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Preliminary analysis of K-DEMO thermal hydraulic system using MELCOR; Parametric study of hydrogen explosion

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1. Introduction

K-DEMO (Korean fusion demonstration reactor) is future reactor for the commercializing the fusion power generation. The Design of K-DEMO is similar to that of ITER but the fusion energy generation is much bigger because ITER is experimental reactor. For this reason, K-DEMO uses more fusion reaction with bigger amount of tritium. Higher fusion power means more neutron generation that can irradiate the structure around fusion plasma. Fusion reactor can produce many kinds of radioactive material in the accident. Because of this hazard, preliminary safety analysis is mandatory before its construction. Although the ITER generate much smaller energy using nuclear fusion, preliminary safety report (RPrS) is issued to prove its safety in the accidents. Concern for safety problem of accident of fusion/fission reactor has been growing after Fukushima accident which is severe accident from unexpected disaster.

To model the primary heat transfer system, in this study, MARS-KS thermal hydraulic analysis is referred. Lee et al. [1] and Kim et al. [2] conducted thermal hydraulic analysis using MARS-KS and multiple module simulation to deal with the phenomena of first wall corrosion for each plasma pulse. They used the results of radiation heat load and neutron wall loading on the in-vessel component first wall [3]. The results shows that the capability of MARS-KS to simulate the K-DEMO blanket module. They focus on the phenomena on the thermal hydraulics in the blanket module.

Hydrogen explosion is recently beginning to take notice from people who knows the Fukushima accident in Japan. Unexpected tsunami with earthquake disables all power supplies and the ability of core cooling inside nuclear power plant. After accident, high temperature of cladding and water generate massive amount of hydrogen. Since enough hydrogen and oxygen concentration is achieved, hydrogen explosion happens which could be seen far from the plant site.

Especially, fusion reactor have concern for the hydrogen explosion. ITER, which is experimental fusion reactor in France, reports its preliminary safety report (RPrS) for the permission of construction. In that report, hydrogen explosion is one of the important accident in the fusion reactor. Fusion reactor use the tritium as fuel in the fusion reaction. Not only tritium, radioactive dust is source term in the severe accident of fusion reactor. Neutron generated by fusion reaction can activate the surrounding structures like divertor, first wall of blanket, coolant and so on. Transient like over power of fusion reaction can cause the sublimation of the surface of those plasma facing structures. This sublimation produces the radioactive dusts. Tungsten, beryllium carbon is main component of those radioactive dust. Those materials have ability of forming hydrogen with water in the high temperature about 500 °C the reaction rate is strongly depends on temperature. In the ITER, 2.4 kilogram of hydrogen can be formed by this reaction. If sufficient oxygen is present in the vacuum vessel, radioactive material leakage can be followed by hydrogen explosion.

In this research, thermal-hydraulic analysis of preliminary design of K-DEMO blanket heat transfer system. Rather than modeling blanket in detail, lumped model of blanket modules is considered. The data of heat flux on first wall, heat generation in blanket material and geometry of blanket referred to the study of MARS-KS study. First and secondary system of heat transfer system is modified by the OPR-1000 system input because design of K-DEMO uses pressurized water cooled loop for the blanket cooling system. After part of the system in the K-DEMO is modeled, preliminary thermal hydraulic analysis of hydrogen explosion accident is performed. Parametric study for the pressurizing pulse and rupture area is discussed for the aerosol release to the environment to suggest the guideline of safety systems of the K-DEMO

2. Modeling K-DEMO system using MELCOR

2.1. Lumped blanket modeling

Preliminary design of K-DEMO shows that 16 equivalent sectors with top and bottom symmetrical geometry. Each sector contains 3 different geometry of outboards and one geometry of inboards. Outboards are divided by 5 different geometry of blankets for each upper and lower part. Inboards are divided by 4 different geometry of blankets for each part. This geometry and each single blanket are given in figure 1. Each blanket consists of 12 coolant channel with first wall, inlet/outlet header, 10 breeder/multipliers and

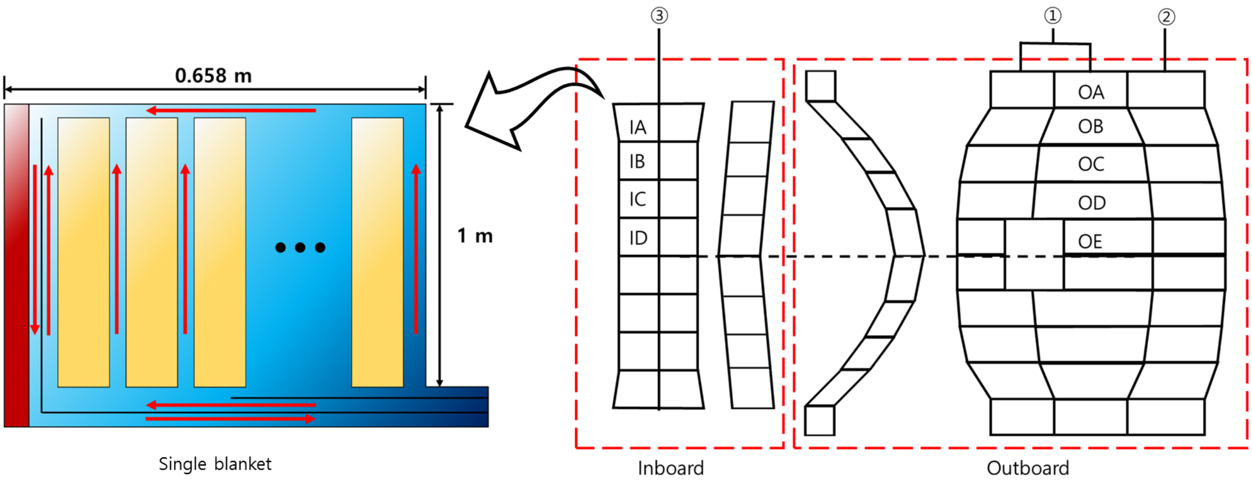


Figure 1. Single sector blanket geometry and single blanket geometry

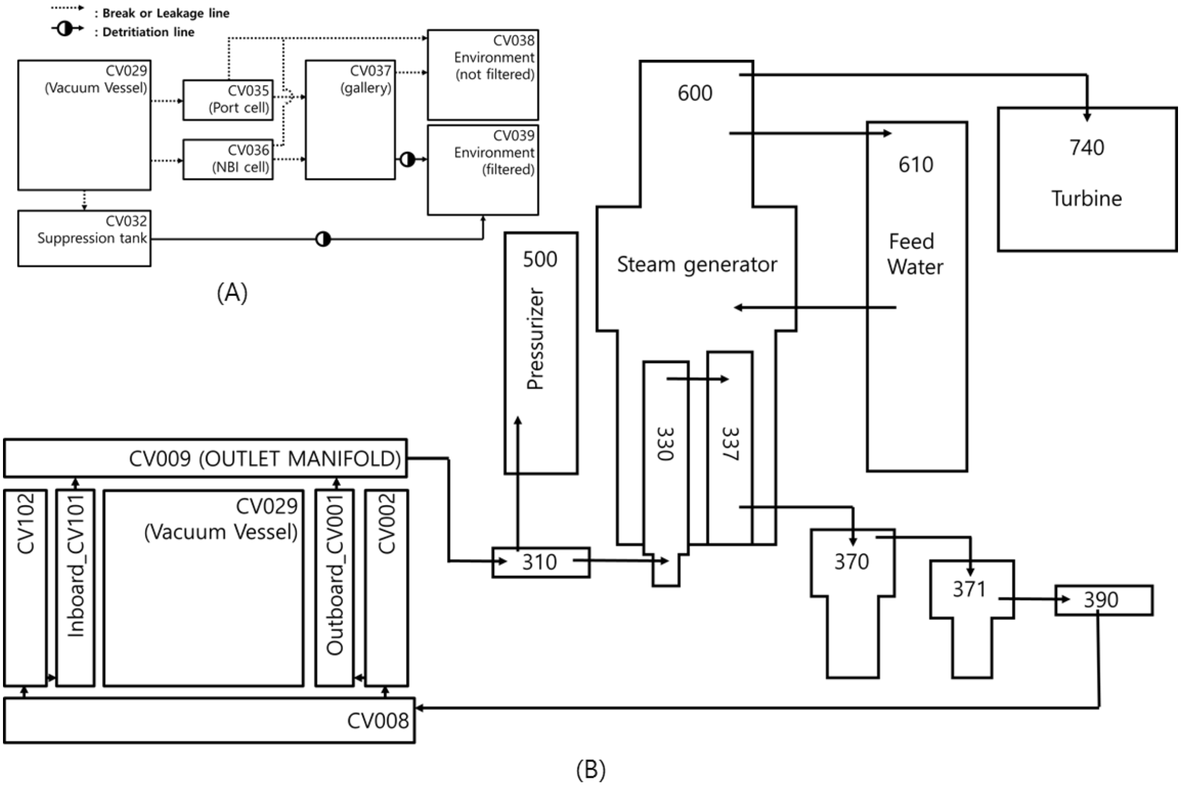


Figure 2. (A) Control volumes for aerosol leakage, (B) Nodalization of primary heat transfer system (one loop)

outlet pipes. Coolant flows into inlet header, divided into 11 channel, accumulate in outlet header and flows into 1st coolant channel. Because the integrity of first wall is important for the safety, largest flow rate is conditioned. This full geometry of 16 sectors of different blankets is integrated into 2 parts of lumped blanket systems; inboard blanket and outboard blanket. Each lumped blanket consists of 2 control volumes; first wall coolant channel and other lumped 11 coolant channel. Heat structure is modeled into 3 parts; first wall composed with tungsten and vanadium, heat structure between first coolant channel and other channels and heat structure with in the other (2nd to 12th channel) 11 channels. In the process of lumping method, the effect of blanket geometry for heat transfer is not applied.

2.2 Primary Heat transfer system modelling

Preliminary design of K-DEMO primary heat transfer system uses pressurized water cooling system. In this study, general OPR-1000 primary heat transfer system is used. 4 loops with 2 steam generator and 1 pressurizer is maintained. Table I shows conditions for the primary heat transfer system. Core part of OPR -

1000 primary input is substituted with lumped K-DEMO blanket system. Heat generation in the blanket and heat flux on the first wall is given in the table II.

2.3 Main K-DEMO system modelling

The main system of K-DEMO is assumed to be similar to that of ITER. Main safety systems like detritiation system, (DS), vacuum vessel suppression system and HVAC isolation system are applied. To analyze the aerosol leakage, main path of aerosol is modelled. Control volume of vacuum vessel, NBI (Neutron Beam Injection) cell, port cell, gallery and environment is assumed that their volume is proportional to the scale ratio between ITER vacuum vessel and K-DEMO vacuum vessel. The nodalization of this primary heat transfer system and control volumes for aerosol leakage is shown in the figure 2. It is assumed that the geometry of the K-DEMO spaces (Vacuum vessel, suppression pool, port cell, NBI cell, gallery) are proportional to the ITER systems. And the design criteria of safety system and main conditions are referred to that of ITER system the summary is shown in Table III.

Table I. K-DEMO primary heat transfer system

Parameters	
Number of loops	4 loops (2 SG, 1 PZR)
Pressure	17 MPa
Mass flow rate	8320 kg/s
Tin	561 K
Tout	597 K
Pin-Pout	110 kPa

Table II. Blanket heat flux and heat generation data for MELCOR input

[MW]	*Outboard*	*Inboard*
First wall surface	183.83	76.40
First wall volume	87.68	39.07
Blanket_1	36.92	16.14
Blanket_2	1188.80	505.42

Table III. K-DEMO assumed geometry and its design criteria

Parameters	
Vacuum vessel volume	598 m^3
Suppression tank volume	835.95 m^3
Suppression tank pool volume	416.5 m^3
NBI cell volume	74 m^3
Port cell volume	810 m^3
Gallery volume	26701.96 m^3
VV rupture pressure	565 kPa
Port cell rupture pressure	160 kPa
NBI cell rupture pressure	200 kPa
Gallery rupture pressure	105 kPa
HVAC isolation	1.833 gHTO/ m^3

3. Parametric study of K-DEMO ; hydrogen explosion accident

In the Fusion reactor, hydrogen is formed by reaction between dust and water in the high temperature. If high temperature of 6 kilograms of tungsten, beryllium and carbon dust is reacted with water, 2.4 kg hydrogen can be generated. This amount is design parameter of ITER. 1 tons of dust and 2.4 kg of hydrogen can be explode with oxygen. Before explosion happens, vacuum vessel rupture between VV and port cell is assumed that is source of oxygen. This rupture area is considered in the parameter study.

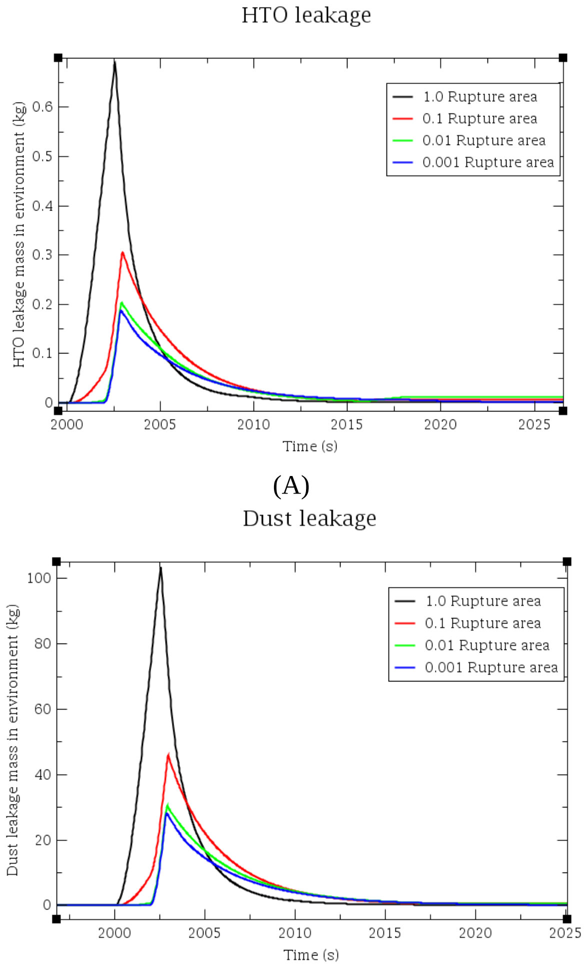
In this study, parametric study of vacuum vessel rupture area and aerosol leakage from vacuum vessel to environment is performed. Total 1 kg (6.69 HTO) tritium and 1 ton dust aerosol is assumed which is guideline of ITER. The pressurizing is important. If vacuum vessel is pressurized, more radioactive material release to outside. Conservatively, It is assumed that heat generation is not stopped after explosion happened. And other trips (pump, heat exchanger and pressurizer) are not considered. Detritiation system and HVAC isolation system and VV suppression system are activated. This is summarized in table IV.

Table IV. Safety systems in the fusion reactor

Safety systems	*Parameters*
HVAC isolation	24 air volume/day 30 seconds delay of isolation Gallery HTO 0.2766 gT/m^3
Suppression bleed line	Vacuum vessel pressure 97 kPa
S-DS	Processing rate 150 m^3/h 300 seconds delay 0.2766 gT/m^3
Pump	Trip

4. Parametric study results and discussion

Table V shows the 4 cases of area of vacuum vessel rupture. The rupture size is important because this can be the path of radioactive material leakage. Figure 3. Shows the result of aerosol leakage for each case. The behavior of HTO aerosol and Dust is almost same. Area gets smaller, smaller aerosol released to environment. The result of 0.01 m^2 rupture area is similar to the 0.0001 m^2 rupture area size. The leakage response of port cell shows in figure 4. Rupture starts 60 s before hydrogen explosion starts (2000 s). Because rupture size is bigger, 1st case shows the fastest response. But the flow rate after hydrogen explosion doesn't seems related to the flow path area.



(A)

(B)

Figure 3. (A) HTO leakage (B) Dust leakage

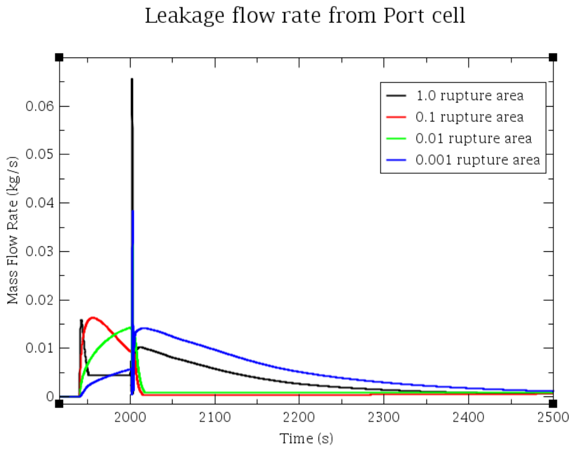


Figure 4. Mass flow rate response after rupture

4. Conclusions

This study shows the relationship between vacuum vessel rupture area and source term leakage after hydrogen explosion. For the conservative study, first wall heating is not terminated because the heating inside the vacuum vessel increase the pressure inside VV. Pressurizer, steam generator and turbine is not damaged. 6.69 kg of tritiated water (HTO) and 1 ton of dust is modeled which is ITER guideline. The entire system of K-DEMO is smaller than that of ITER. For this reason, lots of aerosol is release into environment although the safety system like DS is maintained. This result shows that the safety system of K-DEMO should use much more safety system.

Furthermore, the primary heat transfer system analysis is needed. The amount of aerosol mobilization has relation with coolant interaction. If there is coolant, aerosol can be agglomerating in the water coolant.

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