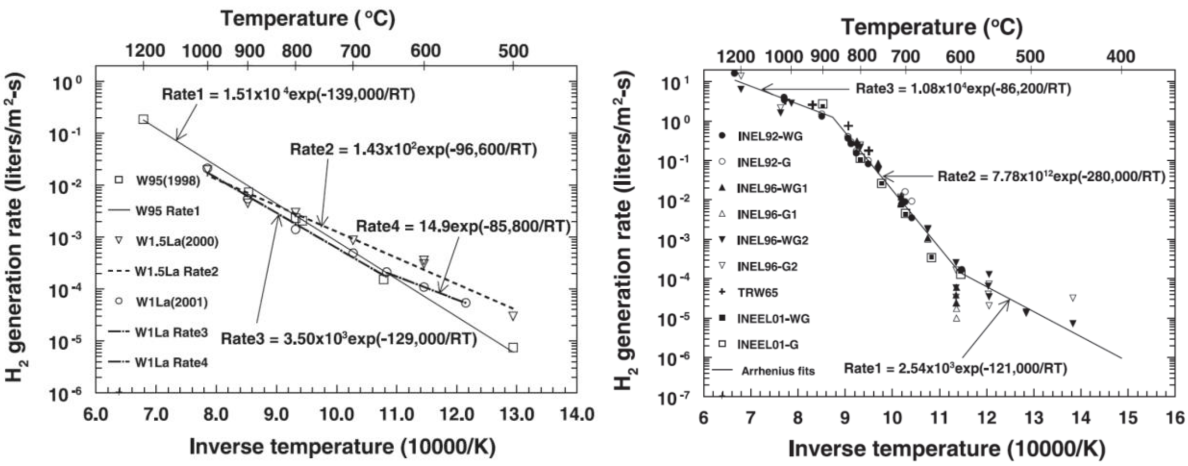

Figure 2. Hydrogen generation from steam oxidation of PFC materials beryllium (left) and tungsten (right) [8]

As all mentioned scenarios lead to a pressurization of the VV (admissible max. pressure of 200 kPa), a vacuum vessel pressure suppression system (VVPSS) is foreseen in order to comply with the design rules in the case of an accident. In the initial design (Fig. 3), the VVPSS includes a suppression tank (ST) and a drain tank (DT) [9]. Newer designs are still under discussion and foresee the combination of ST and DT in several small tanks. In the initial design (see Tab. 1), half of the ST volume is filled with water to condensate the produced steam allowing a pressure reduction in the VVPSS and VV. Under normal operation conditions, ST and DT are separated from the VV by valves and rupture disks. In case of VV pressurization, the bleed lines to the ST and DT open at 80 kPa pressure difference. At a pressure difference of 150 kPa, the rupture disks break and open relief lines with a larger cross section. Liquid water drains through the divertor section into the drain tank and the steam gets sucked into the ST and condenses in the cold water. After the rupture disk break, steams flows through the relief lines into the ST transporting also other non-condensable gases, like hydrogen or in a later stage also air. These gases accumulate in the ST, which may result in the formation of flammable and explosive gas mixtures.

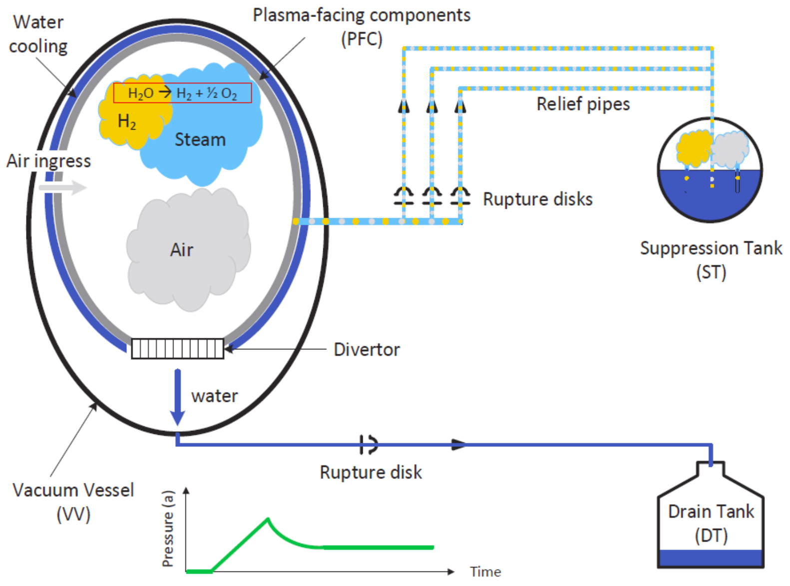

Figure 3. Schematic of the vacuum vessel pressure suppression system (VVPSS)

Table 1. Initial conditions of the suppression tank [9].

Suppression tank volume	1200 m³
Water volume	650 m³
Temperature	30 °C
Initial pressure	4.2 kPa

Baumann et al. [10] investigated the three-dimensional hydrogen distribution for the VV and the connected VVPSS using the GASFLOW code. They simulated a first-wall coolant leakage without plasma shutdown taking into account steam, hydrogen and air sources from best-estimate MELCOR calculations. The MELCOR calculations suggest a hydrogen production of about 15 kg due to beryllium-steam reactions. Calculated molar masses and volume fractions inside the ST are given in Fig. 4. The ST atmosphere consists only of hydrogen and nitrogen and is inert until air ingress occurs. Within short time, flammable mixtures with more than 5 vol.% oxygen (13500 s) will be reached. At

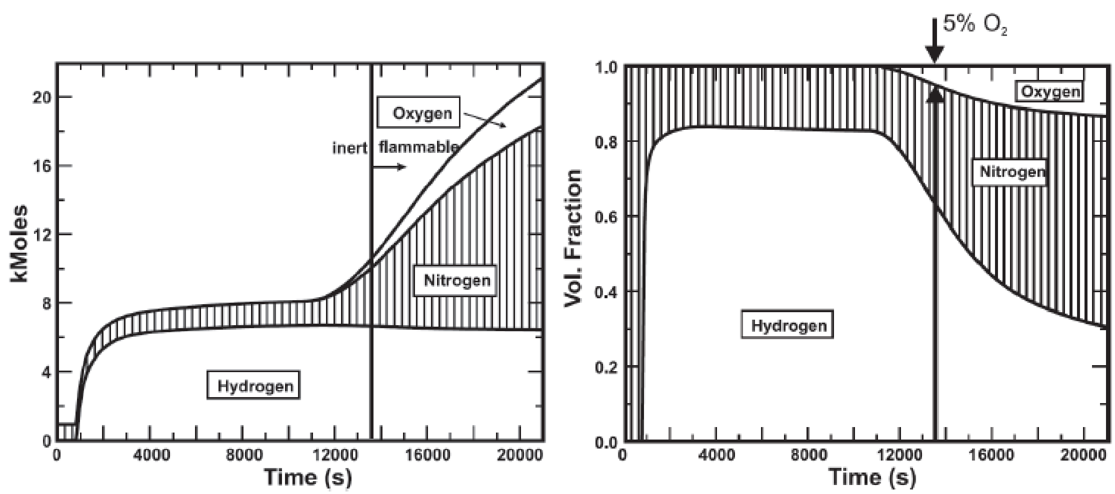

Figure 4. Calculated gas composition inside the ST: molar mass (left) and volume fractions (right) [10]

the end of the scenario (21000 s) there are nearly stoichiometric conditions at approx. 1 bar (a). The study shows that the hydrogen risk is mainly limited to the ST and formation of flammable mixtures in the VV and DT is quite unlikely. Redlinger et al. [11] used this study to assess a possible detonation inside the ST with DET3D. With these pressure loads they carried out a structure mechanical analysis of the ST end-plate with the ABAQUS code. The calculations indicate the violation of the ITER design rules. Further experimental investigations regarding the flammability limits and laminar flame speed of hydrogen-air mixtures at sub-atmospheric conditions performed by Kuznetsov et al. [12] and Sabard [13] additionally contribute to highlighting the relevance of hydrogen mitigation measures inside the ST.

In order to assess hydrogen mitigation measures, Xiao et al. [14] simulated the efficiency of passive autocatalytic recombiners (PAR) in the ST using the GASFLOW code. Similar calculations were performed by Tong et al. [15], who calculated an accident scenario with a carbon dioxide injection system and PARs inside the ST. In both studies, the so-called Siemens manufacturer's correlation was used to calculate the hydrogen recombination rates, and a significant effect of PAR operation on the hydrogen mass reduction was obtained. However, taking into account the above mentioned accident scenarios, the boundary conditions for PAR operation inside the ITER ST are differing significantly from present application inside nuclear power plants:

- Operational pressure: PARs have been qualified for operation starting from atmospheric pressure up to 6 bar (a). For the ITER ST, pressure is approx. 0.4 bar (a) when the air ingress starts and PAR operation takes place between 0.4 bar and 1.0 bar (a).

- Gas mixture: In case of a fission reactor accident, PAR operation starts in a lean hydrogen/air mixture. Oxygen starvation is possible in a late phase of the accident. In an ITER ST scenario, PAR operation starts under oxygen starvation conditions and the oxygen content increases during the scenario.

- Thermal hydraulic conditions: Due to the small vessel volume of the ITER ST compared to fission reactor containments (1200 m^3 vs. ~60,000 m^3) and the gas injection through the spargers, superposed flow conditions up to counter flow are possible and could affect PAR operation.

Neither the Siemens manufacturer's correlation nor any other numerical PAR model has up to now been validated against these challenging conditions. For this purpose, an experimental database has been generated.

3.0 EXPERIMENTAL INVESTIGATIONS

The REKO-4 facility operated at Forschungszentrum Jülich has been used to investigate the operational behavior of a catalytic recombiner under the boundary conditions inside the ST during an ITER accident scenario. The facility consists of a cylindrical steel pressure vessel with a free volume of 5.3 m^3, including wall heating and outer insulation (Fig. 5, left). For the present study, a vacuum pump has been installed and a fan system for superposed flow conditions has been developed and qualified. Gases (hydrogen, air, nitrogen) are injected into the vessel by means of mass flow controllers. Thermocouples and Pt100 resistance thermometers are used for temperature measurements. To determine the pressure inside the vessel, relative and absolute pressure sensors are applied. Furthermore, hydrogen, oxygen, and humidity sensors are installed to measure on-line the gas distribution in the course of an experiment. Particle Image Velocimetry (PIV) is used to measure the gas flow field at the PAR inlet in order to calculate the recombination rate.

Figure 5. REKO-4 test vessel (left) and PAR (right)

The PAR installed inside the REKO-4 facility has an inlet cross section of 15 x 5 cm² and a total chimney height of 1.2 m (Fig. 5, right). Four catalyst sheets are arranged inside the catalyst section close to the lower inlet. The recombiner box as well as the catalyst sheets are equipped with thermocouples. The test parameters of the present experimental study are given in Tab. 2.

Table 2. Test parameters.

Parameters	**Range**
Pressure	0.2 – 1.0 bar (a)
Counter flow configuration	Reference, horizontal flow, vertical flow, 30° angle
Counter flow velocity	0.5 – 1.5 m/s
Oxygen concentration	0 – 21 vol.%

3.1 PAR Operation under Sub-atmospheric Pressure

A vacuum pump is used to adjust the vessel pressure. After verification of the vessel tightness, the experiments start with a hydrogen injection of 1.9 m³/h until 6 vol.% average concentration is reached. The beginning of the start-up phase is characterized by the heat-up of the catalyst. The reaction starts first at the upper edge of the catalyst sheets and then gradually increases at the lower edge. The reaction heat leads to a temperature rise in the gas between and above the catalyst sheets, which initiates the start-up of the chimney flow. The start-up phase ends when the chimney flow is fully established. Further hydrogen injection phases follow to reach quasi steady state conditions for PIV measurements at the PAR inlet.

For the sub-atmospheric pressure test series, 10 tests were performed, taking into account 5 different pressure levels (1.00, 0.75, 0.55, 0.35, 0.20 bar). Figure 6 shows the catalyst temperature histories during the start-up phase for all tests. Hydrogen injection starts at t = 0. The duration of injection is between 540 s (1 bar) and 140 s (0.2 bar) to reach the intended hydrogen concentration. The injection time has been adapted to the pressure in order to obtain identical hydrogen concentration for all experiments. The catalytic reaction starts in all tests during the injection phase within 200 s. In all experiments, the catalyst temperature at the upper edge reaches values between 50 °C and 70 °C at t = 400 s. The start of the chimney flow can be determined by the sharp increase of the catalyst temperature, due to the enhanced supply of fresh hydrogen-air mixture. For the 1 bar and 0.75 bar tests, the chimney flow establishes in less than 800 s, only shortly after the injection finishes. At pressures below 0.75 bar, a significant prolongation of the start-up phase with lower pressures is observed. During the delayed chimney flow development, a temperature equilibrium of approx. 100 °C is reached. At the 0.2 bar level, no chimney flow is established during the test duration of more than 2 hours. Only the injection of air (9000 s and 11600 s) and the related pressure increase lead to chimney flow start and the observed temperature increase.

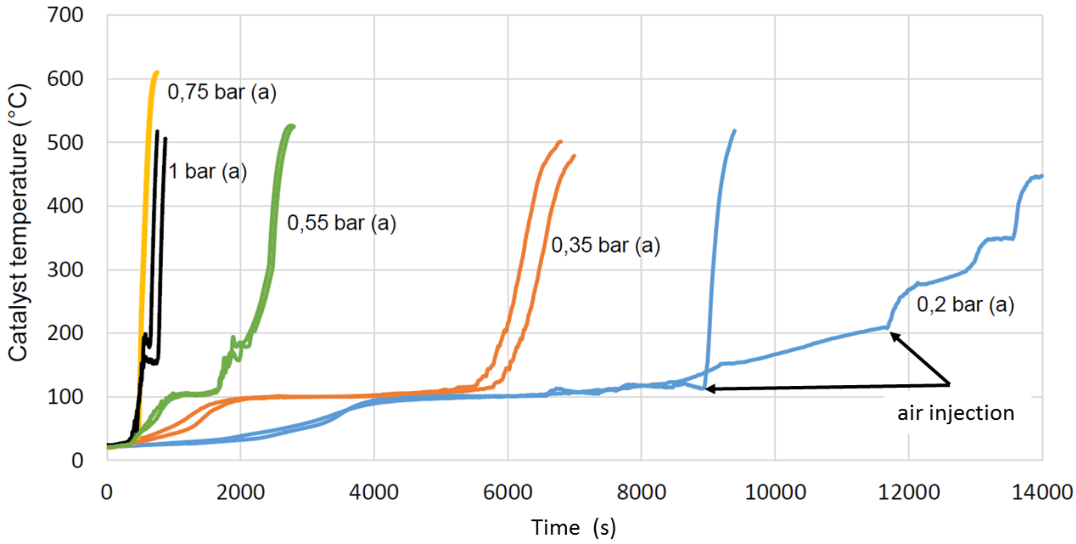

Figure 6. PAR start-up delay at sub-atmospheric pressure

The experimental results are of good reproducibility. The largest deviation occurs in the 0.35 bar tests, with a time difference of 200 s for a total start-up time of approx. 6000 s.

During the quasi steady-state phases after the start-up phase, PIV measurements have been performed in order to determine the PAR inlet velocity. A maximum velocity of 0.62 m/s is reached in the 1 bar tests. With lower pressures, a reduction of the inlet velocity is observed (Fig. 7). Reduced inlet velocities lead to a lower transfer of fresh gas and therefore limit hydrogen consumption.

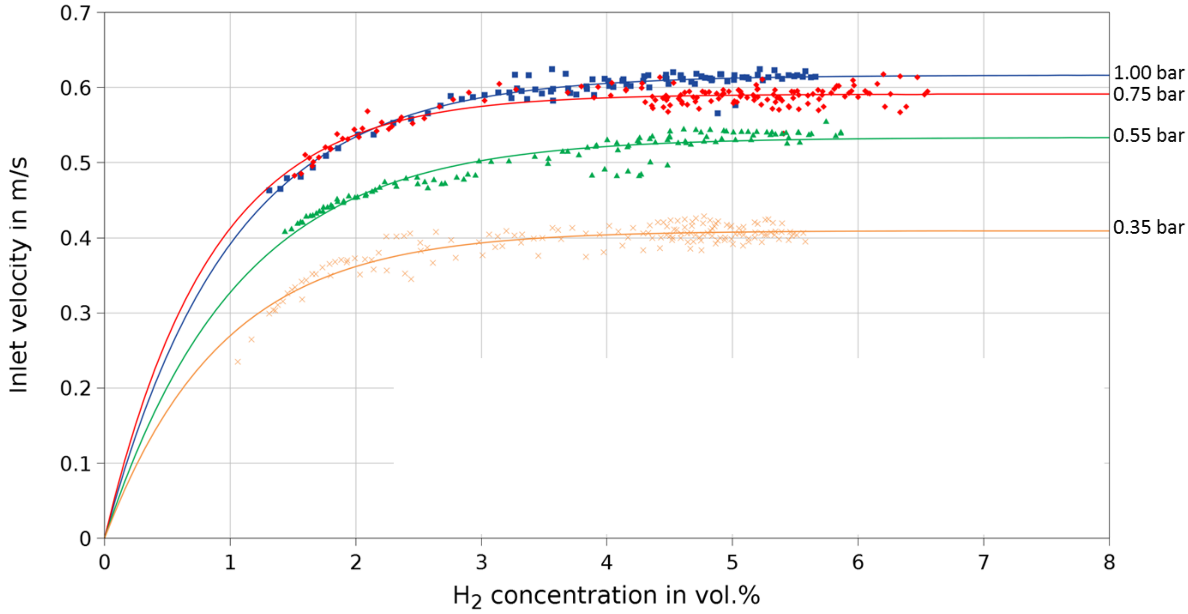

Figure 7. Flow velocity at the PAR inlet for sub-atmospheric pressures

3.2 PAR Operation under Oxygen-lean Conditions

The oxygen starvation tests have been performed at the same initial pressures as mentioned above (0.20, 0.35, 0.55, 0.75, and 1.00 bar). In the preparation phase, the REKO-4 vessel is evacuated and flushed with nitrogen to achieve an oxygen-free atmosphere. For all tests, the initial atmosphere consists of 6 vol.% of hydrogen and 94 vol.% of nitrogen. Ventilator operation ensures well-mixed conditions over the full test duration. Air is injected by a mass flow controller at an elevation of approx. 50 cm above the vessel bottom. The air volume flow in each test is adjusted according to the initial pressure (e.g. 2 m^3/h for 1 bar and 1.1 m^3/h for 0.55 bar), which leads to identical increase of the oxygen fraction over time in all tests.

Like in the low pressure tests (see section 3.1), the catalytic reaction starts immediately after hydrogen/air mixture is available (Fig. 8). In contrast to those tests, the first temperature rise occurs at the leading edge. Again, the start-up of the chimney flow, which is indicated by the steep increase in temperature, is significantly delayed with decreasing pressure and no start-up is achieved for 0.2 bar. Furthermore, there seems to be a minimum oxygen concentration required for full PAR operation as indicated by the marks in the diagram. The chimney flow establishes at an oxygen concentration of approx. 2 vol.% for 1 bar, but needs approx. 5.5 vol.% at a pressure level of 0.35 bar to generate enough heat for the natural convective flow.

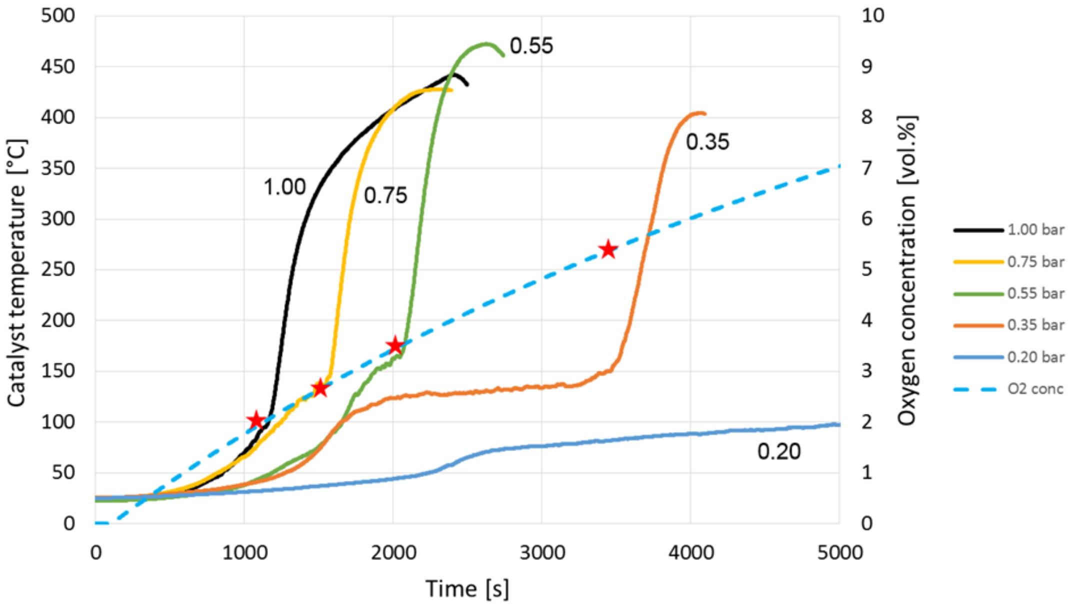

Figure 8. Catalyst temperature and oxygen concentration during start-up

The time delay between start of the air injection and start of the chimney flow as a function of the pressure under oxygen-lean conditions is given in Figure 9. The marks indicate the initial pressure of the test while the lines indicate the pressure increase during air injection. The exponential fit is using the actual pressure at the time of start-up of the chimney flow.

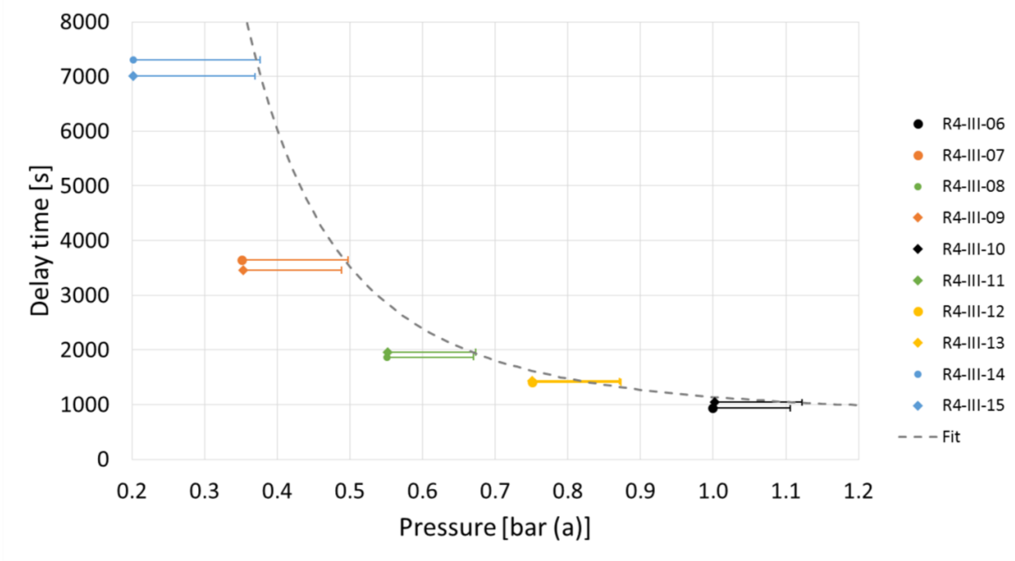

Figure 9. Start-up delay under oxygen-lean conditions

3.3 PAR Operation under Superposed Flow Conditions

A radiator fan unit consisting of a blower with flow conditioner und guide tube has been used to induce different forced flows which are directed against the chimney flow inside the PAR box. The test matrix includes a total number of 32 experiments performed at pressures of 0.55 bar and 1.0 bar with different flow velocities up to 0.9 m/s with three different superposed flow configurations under different angles of incidence (Fig. 10).

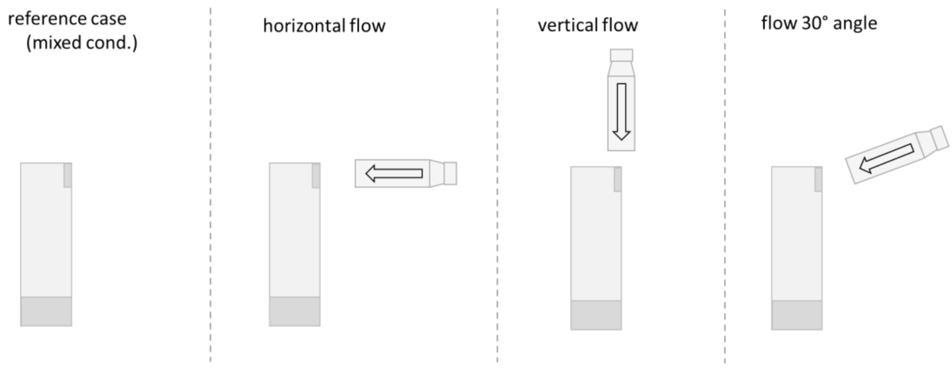

Figure 10. Superposed flow configurations

All tests were carried out with a similar procedure. First, the fan is started and the resulting flow at inlet/outlet of the PAR is measured by means of particle image velocimetry (PIV). Then the hydrogen injection is started and maintained until an average hydrogen concentration of 6 vol.% is reached. The experiments have been performed with both fast injection rates of 1.9 m³/h and slow injection rates of 0.5 m³/h.

The strongest impact on PAR operation is obtained in both the horizontal and 30° angle flow tests. Under these conditions, initial reverse operation of the recombiner can be observed. This means that the recombiner is operating under forced flow conditions with a downward-directed flow from the outlet to the inlet. Fig. 11 gives an example for a horizontal flow test at atmospheric pressure with 18 % ventilator power. The hydrogen injection starts at 1100 s with a constant injection rate. The hydrogen concentrations at the inlet and outlet of the PAR increase until the catalytic reaction starts, which is indicated by the decrease of the hydrogen concentration at the PAR inlet.

As soon as the chimney flow is stronger than the counter flow, the flow direction changes (transition phase around 1500 s) and an upward-oriented flow establishes. The hydrogen concentration at the inlet is now relevant for the recombination reaction and the outlet concentration decreases due to the catalytic reaction. No further negative impact of the on-going superposed flow has been observed.

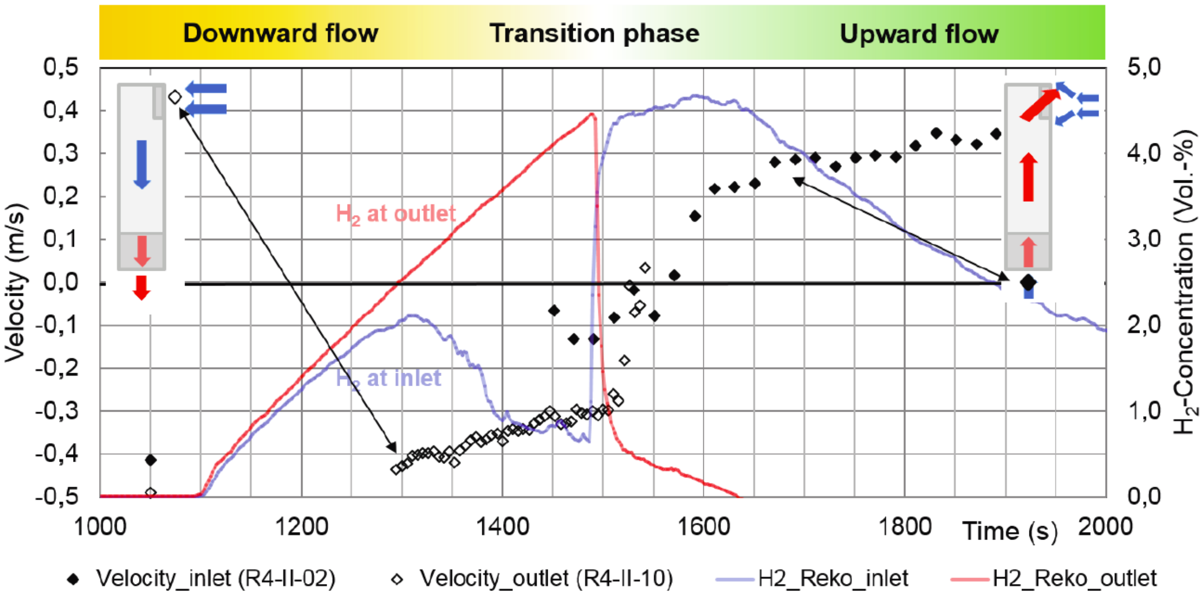

Figure 11. General scheme of counter flow start-up (REKO-4 data)

Flow velocity measurements obtained by means of PIV support these observations (Fig. 11, symbols). Due to the evaporation of DEHS particles inside the hot gas leaving the catalyst section, the simultaneous measurement of the velocity at the PAR inlet and outlet is impossible. Consequently, two different experiments performed under identical boundary conditions were evaluated. We obtain negative values for the flow velocity during the downward directed flow phase and positive values after the transition phase. The establishment of the chimney flow is delayed with higher ventilator powers, and higher hydrogen concentrations are needed to reach the transition point.

Although PAR operation is significantly influenced by the superposed flow conditions, the overall hydrogen conversion efficiency is only slightly affected due to the fact that the PAR operates efficiently during the initial downward flow phase driven by the counter flow. PIV measurements reveal that the counter flow is deflected by the PAR outlet flow as soon as the chimney flow has developed.

4.0 CONCLUSIONS

Hydrogen mitigation measures are considered already in the design phase of the ITER fusion facility. The outcomes of accident scenario analyses to assess the hydrogen risk for the suppression tank (ST) of the vacuum vessel pressure suppression system have caused a vital interest in the application of PARs. Two numerical studies seem to confirm the suitability of PARs for hydrogen removal inside the ST. However, the numerical model used to describe PAR operation has not been validated against the specific ITER boundary conditions.

In order to enhance existing PAR models according to the specific boundary conditions, experimental investigations under sub-atmospheric pressures, oxygen-lean gas compositions and superposed flow conditions were performed. The study reveals several scenario-typical limitations of PAR performance. Most significant is the prolonged start-up of the PAR chimney flow at sub-atmospheric pressures which will cause a significantly delayed start-up after the air ingress. Furthermore, the chimney flow velocity is reduced at lower pressure causing hydrogen conversion efficiency. The effect of superposed flow conditions was found to be negligible as the PAR is working efficiently even under opposed flow direction and operates unaffected after establishment of the natural chimney flow.

Taking into account the experimental results of the present study, two numerical codes, SPARK (IRSN) and REKO-DIREKT (Jülich), which describe the operational behavior of PARs, are going to be further developed and enhanced to assure reliable simulation of PAR operation. As a final step, the simulation of accident scenarios with ANSYS CFX will be performed to assess the efficiency and functionality of PARs under the accident conditions inside the ITER ST. In the light of the present experimental results, former studies may prove to have been too optimistic with regard to the hydrogen mitigation efficiency of PARs in ITER.

5.0 ACKNOWLEDGEMENTS

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