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Reflooding Phenomena in a Single Heated Rod

(Part 1, Experimental Study)*

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Reflooding in a loss of coolant accident involves unsteady and very complicated phenomena such as quenching. In this study the reflooding is examined using a simple apparatus with a single electrically heated rod. The purpose of this paper is to present qualitative examinations relating to the phenomena during reflood, and to obtain ascending speed of the quench front and heat transfer coefficient during transient. The results are as follows: (1) A boiling region can be divided into two main parts. One is a film boiling region which occupies the greater part of the boiling region. The other is a nucleate boiling region appearing in a small area around the quench front. (2) The heat transfer coefficients of a film boiling region and a nucleate boiling region are about tens to hundreds and more than thousand $\text{kcal/m}^2\text{h}^\circ\text{C}$, respectively. (3) The quench front advances upward at a nearly constant speed when the inlet coolant temperature is as low as 20°C .

1. Introduction

The thermal-hydraulic phenomena associated with the reflood portion of a loss of coolant accident (LOCA) are currently deemed important due to their role in light water nuclear reactor safety.

Emergency core cooling systems (ECCS) which are safety facilities in a light water reactor are provided to refill the core with the coolant to prevent loss of structural integrity of the cladding due to overheat.

During the reflood an injected coolant flows through the lower plenum of a pressure vessel and makes fuels cool down gradually. This process involves complicated transient two-phase flow heat transfer problems such as quenching which is important as an unknown process in metallurgy.

In the reflood process the clad temperature and the heat transfer coefficient at a given elevation of fuel change with time as shown by Curves A and B in Fig.1, respectively. A change of heat transfer regime at the elevation follows the sequence: (1) vapor forced convection, (2) film boiling (or transition boiling), (3) nucleate boiling, and (4) liquid forced convection. The quenching occurs when the heat transfer regime changes from film boiling to nucleate boiling.

Several experimental studies regarding the reflood behavior have been done in several countries. These studies, for example FLECHT^{(1),(2)} in U.S.A. and tests of SIMENS in F.R.G.⁽³⁾, used large scale facilities and specified experimental conditions simulating those of actual power plants, therefore the predictions of those tests were difficult due to many experimental parameters.

Andreoni, et al.⁽⁴⁾ and Sudo, et al.⁽⁵⁾ used a simple apparatus with a single rod for their experimental studies. Andreoni investigated the influence of injection rate, heat generation rate, coolant temperature, and initial clad temperature on quench time and heat transfer. Sudo showed that the flow area affected local coolant temperature and flow regimes on account of the existence of a structural wall in a flow section which affected the heat transfer during reflood, and indicated a relation between heat transfer regime and clad temperature.

This report presents an experimental study relating to flow regime, quench front transition, and clad surface heat transfer as a part of evaluation of reflood behavior during LOCA. The study used a simple apparatus with a single electrically heated rod. In tests the rod was cooled down gradually by a coolant which advanced upward.

Fig.1 Typical responses of clad temperature and heat transfer coefficient during reflood

2. Nomenclature

- a : inner radius of a heated rod, cm
- b : outer radius of a heated rod, cm
- h : heat transfer coefficient, $\text{kcal/m}^2\text{h}^\circ\text{C}$
- q' : heat flux, $\text{kcal/m}^2\text{h}$

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q_e : heat generation rate, cal/cm²s
 r : radial length, cm
 T_{wi} : initial clad temperature, °C
 T_{li} : inlet coolant temperature, °C
 T_q : quench temperature, °C
 T_s : water saturation temperature, °C
 T_w : clad temperature, function of time, °C
 t : time after reflood starts, s
 U : flooding speed, cm/s
 U_q : quench front ascending speed, cm/s
 W_e : generated power, kW/m
 X : distance above heated section, cm
 Y_q : quench time, s
 δ : clad thickness, cm
 $(\rho c)_w$: heat capacity of rod, cal/cm³°C

3. Experimental apparatus and procedure

Figure 2 shows a schematic of the experimental apparatus. It consists of a heated test section, coolant injection systems, electric equipment for heating, instruments for measuring temperature and pressure, and recorders. Fig.3 shows two kinds of heated test sections used in this study. Test section 1, comprises a stainless steel tube (1 m long, 10 mm OD, 8 mm ID) with copper electrodes ($\phi 10 \times 500$, $\phi 10 \times 600$) at both ends of the tube and a quartz glass tube (20 mm ID) outside of the heated tube. As shown in Fig. 2, an outermost pyrex glass tube makes another annular flow section, and this extra annular path is flooded to maintain the temperature of the quartz glass at a constant value. Test section 2, a tubular test section, comprises a stainless steel tube (0.95 m long, 15 mm OD, 14.4 mm ID) and copper electrodes. The stainless steel tubes in both test sections are heated electrically. The test section 1 was mostly used in this study. Chromel-alumel thermocouples were installed on the heated wall at five different elevations and in the coolant flow section at three different elevations to measure the local coolant temperature. Fig. 4 shows methods to install thermocouples on the heated wall in the test section 1. (1) A C-A thermocouple, 0.1 mm in diameter, was caulked in a hole (0.4 mm ID) drilled on the outer surface of the heated tube. (2) A sheathed C-A thermocouple, 1 mm OD, was attached to the tube through the inner surface of the tube. Inlet coolant temperature was measured by a copper-constantan thermo-

couple. Pressure at the bottom of the test section was measured by a pressure gage. All measured values were recorded on a magnetic oscillograph or a data recorder. The test section 2 was used to measure the clad temperature response without an effect of liquid boiling, and C-A type thermocouples were installed by spot welding on the outer wall of the tube at ten different elevations. A purified coolant was injected into the bottom of the test section from a high pressure reservoir (3 atg) through a needle valve controlling injection rate, or from a head tank with 1.3 m height above the bottom of the heated tube. In most tests the high pressure reservoir was used to obtain a constant flow rate during the experiments.

The tests were started by injecting a coolant into the test section when the rod was heated and the clad temperature reached a specified value, and they were stopped when all surfaces of the heated rod were cooled below saturation temperature.

Experimental parameters and their ranges are:

Initial clad temperature	250-800 °C
Inlet coolant temperature	16- 86 °C
Flooding speed	1.2-10.3 cm/s
Generated power	0.2-1.0 kW/m

Fig.3 Configuration of Test section 1 and 2.

Fig.2 Schematic diagram of experimental apparatus

Fig.4 Method for thermocouple installation in Test section 1

4. Result and Discussion

4.1 Visual and photographic results

Figures 5 and 6 show photographs which present a flow boiling occurring along the test section during the experiments. In both figures, photos.(1) and (2) were taken at the lower part of the test section, and photos.(3) and (4) at the middle part. When the inlet coolant temperature was low (see Fig.5), immediately after the coolant reached a heated section, boiling occurred and vapor bubbles were generated over the flow area. Since a liquid level advanced at a higher speed than the quench front did, a boiling region was lengthened with time. Photos.(3) and (4) in Fig.5 indicate that sizes of flow bubbles grew large and the number of them decreased as the boiling region advanced upward. Nucleate boiling did

not occur uniformly in the radial direction of the rod, but a wavy distribution on the heated rod existed to connect circumferentially incipient boiling points of nucleate boiling. It was observed that the wavy distribution caused the heated rod to be bent with vibration. Fig.6 shows photographs in a high inlet coolant temperature condition (85 °C). The photographs are a little different from those shown in Fig.5. A vapor film was formed along the rod immediately after reflood started instead of small bubbles over the flow area observed in Fig.5, photo. (1). A vapor film whose existence was more clearly recognized than one in Fig.5 was lengthened with time along the rod. A liquid-vapor boundary with a round shape was formed around the incipient boiling point due to a violent generation of vapor. The generated vapor was not discharged into the liquid but passed through the vapor film.

Fig.5 Boiling pattern in the test section
($T_{wi}=400$ °C, $T_{li}=17$ °C, $U=2.5$ cm/s)

Fig.6 Boiling pattern in the test section
($T_{wi}=400$ °C, $T_{li}=85$ °C, $U=2.5$ cm/s)

4.3 Temperature response and flow regimes

Figure 7 shows responses of clad temperature, local coolant temperature, and inner surface temperature of the quartz tube, and also shows flow regimes observed each time at elevation $X=70.5$ cm. The temperatures were measured by three thermocouples located at the same elevation, which were installed: by (1) in Fig.4 for the clad temperature; around the middle position in the flow area for the coolant; and on the inner surface for the quartz tube. For the response of clad temperature two points were characteristic in the reflood behavior. One is point A which is known as a turnaround point, and the other is point B which is known as a quench point.

Figure 8 shows photographs and a response of clad temperature measured by a thermocouple installed like (2) in Fig.4. In the figure the arrow indicates the location of the thermocouple T1. The other thermocouple T2 was located 30 cm above T1. Event times of photos. (1),(2),(3), and (4) correspond to times shown by 1,2,3, and 4 on the temperature response, respectively. The figure indicates that a turnaround was caused by arrival of the water level, and a quench was caused by nucleate boiling. Flow regimes shown in Fig.7, therefore, consist of vapor cooling appearing before time A, film boiling or transition boiling between times A and B, nucleate boiling around time B, and liquid forced convection after nucleate boiling. Comparison of temperature responses between Figs. 7 and 8 with visual observations indicates that between times A and B the rod was cooled by temporary liquid contact or access of liquid column to the heated wall. Measurements of coolant temperature and inner

Fig.7 Clad surface temperature response and flow regime observed each time

surface temperature of the quartz tube indicated that the coolant temperature between times A and B nearly constant (94-97 °C) and almost uniform over the flow area even if the inlet coolant temperature was as low as 20 °C. This indicates that a large amount of heat was transferred to the coolant around the quench front and the boiling caused the coolant to be mixed due to a small flow area. The coolant temperature after quench front suddenly dropped to a temperature a little higher than the inlet value. The clad temperature around turn-around decreased gradually when the inlet coolant temperature was high, but decreased suddenly when it was low since the liquid might be easier to contact with the rod wall due to a thin vapor film.

Figures 9 and 10 show temperatures measured at quench front. Data in Fig.9 were obtained in test section 1 and data in Fig. 10 were obtained in test section 2. Two figures indicate that the quench temperature has such a trend that it decreases with an increasing elevation although measured values have a large amount of scatter specially shown in Fig.9 and it decreases with an increasing inlet coolant temperature. The quench temperatures distribute between 200 and 300 °C at high inlet coolant temperature. Increment of quench temperature above the elevation $X=70$ cm, shown in Fig.10, might be due to outlet effect or due to a quenching caused by droplets entrained at a lower elevation.

4.3 Transient and ascending speed of quench front

Fig.8 Comparison of clad temperature response with boiling pattern ($T_{wt}=500$ °C, $T_{li}=40$ °C, $U=8.3$ cm/s)

As mentioned before, quenching occurs due to complete liquid contact with a heated wall, and the wall temperature drops to near saturation. In this study to obtain many experimental data at every 5 to 10 cm height instead of limited thermocouple locations, the quench front was visually measured every time by the correspondence between flow regime and clad temperature response which was defined in Section 4.2.

Figures 11 to 14 show measured quench front changes. Figs.11,12, and 13 show measured values for a constant injection rate, and Fig.14 shows them for a constant head. Fig.11 and 13 indicate that the quench front advances at nearly constant speed instead of at different heat generation rates when the inlet coolant temperature is low. As shown in Fig.12 when it is high, in the lower part of the heated rod the quench front advances more slowly than the one with a constant value appearing

in higher part of it. When the injection rate is too small as shown by curve 7 in Fig.12, the quench front is impeded in advance. This phenomenon was due to liquid blowing which was caused by an oscillation of coolant excited by a large vapor bubble generated in the liquid forced convection region. As shown in Fig.14 if the constant head was used for injection, the quench front did not advance at a constant speed. In the figure a broken line shows a change of a water level when the rod is not heated, and $\bar{U}$ is an injected water speed averaged between $X=0$ and 100 cm.

Fig.9 Quench temperature distribution along the level of the heated rod (test section 1)

Fig.10 Quench temperature distribution along the level of the heated rod (test section 2)

Fig.11 Quench front change with a constant injection rate (test section 1)

Figures 15 and 16 show ascending speed of the quench front against coolant injection speed. The ascending speed was calculated by the least mean square method from a slope of the measured quench front change. If the inlet coolant temperature is high as shown in Fig.12, it is represented by a constant slope appearing in the middle part of the rod. Figures 15 and 16 indicate that the ascending speed is a linear function of the injection speed within the range of experimental conditions in this study; the slope of the curve, however, is sensitive to initial clad temperature and inlet coolant temperature.

Figure 17 shows ascending speed versus heat generation rate. Comparison of results for $T_{wi}=500^\circ\text{C}$ indicates that a larger heat generation rate caused the quench front to advance more slowly. This is due to the fact that a temperature rise before the turnaround increases with an increasing heat generation rate and has a large effect on the ascend-

Fig.12 Quench front change with a constant injection rate (test section 1)

Fig.13 Quench front change with a constant injection rate (test section 1)

ing speed of the quench front. The results in the case of high heat generation rate in this figure show that if the injection speed is low, the ascending speed is close to a value for $T_{wi}=700^\circ\text{C}$, but if it is high, it is close to a value for $T_{wi}=600^\circ\text{C}$.

Figures 18 and 19 show the ascending speed of the quench front the initial clad temperature. In both figures at every injection speed the ascending speed decreases linearly with an increasing clad temperature and the slopes of the linear distributions become steeper with an increasing injection speed.

Fig.14 Quench front change with a constant head (test section 1)

Fig.15 Ascending speed of quench front for low inlet coolant temperature at different injection speeds (test section 1)

Fig.16 Ascending speed of quench front for high inlet coolant temperature at different injection speeds (test section 1)

Fig.17 Effect of generated power on ascending speed of quench front (test section 1)

Fig.18 Effect of initial clad temperature on ascending speed of quench front for low inlet coolant temperature (test section 1)

Fig.19 Effect of initial clad temperature on ascending speed of quench front for high inlet coolant temperature (test section 1)

4.4 Heat transfer coefficient in film boiling region

A temperature profile in the heated rod was computed numerically from

$$\frac{\partial T_w}{\partial t} = \alpha \left(\frac{\partial^2 T_w}{\partial r^2} + \frac{1}{r} \frac{\partial T_w}{\partial r} \right) + \frac{q_e'}{(\rho c)_w \delta} \quad (1)$$

The calculation started from the time when the clad temperature turned around at each elevation. The measured clad temperature, which was filtered digitally to eliminate oscillations, was used as one of boundary conditions. Since the inner space of the rod is filled with air, the initial and boundary conditions are given by

$$T_w = T_{wi} \quad t = 0 \quad (2)$$

$$\frac{\partial T_w}{\partial r} = 0 \quad r = a \quad (3)$$

$$T_w = T_w(t) \quad r = b \quad (4)$$

A nodalization to numerically solve Eq. (1) is shown in Fig.20. The clad thickness was divided into ten equal meshes. The temperatures at the meshes were calculated every 0.01 second by the Crank-Nicolson method. Heat transfer coefficient and heat flux were calculated by using the radial temperature profile computed by Eq.(1) from

$$Q' = -(\rho c)_w \frac{\Delta r}{2} \frac{T_{10}^{j+1} - T_{10}^j}{\Delta t} + \lambda \frac{T_{10}^j - T_{11}^j}{2\Delta r} + \frac{\Delta r}{2\delta} q_e' \quad (5)$$

$$\text{where, } T_{10}^j(3/4) = \frac{3}{4} T_{11}^j + \frac{1}{4} T_{10}^j$$

j : time mesh

$$h = \frac{Q'}{T_{11}^j - T_s} \quad (6)$$

where T_s is equal to 100 °C since in the film boiling region the coolant temperature was nearly at saturation as shown in Section 4.2.

The calculated heat transfer coefficient is shown in Fig.21, in which the clad temperature used as a boundary condition (4) is also plotted. Comparison of heat transfer coefficient history with the temperature response indicates that the heat transfer coefficient was thousands kcal/m²h°C around the turnaround, tens to hundreds kcal/m²h°C in the film boiling region, and more than thousand kcal/m²h°C around the quench front.

Fig.20 Computational nodes in the heated rod for computing temperature profile

Fig.21 Relation between heat transfer coefficient history and clad temperature response (test section 1)

However, the heat transfer coefficient around the quench front was not accurate due to difficulty of temperature measurement. The heat transfer coefficient around the turnaround was sensitive to inlet coolant temperature and the magnitude of it decreased with an increasing inlet coolant temperature.

5. Conclusions

Experimental results are summarized as follows:

- (1) The change in heat transfer regimes at a given location of the heated rod during reflood follows the sequence: vapor cooling, film boiling (or transition boiling), nucleate boiling, and liquid forced convection.
- (2) The heat transfer regimes which should be considered during reflood are film boiling which appears in most area of the rod and nucleate boiling which occurs around quench front.
- (3) The heat transfer coefficient is tens to hundreds 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 if the inlet coolant temperature is low (around 20 °C in this study). If it is high (more than 80 °C in this study), the speed is very low at the lower part of the rod, but it increases as the quench front advances and reaches a nearly constant value.

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