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Rewetting temperature during reflood of a single heated rod in a PWR simulated channel: a comparison of experiment, correlation, and simulation

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1. Introduction

The large break loss of coolant accident (LB-LOCA) is a design basis accident (DBA). When it occurs, emergency core cooling systems (ECCS) are immediately actuated to prevent fuel rods from severely damaging. Major steps during the actuation of ECCS includes blowdown, refill and reflood phases, and long-term cooling period. It is important to precisely analyze the three phases for safety analysis. Especially, the reflood phase has complex two-phase flow and heat transfer characteristics depending on various design parameters and operation conditions. In this regard, experimental and theoretical studies about the reflood phase have been continuously conducted to understand and predict the complex phenomena, in particular rewetting process of overheated fuel rods.

Rewetting is a key phenomenon for predicting the cooling behavior of overheated fuel rods during reflood in flow channels. The rewetting temperature means the maximum temperature at which cooling liquid can maintain direct contacts with a heated wall, forming liquid-solid-vapor triple contact lines. At the point, the boiling heat transfer regime changes from film boiling to transition boiling at the temperature. Therefore, the initiation point of the rewetting can be determined by the prediction model for the rewetting temperature.

Most prior studies attempted to correlate the rewetting temperature using inlet flow conditions. Kim and Lee [1] set the initial wall temperature, inlet coolant subcooling, coolant flow rate, property of coolant and wall as variables in the correlation for the rewetting temperature. Lee and Shen [2] evaluated the effect of the inlet vapor quality, coolant flow rate, and initial wall temperature on the rewetting temperature experimentally. Lymperea et al. [3] observed the effects of initial wall temperature, inlet coolant subcooling and coolant flow rate on the rewetting temperature through the experiments and also proposed the correlation of rewetting temperature using experimental data.

Recently, the rewetting temperature of a single heated rod confined in a PWR simulated channel during the reflood phase was experimentally examined at Kyung Hee University (KHU). The measured rewetting temperature was considerably different from the predicted values by the representative theoretical correlation in SPACE [4]. However, the causes of the observed difference could not be clearly addressed.

In this study, to clarify the reason of the disagreement between the rewetting temperature data measured using the KHU reflood facility and the prediction value, the rewetting temperature correlation in the SPACE code and related experimental studies for its development and validation were reviewed. In addition to the literature review, numerical simulation of the KHU reflood test using the SPACE code was conducted. Then, the obtained results of the rewetting temperature from the experiment, correlation and simulation were compared.

2. Rewetting temperature correlation in the SPACE code

In the SPACE code, the rewetting temperature is calculated using the correlation developed by Carbajo [5]. The correlation was developed based on the findings and measurement data in relevant previous studies. Yao and Henry [6] showed that the minimum film boiling temperature increases with increasing pressure. Braidfield [7] and Dhir and Purohit [8] reported the strong effect of liquid subcooling on the rewetting temperature. Nishio and Hirata [9] argued that the rewetting temperature is affected by properties of coolant and wall. Iloeje et al [10] presented that increasing flow rate leads to increasing of rewetting temperature.

Eq. (1) shows the Carbajo correlation applied to the SPACE code.

$$\Delta T_{MFB} = \Delta T_{MFB,ISO}(1+\beta\gamma)(1+rG^{s}) + a\Delta T_{sub} \quad (1)$$

Here, $\Delta T_{MFB,ISO}$ is the minimum film boiling isothermal temperature which is a local temperature where saturated liquid with no flow initially contacts to the solid surface.

$$\Delta T_{MFB,ISO} = \frac{1.372\times 10^{6}}{T_{cr}^{2.3}}\left(\frac{T_{cr}-T_{sat}}{\sqrt{\mu_l}}\right)^{\frac{1}{2}} \quad (2)$$

The factor $(1+\beta\gamma)$ includes the surface oxidation effect shown at Eq. (3), β, and the surface condition factor, γ.

$$\beta = \sqrt{\left(k\rho C_p\right)_l / \left(k\rho C_p\right)_w} \quad (3)$$

G is the mass flow rate. For the coefficient, r, and the exponent, s, in Eq. (1), Carbajo proposed 0.1 and 0.4, respectively. $a\Delta T_{sub}$ represents the effect of liquid subcooling and the coefficient factor a is expressed as

$$a = \frac{4180}{C_{p,l}}\frac{h_{fg}}{h_f}\left(\left(\frac{\left(k\rho C_p\right)_l}{\left(k\rho C_p\right)_w}\right)^{1/2}\frac{h_{fg}}{C_{p,w}\Delta T_{MFB,ISO}}\right)^{0.1} \quad (4)$$

The prediction accuracy of the Carbajo correlation was validated using the experimental data obtained by Yao and Henry [6], Bradfield [7], Dhir and Purohit [8] and Adler [11]. Among them, the work of Yao and Henry was the quenching test of horizontal plates while the others were the quenching experiments of spherical specimens.

From the preceding literature review, it is found that the development and validation of the Carbajo correlation were mostly conducted based on the experimental works in the quenching conditions. The fluid flow condition in the quenching could be quite different from that in the reflood experiments. For instance, the specimen during the reflood test is continuously heated to simulate decay heat in the reactor while the cooling process of the initially heated specimen is monitored in the quenching experiment with no further heating. Whether the specimen is continuously heated or not leads to a considerable difference in the fluid flow condition near the quench front. During the reflood test, vapor is generated by nucleate boiling below the quench front. If the generation rate of vapor is high enough to make large bubbles like slug, those bubbles can make the flow unstable near the quench front whereas there are no more boiling in the region at which upstream of the quench front after the rapid cooling in quenching test.

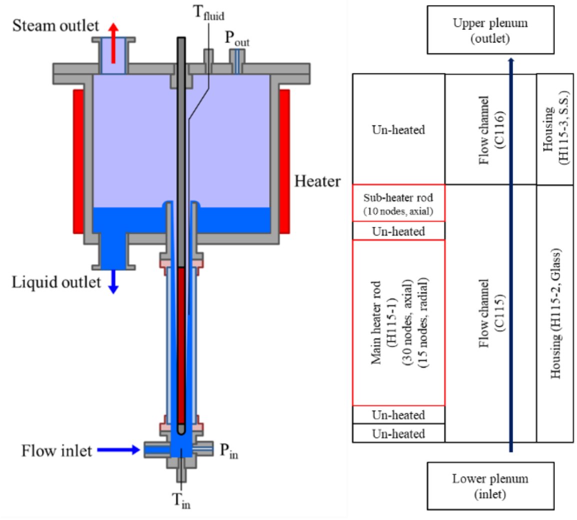
3. Simulation of the KHU reflood test using the SPACE code

Numerical simulation of the KHU reflood test using the SPACE code was attempted. The numerical simulation was conducted to compare the experiments, correlation and SPACE simulation.

For SPACE simulation, the test section of the reflood facility was nodalized as shown in Fig. 1. The main heater rod to simulate a fuel rod had 30 axial nodes for verifying whether local flow conditions were used. 15 radial nodes for heat distribution of test specimen were also nodalized. The flow channel and housing were included into the simulation domain for describing fluid space, Pyrex glass channel and upper reservoir.

Fig. 2 shows the test specimen including the temperature measurement point at the KHU reflood test. This test specimen was nodalized as heat structure existing at left of flow channel for SPACE simulation. The temperature measurement point was located at H115-1-24-15, which is 240 mm above the lower plenum.

In the SPACE code, the Carbajo model was used to calculate the rewetting temperature as a base model. Users can select one of Carbajo model, Dhir [8] model, Henry [12] model, and Groeneveld [13] model in the code. In this study, the Carbajo rewetting temperature model was selected.



(a) (b)

Fig. 1 Schematic diagram (a) of the test section and its nodalization (b) for the SPACE code simulation

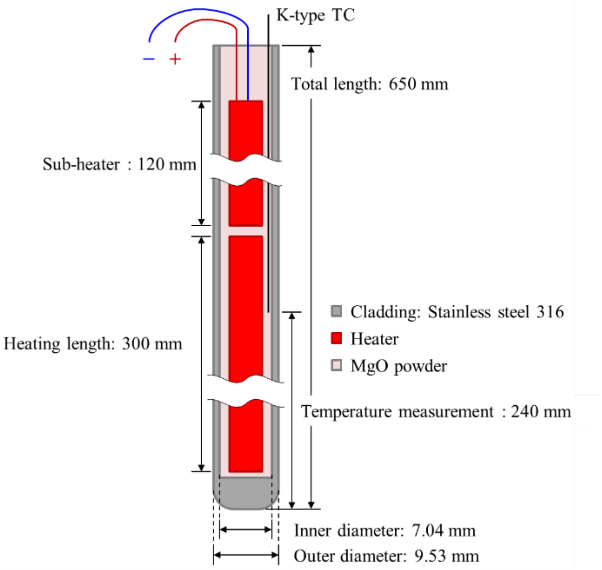


Fig. 2 Test specimen and the temperature measurement point which used for SPACE simulation

Three combinations of reflood tests with different inlet coolant subcooling and reflood rate were simulated using the SPACE code, as summarized in Table. 1, for a comparison with experiment and correlation.

Table. 1 Conditions of simulation set corresponding to the flow conditions in the KHU experiments

	Inlet coolant subcooling (℃)	Inlet flow rates (mm/s)
V25_S10	10	25
V50_S10	10	50
V50_S30	30	50

4. Results

The rewetting temperatures measured in the KHU reflood test, directly calculated using the Carbajo correlation with the inlet flow conditions, and obtained from the SPACE simulation were compared in Fig. 3. In Fig. 3, the experimental results were matched to the simulation results within ±10%. However, the results calculated by the Carbajo correlation using the inlet flow condition were much less than or greater than 10% compared to the obtained results from experiments. It shows that the rewetting temperature from the SPACE simulation has a reasonable agreement with the experimental data while the calculated values of the Carbajo correlation show a considerable difference from the others.

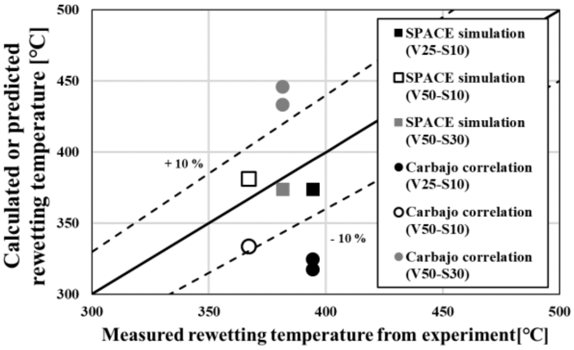


Fig. 3 Difference of rewetting temperature between SPACE simulation and Carbajo correlation from experiments

The numerical simulation results explain that the flow conditions of the bulk flow near the quench front where actual rewetting occurs were significantly differed from the flow conditions at the inlet of the test section. In the typical quenching experiment which are conducted in a pool or a large channel does exist no significant different between the inlet flow conditions at the inlet and near the quench front. However, in the typical reflood experiment conducted in a confined flow channel such as the PWR subchannel, the flow conditions at quench front could be significantly different from the inlet flow conditions due to large vapor like slug bubbles generated at the upstream of the quench front. In fact, this situation was observed in the visualization results of the KHU reflood experiment, as given in Fig. 4.

The calculated liquid velocity at a local position in the numerical simulation was higher than the bulk liquid velocity at the inlet of the test section and it was shown at Table.2. Especially, Park [4] reported a large increment in the local liquid velocity at the low subcooling condition of the KHU reflood test. Under the low subcooling condition, nucleate boiling bubbles were vigorously generated on the heated fuel rod and large slug bubbles due to agglomeration of small bubbles were formed, resulting in the considerable increase in local liquid velocity. Consequently, since the simulation and the experimental analysis results coincided, it is clear that the liquid velocity near the quench front is much faster than the inlet liquid velocity in the reflood situation.

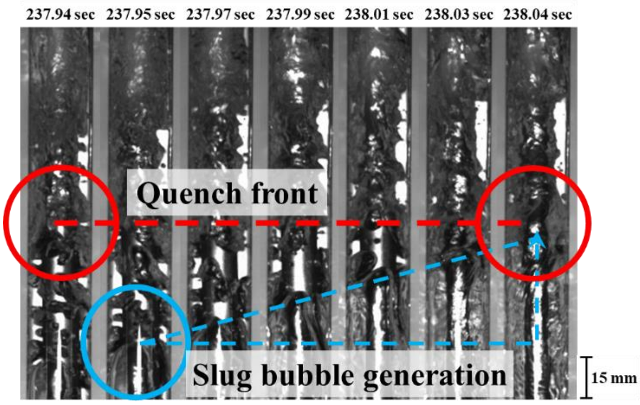


Fig. 4 Visualization of the rapidly rising slug bubble toward the quench front from the bottom of the test heater in the KHU reflood test

Table. 2 Inlet liquid velocity and local liquid velocity at the point of rewetting occurs in H115-1-24-15 node with SPACE simulation

	Inlet liquid velocity (mm/s)	Local liquid velocity at H115-1-24 -15 (mm/s)
V25_S10	25	55
V50_S10	50	69
V50_S30	50	62

In this situation, there may be a significant difference in the experimental results and the calculated results using the inlet flow conditions. Therefore, if the existing correlation is applied to the reflood situation, the prediction of the rewetting temperature is well matched with the experimental results using the local flow conditions on the quench front, not using the inlet flow conditions. Moreover, as previously mentioned, the SPACE code uses the local flow condition like local liquid velocity. Therefore, it was reasonable that the results using the local flow conditions were well matched to the obtained results from the experiments.

5. Conclusions

This study was motivated from the fact that the measurement rewetting temperature in the KHU reflood test showed a considerable discrepancy from the calculation value using the Carbajo correlation, which is the default rewetting temperature model of the SPACE code. To interpret the reasons of the observed difference, open literatures related to the development of the Carbajo model were carefully reviewed and numerical simulation of the KHU reflood test was conducted using the SPACE code.

It was found from the literature review that the Carbajo correlation was developed based on the quenching tests where the flow conditions at the inlet of the flow channel remains almost constant along the flow direction unlike those in the reflood condition. It was found that the rewetting temperature measured in the KHU reflood test could be reasonably predicted in the numerical simulation where the changes in the local flow conditions near the quench front from the inlet were appropriately simulated in comparison with the visualization images obtained during the reflood tests. Therefore, it is concluded that the variations in the local flow conditions due to the continuous heating of the heater rod during reflood should be suitably accounted for the accurate prediction of the rewetting temperature using the Carbajo correlation.

Nomenclature

a	subcooling parameter
C_p	isobaric specific heat, J/kg℃
G	mass flow rate, kg/m^{2}s
h_{fg}	specific enthalpy of vaporization, J/kg
h	specific enthalpy, J/kg
k	thermal conductivity, W/m℃
r	coefficient used in eq. (1)
s	exponent used in eq. (1)
T	Temperature, **K**

Greek

$\boldsymbol{\beta}$	Thermal inertia as defined by eq. (4)
$\boldsymbol{\gamma}$	surface condition factor
$\boldsymbol{\mu}$	viscosity, N·s/m^2
$\boldsymbol{\rho}$	density, kg/m^3

Subscripts

cr	critical
f	fluid
ISO	isothermal
l	liquid
MFB	minimum film boiling
sat	saturation
sub	subcooling
w	wall

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