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Numerical Simulation on Passive Autocatalytic Recombiner in SPARC Facility

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1. Introduction

Nuclear power plants rely on various equipment and systems to ensure safe and efficient operation. The SPARC (Spray, Aerosol, Recombiner, and Combustion) is a test facility to simulate the hydrogen behavior within a nuclear reactor containment under a severe accident environment [1]. The facility is capable of conducting experiments on hydrogen release, mixing, and removal through passive auto-catalytic recombiners (PARs) and spraying systems [2]. PAR reduces the concentration of hydrogen, thereby lowering the risks of deflagration or detonation. In the present study, we performed numerical simulations of PAR system where the reaction happens between the air and hydrogen on the catalytic plates and analyzed the effects of its shape on the performance of the hydrogen concentration reduction. Additionally, we investigated the physical phenomena that occur in the SPARC test facility under different experimental conditions.

2. Numerical model

In the present study, the physical phenomena occurring in the SPARC facility are described by a set of governing equations. These equations include the linear momentum equation for fluid flow and the energy conservation equation for temperature. Additionally, the reaction equation is solved on the catalytic plate of PAR, and the transport equations for various species are solved. The following are the governing equations that were solved in this study:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho UU) = -\nabla p + \nabla\left[\left(\mu\left(\nabla U + \nabla U^T\right)\right) - \frac{2}{3}\nabla.UI\right] \tag{2}$$

Energy Equation:

$$\frac{\partial \rho h}{\partial t} + \nabla.(\rho Uh) + \frac{\partial \rho k}{\partial t} + \nabla.(\rho Uk) - \frac{\partial p}{\partial t} = -\nabla.q + \nabla.(\tau U) + \rho r + \rho g U \tag{3}$$

Species transport Equation

$$\frac{\partial \rho Y_i}{\partial t} + \nabla.(\rho U Y_i) = \nabla u_{eff} \nabla Y_i + RR \tag{4}$$

Reaction equation:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + (Q) \tag{5}$$

where the value of 1.2×10^8 J/kg represents the amount of heat released due to the reaction, with Q being the corresponding symbol. The reaction rate is determined using the Arrhenius equation,

$$Rate = 14 * \exp\left(-\frac{14.9*10^6}{R_u T}\right) * [H_2] \left[\frac{kmol}{m^2 s}\right] \tag{6}$$

In order to model the spray, we utilize the Discrete Phase Model (DPM). This model allows us to calculate the trajectories of the particles within the spray by solving the governing equations. To track the speed and location of these particles, it is necessary to determine their values at each time step, as shown in the general form equation below:

$$m_P \frac{du_P}{dt} = \vec{F}_{drag} + \vec{F}_{gravitation} + \vec{F}_{other} \tag{7}$$

3. Results and Discussion

3.1. Effects of PAR on convection flow

Prior to simulating the SPARC facility with PAR, we conducted a validation of our numerical model for PAR by comparing it with other experimental results, and analyzed the effects of chimney height on the convection flow. Figure 1 illustrates the 3D design and the results of the mesh generation of PAR. To analyze the impact of chimney height, we compared three different heights of PAR: 250mm, 500mm, and 750mm, measured from the top position of the catalytic plate.

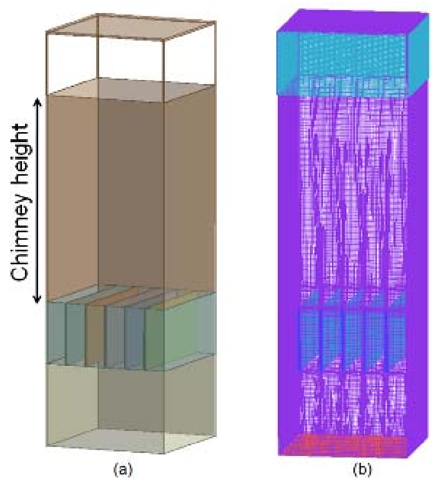

Fig. 1. (a) 3D design of PAR, (b) mesh

As shown in Figure 2, an increase in the velocity of the convection flow is observed with an increase in the chimney height of PAR. The highest velocity among the three cases was observed when the chimney height was 750mm. This can be attributed to the fact that, for the same heat input and boundary conditions, an increase in the volume of the chimney interior leads to a greater difference in total heat energy between the interior and exterior of PAR. This difference in energy results in an increase in flow, as depicted in Figure 3.

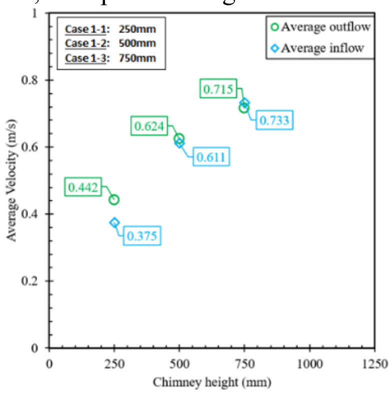

Fig. 2. Inlet/outlet velocity for different chimney heights.

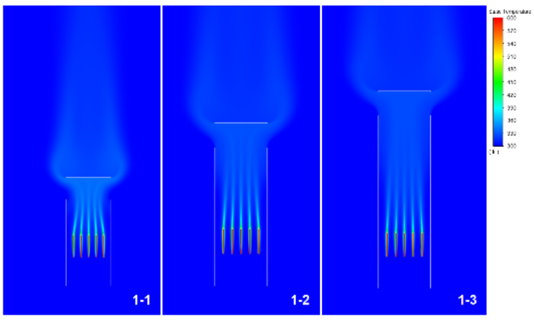

Fig. 3. Temperature fields of 1-1, 1-2, 1-3

3.2. Simulation of SPARC facility

In Figure 4, the 3D design of the SPARC facility is illustrated along with the generated mesh inside it, including a magnified image of the mesh near the PAR system. To reduce computational cost and ensure reliable results, a structured mesh with the cut-cell method was utilized. The SPARC facility comprises several systems, such as those for spray, hydrogen injection/removal (via PAR), and vapor injection.

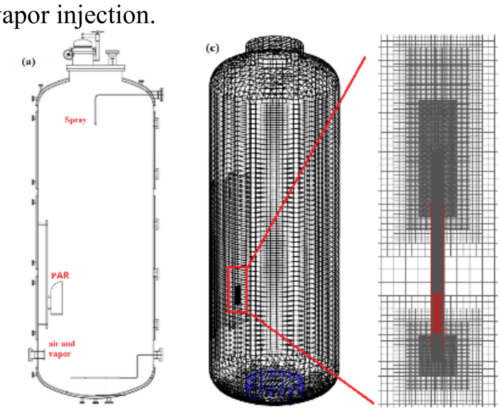

Fig. 4. (a) SPARC design, (b) computational domain

In Figure 5, contours of hydrogen concentration and temperature near the PAR system are depicted at the moments when the reaction initiates. The reduction in hydrogen concentration is observed due to the occurrence of the reaction on the catalytic plates, which generates heat and convection flow. We also investigated the behavior of hydrogen concentration over time under varying operating conditions.

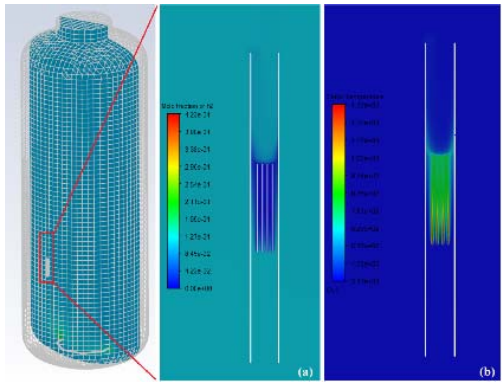

Fig. 5. Simulation results of the SPARC facility

3. Conclusions

In this study, we examined the impact of PAR on reducing hydrogen concentration. The proper operation of the PAR system is highly dependent on the strength of the convection flow. Thus, we numerically analyzed the effects of varying chimney height on convection flow, and our results demonstrated that flow velocity increases with increasing height. Additionally, we simulated the flow and hydrogen behavior inside the SPARC facility, incorporating the PAR and spray system. Our findings indicate that the PAR system effectively reduces hydrogen concentration. This study aimed to establish numerical capabilities for analyzing the physical phenomena that occur in the SPARC facility. Using these capabilities, we plan to investigate the behavior of hydrogen under various operating conditions in future work.

5. Acknowledgment

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