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Innovative hydrogen recombiner concept for severe accident management in nuclear power plants

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HIGHLIGHTS

- A concept PAR operating at high hydrogen concentration (~16% V/V) is presented.
- It consists of catalyst coated reaction channels with internal gas mixture flow.
- CFD studies performed with surface reactions and pool boiling heat transfer.
- Results show that the device works passively and safely at high H_2 concentration.
- Such a PAR can be installed at places of high H_2 concentration within containment.

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ABSTRACT

Excursion of catalyst surface temperature is an important safety concern in deployment of a passive catalytic recombiner device in the nuclear reactor containment. In order to minimize the temperature on the catalyst surface, heat transfer from the surface has to be enhanced. In the present paper, a conceptual design of an innovative PAR is presented. This recombiner uses pool boiling of water to enhance heat transfer from the catalyst surface and limit its temperature. Numerical studies are presented to demonstrate the efficacy of this design. An in-house numerical code called HDS that couples CFD techniques with models for reaction kinetics and water pool boiling heat transfer is used in the analysis. It is shown that unlike conventional recombiner designs, the present design limits the surface temperature even at very high hydrogen mole fractions. The recombiner ensures passive and safe operation for hydrogen mole fraction as high as 16% and for the duration in which high hydrogen concentration is expected. The recombiner can be installed in areas such as the fuelling machine vault and pump room, where high hydrogen concentration is expected.

1. Introduction

The current nuclear reactors are designed to withstand a wide spectrum of postulated initiating events and safety analyses are carried out to ensure that the protection and mitigation systems prevent any postulated initiating event from translating into a severe accident. Nevertheless, considering the events at the Fukushima Daiichi nuclear power plants in Japan, severe accident conditions are being analyzed and provisions are being made in the nuclear power plant design to manage these accidents.

During the progress of a severe accident in a thermal nuclear reactor (BWR, PWR and PHWR), large quantity of hydrogen will be generated due to oxidation of zircalloy and other core materials, radiolysis, corium concrete interaction and a few other mechanisms. Every type of nuclear power plant has its own sequence of progression of severe accident and the resultant rate and quantity of hydrogen generation and release into the containment. A guide for analysis of severe accidents in Pressurized Heavy Water Reactors (PHWRs) is given by IAEA (2008).

Lumped parameter codes like MAAP, MELCORE, ASTEC, CONTACT-SEVAX, etc., have been used to assess the progress of a severe accident and the quantity of hydrogen generated during the entire sequence of events in the accident progression (IAEA, 2013). It is reported that hundreds of kilograms of hydrogen is generated during the in-vessel phase of an accident and over a thousand kilogram is generated during the ex-vessel phase of the accident. The hydrogen generated is released into the break compartment where the concentration can reach very high value for

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Nomenclature

A	pre-exponential factor of Arrhenius equation for rate of reactions [m^2/kmol s]
C_p	heat capacity [J/kg K]
[C]	molar concentration of gaseous species C near the catalyst plate [kmol/m^3]
D	diffusion coefficient [m^2/s]
E_a	activation energy [J/kmol]
F	shape factor for radiation calculations
g	acceleration due to gravity [m/s^2]
H	heat of reaction [J/kmol]
h	heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/(mK)]
M	molecular weight [kg/kmol]
p	pressure [N/m^2]
q''	heat flux [W/m^2]
R_u	universal gas constant (8314.3 J/kmol K)
R''	overall reaction rate [kmol/m^2 s]
r	radial coordinate [m]
T	temperature [K]
t	time [s]
u_r, u_z	radial and vertical components of velocity vector [m/s]
V	volume [m^3]
X	mole fraction of a species [dimensionless]
Y	mass fraction of a species [dimensionless]
z	axial coordinate [m]

Greek symbols

γ	coefficient in the balanced reaction equation
θ	fraction of the total active catalyst site covered by adhered species
μ	dynamic viscosity, [Ns/m^2]
ρ	density [kg/m^3]
σ	Stephan Boltzmann constant

Suffix

cond	conduction
conv	convection
rad	radiation
H	hydrogen radical
H2O	adsorbed water molecule
i	ith species
mix	mixture of species
STP	standard temperature and pressure
BWR	Boiling Water Reactor
PWR	Pressurized Water Reactor
PHWR	Pressurized Heavy Water Reactor

a short duration. The assessment of hydrogen generation and the transients of hydrogen concentration in various parts of the containment are among the important steps in management of a severe accident. The peak concentration of hydrogen in Fueling Machine Vault (break compartment of the containment in PHWR) can be about 15% but this lasts for a short duration (NPCIL, 2015). Similar high concentration is expected in the break compartments of PWR and BWR containments.

The hydrogen mitigation strategy deployed in the nuclear power plants should not only manage the total quantity of hydrogen released into the containment but should also address the rate of concentration buildup within rooms of the containment and the consequence of the same. The spontaneous reaction of hydrogen with oxygen over catalyst (platinum or palladium) coated surfaces is an important method for removal of hydrogen accumulated in confined spaces within the containment.

A passive auto-catalytic recombiner (PAR) is a catalytic device that stands by during normal operation, starts spontaneous reactions when gas mixture containing hydrogen reaches the catalyst surface and passively removes hydrogen from its vicinity by converting to water. A conventional PAR is a box like enclosure that is open from bottom and top and has an array of catalyst coated plates. Gas mixture flows on both sides of the catalyst coated plates and hydrogen recombination reactions take place as schematically shown in Fig. 1. Gaseous mixture coming in contact with the plates undergoes spontaneous reaction generating heat and sets up buoyancy driven flows.

If gas mixture of high hydrogen concentration reaches the catalyst plates, then it leads to high reaction rate and high surface temperature. This, coupled with high hydrogen mole fraction, can lead to gas combustion that can propagate out of the PAR and lead to large scale deflagration in the containment which is an important safety concern in deployment of such a device in the nuclear reactor containment. It has been found that the catalyst plate temperature reaches the auto-ignition temperature ($\sim$809 K) at hydrogen concentration of 7–8% and the PAR can initiate deflagration within the containment compartment at this concentration. In the release duration, the concentration of hydrogen in few containment compartments is very high. Hence, deployment of a PAR in areas of hydrogen release and high concentration is laden with combustion hazard.

The arrangement of catalyst plates in a vertical array with reactions on both sides leads to adiabatic heat transfer boundary condition on the boundaries of narrow vertical channels. The low rate of heat transfer from the catalyst plates is the main reason for excursion of the catalyst plate temperature. If the heat transfer from reaction zone is enhanced, then the catalyst plate temperature can be limited, PAR induced deflagration can be avoided, and safety in the recombiner device can be enhanced. In a previous publication (Agrawal et al., 2015), the effect of change in heat transfer mechanism around the catalyst surface on the reaction parameters and the surface and gas temperature and concentration profiles were presented.

In the present paper, a conceptual design of an innovative PAR is presented. This PAR uses boiling water heat transfer around the catalyst coated surface to limit the surface temperature while the reactions take place and hydrogen is removed from the gas mixture. The numerical studies presented in the paper are meant to support the concept of the PAR. The numerical studies are carried out using an in-house CFD code called the Hydrogen Distribution Simulator (HDS). This code has previously been used for study of hydrogen distribution in Cartesian enclosures (Agrawal et al., 2011; Agrawal and Das, 2013). The models used in the analysis and the results obtained are presented in the subsequent sections. Details of the code and its validation for various flow, heat transfer and mass transfer problems can be found elsewhere (Agrawal, 2013).

2. Conceptual design of the PAR

The innovative PAR is an assembly of reaction channels in which hydrogen rich gas mixture flows within the reaction channels and the cooling water is present outside. It consists of two catalyst coated regions: a lower reaction region that is submerged in water and an upper reaction region that is in air. In between these

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