Implementation of the crud layer model into the SPACE code

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1. Introduction

The build-up of corrosion products on fuel cladding surface have made a significant impact on reactor operation. These unidentified deposits are referred to as CRUD (Chalk River Unidentified Deposit or Corrosion Residual Unidentified Deposit). The formation of crud may lead to various undesirable consequences such as crud-induced power shift (CIPS) and crud-induced localized corrosion (CILC) [1]. CIPS and CILC should be addressed on the safety of nuclear reactors due to core peaking factors, shutdown margin, and fuel integrity [2].

In addition to CIPS and CILC, the crud deposition may have an effect on the peak cladding temperature (PCT) during the reflood phase in the LOCA scenario. The addition deposition on the cladding has been known to simply increase the PCT in terms of thermal resistance and capacitance. However, the surface characteristics may decrease the PCT and change the quenching time.

The effect of the crud layer is twofold. One is the additional thermal resistance, and the other is the modification of the wall heat transfer models. In this study, the crud material model is implemented into the SPACE code. The effects of the crud layer on the reflood phenomenon are tested by intentionally adjusting the wall heat transfer models.

2. Crud Material Model

This study implemented the crud layer model [3] developed based on the following assumptions:

- The crud layer consists of a porous solid part and a fluid part. The fluid volume porosity ε is used to quantify the ratio of the fluid volume to the total volume of the crud layer.
- The solid part is made of NiO, $NiFe_2O_4$ and Fe_3O_4 with the volume fractions of 0.15, 0.75 and 0.1, respectively. They are homogeneously mixed.
- For the sake of simplicity, the void fraction and temperature in the fluid part are the same as those in the neighbouring hydro volume.

The effective thermal conductivity of the crud layer k_{crud} is computed as

$$k_{\text{crud}} = \frac{1}{0.5/k_{\max} + 0.5/k_{\min}}, \quad (1)$$

where

$$k_{\max} = (1-\varepsilon)k_s + \varepsilon k_w,$$

$$k_{\min} = \frac{1}{(1-\varepsilon)/k_s + \varepsilon/k_w},$$

$$k_s = 0.15k_{\text{NiO}} + 0.75k_{\text{NiFe}_2\text{O}_4} + 0.1k_{\text{Fe}_3\text{O}_4},$$

$$k_w = \alpha_g k_g + \alpha_l k_l.$$

k_s and k_w are the thermal conductivities of the crud solid and fluid, respectively, inside the crud layer. ε denotes the fluid porosity of the crud layer.

The volumetric specific heat of the crud layer $c_{p,\text{crud}}$ is calculated as

$$\rho_{\text{crud}} c_{p,\text{crud}} = (1-\varepsilon)\rho_s c_{p,s} + \varepsilon \rho_w c_{p,w}, \quad (2)$$

where

$$\rho_s c_{p,s} = 0.15\rho_{\text{NiO}} c_{p,\text{NiO}} + 0.75\rho_{\text{NiFe}_2\text{O}_4} c_{p,\text{NiFe}_2\text{O}_4} + 0.1\rho_{\text{Fe}_3\text{O}_4} c_{p,\text{Fe}_3\text{O}_4},$$

$$\rho_w c_{p,w} = \alpha_g \rho_g c_{p,g} + \alpha_l \rho_l c_{p,l} + \alpha_d \rho_d c_{p,d}.$$

Table 1. Material property references

Materials	k	c_p
NiO	[4]	[7]
$NiFe_2O_4$	[5]	
Fe_3O_4	[6]	
ZrO_2	[8]	[9]

3. SPACE Code Input

The effect of the crud layer is tested for the FLECHT SEASET reflood experiment [16]. The SPACE nodalization is shown in Fig. 1. The experimental conditions are listed in Table 2.

Table 2. FLECHT-SEASET 31504 reflood conditions

Flooding rate (cm/s)	2.40
Upper plenum pressure (MPa)	0.28
Reflood water temperature (°C)	51
Initial rod peak power (kW/m)	2.3

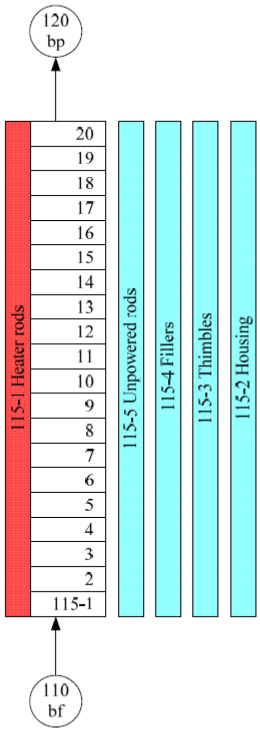

Fig.1 Nodalization for FLECHT-SEASET reflood test

4. Preliminary results

The crud layer surface is not smooth but roughened. Therefore, the quenching temperature, the critical heat flux, and the single-phase vapor flow heat transfer coefficient are expected to increase, compared to the bare surface. A series of simulations were carried out modifying the wall heat transfer models, while the additional crud layer is not considered. Figure 2 shows the effect of the minimum film boiling temperature, which directly affects the quenching phenomenon. It is shown that the increase in the minimum film boiling temperature facilitates the quenching time. The transition boiling heat transfer is obtained by the interpolation between the critical heat flux and the minimum film boiling. Figure 3 shows that the critical flux has little effect on the quenching phenomena. Figure 4 shows the effect of the convective heat transfer for the vapor flow. The peak wall temperature is clearly reduced as the heat transfer coefficient increases.

Next, the effect of the crud properties is tested. The oxide and crud layers are added to the rod heaters as shown in Fig. 5. To exclude the other effects, the wall heat transfer models are not included in the test. It is shown in Fig. 6 that the peak wall temperature remains nearly unchanged, however the quenching time is decreased. This can be attributed to the fact that the minimum film boiling temperature depends on the surface material properties.

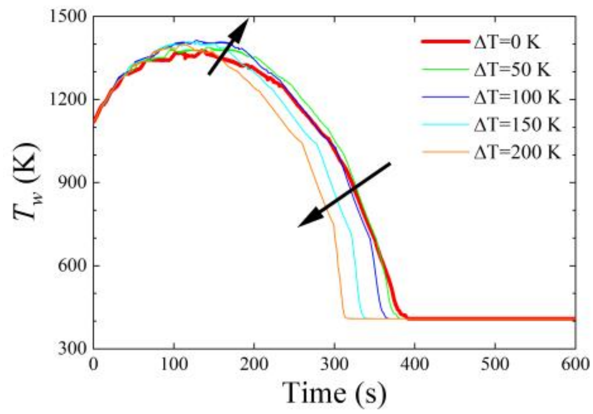

Fig 2. Effect of the minimum film boiling temperature

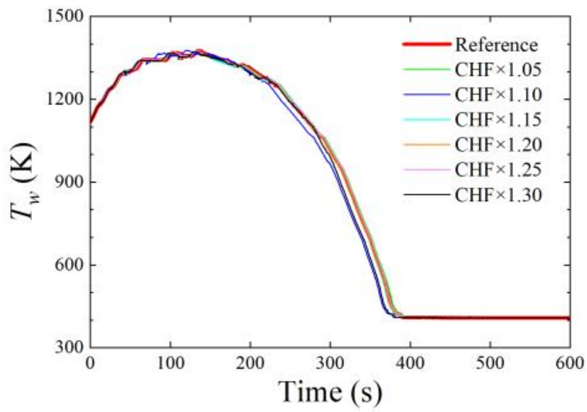

Fig 3. Effect of the critical heat flux

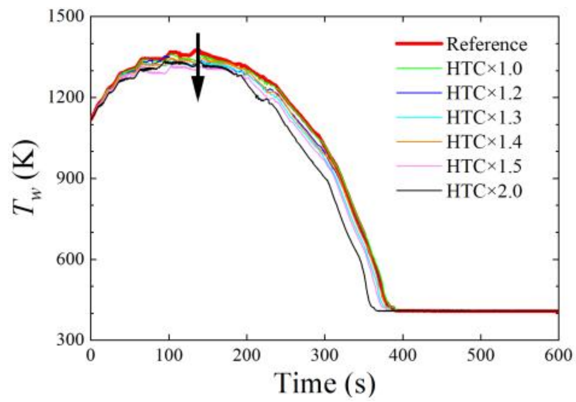

Fig 4. Effect of the convective heat transfer coefficient for single-phase vapor flow.

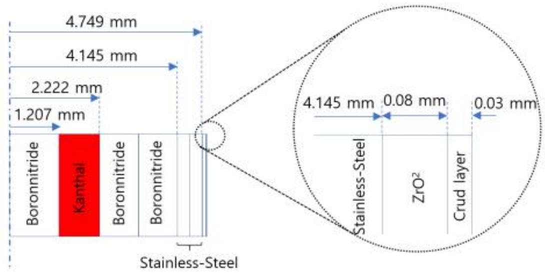

Fig 5. Modeling of the crud and oxide layers

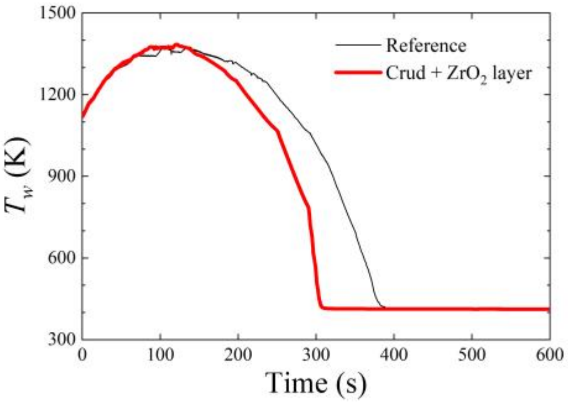

Fig 6. Effect of the crud and oxide layers

4. Summary

A crud layer material model has been successfully implemented into the SPACE code. Various effects of the crud layer were tested. As the minimum film boiling temperature increases, the quenching time decreases. The critical heat flux has little influence on the reflood. The single-phase convective heat transfer has a considerable effect on the peak wall temperature.

In the future, the minimum film boiling temperature model will be developed based on the experimental data. After implementing the developed model into the SPACE code, integral effect tests will be simulated with the crud layer.

Acknowledgement

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