The Safety Implication of Hydrogen Production and Explosion for KFDP

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1. Introduction

According to national fusion road map, Korea is going to establish engineering foundation such as associated design techniques, analysis techniques, and fabrication techniques by 2020. The plan to build a demonstration plant in 2030 is being promoted. Even though the blanket type of Korea Fusion DEMO Plant (KFDP) is not specified clearly yet, H_2O seems a competitive coolant for the demonstration plant to confirm technical feasibility. In case in-vessel Loss Of Coolant Accident (LOCA) is handled by using water cooling method, hot dust of Be, W, and C consisted of Plasma Facing Component (PFC) could react with steam and produce hydrogen [1]. The hydrogen produced by above reaction could explode by reaction with oxygen. In such a scenario the structural integrity would be a prime concern. In case of the hydrogen produced at a vessel wall, it is also expected that steam and air ingress into the vessel can disturb the formation of flammable mixture. From these motivations, we preliminarily reviewed the effects resulting from hydrogen explosion induced by the PFC materials, for instance, hot dust of Be, W, and C react with steam. In this study, the explosion induced by a tritium plant is excluded because tritium system design is not yet specified.

2. Methods and Results

In case of water cooling method, the well known characters of H_2O and abundant operating experience as coolant for the fission power plants are strength point. However, when a LOCA occurs at the coolant system adapting water-cooled method, it should be a concern that leaked coolant passing through the vessel could react with hot dust of Be, C, and W then hydrogen is produced. These reactions are significant above 500 ℃. In the vessel, this high temperature is found mainly in the divertor surface. The condition of high temperature for producing significant reaction is found to be satisfied at divertor. Consequently, the hydrogen production reaction mainly occurs at the divertor surface, where a large amount of dust is available as the accumulation for this reaction. Reaction equations of each material are as follows [2]:

$$Be + H_2O \rightarrow BeO + H_2 \quad (1)$$
$$C + H_2O \rightarrow H_2 + CO \quad (2)$$
$$W + 3H_2O \rightarrow H_2 + WO_3 \quad (3)$$

International Thermonuclear Experimental Reactor (ITER) collaboration sets the guidelines regarding amount of dust to limit the hydrogen production as presented in Table I [3].

At the Table I, there are expected values not only total mass of dust but also the mass of hot dust which contributes to reaction.

Table I: Inventories of Beryllium, Carbon, Tungsten Dust.

Materials	Total [kg]	Hot [kg]
In-vessel heavily activated dust (W, Cu, steel etc)	100	6
in-vessel Be dust	100	6
in-vessel C dust	200	6

To meet the limit value of 4 kg of the hydrogen production presented in safety analysis report, ITER suggests the reaction rate for Be, W, and C should be controlled as shown in Figure 1 [4].

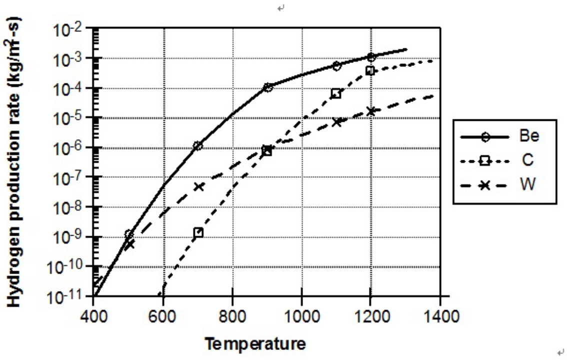

Fig. 1. Hydrogen Production Rates for Beryllium (dense), Carbon, and Tungsten.

The relative reactivity of dust constituents are given in units of amount of hydrogen produced per unit mass of dust component as 0.22kg-H_2/kg-Be, 0.17kg-H_2/kg-C, and 0.033kg-H_2/kg-W. Tungsten seems to be less important because it has relativity lower reactivity value [4].

The reaction of Be-steam is exothermic and 370 kJ/mole of thermal energy is released. Concerning about 13 tons of beryllium in the ITER first wall, 500 GJ of total thermal energy is expected to release by this reaction. This energy is a potential risk factor in the aspect of integrity of vessel. In case of C-steam reaction, the reaction is endothermic and could not progress at rapid rate. But due to high temperature of PFC, this reaction still requires attention for further exploration.

From the reactivity above mentioned values and effective and dominant mass of hot dust in Table I, mass of hydrogen which would result from each material as, Be:1.32 kg-H_2, C:1.02 kg-H_2, and W:0.198 kg-H_2 could be calculated. Total mass of hydrogen produced here is below limit of 4 kg [4].

However, deflagration or detonation can occur, when ingress air reacts with hydrogen resulting from reaction with effective and dominant mass of hot dust on the entire vessel. If there is a mixture of air and hydrogen, flammable mixtures may be produced. When ignition is occurred, a flame front propagates either as a deflagration or a detonation as in the case of most gas explosions. The combustion wave propagates at subsonic velocities to the unburned gas immediately [5].

For most hydrocarbon fuels, deflagration of a stoichiometric fuel-air mixture with an initial pressure of 1.0 bar results in several times pressure in a vessel. For hydrogen-air mixtures the lower flammability limit (LFL) is 4.0 vol% H_2 and the upper flammability limit (UFL) is 75.0 vol% H_2.

A detonation is defined as a supersonic combustion wave which propagates into the unburned and undisturbed gas ahead. In fuel-air mixtures at atmospheric pressure, the detonation velocity is typically 1500 - 2000 m/s and the peak pressure is above 10 bar. For hydrogen-air mixtures, the LFL is about 10 vol% H_2 and the UFL could be 75.0 vol% H_2 [5].

LFL can be found using equation (4).

$$LFL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{LFL_i}} \quad (4)$$

LFL_i: volume of element i in mixture
y_i: mole fraction base on flammable element
n: the number of combustibility elements

Concerning the design pressure of a vacuum vessel (~200 kPa), the deflagration is harmful but detonation is more dangerous due to its high combustion wave which will exert enormous pressure on the vessel wall. If detonation occurs, the integral momentum transferred to the wall I_{wall} is calculated as follow;

$$I_{wall}(p_0, \rho_0, V_v, x_{H_2}) = 2f_{MOM}(x_{H_2})\rho_0 V_v M_{CJ}(x_{H_2})\sqrt{\frac{\gamma p_0}{\rho_0}} \quad (5)$$

p_0: pressure of mixture before burn
x_{H_2}: mole fraction
f_{MOM}: ratio of the momentum of the detonation wave and the theoretical Chapman and Jouguet momentum
M_{CJ}: match number of the detonation front relative to the velocity of sound
V_v: vessel volume
γ: ratio of the heat capacities at constant pressure and volume

Currently the radioactive hazard is estimated in another research project assuming the breach of the vacuum vessel.

3. Conclusions

The steam-dust reaction is significant above 500 ℃. In the vessel, this high temperature is found mainly in divertor surface. Thus, though the development of removing methods of accumulated dust in divertor, the source of hydrogen production can be prevented and mitigated. Then hazard of explosion is originally reduced due to its concentration below LFL of deflagration and detonation.

As an option, produced hydrogen can be maintained below LFL of deflagration and detonation using spark ignition method which is a pre-ignition technique before that hydrogen is accumulated above LFL . The installation feasibility of this technique may be dependent on the design of the vacuum vessel. We need to consider the external structures around the vacuum vessel. For example, the cryostat is maintained in almost vacuum state, which can prevent the mixing of hydrogen and air.

Due to the current state of Korea in the stage of initial design of KFDP, there are no specification of vacuum vessel which will be used in calculation of hydrogen production and LFL. Because there are no specific divertor designs for analysis, we will calculate using European Fusion Power Plant Conceptual Study (PCCS) type A research data. Based on it, we will establish methodology for those calculations, and our study will proceed focusing on this area.

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