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Effect of hydrogen combustion in the primary pump compartment

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Abstract Hydrogen combustion in a nuclear power plant may threaten the integrity of some important systems and components. In this paper, the effect of hydrogen combustion in the primary pump compartment is analyzed by different initial hydrogen concentration and igniter locations using Computational Fluid Dynamics method. The results show that the combustion is confined to a limited area without pump damage at about 6.6% hydrogen volume fraction. Once igniting the hydrogen, the combustion affects the whole compartment at the 12% hydrogen volume fraction. The stress caused by the great temperature gradient or high temperature may damage the primary pump. Igniters at the lower location accelerate the combustion process and cause a threat to the pump integrity.

Key words Primary pump compartment, Hydrogen combustion, Computational fluid dynamics

1 Introduction

New designed Pressurized Water Reactor (PWR) should be contributed to the prediction and mitigation of hydrogen risk during severe accidents. Due to the reaction of zircaloy with water or steam, a large amount of hydrogen will be generated, migrated, and accumulated in the compartments of containment. The active or passive ignition in the containment can cause the hydrogen in the proper concentration area to combust or explode, thus damaging some important components, such as primary cooling pumps and steam generators, and losing their function[1,2].

The post TMI accident analysis showed that ~45% fuel cladding was oxidized, to produce hundreds kilos of hydrogen. Calculated by integrated code, the average molecule fraction of hydrogen in the containment compartments is more than 10% during a large break loss of coolant accident (LB-LOCA)[3], this has the risk of hydrogen combustion, and damages local compartments or the containment integrity, even the radioactive materials release into the environment. Therefore, hydrogen mitigation should be measured to control its risk in the process of severe accident, which requires designing hydrogen removal system. Also, the regulatory body and IAEA technical document[4] require considering the risk of combustible gas on local containment compartments.

The passive autocatalytic recombiners (PARs), a hydrogen mitigation measure, use catalytic coatings to turn the hydrogen and oxygen gases into water vapor, self-starting and self-feeding, even under cold and wet conditions without any power supply. For example, the PARs in EPR are used to measure hydrogen control. The ignition of the flammable gas mixture is also deliberate[5–7], 64 igniters in AP1000 nuclear power plant for combustible gas control are recommended during severe accidents. The hydrogen concentration was reduced by igniting the hydrogen in some compartments, but the negative affect on the compartments can be induced by the combustion of hydrogen. Therefore, it is necessary to analyze the hydrogen combustion in the compartment under typical accidents.

In this paper, Computational Fluid Dynamics (CFD) method is used to simulate the process of hydrogen combustion in the primary pump

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compartment. Assuming that the pipe connecting to the primary pump is ruptured and the damage to the primary pump is analyzed.

2 Combustion Model and Verification

2.1 Combustion Model and Governing Equation

The essential condition of hydrogen combustion[8] is the molecule fraction of 30%–60% vapor and the molecule fraction of 4%–12% hydrogen. Above the molecule fraction of 60% vapor, the hydrogen becomes inert, and apart from the continuity, momentum and energy equations, the finite-rate/eddy dissipation reaction model is activated at the available prerequisite hydrogen combustion. The reaction rate (R_i) of H_2 with O_2 is determined by Eqs.(1), (2), (4), and (5).

$$-\frac{\mathrm{d}C_{\mathrm{H}}}{\mathrm{d}t} = -2\frac{\mathrm{d}C_{\mathrm{O}}}{\mathrm{d}t} = \frac{\mathrm{d}C_{\mathrm{HO}}}{\mathrm{d}t} = R_i \quad (1)$$

where, C_{H}, C_{O}, C_{w} are the molecule fraction of H_2, O_2 and water vapor, respectively.

$$R_i = KC^2_{\mathrm{H}}C_{\mathrm{O}} \quad (2)$$

The Arrhenius equations are

$$K = A_{\mathrm{r}}\exp(-E_r/\mathrm{RT}) \quad (3)$$

where, K is the reaction rate coefficient, A_{r} is the frequency factor, E_r is the activation energy (J/mol).

The Magnussen and Hjertager's eddy dissipation equation[8] can be expressed as

$$R_i = \upsilon_{\mathrm{H}}M_{\mathrm{H}}A\rho_{\mathrm{H}}\varepsilon\kappa^{-1}\min(Y_R/V_RM_R) \quad (4)$$

$$R_i = \upsilon_{\mathrm{H}}M_{\mathrm{H}}AB\rho_{\mathrm{H}}\varepsilon\kappa^{-1}Y_{\mathrm{w}}\,\upsilon^{-1}_{\mathrm{w}}\,M^{-1}_{\mathrm{w}} \quad (5)$$

where, v_{H} is stoichiometric coefficient of H_2, M_{H} is its molecule weight, A and B are empirical constant, ρ_{H} is its density, ε is the turbulent dissipation energy, k is the turbulent kinetic, Y_{w} is the mass fraction of water vapor, M_{w} is the molecule weight of water, Y_R is the mass fraction of reactant, M_R is the molecule weight of reactant, and v_R is the stoichiometric coefficient of the reactant.

2.2 Verification of Hydrogen Combustion Model

The effect on known concentrations of hydrogen, air, and steam was evaluated by Lawrence Livermore National Laboratory using the igniters. As shown in Fig.1[9], the igniter test facility includes a pressure vessel, gas and air supplies, a steam generator, and the control/instrumentation system, the combustion was in the compressed air storage tank with the Φ50.8 cm diameter, the 60-in-long, and 3/16-in-thick walls. The working pressure is 200 psi; and the free volume is 10.6 ft^3.

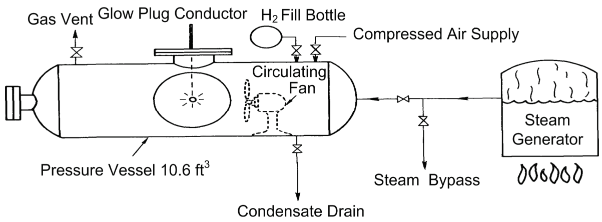

Fig.1 Hydrogen combustion experiment.

Two tests are selected to verify the combustion model, and the initial conditions are listed in Table 1, and measured temperatures are 744 K and 810 K which are average value in the recorded period. Because the hydrogen combustion rate is very high, the temperature surrounding the igniter location grows rapidly, and then decreases, the maximum temperature is 866 K and 880 K at 0.44 s and 0.425 s (Fig.2). There are 16.4% and 8.4% errors for the two cases of the simulated and test results, indicating that the model can be used to simulate the hydrogen combustion.

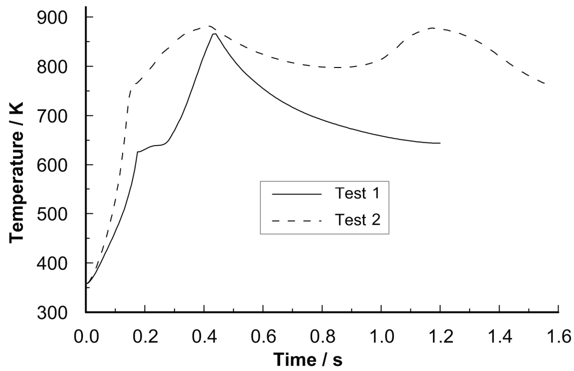

Fig.2 Simulation temperature for test cases.

Table 1 Combustion test and calculation of uniform gas distribution.

Test	H%	Vapor %	T / K
1	10	10	335
2	12	30	357

2.3 Primary Pump Compartment Model and Initial Combustion Conditions

The seal primary pump is consisted of lower impeller and upper motor, and installed in its compartment. The compartment of 15.5-m height is of the semi-fan bottom of 28 m^2, and the 3D grid of 178 462 modeling, as shown in Fig.3.

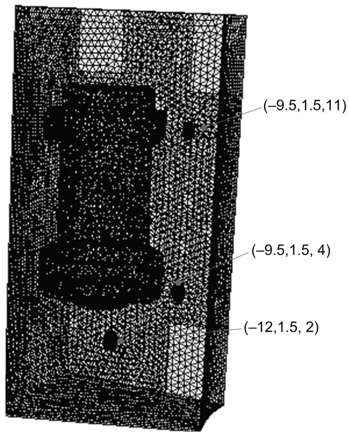

Fig.3 The compartment model.

Assuming there is LB-LOCA in the primary pump compartment, the relevant hydrogen scenario is calculated by an integrated code. As shown in Fig.4, the mass flow rates of H_2 and vapor at the break under LB-LOCA from 300 s to 450 s are referred as simulation input conditions. The H_2 at the time of 360 s and 450 s are 6.5% and 12%, respectively, these two hydrogen concentrations belong to the acceleration limit region and flammability limit region according to NEA document[9], and the combustion under these two scenarios may induce different consequences. Moreover, the hydrogen concentration changes with time and the spark occurs accidentally under the severe accidents, e.g., on hot surfaces, electric motors or other electrical equipment. Considering accidental ignition location, the height in the compartment, the distance to the RCP, and the pipe break location, and the three locations of (–9.5, 1.5, 11), (–9.5, 1.5, 4) and (–12, 1.5, 2) are selected to evaluate combustion effects. The initial pressure and temperature in the compartment is 315 Pa and 405.8 K (Fig.3).

3 Results and Discussion

3.1 Combustion Analysis at Different Hydrogen Concentration

Two cases with different initial hydrogen volume fraction and the igniter mounted at same position are calculated as follows. (1) Case **a**: the average hydrogen volume fraction is 6.6%, the igniter is mounted at the location (–9.5, 1.5, 11). (2) Case **b**: the average hydrogen volume fraction is 12%, the igniter is mounted at the location (–9.5, 1.5, 11).

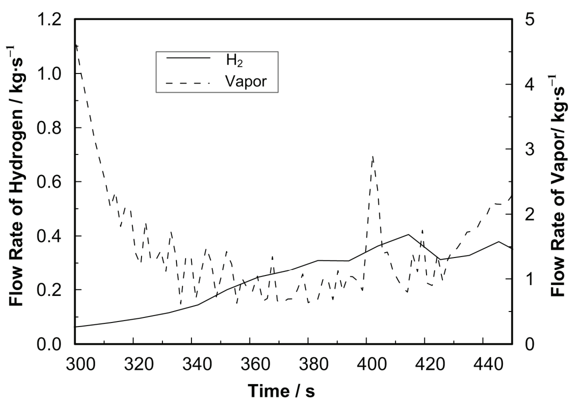

Fig.4 Mass flow rate at the break.

The calculated results show when the igniter produces a spark in the case of the low hydrogen volume fraction, the combustion is not drastic due to the ignition location at the upper part of the compartment, the flame is confined to an area around the igniter, and the combustion shifts to the top of the compartment, then the hydrogen in the lower part of the compartment still remains un-ignited. The volume fraction of hydrogen in the compartment drops from 6.6% to 5.8% within 6.1 s (Fig.5), the maximum temperature in the upper part of the compartment is about 1 000 K, which is far from the temperature of pump. The maximum temperature on the pump just rises to 420 K and the average temperature on the pump remains about 405 K (Fig.6), which have no influence on the pump in case **a**. Therefore, it is strongly recommended that the igniter should be used in this situation to mitigate the hydrogen risk because hydrogen is burned off by slow deflagration.

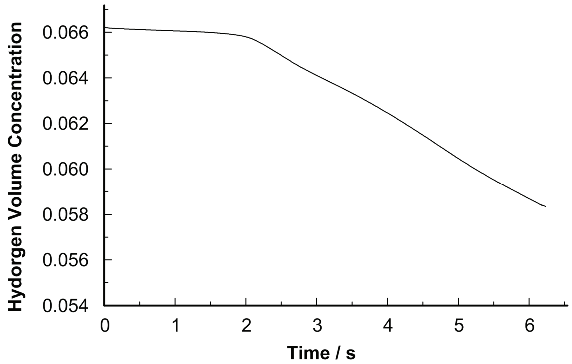

Fig.5 Hydrogen volume concentration in case **a**.

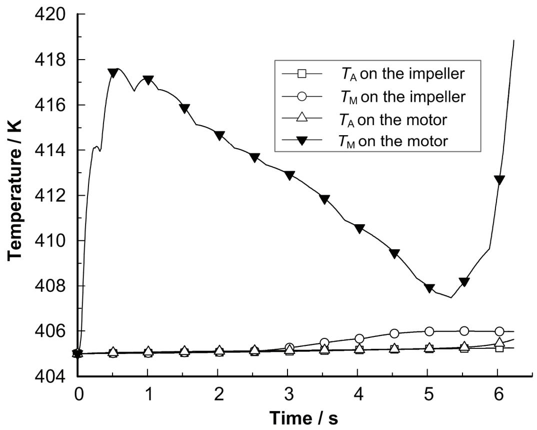

Fig.6 Temperature on primary pump in case **a**.

In the case of high hydrogen volume fraction, the hydrogen concentration at the top of the compartment is higher in case **b** than in case **a**, the calculated results show that the combustion is very drastic, the flame can spread to the whole compartment at 2.45 s, the volume fraction of hydrogen in the compartment drops from 12% to 2% within 2.45 s (Fig.7). The maximum temperature in the compartment is about 1 700 K, and higher in case **a**, this maybe have a big influence on the pump or destroy instruments. The maximum temperature (T_M) on the motor induced by hydrogen ignition has exceeded 1600 K from the beginning of ignition to the end of ignition, and the average temperature (T_A) on the motor just remains about 550 K at the first stage of ignition and exceeds 1 500 K at the end of ignition (Fig.8), this may cause the pump damage. The whole combustion in case **b** just lasts about 2.5 s, and faster than in case **a**. Although hydrogen can be eliminated from 12% to 2%, it is not advised to reduce the hydrogen in this situation because of its negative effects on the pump or destroy to instruments.

3.2 Combustion Analysis at Different Igniter Locations

Since hydrogen moves through the break into the compartments, this means that ignitable concentration could be reached firstly at the lower compartments, the locations of igniters may have the influence on the igniter efficiency. The case with 12% hydrogen concentration is selected to investigate the effect of different igniter locations. As case **c,** the igniter is installed at the location (–9.5, 1.5, 4); and as case **d,** installed at the location (–12, 1.5, 2).

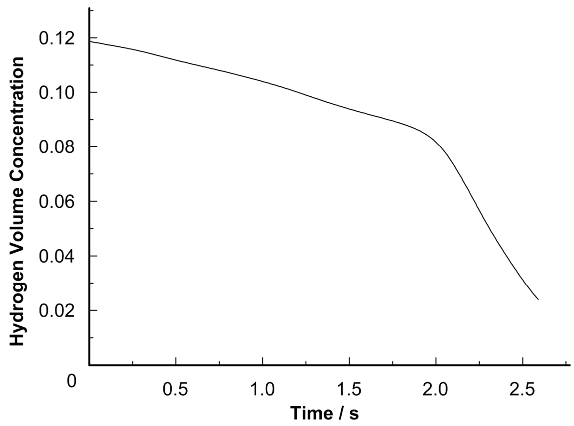

Fig.7 Hydrogen volume concentration in case **b**.

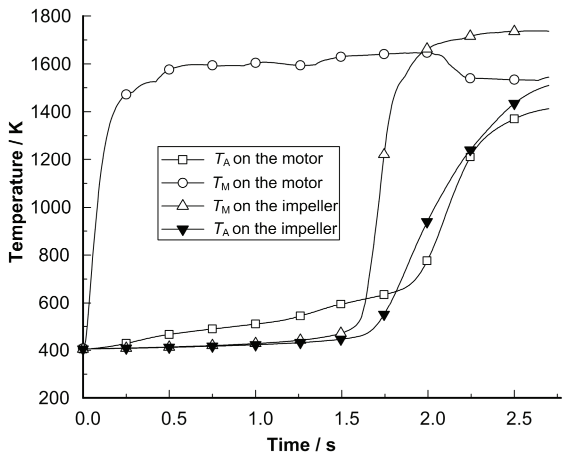

Fig.8 Temperature on primary pump in case **b**.

The temperature distributions in two cases express the same combustion propagation. When the reaction of H_2 with O_2 occurs firstly at the location of the igniter, the mixture with high temperature flows to the upper part of the compartment and ignite the hydrogen in the path. When the mixture reaches the top of the compartment, the ignition based on convection gradually comes to cease because the hydrogen in the area has been combusted, thus leading to a high temperature gradient in the compartment. As a result, the hydrogen reaches the ignition point in the lower part of the compartment, ignites rapidly, and the combustion finally shifts from convection to thermal diffusion.

On the surface of low part of pump at the beginning of the combustion, the maximum temperature reaches 1 800 K in case **c**, and the combustion lasts 2.4 s (Fig.9); and 1 900 K in case **d** due to igniter location close to the pump(Fig.10), while the average temperature of the low part of pump is just around 550 K. The high temperature gradient may cause considerably stress on the pump, but the hottest part on the surface may be melt due to the temperature reaching the melting point of the material. The calculated results in the two cases show that the igniter in the lower position will accelerate the combustion process, and causes more threat to the pump. Therefore, it is recommended that the igniters used as hydrogen control measures should be installed at the higher position in a compartment, this is better for hydrogen ignited at the low concentration.

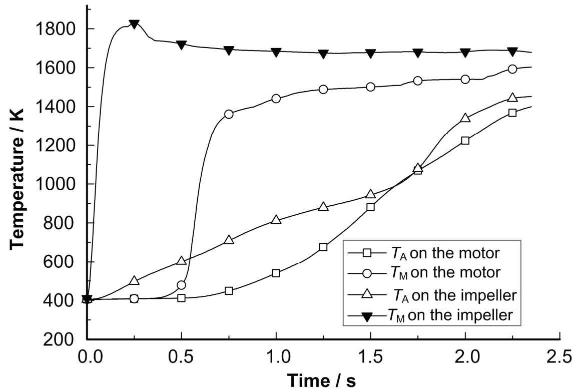

Fig.9 Temperature of primary pump in case **c**.

4 Conclusions

Hydrogen combustion for different volume fractions and different ignition positions in the compartment of pump is investigated by using CFD method. The thermal loads on the pump induced by hydrogen combustion are analyzed. The results show that different initial hydrogen concentration has a different influence on combustion consequence. If the igniter position is at the upper part of the compartment, the influence induced by combustion on the pump is very low at the case of the low hydrogen concentration. When the average hydrogen volume fraction reaches 12%, the combustion will propagate to the whole compartment, and the pump will be threatened by thermal stress or high temperature. The ignition at the lower position will accelerate the combustion process, shorten the period of combustion, and give higher temperature on the pump. Therefore, it is recommended that the igniter as hydrogen control measures should be installed in the upper part of the compartment and not too close to the pump. Furthermore, the igniter should be sparked at the early stage of the accident when the hydrogen concentration is not very high.

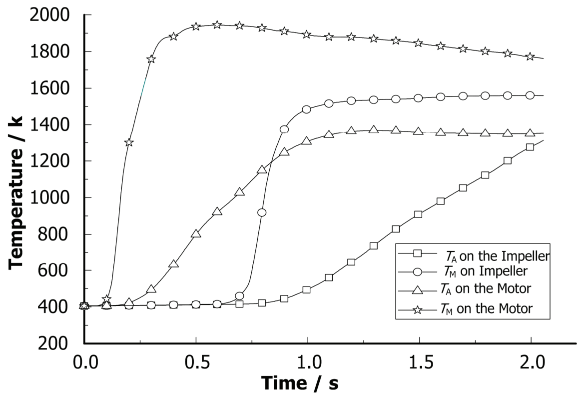

Fig.10 Temperature of primary pump in case **d.**

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