Modeling the CRUD Effects on Heat Transfer in the Subchannels of Pressurized Water Reactor

Hyeon Ji Kim, Ji Yong Kim, In Cheol Bang*
Department of Nuclear Engineering
Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gil, Ulju-gun, Ulsan, 44949, Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

1. Introduction

The fouling product called Chalk River Unidentified Deposit (CRUD) can accumulate on the upper side of nuclear fuel rods during subcooled nucleate boiling. While CRUD can cause additional thermal insulation effects on the rods, its rough surface can also contribute to increasing local heat transfer through turbulent kinetic energy. Several computational fluid dynamics (CFD) studies have been conducted to study the effects of CRUD deposition on heat transfer. Cinosi and Walker performed a single-phase analysis to investigate the effect of CRUD on pressurized water reactor (PWR) subchannels with crudded rods [1]. The CRUD was modeled as roughness, which resulted in a reduction of mass flow rate and coolant velocity, but also locally improved heat transfer. Guzzetta examined the effect of CRUD in a single subchannel, considering factors such as surface roughness, thermal conductivity, and modified subcooled nucleate boiling parameters on the CRUD surface, as well as wick boiling [2]. Under the high heat flux conditions, the heat transfer rate on the crudded surface was superior to the clean surface. However, there is still a lack of research on the separate and combined effects of CRUD with thermal resistance and roughness at the fuel assembly level.

In this paper, the location of CRUD deposition was estimated where the subcooled boiling occurs by two-phase flow CFD analysis, and the CRUD effect on heat transfer in 7x7 subchannels was investigated. CRUD was partially simulated on the walls of subchannels and modeled as a thermal insulation layer with a rough surface. To comprehensively understand the combined and separate effect of CRUD-induced thermal resistance and roughness, ANSYS Fluent was utilized.

2. Numerical Methods

This section outlines the methodology used to model CRUD deposition on nuclear fuel rods within the 7x7 PWR subchannels. The approach for reducing computational costs and the selection of physical models for simulation are also discussed in detail.

2.1 Computational Domain

The total height of the computational domain is 3.81 m long and especially two-phase flow analysis for assuming the location of CRUD demands high computational costs. To reduce computational costs, the plane symmetry method was applied to the computational domain of 7x7 PWR subchannels, as illustrated in Fig. 1. The analysis used the boundary conditions outlined in Table I, which were set for normal operating conditions of PWR. The first layer of mesh was situated at y^+=150 and the realizable k-ε model with standard wall function was employed.

Initially, the two-phase flow analysis was conducted to find the location where subcooled nucleate boiling occurs in the subchannel. Once the location of boiling was identified, CRUD was partially simulated for the red circled rods in Fig. 1 at the height where subcooled boiling occurs. This was followed by a single-phase analysis to assess the CRUD effect on heat transfer.

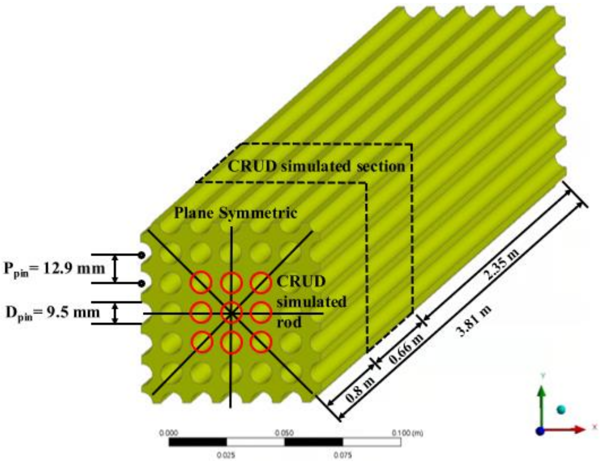

Fig. 1. Domain shortening method applied to the computational domain of PWR subchannels and the location of CRUD simulated.

Table I: Boundary conditions of single-phase analysis in full scope domain

Location	Boundary type	Boundary condition	Value
Inlet	Velocity Inlet	Velocity	4.7 m/s
		Temperature	563.75 K
Outlet	Pressure Outlet	Gauge Pressure	15.5 MPa
Heater	Source term	Volumetric heat source	Axial peaking factor: 1.47

			Radial peaking factor: 1.29

2.2 CRUD Modeling

The CRUD is mainly deposited on the cladding during the subcooled nucleate boiling process [3]. In this research, it was assumed that CRUD is deposited at the height where subcooled boiling occurs. The Eulerian two-phase model was used to identify the location at which boiling occurs. The phase exchange coefficient models were selected, Ishii for the drag force, Moraga for the lift force, Antal-et-al for the wall lubrication, Lopez-de-bertodano for the turbulent dispersion, and Sato for the turbulent interaction. Boiling occurs within the height range of 2.35 m to 3.01 m. The CRUD is partially simulated on the heater wall in that section as shown in Fig. 1.

This study aimed to simulate CRUD using two parameters: thermal resistance and roughness. The properties of CRUD, including its morphology and thermal conductivity, were determined using data from the Westinghouse Advanced Loop Testser experiment [4]. The densified CRUD thickness in the experiment was assumed to represent the thickness with thermal resistance, while the remaining thickness represented the rough surface. Solid domain of insulation layers with a thermal conductivity of 1.18 W/m-K and a thickness of 18 μm were additionally modeled on the cladding surface to show the temperature distribution beneath the crud. The skeleton thermal conductivity of CRUD was used, not the effective thermal conductivity.

The effect of the rough surface was considered through the wall function of turbulence model, with a roughness height of 24 μm set for the analysis. The Realizable k-ε model, with standard wall functions, was utilized in this study. One limitation to note is that the simulated roughness layer does not offer any thermal resistance; instead, it only contributes to the generation of turbulence and flow resistance, combined with the turbulence model.

To investigate the effect of the two CRUD parameters on heat transfer, separate analyses of each CRUD parameter with each selected height were conducted, as well as an overall analysis considering their combined effects.

3. Results

The wall temperatures of the clean rod, two types of rods with CRUD simulation, and the rod with the combined effect simulation were similar up until the coolant reached the region where CRUD was simulated. However, at the CRUD simulated area, the wall temperature varied depending on how the CRUD was simulated. When only roughness was simulated, the temperature of the cladding surface decreased compared to the clean rod, indicating that the local heat transfer in that section increased due to the CRUD. This suggests that the effect of increased turbulent kinetic energy has a greater effect than the decreased velocity of the coolant, as shown in Fig. 3. This result is similar to a previous study done by Cinosi and Walker [1].

In the case of the rod with a thermal resistance simulated, the temperature increased. The thermal insulation effect of the CRUD layer played a role. The wall temperature of the rod with the combined CRUD effect simulation showed a similar temperature distribution to that of the clean rod, indicating that the effect of roughness and thermal resistance were offset in the case of the characteristics of CRUD morphology used in this study. The point to note here is that the CRUD has a porous medium, which may include water or vapor. The thermal conductivity of the CRUD layer, considering the porous medium, is referred to as effective thermal conductivity. However, the thermal conductivity used in this analysis is the thermal conductivity of the skeleton CRUD, which implies that the temperature of the cladding in the CRUD deposition section could actually increase further.

The rapid decrease in temperature after passing the CRUD simulation region was found to be due to the height difference with the CRUD layer, and this was not dealt with significantly. However, as shown in Fig. 3, if the CRUD includes a roughness factor, the flow redistributed to adjacent subchannels is not restored until exits the core. As a result, the rod with simulated CRUD deposition shows a higher temperature distribution than the clean rod until it exits the core.

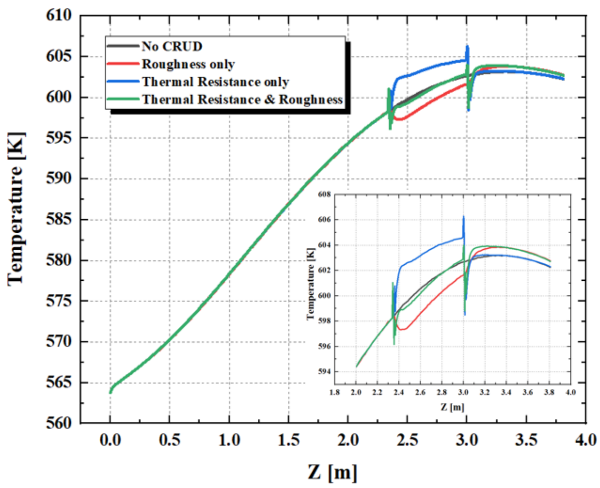

Fig. 2. Wall temperature distribution of clean rod(black), crudded rod with roughness simulated(red), crudded rod with thermal resistance simulated(blue) and both parameters simulated(green).

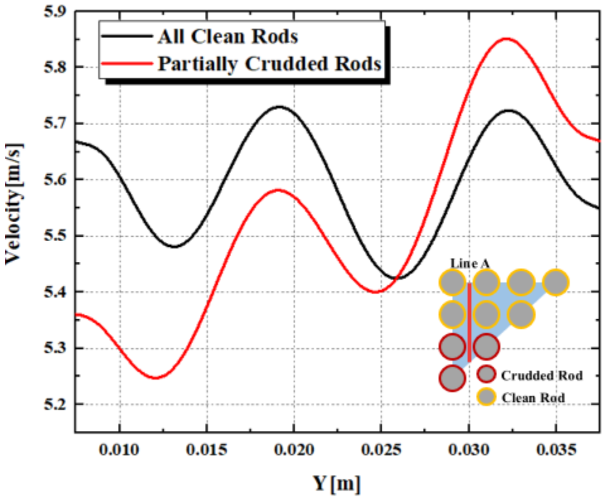

Fig. 3. Velocity distribution of the working fluid at Line A (z=3.81m) in the domain with all clean rods(black) and with partially crudded rods(red).

4. Conclusion

In this study, the effect of CRUD deposition on heat transfer in 7x7 subchannels of PWRs was investigated through computational fluid dynamics simulations. The location where CRUD was deposited was estimated using the Eulerian two-phase model, and the CRUD was partially simulated as a thermal insulation layer with a rough surface. The two parameters used to simulate CRUD were thermal resistance and roughness, and separate analyses of each parameter were conducted, as well as an overall analysis considering their combined effects.

In the case of simulating CRUD as roughness, the results showed that the effect of increased turbulent kinetic energy due to the roughness of CRUD is more dominant than the decreased velocity of the coolant. The thermal insulation effect of the CRUD layer plays a role in increasing the temperature. However, when simulating CRUD as roughness and thermal resistance combined, the effect of roughness and thermal resistance were offset in the case of the CRUD morphology used in this study. But in reality, the temperature increase could be large in that CRUD being a porous sediment contains water or vapor. It has been determined that the presence of CRUD causes a reduction in flow rate, and this reduction is not restored within the corresponding subchannels until the coolant has left the core. As a result, we concluded that the heat transfer degradation caused by the CRUD-induced flow resistance can continue to affect the subchannel in which CRUD formed. The findings presented in this paper are based on assumed factors, such as the morphological characteristics of CRUD and its deposition location. Therefore, it is essential to model heat transfer based on the deposition location and thickness of CRUD in both normal operating and accident scenarios of PWRs.

Overall, this study provides insights into the separate and combined effects of CRUD-induced thermal resistance and roughness. Future studies may consider the effects of CRUD with more CRUD characteristics, and various morphological characteristics.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. 2106022)

REFERENCES

[1] N. Cinosi and S.P. Walker, CFD analysis of localized crud effects on the flow of coolant in nuclear rod bundles, Nuclear Engineering and Design, Vol. 305, p.28-38, 2016.
[2] A.S. Guzzetta, Modeling the Effects of Fuel Rod Crud Formation on Boiling Heat Transfer in Pressurized Water Reactor Using Eulerian Two-Fluid CFD, Master Thesis, The Pennsylvania State University Park, PA, USA 2010.
[3] J. Deshon, PWR Axial Offset Anomaly (AOA) Guidelines, Revision 1, EPRI, Palo Alto, CA, 1008102, 2004
[4] J. Deshon, G. Wang, A. Byers and M. Young, Simulated fuel crud thermal conductivity measurements under pressurized water reactor conditions, EPRI, Palo Alto, CA, 1022896, 2011.