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Reflooding Phenomena in a Single Heated Rod*

(Part 2 Analytical Study)

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This study presents analysis for transients of clad surface temperature and quench front. It was said that film boiling which occurs on the wall surface above the quench front was a predominant heat transfer during the reflood portion in LOCA. Comparison of experimental results with analysis indicated that the heat transfer for the film boiling was correlated considering the effect of flooding speed as follows:

$$h = (0.023 U^{1.6+0.8}) \{ \lambda_v^3 \rho_v (\rho_l - \rho_v) g H f_g \}^{0.25} \{ \mu_v L_x (T_w - T_s) \}^{-0.25}$$

1. Introduction

We presented in the previous report, Part 1 the experimental studies which used a single heated rod for simulating the reflood phenomena during LOCA in light water reactor. The results are summarized as follows.

(1) The change of heat transfer regime at a given elevation of the heated rod during reflood has the following sequence: vapor cooling, film or transition boiling, nucleate boiling, and liquid forced convection. The wall surface is quenched when the heat transfer changes from film to nucleate boiling.

(2) The film boiling occupies most areas of the boiling heat transfer region and the nucleate boiling occurs in a small area around quench front.

(3) The heat transfer coefficient is tens to hundreds of kcal/m²h°C in the film boiling region, and more than thousand kcal/m²h°C in the nucleate boiling region.

(4) The quench front advances upward at a constant speed when the inlet coolant temperature is as low as 20 °C; when it is as high as 80 °C, the speed is very low at the lower part of the rod, but it increases as the quench front advances and ultimately settles to a nearly constant value.

(5) The clad surface temperatures on quenching distribute between 300 and 200 °C, and decrease with an increasing elevation on the heated rod.

Several analytical works have been done on the reflood phenomena using a single heated rod. Martini et al.⁽¹⁾ compared a measured clad temperature with a prediction using a heat transfer model. The model divided a boiling heat transfer into two regimes: dispersed flow and annular flow, and used measured values as their heat transfer coefficients. The prediction calculated clad surface temperature responses according to a heat balance among coolant liquid,

steam, and rod assuming quality and clad temperature at a transition point from dispersed to annular flows. However, this analysis did not consider an effect of nucleate boiling. Murao et al.⁽²⁾ investigated quenching during reflood by using data of FLECHT⁽³⁾, and presented three models for quenching: Types of liquid column, dryout, and deentrained droplets. They also considered an effect of coolant subcooling, and indicated that ascending speeds of quench front in liquid column and dryout quenching types are given by $U_q = 1.2(10^{-5}) T_{sat}^{3+0.8 \pm 0.3}$ and $U_q = 0.8 \pm 0.3$, respectively and that quench temperatures distributed between 370 and 510 °C. Sudo⁽⁴⁾ investigated a heat transfer in a film boiling region which was assumed to be nearly steady state due to a gradual change of clad temperature in that region. He suggested a heat transfer coefficient for the saturated film boiling: $h_c = 0.94 \lambda_v (\rho_v \rho_l g H f_g)^{0.25} \{ \mu_v L_x \lambda_v (T_w - T_s) \}^{-0.25}$. He also presented qualitatively the heat transfer rate of the film boiling with subcooling by using data of FLECHT⁽³⁾.

This report provides an analytical model to predict quench front which affects overheat and damage of the fuel rod. This study gives predictions of clad temperature history from turnaround to quench, and indicates that the clad temperature history is very sensitive to the rate of the film boiling heat transfer which occurs most areas of the heat transfer region. The heat transfer in the film boiling region is correlated considering effects of initial clad temperature, flooding speed, and coolant temperature. This study was performed to analyze the reflood behavior of coolant with little subcooling, since a large subcooling caused a sudden clad temperature drop due to a thin vapor film around a turnaround point. The heat transfer correlation in the film boiling region is used to predict clad temperature history and quench front response according to a proposed heat transfer model and a heat balance on the heated wall. Temperature at the quench front is examined by comparison of predictions and experimental results relating to quench front responses.

2. Nomenclature

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- b : vapor film thickness, cm
 c : specific heat, cal/g°C
 C_1 : factor in Eq.1
 g : gravitational acceleration, cm/s²
 H_{fg} : latent heat of water, cal/g
 h : heat transfer coefficient, cal/cm²s°C
 L_x : distance above quench front (function of time), cm
 q_e' : internal heat generation rate, cal/cm²s°C
 T_{li} : inlet coolant temperature, °C
 T_q : quench temperature, °C
 T_s : saturation temperature of water, °C
 T_w : clad temperature, °C
 T_{wi} : initial clad temperature, °C
 ΔT_{sat} : subcooling of coolant, °C
 t : time after reflood starts, second
 U : flooding speed, cm/s
 U_q : ascending speed of quench front, cm/s
 U_t : ascending speed of turnaround point, cm/s
 W_e : generated power, kW/m
 X : length above the heated section, cm
 Y_q : quench time, second
 Z : coordinate moving with quench front, cm
 α : thermal diffusivity, cm²/s
 δ : clad thickness, cm
 λ : thermal conductivity, cal/ms°C
 μ : viscosity, g/cms
 ρ : density, g/cm³
 Subscripts
 l : liquid
 v : vapor
 w : rod wall

3. Analysis

For predicting clad surface temperature history during reflood, heat transfer by conduction in the axial direction of a heated rod should be taken into consideration around the quench front in addition to convective heat transfer from the heated rod to the coolant. The convective heat transfer occurred on the high temperature wall with boiling. In this study two effective heat transfer regimes to clad temperature history: nucleate and film boillings, were considered to model reflood heat transfer. Based on Appendix 1 it is clear that clad temperature is the most sensitive to the heat transfer rate of film boiling which occupies most parts of the boiling region. Note that the film boiling heat transfer might be treated as a nearly steady state due to the gradual change of clad temperature. This study proposed the following equation for the heat transfer correlation mostly identical in form with Eq.(12) shown in Appendix 2, in which the heat transfer correlation was derived in a steady state condition,

$$h = C_1 \{ \lambda_v^3 \rho_v (\rho_l - \rho_v) g H_{fg} \}^{0.25} \{ \nu L_x (T_w - T_s) \}^{-0.25} \quad (1)$$

where L_x is a distance above a quench front and a function of time, and T_w is a clad temperature at elevation L_x . Appendix 2 indicates that factor C_1 in Eq.(1) has a nearly constant value along the rod even at

low inlet coolant temperature if the quench temperature is assumed to have an axial distribution with the trend observed in the experiments. In this study clad temperature history has been predicted and compared with experimental data only for high inlet coolant temperature to exclude an undefined quench temperature distribution, since at high inlet coolant temperature a quench temperature changes less along the rod than at low inlet coolant temperature.

First, measured quench front transients were compared with predictions. Fig.1 shows a heat transfer model used in this study. The heat transfer model contains film and nucleate boillings and those heat transfer coefficients are given by

$$\text{Film boiling: } h = C_1 \{ \lambda_v^3 \rho_v (\rho_l - \rho_v) g H_{fg} \}^{0.25} \{ \nu L_x (T_w - T_s) \}^{-0.25} g$$

$$\text{Nucleate boiling: } h = 10000 \text{ kcal/m}^2 \text{h}^\circ\text{C}$$

Since a heat transfer rate of nucleate boiling does not affect clad temperature response as shown in Appendix 1, the constant value was used for the coefficient.

Fig.1 Heat transfer model corresponding to flow regimes

Clad temperature response can be computed numerically by Eq.(2) considering the axial heat conduction of the rod.

$$\frac{\partial T_w}{\partial t} = \alpha \frac{\partial^2 T_w}{\partial X^2} - \frac{h}{(\rho c)_w \delta} (T_w - T_s) + \frac{q_e'}{(\rho c)_w \delta} \quad (2)$$

where the heat transfer coefficient h in Eq.(2) is determined by the heat transfer model shown in Fig.1, and initial and boundary conditions are given by

$$t=0 \quad T_w = T_{wi} \quad (3)$$

$$X=U \cdot t \quad T_w = T_{wi} \quad (4)$$

$$X=X_{i+1} \quad T_w = T_b (=100^\circ\text{C}) \quad (5)$$

where X_{i+1} is a lower elevation by one calculational mesh than X_i , the highest elevation of which temperature is less than 120 °C, and T_b means a temperature where nucleate boiling ceases. The quench temperature was assumed to be 250 °C in terms of an averaged value of the measured data shown in the previous report.

Figures 2 and 3 compare measured quench front transients with predictions with several values of factor C_1 in Eq.(1). Comparison between experimental results and predictions indicates that the prediction at factor $C_1=0.9$ agrees with the data for flooding speed $U=2.5$ cm/s and a high inlet coolant temperature, and that the fitted

value of factor C_1 is not dependent on initial clad temperature. The heat transfer model shown in Fig.1 is not applicable to the prediction for a low inlet coolant temperature (around 20 °C) since a stable vapor film is not formed and a large temperature drop exists around turnaround.

As shown in Appendix 2, the value of factor C_1 is independent of initial clad temperature but dependent on flooding speed. The experimental data for $U=5.0$ and 7.4 cm/s were compared with predictions to obtain a fitted value of factor C_1 predicting a good agreement. The values of factor C_1 can be correlated to flooding speed by

$$C_1 = 0.023 U^{1.6} + 0.8 \quad (6)$$

Figure 5 compares predictions using Eq. (6) for a value of factor C_1 with experimental results for several flooding speeds. Good agreement in Fig.5 indicates that Eq. (6) is applicable to experiments with the flooding speed ranges reported in the previous study.

As shown in Figs.2,3, and 5, however, a discrepancy between experiments and predictions is large at the lower elevation of

the rod specially for a high flooding speed. This might be caused by actual quench temperature distributing along the rod elevation. As shown by Figs.9 and 10 in the previous report, the quench temperature decreases with an increasing elevation and even for high inlet coolant temperature the quench temperature changes at the lower elevation. Therefore, the quench temperature difference at the lower elevation between the measured and the assumed values might cause the discrepancy between experiments and predictions.

Figure 6 presents clad temperature responses measured and predicted instead of the quench front responses shown in Figs.2, 3, and 5. For both flooding speeds, between the predictions and experiments, decreasing rates of clad temperature during the film boiling are quite similar, but turnaround times are different. This difference might be due to an underestimated water speed around turnaround. The actual water speed around turnaround was greater than the flooding speed U assumed as the water speed in this study by a large void fraction (i.e.

Fig.2 Transient of quench front

Fig.4 Relation between factor C_1 and flooding speed

Fig.3 Transient of quench front

Fig.5 Transient of quench front

a narrowed liquid flow area) due to generated steam. Since the void fraction around turnaround increased with a decreasing flooding speed, the turnaround time difference became large as the flooding speed decreased. The predicted values of clad temperature around quench front and during film boiling heat transfer region are a little higher than the measured values. This might be due to the fact that the experimental values were measured by thermocouples located on the rod surface, while on the other hand the clad temperature was computed by a one-dimensional conduction equation with the radial direction of the rod.

The quench temperature was examined through comparison between predictions and experiments for quench front responses. The quench temperature was assumed to be 250 °C and constant along the rod, but the experimental results indicated that it was not constant along the rod. Since to date the quench temperature has not been well correlated and analyzed, in this study it is investigated in the following manner. The analytical method discussed previously: the heat transfer model shown in Fig.1, Eqs.(2), (3), (4), and (5) and the assumed quench temperature, is used to predict quench front responses. If a quench front response is known, quench temperatures at each elevation will be able to be calculated using the analytical method. In this study required quench front response curves are approximated by a polynomial function from several experimental data. Fig.7 shows quench tem-

perature at each elevation calculated in the above mentioned analytical manner. In the figure black symbols present values measured in the test section 1 and white symbols measured in the test section 2, and the symbols, ■, ●, ▲, show data measured on the clad surface, and the symbol, ▼, measured in the clad. This figure indicates that calculated quench temperatures decrease with an increasing elevation with the same trend as observed in the experimental data, and that they distribute between 200 and 300 °C with a small change in the axial direction above the 30 cm elevation. However, 50 to 100 °C temperature difference still exists between calculated and experimental results. This difference might be caused by the following effects: (1) In the experiments initial clad temperatures at the lower part of the rod were less than those at the middle part due to some heat conduction to the electrodes. If an initial clad temperature had a constant and flat distribution, a quench time at the lower part would be longer than measured values. (2) Turnaround was assumed to advance at the same speed as the flooding speed, but actually it advanced at a higher speed, for instance, as shown in Fig.6 the turnaround at the 70.5 cm elevation occurred by about 5 seconds earlier than estimated by the flooding speed, $U=2.5$ cm/s.

4. Conclusions

A method to predict a clad temperature history and quench front response was examined. The following conclusions have been reached in analyzing the predictions and the experiments.

During reflood the film boiling heat transfer has a predominant effect on the clad temperature response, and its coefficient can be correlated considering the effect of a flooding speed by $h=(0.023 U^{1.6} + 0.8)\{\lambda_v^3 \rho_v(\rho_l - \rho_v)gH_{fg}\}^{0.25}\{\mu_v L_x(T_w - T_g)\}^{-0.25}$. The heat transfer model derived from the experimental results shown in Fig.1 was used to predict clad temperature responses in addition to the basic equations.

The quench temperature was investigated by comparison of predictions with experiments relating to quench front histories. This investigation provided the quench temperature distribution along the rod predicted with the same trends as the measured values. To obtain better predictions should be considered an initial clad temperature profile along the rod and earlier turnaround times than those estimated by the flooding speeds.

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Fig.6 Clad temperature response at the 70.5 cm elevation

Fig.7 Quench temperature distribution along the rod elevation

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Appendix

1. Effect of heat transfer

To examine the effect of a heat transfer rate in nucleate and film boiling regions on a clad temperature response experimental results relating to quench front and turnaround point transients were used. Fig.8 shows a heat transfer model simply simulating heat transfer regimes observed in this study. The heat transfer coefficients in the nucleate and the film boiling regions are both constant and denoted by h_1 and h_2 , respectively. It was examined how the magnitude of the values, h_1 and h_2 , affects a clad temperature. Considering only axial heat conduction of the rod, the constitutive equation for the rod is given by

$$\frac{\partial T_w}{\partial t} = \alpha \frac{\partial^2 T_w}{\partial Z^2} - \frac{h}{(\rho c)_w \delta} (T_w - T_s) + \frac{q_e'}{\rho c_w \delta} \quad (7)$$

In a coordinate system Z moving with a

Fig.8 Simplified heat transfer model corresponding to flow regimes

Fig.9 Clad temperature response predicted at three different elevation

quench front at a constant speed U_q , Eq.(7) can be reformed as

$$\frac{\partial T_w}{\partial t} = \alpha \frac{\partial^2 T_w}{\partial Z^2} + U_q \frac{\partial T_w}{\partial Z} - \frac{h}{(\rho c)_w \delta} (T_w - T_s) + \frac{q_e'}{(\rho c)_w \delta} \quad (8)$$

where h is a heat transfer coefficient shown in Fig.8, and no subcooling was considered by $T_s=100^\circ\text{C}$. The width of nucleate boiling Z_0 shown in Fig.8, was assumed to be 5 mm based on the experimental results. The initial and boundary conditions given by

$$\begin{aligned} t=0 & \quad T_w=T_{wi} \\ Z=0 & \quad T_w=T_b(110^\circ\text{C}) \\ Z=(U_t-U_q)t & \quad T_w=T_{wi} \end{aligned}$$

where U_t is an advancing speed of turnaround in a clad temperature history and was assumed to be equal to the flooding speed U .

Figure 9 shows clad temperature response predicted in the analytical manner above explained at elevations 10.3, 39.7, and 70.6 cm for four cases with different heat transfer coefficients. Comparison between those predicted results indicates that a quench temperature increases as the heat transfer coefficient of the nucleate boiling increases (this figure does not present apparently, but the temperature in the case of $h_1=100000$ and $h_2=500$ is higher by about 20°C than that in the case of $h_1=500$ and $h_2=500$). Two curves in the cases of $h_1=10000$, $h_2=500$ and $h_1=5000$, $h_2=500$ are similar and do not show apparent difference in the figure. On the other hand, the heat transfer coefficient of the film boiling much affects the clad temperature transient due to presence of a large area in the heat transfer regions.

2. Film boiling heat transfer correlation

The heat transfer correlation will be derived relating to a geometry shown in Fig. 10. A vapor temperature is assumed to have a linear profile in a thin vapor film and a fluid temperature is assumed to be at saturation, $T_s=100^\circ\text{C}$. Constitutive equations

Fig.10 Distributions of vapor temperatures and vapor velocities in a vapor film

for the vapor are given by

$$\text{Mass: } \int_0^Z \dot{W}_v dZ = \int_0^b U_v dZ \quad (9)$$

$$\text{Energy: } \lambda_v(T_w - T_s)/b = W_v \rho_v h_{fg} \quad (10)$$

$$\text{Momentum: } \rho_v U_v \frac{\partial U_v}{\partial Z} = - \frac{\partial P}{\partial Z} + \mu_v \nabla^2 U_v - \rho_v g \quad (11)$$

where U_v is a steam velocity in the direction Z and $\dot{W}_v$ is a steam generation rate per unit length and unit time. If steam velocities on a heated wall and a liquid boundary are equal to zero and is constant and independent of Z , the heat transfer correlation can be given by solving Eq.(9), (10), and (11),

$$h = 0.54 \{ \lambda_v^3 \rho_v (\rho_l - \rho_v) g h_{fg} \}^{0.25} \{ \mu_v L_x (T_w - T_s) \}^{-0.25} \quad (12)$$

Table 1 Explanation of symbols used in Figs.11 and 12

	$T_{wi} \text{ } ^\circ\text{C}$	$U \text{ cm/s}$	$U_q \text{ cm/s}$	$\dot{W}_e \text{ kW/m}$
○—○	400	1.2	0.97	0.23
○- - -○	400	2.5	1.96	0.23
○—○	400	5.0	3.84	0.23
△—△	500	1.2	0.96	0.36
△- - -△	500	2.5	1.81	0.36
△—△	500	5.0	3.45	0.36
□—□	600	1.2	0.89	0.54
□- - -□	600	2.5	1.65	0.54
□—□	600	5.0	3.20	0.54
▽—▽	700	1.2	0.77	0.85
▽- - -▽	700	2.5	1.46	0.85
▽—▽	700	5.0	2.83	0.85

Fig.11 Distribution of factors C_1 against elevation X using a constant quench temperature, $250 \text{ } ^\circ\text{C}$

The following correlation replacing 0.54 in Eq.(12) with factor C_1 was examined to be used for transient analysis of film boiling heat transfer during reflood.

$$h = C_1 \{ \lambda_v^3 \rho_v (\rho_l - \rho_v) g h_{fg} \}^{0.25} \{ \mu_v L_x (T_w - T_s) \}^{-0.25} \quad (13)$$

Based on the lumped method for a heat balance between the heated rod and the fluid, the following equation was used to predict a clad temperature of the rod.

$$-(\rho c)_w \delta \frac{\partial T_w}{\partial t} + q_e' = C_1 \left(\frac{\lambda_v^3 \rho_v (\rho_l - \rho_v) g h_{fg}}{\mu_v L_x (T_w - T_s)} \right)^{0.25} (T_w - T_s) \quad (14)$$

where L_x is a distance above the quench front and is formed by $L_x = X - (U_q/U_t) \cdot X - U_q t$. The ascending speed of quench front U_q was given by the selected experimental data which maintain a constant value over the entire elevation of the rod. The ascending speed of the turnaround point U_t was assumed to be equal to the flooding speed U . In this analysis a temperature at the quench front where film boiling changes to nucleate boiling is a given finite value as an extra condition, therefore the two conditions are given by

$$t=0 \quad T_w = T_{wi} \quad (15)$$

$$t = X/U_q - X/U_t - 0.2/U_q \quad T_w = T_q \quad (16)$$

where the value 0.2 in Eq.(16) means that the clad temperature at $L_x = 0.2 \text{ cm}$ is equal to the quench temperature, and U_q and U_t are given by the experimental data. Eq.(14) was solved by the Runge-Kutta method to obtain a clad temperature response satisfying the conditions Eqs.(14) and (15) by changing parametrically a value of factor C_1 .

Figures 11 and 12 show values of factor C_1 satisfying both conditions. The values of U_q and U_t used in this analysis and symbols in Figs.11 and 12 are shown in Table 1. The quench temperature was a constant value,

Fig.12 Distribution of factors C_1 against elevation X using a distributed quench temperature

250 °C, along the rod elevation in Fig.11, but it was given by the equation $T_q = (T_{wi} - T_s) \exp\left\{ X/100 \cdot \ln\{(200 - T_s)/(T_{wi} - T_s)\} \right\} + T_s$. The quench temperature correlation was obtained by the experimental data shown in Figs.9 and 10 in the previous report. Fig.11 indicates that the factor C_1 is sensitive to

elevation, while Fig.12 does that the factor C_1 is not sensitive to elevation. In both figures factor C_1 is not sensitive to initial clad temperature, but sensitive to flooding speed. Therefore, it is clear that the effect of flooding speed should be considered in factor C_1 .