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Operational behavior of a passive auto-catalytic recombiner under low pressure conditions

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HIGHLIGHTS

- We studied the start-up behaviour of a PAR under low pressure.
- We performed several identical experiments under different pressures.
- A significant delay of start-up under lower pressures is observed.
- A significant reduction of inlet velocity under lower pressures is observed.
- Modelling of the performed tests was done and a first orienting simulation with ANSYS CFX was performed.

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ABSTRACT

In the case of a severe accident inside a water-cooled fusion facility, like ITER, there exist several scenarios in which hydrogen may be produced and released into the suppression tank. Assuming the accidental ingress of air, the formation of flammable gas mixtures may lead to explosions and severe component failure. One option to mitigate such hypothetical scenarios is the installation of passive auto-catalytic recombiners (PARs), which are presently used as safety devices inside the containments of nuclear fission reactors. PARs convert hydrogen into water vapor by means of passive mechanisms and support the prevention of large accumulations of combustible gases. Experimental investigations of PAR operation have been performed with a scaled-down model of a conventional PAR inside the REKO-4 facility (JÜLICH), a pressure vessel with a volume of 5.3 m^3. A first low-pressure test series has been performed with absolute pressures between 0.2 and 1 bar (a), and hydrogen concentrations of up to 6 vol.%.

The test results show a strong dependence of the pressure on the PAR start-up behavior. The start-up delay is proportional to the pressure level. Furthermore, the recombination rate is significantly reduced with decreasing pressure.

1. Introduction

In the event of a loss of coolant accident (LOCA) inside a water-cooled fusion facility, like ITER, the generation of hydrogen poses a significant risk. In combination with an air ingress (LOVA), flammable mixtures may form and lead to a severe component failure [1]. For the ITER facility, one of the main goals during an accident is to keep the integrity of the vacuum vessel. Therefore, the pressure needs to be maintained below the design pressure limit of 2 bar (a) [2]. To meet these requirements a vacuum vessel pressure suppression system (VVPSS) is foreseen, which is separated by rupture disks under normal operation. In the initial design presented to IRSN, the VVPSS consists of a suppression tank (ST) and a drain tank (DT) (Fig. 1). Newer designs are still under discussion and foresee the combination of ST and DT in several small tanks. For the initial design, half of the suppression tank volume is filled with water to condensate the produced steam allowing a pressure reduction in the VVPSS and VV [3].

In the case of a failure of the plasma-facing components (PFCs), a water ingress can occur. The water evaporates at the hot walls

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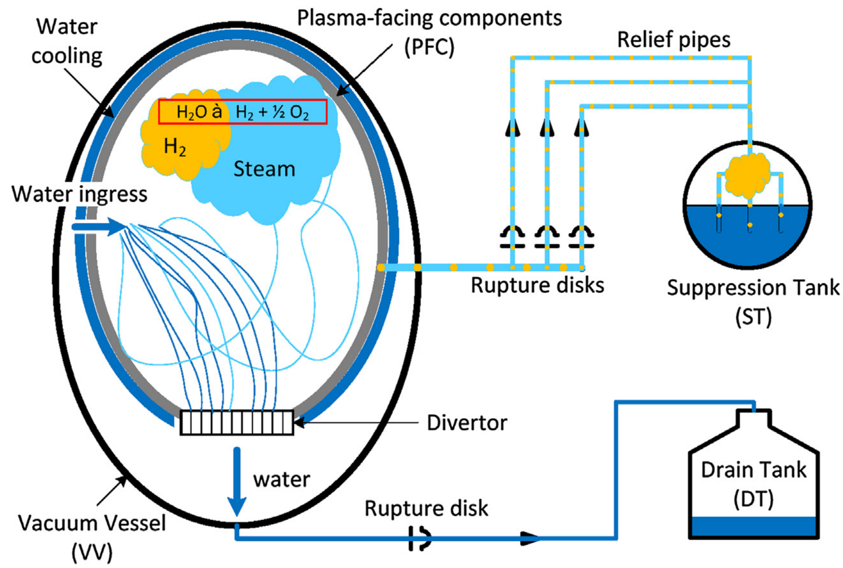


Fig. 1. Water ingress and break of rupture disks.

and the hot metallic surfaces oxidize (Fig. 1). This oxidation reaction generates hydrogen, which contributes together with the Deuterium and Tritium, used for the fusion reaction, to the full hydrogen inventory. The hydrogen generation rates under different temperatures were investigated by Anders et al. [4]. The oxidation of tungsten from the divertor and beryllium (PFC components) are the main contributing reactions for the hydrogen generation. These reactions are strongly dependent on the metallic temperatures and lead to higher hydrogen production rates with higher temperatures.

In the course of a LOCA, the increasing pressure leads to a break of the rupture disks and the mixture of non-condensable (H_2) and condensable (H_2O) gases flows, due to pressure differences, into the ST. The gas inflow is divided between several spargers to achieve full steam condensation. The hydrogen accumulates inside the ST's gas phase while liquid water is drained through the divertor into the DT (Fig. 1).

In the last phase, further component failure can lead to an air ingress and induce a LOVA. As a consequence, the air accumulates with the hydrogen inside the ST and may form ignitable mixtures (Fig. 2). An explosion inside the ST could lead to severe damage and to the release of dust into the environment.

One option to mitigate the risk of a hydrogen explosion is the implementation of passive auto-catalytic recombiners (PARs) inside the ST. PARs are well known safety devices for nuclear power plants (NPPs) and consist of a catalyst section with numerous thin catalyst sheets. These metal sheets are coated with a wash-coat and platinum or palladium as catalyst. The precious metal reduces the activation energy required for the conversion of hydrogen and oxygen to water. The reaction is strongly exothermic and heats up the resulting air-steam mixture. Due to the decreased density, a chimney flow forms supplying fresh hydrogen-air mixture from the surrounding atmosphere. This principle works already at hydrogen fractions below 1.0 vol.% and is completely passive. The boundary conditions for the PAR inside the ITER ST are completely different concerning the pressure, oxygen content and superposed flow conditions. In the frame of the present paper, the PAR behavior under low pressure is investigated and the applicability assessed.

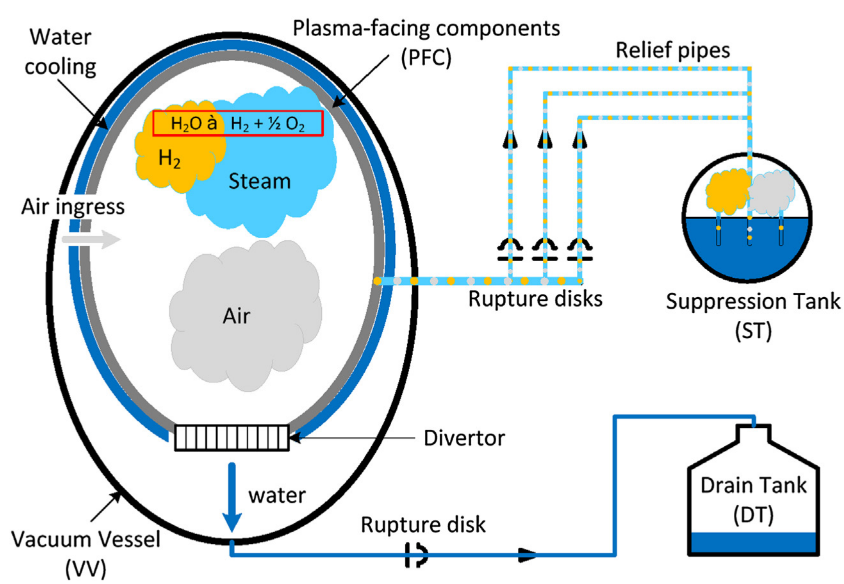


Fig. 2. Air ingress and formation of ignitable mixtures.

Fig. 3. Test facility: REKO-4.

2. Experimental program

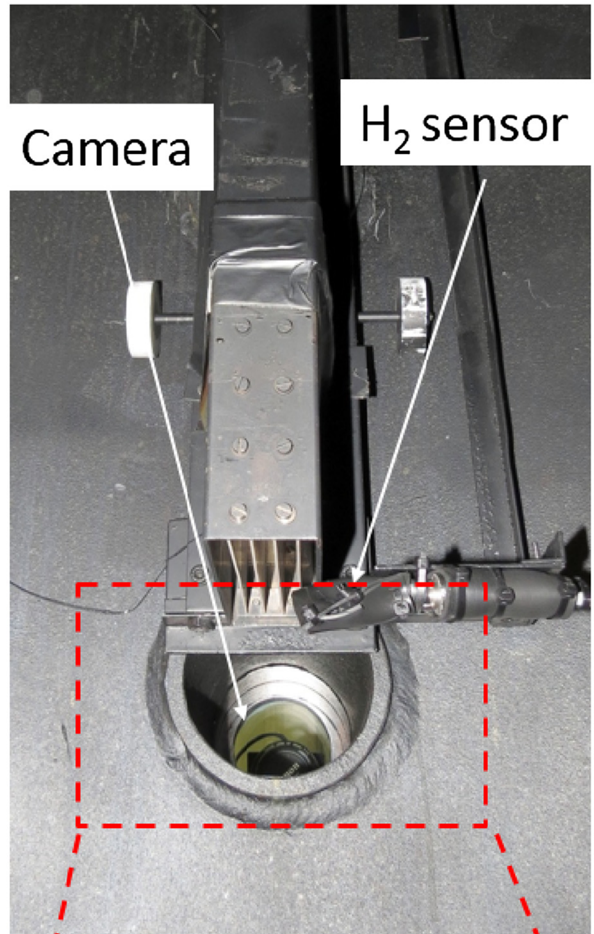
The experiments were performed in the REKO-4 facility (Fig. 3), a pressure vessel with a volume of 5.3 m^3.

The vessel was built to investigate the behavior of PARs under natural flow conditions [5]. For the present investigation, a scaled model of a PAR with four catalyst sheets is installed. The hydrogen injection is located 55 cm above the lowest point of the vessel and is controlled by a mass flow controller (MFC).

2.1. Instrumentation

The facility is instrumented with different measurement techniques. 20 heat conductivity sensors are installed to measure the hydrogen concentration. 15 of them are positioned at three different levels on mounting rails. The remaining sensors are used for PAR instrumentation, e.g. inlet and outlet of the PAR. In addition, 70 thermocouples are installed, measuring gas temperatures, wall temperatures and catalyst temperatures. Furthermore, two humidity sensors and two oxygen sensors are used to determine the gas mixture composition.

The recombiner with a width of 5 cm and a depth of 14 cm is equipped with four catalyst sheets. The PAR chimney has a length of 85 cm. The catalyst sheets are 1.6 mm thick, which allows to insert thermocouples into drillings to measure the temperature profile of the sheets. The two middle sheets are both equipped with ten TCs measuring temperatures from the lower edge up to the upper edge. The inflow into the PAR is measured by particle image velocimetry (PIV). For this purpose, a laser beam passes through a glass flange into the vessel forming a vertically positioned light sheet below the recombiner. A perpendicular positioned camera is taking double frame pictures through an optical access (Fig. 4). For the seeding, DEHS particles are used. Investigations have shown that they do not interfere with the catalyst.



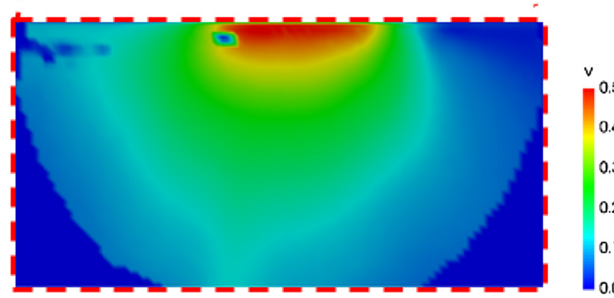


Fig. 4. H_2 sensor and PIV measurement at the PAR inlet.

2.2. Test procedure

Fig. 5 gives an overview over the test procedure. A vacuum pump is used to adjust the pressure of the vessel (1). After verification of the vessel tightness, the experiments start with a hydrogen injection up to 6 vol.% average concentration (2). The injection rate is set to 1.9 m^3/h in all experiments to reach the intended hydrogen content as fast as possible. The injection is limited by the MFC, with a maximum flow rate of 2 m^3/h.

The experiments were conducted without any ventilation. Consequently, the hydrogen injection leads to a stratified hydrogen-air mixture and higher concentrations are locally achieved. Due to density differences, highest hydrogen concentrations are reached in the

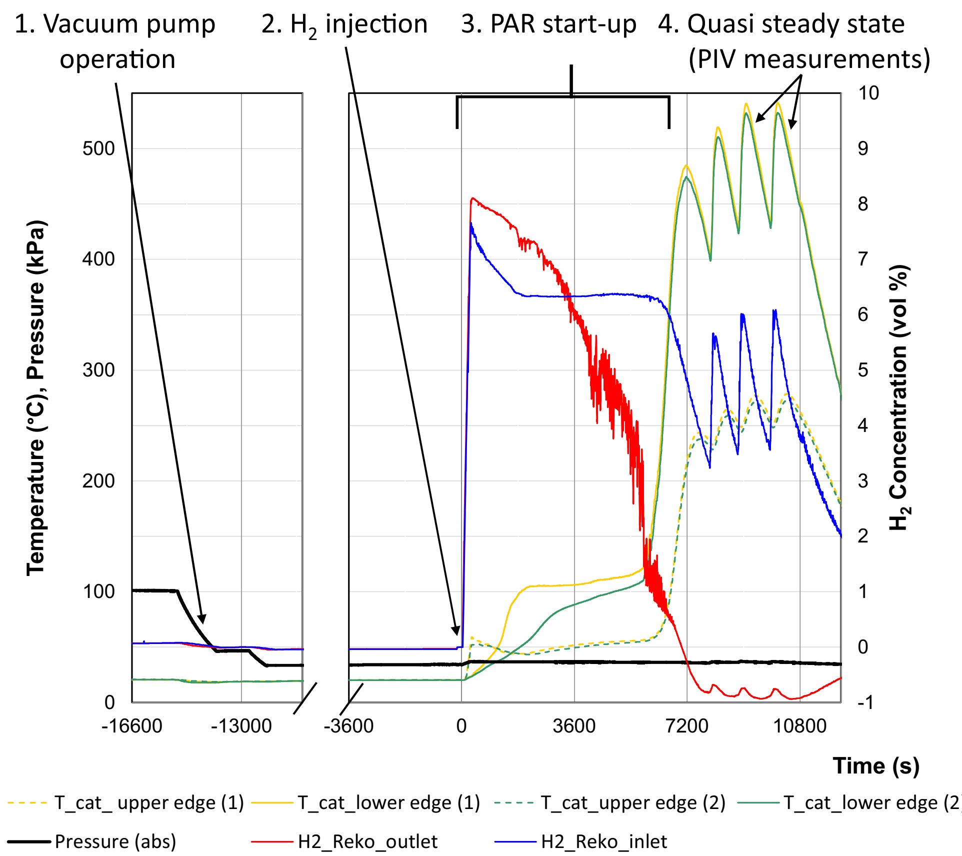


Fig. 5. Test procedure of low pressure tests.

upper part of the vessel. Also the concentrations at PAR inlet and outlet can reach shortly higher concentrations until the PAR operation starts or the hydrogen diffusion leads to a homogenization.

The start-up phase is characterized by the heat-up of the catalyst (3). The catalyst starts first at the upper edge and then the reaction gets stronger at the lower edge (Fig. 6). The reaction heat leads to a temperature rise in the gas between and above the catalyst sheets, which initializes the start-up of the chimney flow. The start-up phase ends when the chimney flow is completely established. Further hydrogen injection phases follow to reach quasi steady state for PIV measurements at the PAR inlet (4).

For the present investigations 11 tests were performed. Five different pressure levels (1.00, 0.75, 0.55, 0.35, 0.20 bar (a)) were taken into account. The 1 bar (a) tests were repeated twice, because the

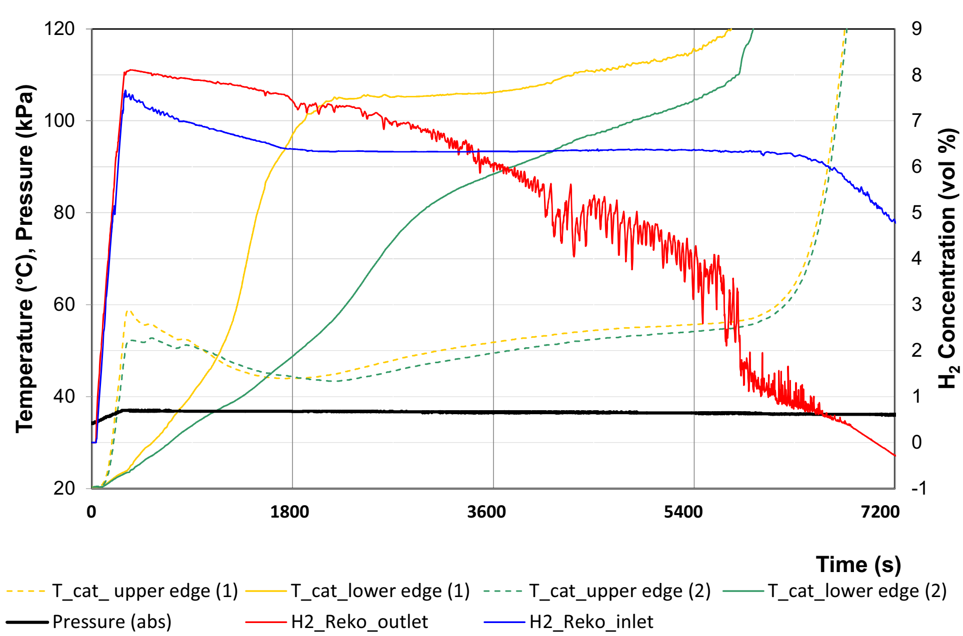


Fig. 6. PAR start-up phase.

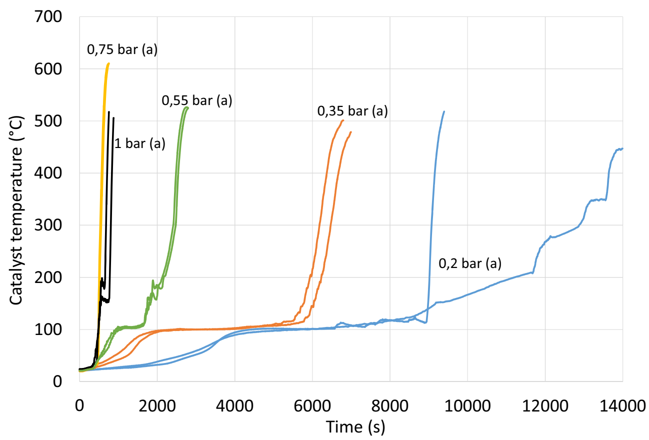


Fig. 7. Catalyst temperatures at lower edge.

catalyst sheets were newly coated and needed an activation for the first use.

2.3. Experimental results

In the low pressure tests a significant prolongation of start-up with lower pressures is observed. The starting time (t = 0) is defined with the start of the hydrogen injection. The duration of injection is between 540 s (1 bar) and 140 s (0.2 bar) to reach the intended hydrogen concentration. The start-up is divided into two phases, the start of the catalytic reaction and the start of the chimney flow. The catalytic reaction starts in all tests in less than 200 s, still in the injection phase. This is observed by the TC at the upper edge of the catalyst sheets.

In all experiments, the catalyst temperature at the upper edge reaches values between 50 °C and 70 °C at 400 s after injection start. Afterwards, as long as the chimney flow is not established, the temperature at the upper edge decreases and the lower edge temperature increases (Fig. 6). For the 1 bar and 0.75 bar tests the chimney flow establishes in less than 800 s, only shortly after the injection finishes (Fig. 7).

For pressures below 0.75 bar, the chimney flow start is significantly delayed. The catalyst temperature increases up to around 120 °C and a temperature equilibrium is reached without a chimney flow. This phase leads to a severe prolongation of the whole start-up process. The start of the chimney flow can be determined by the sharp increase of the catalyst temperature, due to the supply of fresh hydrogen-air mixture. In addition, the start-up of the chimney flow is observed by PIV, which also confirms the starting time of the chimney. At the 0.2 bar level, no chimney flow is established. Only the injection of air (9000 s and 11600 s) and the related pressure increase lead to a chimney start.

The results are of good reproducibility (Fig. 7). The largest deviation occurred in the 0.35 bar tests, with a time difference of 200 s for a total start-up time of around 6000 s until the start of the chimney flow.

During the quasi steady state phases (Fig. 5 phase 4.), PIV measurements are 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. 8). Reduced inlet velocities lead to a lower recombination rate and therefore less hydrogen consumption.

3. Modelling and simulation

Two codes are used for the modelling of PAR operation. SPARK, developed by IRSN, uses a full chemistry model and an implicit newton reactive flow solver [6]. It is able to model the surface reactions in detail. REKO-DIREKT, a FZJ development, has a mass transfer approach for the reaction kinetics [7]. This approach is very fast and allows the coupling of the code with ANSYS CFX for a 3D simulation. Both codes have already been validated with experiments under NPP accident conditions.

For the conditions inside the ST, models are enhanced and validated against experiments with low pressure, superposed flow conditions and oxygen starvation. Modelling results under low pressure show a good agreement with the experimental tests (Fig. 8).

A first orienting simulation of the ST with ANSYS CFX coupled with REKO-DIREKT was performed. The scenario is based on a GASFLOW calculation by Redlinger et al. [8]. For the simulation, one PAR (Type: AREVA FR360) is inserted in a section of the suppression tank (1/6) with a homogenous mixture of nitrogen (17 vol.%) and hydrogen (83 vol.%) The simulation starts in the fourth phase of the accident with the ingress of air.

The reference simulation without recombiner shows that the air content inside the ST rises and both deflagration and detonation limit are passed. In the simulation with PAR, the PAR starts to work as soon as air reaches the PAR inlet and it keeps the oxygen fraction

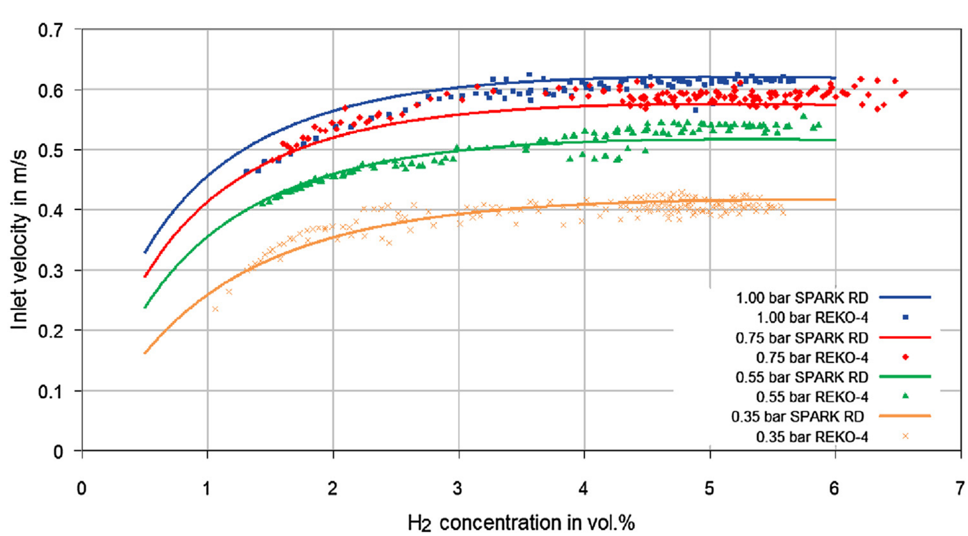


Fig. 8. Modelling of inlet velocity with SPARK.

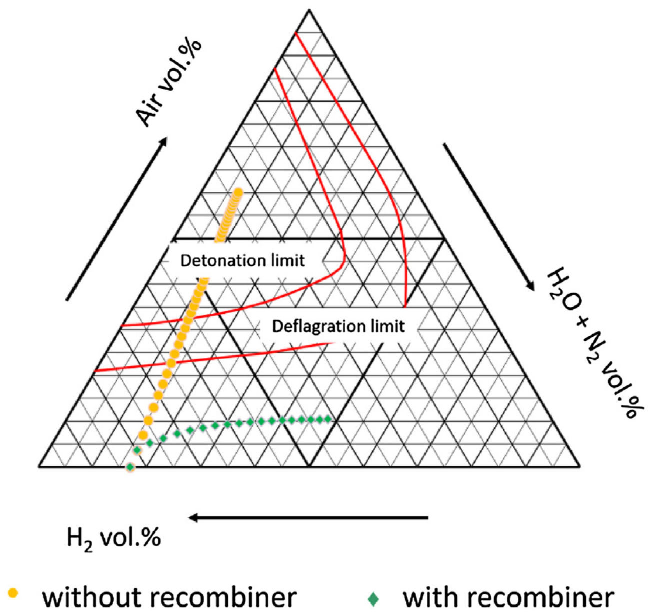


Fig. 9. Course of accident with and without recombiner.

below 2.5 vol.% average concentration. The ternary diagram shows that the explosion risk is significantly reduced by PAR operation (Fig. 9).

4. Conclusions

A combined LOCA and LOVA may pose a significant risk for the integrity of water-cooled fusion facilities. In the frame of the present study, a test series has been performed to investigate the behavior of PARs under low pressure conditions.

A total of eleven experiments were performed in the REKO-4 facility under similar boundary conditions. All tests were repeated at least once to confirm the results. In all experiments a local start-up of the reaction at the upper edge of the catalyst was observed. However, the establishment of the chimney flow required significantly more time for pressures below 0.75 bar (a). For a pressure of 0.2 bar (a) a start could only be achieved by increasing the pressure.

Furthermore, the numerical models SPARK and REKO-DIREKT were validated against the low pressure results and a first orienting simulation was performed. The simulation shows that the PAR can significantly reduce the risk of an explosion inside the ST. However, further enhancement of the models is required in order to confirm these first results. Therefore, further experiments are needed under superposed flow conditions and oxygen starvation.

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