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CRUD Adhesion Test Equipment Set-up Logics under Heat Transfer, Thermohydraulic and Computational Simulation Analysis

Junhyuk Ham [a], Taeho Kim [a], Yunju Lee [a], Ji Hyun Kim [a*]
[a] *Department of Nuclear Engineering, School of Mechanical, Aerospace and Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919*
**Corresponding author: kimjh@unist.ac.kr*

1. Introduction

As commercial nuclear power plant, has been operated for a long term, there are some unwanted deposit on the upper side of cladding surface, which was observed from Callaway pressurized water reactor (PWR) in United States during the 9th cycle.

This kind of problem is caused by combination of heat transfer and corrosion phenomenon. According to coolant flow direction through the fuel assembly, surface temperature of cladding at the upper side is higher than that of lower side. When surface temperature rises over saturation temperature of the coolant, sub-cooled boiling can occur on that point and this can form porous corrosion related unidentified deposit (CRUD) on it.

CRUD can cause several problems during the normal operation period. For example, if boron, inside of coolant, enters into the CRUD, this compound will absorb neutron a lot which causes severe problem related with neutron flux named axial offset anomaly (AOA) or CRUD induced power shift (CIPS)

And also, CRUD may cause a problem concerned with corrosion mechanism. Since the characteristic of CRUD is porous as abovementioned, some corrosive solution can permeate into the pore of CRUD. If it stays for a long time, CRUD induced localized corrosion (CILC) problem occurs.

In this point of view, investigating CRUD should be conducted to solve the problems AOA and CILC. Following this motivation, we were planning to construct CRUD adhesion test equipment for various research related with CRUD. In this paper, the equipment set-up logics will be explained under heat transfer, thermohydraulic and computational simulation analysis.

2. Methods and Results

In this section, the test equipment set-up logistics for CRUD adhesion test will be introduced. The test environmental conditions were set by following several heat transfer and thermohydraulic calculations which can make sub-cooled boiling phenomenon on the specimen surface. And computational simulation such as ANSYS for designing test equipment was also conducted.

2.1 Specimen Surface Temperature

To simulate CRUD adhesion on the specimen surface, generating sub-cooled boiling on it is the most important, which has been known as the main mechanism of CRUD adhesion on the cladding surface.

Sub-cooled boiling phenomenon occurs when heated surface temperature becomes higher than saturation temperature of liquid whose bulk temperature is lower than that. In this situation, some bubbles are generated on the heated surface, and this process continues until phase change of boiling to film boiling.

In this study, the basic water chemical conditions are followed as that of primary circuit environment of commercial nuclear power plant; pressure is 15.5 MPa. Therefore, we should set the temperature of specimen surface over the saturation temperature of coolant in 15.5 MPa environment.

Referring to thermodynamics properties table, 1st order extrapolation was conducted to calculate the saturation temperature of water in 15.5 MPa. The result of this calculation fits with that of real condition in primary circuit water chemistry of PWR, 345 ℃.

To set the exact temperature of specimen surface, sub-cooled boiling conditions in PWR and permissible range of cladding surface temperature should be considered. According to text book of Neil E et al. [1], sub-cooled boiling starts occurring when the cladding surface temperature becomes higher about 0.1 ℃ more than the saturation temperature of coolant, 345 ℃. And IAEA sets regulation of cladding surface temperature as 347 ℃ [2].

Following these considerations, we give engineering margin from the minimum temperature to generate sub-cooled boiling but not to be exceeded the limitation. Therefore, our test condition of surface temperature was set as 346 ℃.

2.2 Heat Flux for Sub-cooled Boiling

By using the surface temperature set from previous section, we can estimate how much heat flux is needed on the specimen surface.

The heat flux for sub-cooled boiling can be calculated by using the empirical equation suggested by Rohsenow et al. in 1952 [3]. According to his research, heat flux to generate sub-cooled boiling can be written as below equation 1.

$$\dot{q}_{nucleate} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{\frac{1}{2}} \left[\frac{C_{pl}(T_{sur} - T_{sat})}{C_{sf} h_{fg} Pr_l^n} \right]^3 \quad (1)$$

$\dot{q} = heat\ flux$
$\mu = dynamic\ viscosity$
$h_{fg} = enthalpy\ of\ vaporization$
$g = acceleration\ of\ gravity$
$\rho = density$
$\sigma = surface\ tension$
$C_{pl} = specific\ heat$
$C_{sf} = experimental\ constant$
$Pr_l = Prandtl\ number$
$n = experimenatl\ constant$

Putting whole variables of our test conditions into the above equation, especially 1 ℃ on T_{sur}-T_{sat}, then we can get the heat flux for sub-cooled boiling in the test environment, $1.10 \cdot 10^4$ W/m^2.

The maximum heat flux for sub-cooled boiling, not to change boiling regime, can be calculated by following the empirical equation of S.S. Kutateladze et al. in 1948 [4]. According to his research, the critical heat flux (CHF) can be written as below equation 2.

$$\dot{q}_{max} = C_{cr} \cdot h_{fg} \cdot \left[\sigma g \rho_v^2 (\rho_l - \rho_v) \right]^{\frac{1}{4}} \quad (2)$$

$$C_{cr} = experimental\ constant$$

Putting whole variables of our test conditions into the above equation again, then we can estimate the CHF. The CHF for our case is $2.54 \cdot 10^6$ W/m^2.

Finally, we can gather these results into a single plot by inverse operation from CHF calculation to nucleate boiling heat flux calculation to get the temperature difference when the heat flux reaches CHF. The result of abovementioned process, is plotted as below Fig. 1.

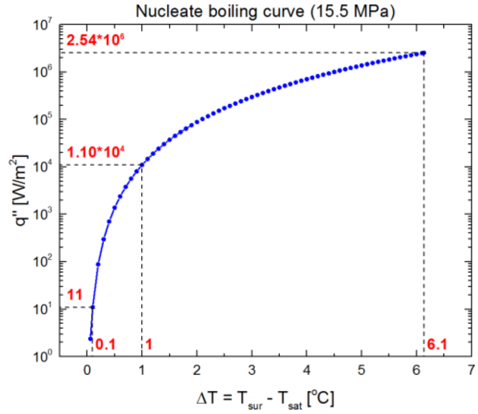


Fig. 1. Nucleate boiling curve for water in 15.5 MPa condition

According to the above graph, it can be said that our setting for specimen surface temperature is safe and proper, since it has an engineering margin from the minimum temperature difference and it is not close to the maximum temperature difference.

2.3 Heater Transfer Coefficient

At last, we must calculate heater power to realize our plan. As inlet and outlet temperature of autoclave was set under considering ratio of the test specimen dimension and the real fuel cladding dimension, the total power needed to heat the coolant can be calculated like below equation 3.

$$\dot{Q} = \dot{m} C_p (T_{out} - T_{in}) \quad (3)$$

This total power is caused by flow boiling which is combined phenomenon of forced convection and pool boiling. In the previous section, we already get the heat flux of nucleate boiling of pool boiling situation. Therefore, finding the heat flux for forced convection is just left.

The heat flux for forced convection can be calculated by Newton's cooling law, equation 4 below. As the equation shows, we need to find heat transfer coefficient only to calculate heat flux for forced convection.

$$\dot{q} = h \cdot (T_s - T_\infty) \quad (4)$$

Heat transfer coefficient can be calculated from Nusselt dimensionless number, below equation 5.

$$Nu = \frac{D_H h}{k} \quad (5)$$

$$D_H = hydraulic\ diameter$$
$$k = thermal\ conductivity$$

There are several ways to find Nusselt number, but the model of Gnielinski et al. in 1976 is known as the most reliable empirical equation, below equation 6 [5]. Thus, in this study, we chose Gnielinski's model to calculate Nusselt number and further to get the heat flux for forced convection on the heated surface.

$$Nu = \frac{\left(\frac{f}{8}\right) \cdot (Re - 1000) \cdot Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{\frac{1}{2}} \cdot \left(Pr^{\frac{2}{3}} - 1\right)} \quad (6)$$

$$f = friction\ factor$$
$$Re = Reynolds\ number$$

2.4 Geometry of Test Equipment

Test equipment was constructed under the several heat transfer and thermohydraulic calculations. But geometry of test equipment cannot be logically proved by that method. So, in this study, we conducted additionally computational simulation, ANSYS, to figure out tendency of flow distribution inside of the test equipment.

In this point of view, the important changeable thing is finishing of the test specimen end. There are three different cases measured by ANSYS. One is ended by union, another is ended by cap, and the other is ended by specially fabricated nut.

The total length of the specimen is 400 mm. So, we checked the velocity contour of cross-section at every 100 mm points. The result of it is below Fig. 2.

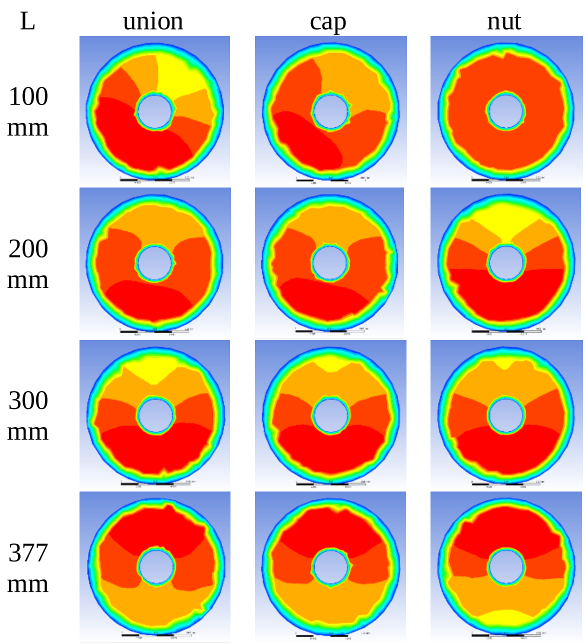
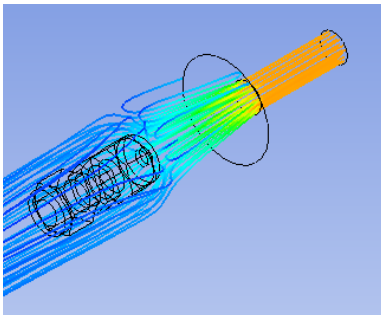


Fig. 2. Velocity contour of cross-section at every 100 mm points of the specimen

According to the contour analysis, there is no big difference among these cases. Although the case of nut, very ideal distribution was shown at 100 mm position, but the expected region of CRUD adhesion is upper side of specimen, so it doesn't have any advantage.

(1)



(2)

(3)

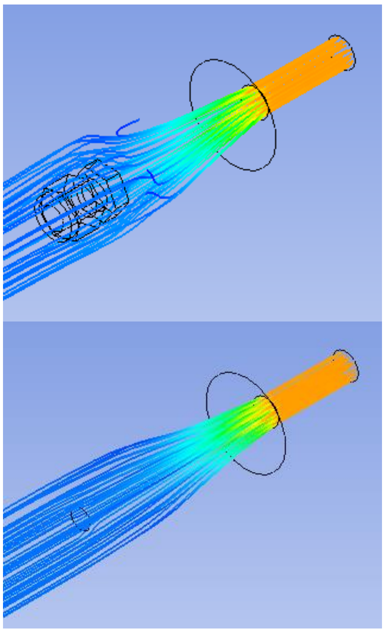


Fig. 3. Streamline analysis at the entrance of autoclave with (1) union, (2) cap, and (3) nut

Streamline analysis result, in Fig. 3, shows the flow resistance of the specimen tip because of its geometry. As the figure shows, union and cap block some streamline which can cause turbulent inside of autoclave during flow.

(1)

(2)

(3)

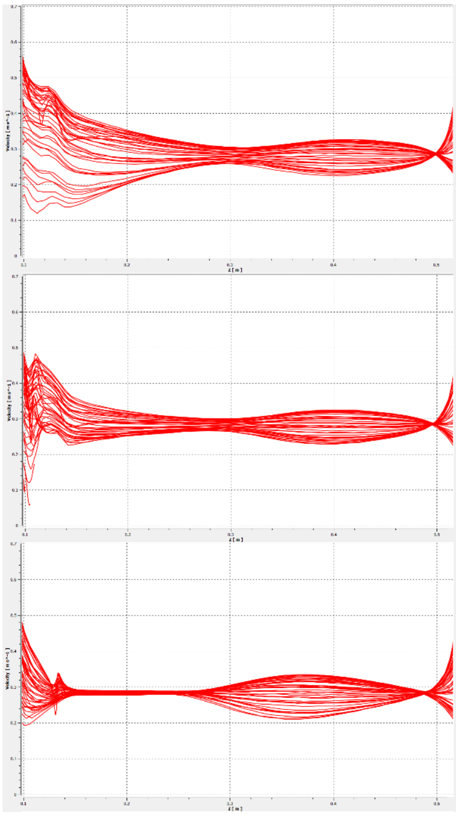


Fig. 4. Flow chart deduced from streamline with (1) union, (2) cap, and (3) nut

Data re-processing for the result of streamline into the flow chart shows the above Fig. 4. As it said, the result of velocity distribution, nut case, along the distance from bottom to top has the most uniform trend. By gathering whole results of ANSYS analysis, it is expected that the flow of nut case will uniformly pass through the autoclave.

3. Conclusions

Several heat transfer and thermohydraulic calculations were conducted to set the test conditions for CRUD adhesion test which can simulate real environment of primary circuit water chemistry of commercial nuclear power plant. And computational simulation analysis to figure out flow distribution inside of autoclave was also conducted by using ANSYS tool.

The heat flux to generate sub-cooled boiling and to heat the coolant to the target temperature was calculated by using various equations. To get heat flux of flow boiling, the summation of forced convection and pool boiling phenomenon was done in point of heat flux estimation.

The geometry design for tip of specimen was chosen under the logics of ANSYS simulation. According to the result of finite element method, the specially fabricated nut design is the best choice to reduce resistance of flow at the entrance of the autoclave, and to make flow distribution uniform.

In the near future, fabrication of test equipment such as cladding specimen will be conducted by following the result and the logic of this study.

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REFERENCES

[1] N. E. Todreas, and M. S. Kazimi, Nuclear Systems Thermal Hydraulic Fundamentals, CRC Press, 2012

[2] J. Peybernes, Evaluation of the Forces Generated by Cross-flow on PWR Fuel Assembly, Proceedings of a Technical Meeting Held in Cadarache, France, IAEA-TECDOC-1454, pp.13-22, Nov.22-26, 2004

[3] W. M. Rohsenow, A Method of Correlating Heat Transfer Data for Surface Boiling of Liquids, ASME Transactions 74, pp.969975, 1952

[4] S.S. Kutateladze, On the Transition to Film Boiling under Natural Convection, Kotloturbostroenie 3, p.48, 1948

[5] V. Gnielinski, New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow, International Chemical Engineering 16, pp.359-368, 1976