Phase change of First Wall in Water-Cooled Breeding Blankets of K-DEMO for Vertical Displacement Events

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1. Introduction

As a part of National Fusion Roadmap of Korea [1], preliminary concept for the Korean fusion demonstration reactor (K-DEMO) has been studied by the National Fusion Research Institute (NFRI) [2]. The thermal design, evaluation and validation have been performed in order to establish the conceptual design guidelines of the water-cooled breeding blanket for the K-DEMO reactor [3]. As a part of the NFRI research, Seoul National University (SNU) is conducting transient thermal-hydraulic analysis to confirm the integrity of blanket system for plasma disruption events.

The purpose of this study is to simulate thermal-hydraulic behavior of a single blanket module when plasma disruption occurs. Plasma disruptions, such as vertical displacement events (VDE), with high heat flux can cause melting and vaporization of plasma facing materials and also burnout of coolant channels. In previous works, there was a limitation for melting simulation in MARS-KS so that, in this work, independent first wall module was adopted to first wall as shown in figure 1. In order to simulate melting of first wall in blanket module when VDE occurs, one-dimensional heat conduction equations were solved numerically with modification of the specific heat of the first wall materials using effective heat capacity method. Also, a nuclear reactor thermal-hydraulic analysis code, MARS-KS, was adopted for solving hydrodynamics in coolant channels and heat equations in other components of blanket except first wall. One VDE simulation condition was selected for first wall heat flux values of 600 MW/m^2 (0.1 sec). Melting of first wall materials were simulated and modified boundary conditions including evaporation thickness and reduced heat flux value [4] were applied.

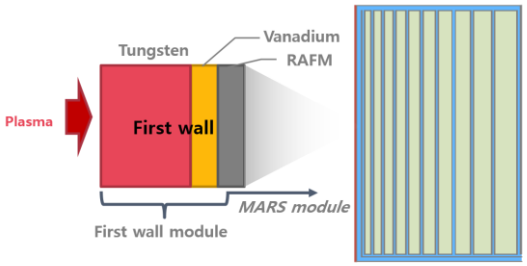

Fig. 1. Modeling range of first wall module and MARS code in a single blanket module

2. Phase Change Modeling and Validation

Plasma facing components like first wall of blanket can be seriously damaged due to high heat flux of VDE. In case of first wall in K-DEMO blanket, tungsten is plasma facing material and its melting and evaporation can occur due to high heat flux of VDE. In this section, one-dimensional heat conduction equations were solved for first wall with effective heat capacity method which can simulate melting phenomena and it was validated with Stefan's problem [5]. Furthermore, dynamic linked library (DLL) version of MARS-KS [6] was adopted for a single blanket module except first wall and coupled with heat conduction equations solving first wall, as shown in figure 2. Also, validation was conducted for normal operation and its results were compared with results of MARS-KS.

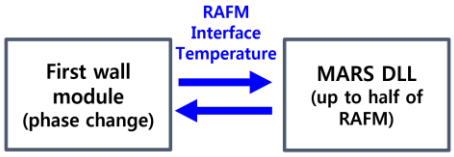

Fig. 2. Concept of coupling between first wall module and MARS DLL

2.1 Effective Heat Capacity Method

In effective heat capacity method shown in figure 3, heat capacity is treated as a function of temperature between melting and solidification temperature range as below.

$$C_p = \begin{cases} C_{p,solid} & T < T_m \\ \dfrac{L}{T_s - T_m} + C_p(T_m) & T_m \le T \le T_s \\ C_{p,liquid} & T > T_s \end{cases} \quad (1)$$

Here, C_p is the heat capacity, T_m and T_s are the melting and solidification temperature each, and L is the latent heat of fusion. During phase change, temperature of the material is treated by almost isothermal until the amount of additional heat stored as specific heat reaches that of latent heat.

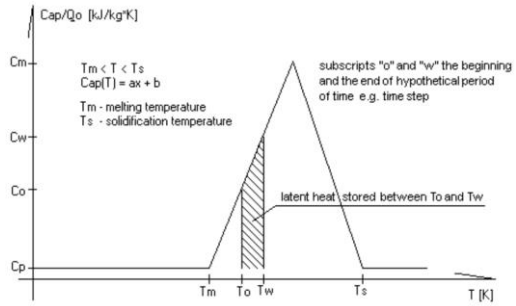

Fig. 3. Graphical representation of effective heat capacity method [7]

Although T_m and T_s have same value physically, temperature range is needed to simulate melting numerically with this method. The temperature range can be modified properly considering time step. In case of model validation in Stefan's problem, range of 1°C was selected and the other case, e.g. VDE, range of 10°C was selected.

2.2 Validation of Melting Model

The melting model of first wall was adopted to one-dimensional heat conduction equation which was solved with finite volume method and fully implicit scheme. Validation of melting model was conducted for analytic solution of one-dimensional Stefan's problem [5, 8] as shown in figure 4. Paraffin wax was selected for phase change material (PCM) and problem description including boundary condition is summarized in table I. Sufficient thickness of PCM was adopted for numerical modeling because analytical solution is stand for semi-infinite geometry. Analytic solution [5] of one-dimensional Stefan's problem is

$$T(x,t) = T_w - (T_m - T_w)\frac{erf(x/2\sqrt{\alpha t})}{erf(\beta)} \quad (2)$$

where

$$\beta e^{\beta^2} erf(\beta) = \frac{C_p(T_w - T_m)}{L\sqrt{\pi}} \quad (3)$$

$$\alpha = \frac{k}{\rho C_p}, \beta = \frac{\delta(t)}{2\sqrt{\alpha t}} \quad (4)$$

Here, α is the thermal diffusivity, T_w and T_m are the wall and melting temperatures of PCM, and $\delta(t)$ is the length of melting front. Comparison results are shown in figure 5. Melting front goes forward as time goes. In fig. 5, solid line depicts analytic solution and dot symbol depicts numerical solution. In result, comparison result showed good agreement with maximum error of 1.34 K (0.43%).

Table I: Problem description

Problem conditions	
Material	Paraffin wax
Initial and boundary conditions	$T = T_w(350K) \quad x = 0, t > 0$ $T = T_m(313K) \quad t = 0$
Assumptions	Material properties are independent of temperature
Calculation conditions	
Simulation time	16 hours
Time step	10 sec
Mesh size	0.5 cm

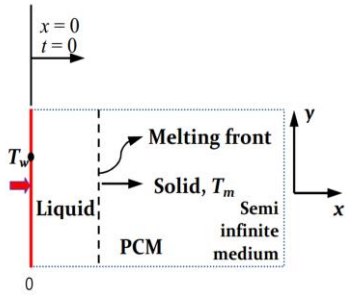

Fig. 4. One-dimensional Stefan's problem for semi-infinite medium [8]

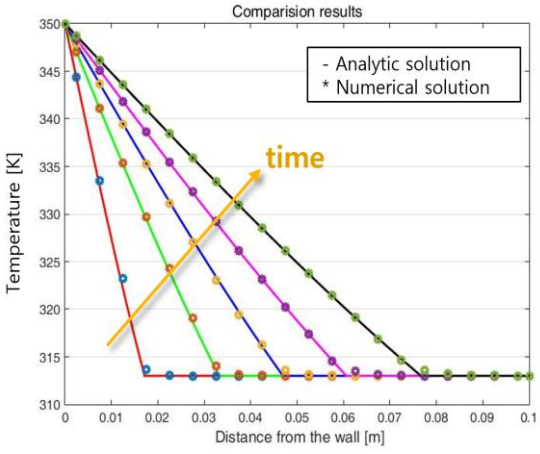

Fig. 5. Comparison results between analytic and numerical solutions

2.3 Code Validation Coupled with MARS

In previous section, melting model validation was conducted regardless of MARS code. But in this section, capability of code coupling between first wall module and MARS DLL was confirmed. As shown in figure 1, first wall up to half of RAFM was modeled with first wall module and the other components like coolant channels and pebble beds were modeled with MARS code. Besides, DLL version of MARS-KS was adopted and coupled with first wall module as shown in figure 2.

Code validation was conducted for steady state and transient case. Normal operation condition which has first wall heat flux value of 0.5 MW/m^2 was selected and heat flux value rapidly raised to 1.0 MW/m^2 to make transient situation. Comparison results were shown in figure 6. In this graph, the black line (MARS only) depicts the case that single blanket module is just modeled with MARS and the red line (MARS+WVR) depicts the case that first wall module is coupled with MARS DLL. The results show good agreement with maximum error of 1.12 °C and 4.4 °C for steady and transient case each. The main reason of error is difference in material property calculation between first wall module and MARS. If material value is constant regardless of temperature, the temperature distribution is exactly same between two codes.

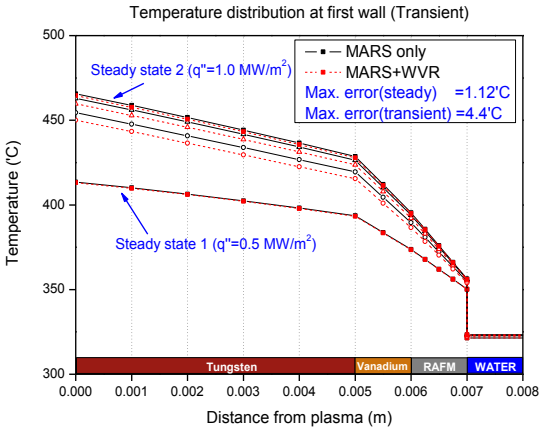

Fig. 6. Comparison results between MARS code and first wall module coupled with MARS DLL

3. Simulation for Vertical Displacement Events

In this section, transient thermal-hydraulic analysis was conducted for vertical displacement events (VDEs). VDE with high heat flux can cause melting and vaporization of first wall in blanket and burnout of coolant channels. In addition, high thermal stresses due to rapid changes of temperature can degrade the integrity of PFCs like first wall of blanket module. For that reason, first wall module validated in previous section was adopted to simulate phase change and MARS-KS code was adopted to predict two-phase flow and critical heat flux (CHF) value in coolant channels. In case of first wall in K-DEMO blanket, tungsten is plasma facing material and its melting and evaporation can occur due to high heat flux of VDE. First wall is composed of 5 mm thick tungsten, 1 mm thick vanadium, and 1 mm thick reduced activation ferritic/martensitic (RAFM) steel. For VDE simulation, single case was selected for first wall heat flux value. In result, melting of first wall was simulated. But, evaporation was adopted by applying modified boundary conditions including evaporation thickness and reduced heat flux values [4] because first wall module has a limitation for simulating evaporation.

3.1 Simulation Conditions of VDE

Simulation conditions of VDE are summarized in table II. Evaporation can occur due to its high heat flux [4]. Evaporation removes considerable heat from plasma so that heat flux boundary condition was modified to reduced value commented in table II as 'final heat flux'. For initial and boundary condition, evaporation thickness was initially removed from thickness of tungsten and final heat flux value was initially applied as boundary condition at tungsten.

Table II: Simulation conditions of VDE [4]

Parameters	values
Duration time [sec]	0.1
Initial heat flux [MW/m^2]	600
Evaporation thickness [μm]	277
Final heat flux [MW/m^2]	319.3

3.2 Simulation Results

Temperature profiles in first wall for VDE are shown in fig 7 ~ 9. At first, temperature of tungsten rapidly raised and even exceeded its melting temperature (Fig. 7). When VDE just ended at 0.1 second, 0.83 mm thick of tungsten melted. But the other materials including vanadium and RAFM didn't exceed their melting temperatures after 500 seconds (Fig. 8). For coolant channel, heat flux value through channel wall exceeded critical heat flux (CHF) value due to subcooled film boiling in coolant channel, and then, temperature of structural material (RAFM) rapidly raised. But it didn't reach its melting temperature as shown in figure 9.

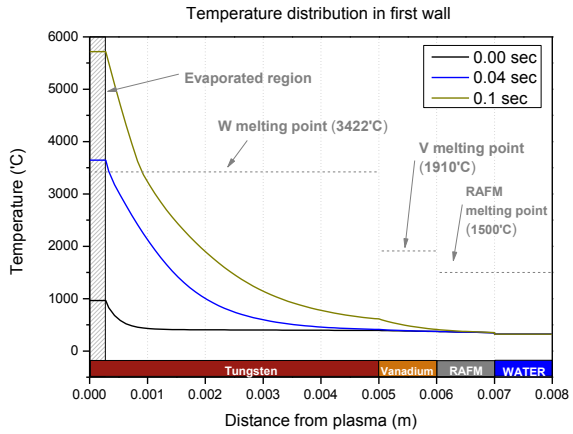

Fig. 7. Temperature distribution in first wall (0.0 ~ 0.1 sec)

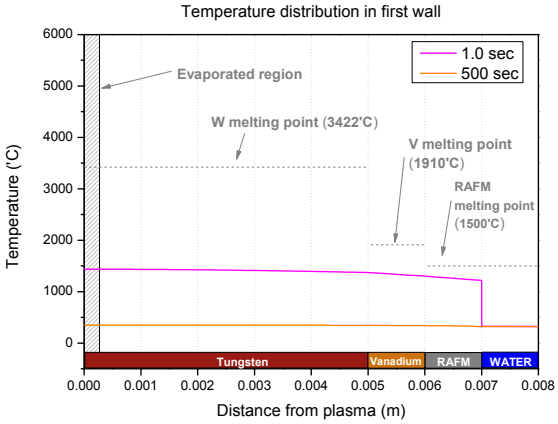

Fig. 8. Temperature distribution in first wall (1.0 ~ 500 sec)

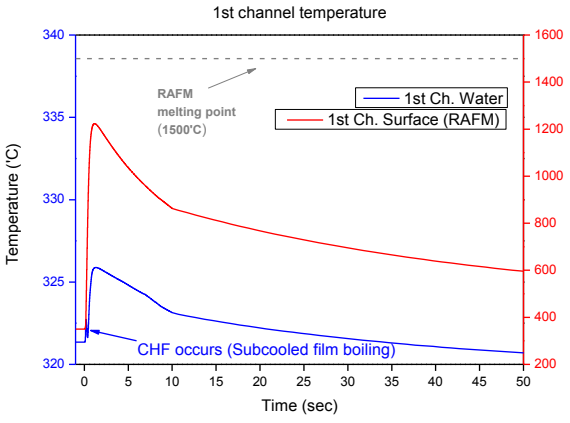

Fig. 9. 1st channel surface and coolant temperature

4. Conclusions

Vertical displacement events (VDE) with high heat flux can cause melting and vaporization of plasma facing materials (PFCs) and also burnout of coolant channels. In order to simulate melting of first wall in blanket module when VDE occurs, one-dimensional heat conduction equations were solved numerically with modification of the specific heat of the first wall materials using effective heat capacity method. Also, a nuclear reactor thermal-hydraulic analysis code, MARS-KS, was adopted for solving hydrodynamics in coolant channels and heat equations in other components of blanket except first wall due to its prediction capability for two-phase flow and critical heat flux (CHF) value in coolant channels. A water-cooled breeding blanket concept of K-DEMO was selected for simulation target. It includes 7 mm thick first wall as plasma facing components which consists of 5 mm thick tungsten, 1 mm thick vanadium, and 1 mm thick reduced activation ferritic/martensitic (RAFM) steel. VDE simulation for first wall heat flux values of 600 MW/m^2 (0.1 sec) was conducted. Simulation result showed that temperatures of tungsten exceeded its melting temperatures so that 0.88 mm thick tungsten was melted but melting of the other materials did not occur. In coolant channel, heat flux through channel wall exceeded CHF value but structural material (RAFM) did not exceed its melting temperature.

Acknowledgement

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