CFD Analysis of Passive Autocatalytic Recombiner and its Interaction with Containment Atmosphere

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Abstract

In water cooled nuclear power reactors, significant quantities of hydrogen could be produced due to metal water reaction, following a postulated Loss-Of-Coolant-Accident (LOCA) along with non availability of Emergency Core Cooling System (ECCS). Passive Autocatalytic Recombiners (PAR) are implemented in the containment of water cooled power reactors to mitigate the risk of hydrogen combustion. For the assessment of the PAR performance in terms of maximum temperature of catalyst surface and outlet hydrogen concentration, an in-house 3D Computational Fluid Dynamics (CFD) model has been developed. In addition, CFD analysis of interaction of a representative nuclear power plant containment atmosphere with PAR was simulated, using the commercial CFD code for PAR Interaction Studies (PARIS benchmarks) exercise.

Keywords: hydrogen, containment, nuclear power plant, catalytic recombiner, CFD.

Introduction

Within the nuclear industry, PARs are installed in advanced water cooled power reactor containments, as combustible gas control systems during severe accident conditions. During a severe accident in a nuclear power plant, the high temperature zirconium fuel cladding can react with high-temperature steam, to produce hydrogen. Hydrogen thus generated has the potential to cause uncontrolled combustion in the containment building, which represents a threat to the integrity of the confinement, due to pressure and temperature levels. Numerous techniques have been developed, for mitigating the potential for such accidents. Pre-inerting, post-accident inerting, electrical recombiner, catalytic recombiner, igniters, mixing by use of fans are several methods, to mitigate the hydrogen hazards in nuclear containments. Passive catalytic recombination of H₂ with O₂ in air, appears to be the most promising one [1]. Autocatalytic recombiners are passive, since they are self-starting and self-feeding; they have no moving parts and require no external energization. The gas mixture flows through the recombiner by natural convection, pushed by the gas heated as a result of the reaction. These natural convective flow currents, promote mixing of combustible gases in the containment. To provide optimal and reliable conditions and to understand the internal processes inside the recombiner, modeling of the device in detail is required. For the analysis of the processes inside a passive autocatalytic recombiner, such as reaction kinetics or heat and mass transfer, a 3D in-house CFD code has been developed. The code calculates the catalyst temperature and the concentration regression along the catalyst plates.
The code has been validated against REKO experiment [2] and has been used to predict maximum catalyst surface temperature and recombiner outlet hydrogen concentration.

Apart from this, a PAR model is developed based on the manufacturer’s correlation to integrate with commercial CFD codes, used for hydrogen distribution modeling. The model has been used to simulate PAR Interaction Studies (PARIS-1) benchmark problem. A 2D geometrical model of the simulation domain was used. The containment was represented by an adiabatic rectangular box with two passive autocatalytic recombiners located at intermediate elevations near opposite walls. In this approach, PAR volume has been modeled as fluid region and separate energy equation was solved, for heat transfer to solid plate from reaction and from solid plates to fluid media, through user coding.

**CFD Analysis of PAR**

The REKO test facility consists of a vertical flow channel with a rectangular cross section 46 mm wide (W) and 146 mm deep. The simplified geometry for the computation is shown in Fig. 1. The channel is 504 mm high (L1 + L2 + L3) with about 180 mm of channel length above the sheets (L1). For the current experiments, four sheets made of stainless steel and coated with wash coat/platinum catalyst material were arranged in parallel, inside the flow channel. The plates used were 1.5 mm thick and 143 mm high (L2). In the experimental setup, they were arranged in parallel with a separation of 8.5 mm. Experiments have been performed for different flow velocities (0.25, 0.50, and 0.80 m/s) at different inlet temperatures (298, 343 and 383 K). Inlet hydrogen concentrations were varied between 0.5 and 4% v/v. REKO-3 experimental data was used to validate our inhouse code [3]. Figs. 2 and 3 show the steady state average hydrogen concentration and catalyst surface temperature along the catalytic sheet, obtained from present computation along with experimental results. As the

![Fig. 1: Simplified geometry for CFD computation (All Dimensions are in mm)](image1)

![Fig. 2: Steady state average hydrogen concentration in the recombiner section for REKO facility, comparison of CFD results with experimental results for inlet hydrogen mole fraction 2% & 4% and temperature 343 K)](image2)
mixture enters the recombiner section, the reaction occurs at the leading edge of the catalyst sheet. The reaction rate is highest at the leading edge of the plate. This is manifested by sharp decrease in hydrogen concentration and maximum catalyst surface temperature near the leading edge of the plate. As flow takes place over catalytic plate, boundary layer is formed over the plate surface and hydrogen diffuses from the bulk of the mixture towards plates for recombination. With the flow along the catalyst sheet, concentration gradient decreases, thus reaction rate also decreases along the sheet. Both reaction kinetics and diffusional mass transport phenomenon control the recombination. Figs. 4 and 5 show the temperature and hydrogen concentration, for air hydrogen mixture of 2% v/v hydrogen concentration entering at 383 K for REKO test facility.

**CFD Analysis of PAR Interaction with Containment Atmosphere**

As part of this study, a PAR of the AREVA FR90/1-150 design was considered in a 2D rectangular domain. Height of PAR (h) was 1 m and width (w) was 0.2 m. PAR entry and exit section widths are also equal to 0.2 m. Each PAR has 15 autocatalytic plates with dimensions of 0.15 m x 0.15 m x 0.0001 m (height x depth x width), and an inter-space of 0.01 m. There are two PARs located in the containment (Fig. 6). No heat or mass transfer (steam condensation) occurs on the walls. The starting point for the calculation was a homogeneous mixture at 3.36 bar, 393 K, oxygen mass fraction 0.1203, hydrogen mass fraction 0.0018 and steam mass fraction 0.4817. The 2D transient Navier-Stokes equation along with the energy and species transport was solved, using commercial CFD.
software CFD-ACE+ [4]. The pressure loss across the catalyst plates was modelled as a sink term in momentum equation through user coding. The hydrogen conversion was modelled by means of the empirical AREVA correlation [5]. The heat generated due to recombination and taken by solid plates was further transferred to fluid in the recombiner section, by natural convection. Hydrogen conversion rate was used, to obtain the solid plate temperature based on energy balance and then the heat convected by fluid mixture through the recombiner section was computed and was used as source term, for energy equation solved for recombiner section [6].

Initially, the hydrogen concentration was high, the conversion rate was directly proportional to hydrogen concentration thus hydrogen removal takes place sharply. Fig. 7 shows the amount of total hydrogen in the representative containment, as a function of time. As the hydrogen is consumed, heat is generated and a flow field is developed and hydrogen moves from the bottom of the recombiner towards the top outlet. Fig. 8 shows the variations of the average temperature in the containment vessel. Fig. 9 shows the hydrogen mass fraction contour inside the representative containment at 20 s. The recombiner reduces the hydrogen concentration in the upper region significantly in nearly 900 s. After that, only diffusional control recombination takes place and concentration reduces very slowly.

**Conclusion**

A 3D CFD analysis of PAR has been carried out, for the literature quoted experimental geometries. The present in-house CFD model can be used, for a plate type recombiner of any chosen dimensions for predicting its behaviour. Apart from this, homogeneous transient model of
hydrogen recombiner, to simulate the PAR in accidental condition inside containment atmosphere has been developed. Specific PARs with prescribed manufacturer’s correlations for hydrogen conversion can be simulated for its performance evaluation, with the methodology presented in this paper. The present approach can be used for optimizing PAR location inside the reactor containment and assessing PAR efficiency in different scenarios.

Fig. 9: Hydrogen Mass Fraction at 20 sec

References