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《Original》

Experimental Study of Rewetting Phenomena

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Abstract

Reflood experiments under atmospheric pressure have been conducted with a single heated tube to investigate basically the rewetting phenomena following a LOCA.

Experimental conditions are 180cm length of test tube, wall temperature range of 300-800°C, coolant flooding rate of 5-30cm/sec. and subcooling of 35-85°C.

Experiments show that the rewetting velocity is dependent on the initial wall temperature of test tube, coolant flow rate and coolant subcooling. It is required to develop the proper method to evaluate the rewetting temperature and the heat transfer coefficient.

요 약

냉각재 상실사고에 따르는 rewetting 현상을 연구하기 위하여 대기압에서 단일가열관을 사용한 재관수 실험을 수행하였다.

Yamanouchi 이론을 바탕으로한 1차원 및 2차원 열전도 해석을 본 실험조건과 일치시키기 위해 수정하여 실험결과와 비교 검토하였다. 하부재관수 해석에서는 unrewetted 구역에서 증기의 열전달이 고려 되어야 한다는 것을 알았다.

실험을 통해 rewetting 속도는 시험관의 초기벽온도, 냉각재 유량, 냉각재 온도에 따라 달라진다는 것을 알았다.

rewetting 온도와 열전달 계수를 평가하기 위한 보다 나은 방법의 개발이 필요하다.

I. Introduction

The loss of coolant accident(LOCA) initiated by the rupture of the primary coolant piping is the most severe postulated accident in a nuclear power plant. It is known that the occuring probability of the LOCA could be less than 10^{-6}, but venders should submit the accident analysis report of the LOCA to the Nuclear Regulatory Committee, in order to acquire the construction licence of the nuclear power plant. It is therefore important to investigate the physical phenomena following a LOCA and the emergency core cooling water injection.

Although the reactor could be shut down immediately following a LOCA the fuel cladding temperatures begin to increase because of the heat stored in the fuel rods and of the decay heat from the radioactive fission products.

If the temperature rise of the fuel cladding could not be prevented, the cladding would experience the, so called, "boiling crisis". As a result, some parts of the cladding would be damaged to leak out the radioactive materials to the containment. To prevent this undesirable inicident, emergency *core cooling* system(ECCS) is provided. Therefore, it is very important to investigate the physical phenomena during a LOCA, and to analyze the performance of ECCS for the evaluation of the reactor safety.

Following a LOCA, the phases of the accident can be considered as; subcooled and saturated blowdown, refill, reflood and long term cooling.

Rewetting, which occurs in the reflood phase, can be defined by the change in heat transfer regime during the cooling process of a hot surface from film to nucleate boiling.

In case of film boiling the heat transfer from the hot surface to the coolant takes place mainly through a vapor film covering the hot surface. When the hot surface is cooled down to a temperature where direct contact between coolant and surface

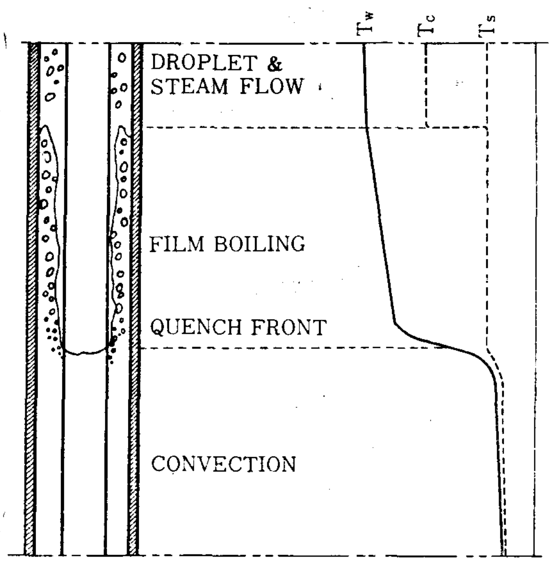

Fig. 1. Rewetting Phenomena

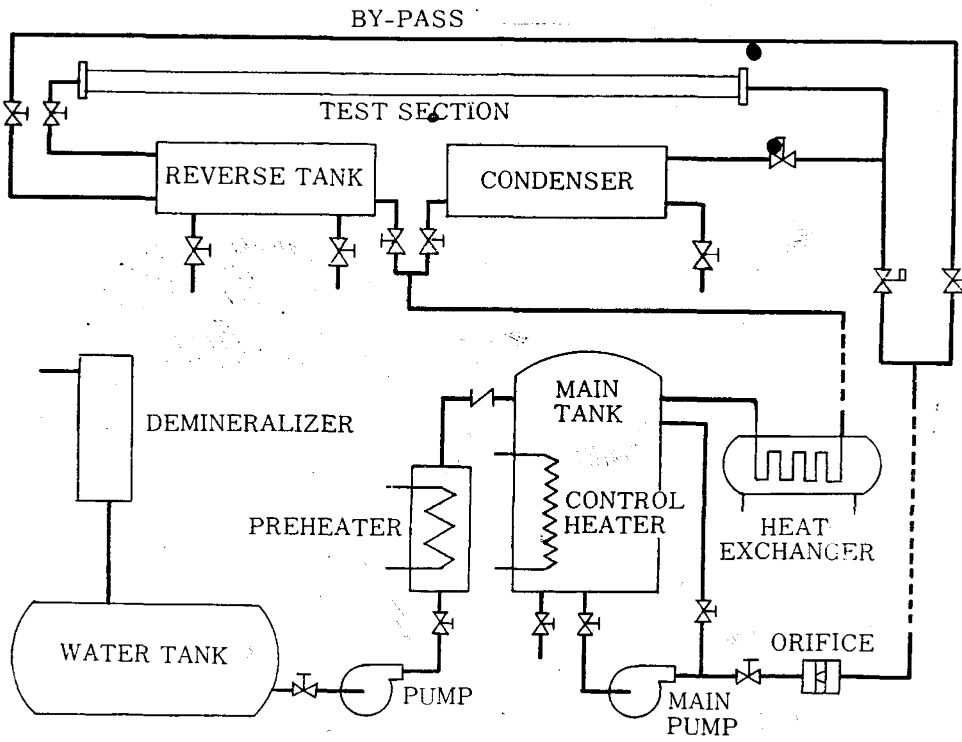

Fig. 2. Schematic Diagram of Test Loop

takes place, nucleate boiling is then possible. In this case the hot surface is said to be quenched or rewetted. The rewetting phenomena are shown in Fig. 1.

Present study in this paper aims to investigate the physical characteristics of rewetting phenomena experimentally. Rewetting velocity in the single heated tube was measured under the atmospheric pressure with the parameter of initial wall temperature, coolant flow rate, and coolant subcooling.

Ⅱ. Experimental Apparatus

Fig. 2 shows the schematic diagram of test loop. The loop consists of 2 parts, one is fixed part, the other is test part. The fixed part is installed to supply the coolant to the test section and consists of demineralizer, water tanks, preheater, control heater, pump, heat exchanger and flowmeter.

The coolant is heated up to 85°C to maintain a given temperature and the flow rate can be varied in the range of 5-30cm/sec through the flowmeter.

Test part consists of single tube test section, condenser tank and reverse tank. The worm gear is installed to set the test section at any angle between horizontal and vertical position. Vapor from the test section is condensed in condenser tank and returns to the main tank.

Test section is heated by 5 KVA, 1000 ampere max., D.C. power supply. Temperature controller is set and prevents the test section from overheating. Wall temperature can be heated up to 800°C and the outside of test section is insulated with asbestos to prevent heat loss. Outlet part of the test section is connected to the U-shaped flexible hose to prevent the test section from damaging by thermal expansion. Physical characteristics of test section are summarized in Table 1.

Table 1. Physical Characteristics of Test Section

Material	S.S 304
Tube O.D.(mm)	19.4
Tube thickness(mm)	0.89
Tube length(m)	1.8

To measure the temperature change of the tube wall alumel-chromel thermocouples are spotwelded onto the outside wall of test section, 20cm spacing in axial direction and 4 circumferential points of each elevation as shown in Fig. 3.

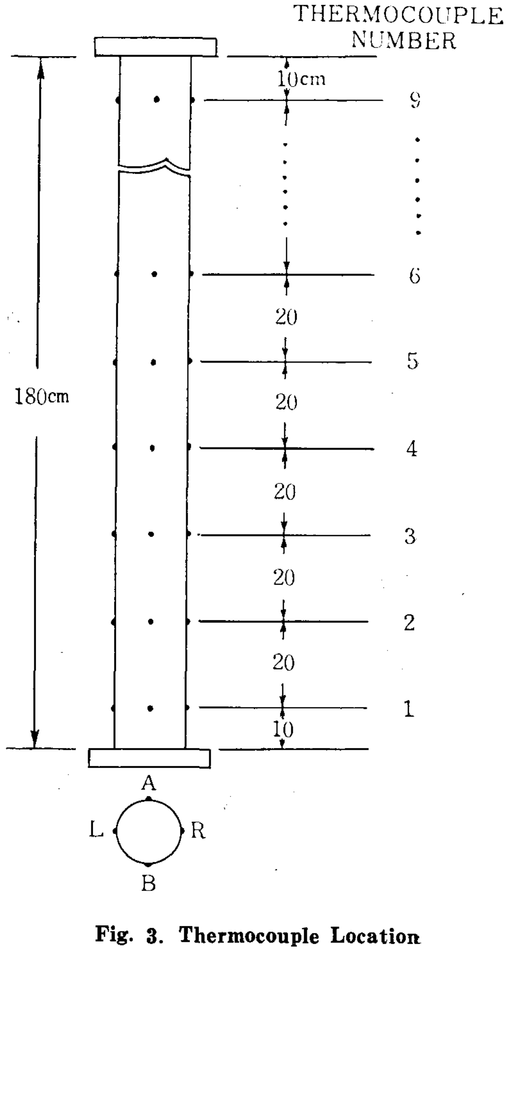

Fig. 3. Thermocouple Location

Ⅱ. Experimental Procedure and Data Reduction

As a coolant, pure water is used, which is produced by the demineralizer and stored in the water tank. This stored coolant is then supplied to the main tank through the preheater which could heat the coolant near the desired temperature. And the control heater maintains the temperature of the coolant to the set point.

During the heating of the test section, power is increased stepwise until the necessary temperature is obtained. After the temperature of the test section reaches the set point, the quick acting valve is opened and the coolant is injected to the test section with the predetermined flowrate. Power is shut off at the moment of coolant injection to the test section. The temperature changes of test section are detected by thermocouples and recorded by strip chart recorder and digital data aquisition system (Hewlett Packard 9815).

During the experiments, some of the thermocouples were damaged by repeated thermal expansion. But the remained thermocouples were enough to get sufficient data. The typical temperature-time traces are shown in Fig. 4.

The rewetting velocity is defined as

$$U_{ij}=\frac{\Delta Z_{ij}}{\Delta t_{ij}}$$

where U_{ij} is the rate of the rewetting front propagation between two particular thermocouples of interest, ΔZ_{ij} is the axial distance between the thermocouples, and Δt_{ij} is the time interval taken between the two rewetting front. It is therefore necessary to

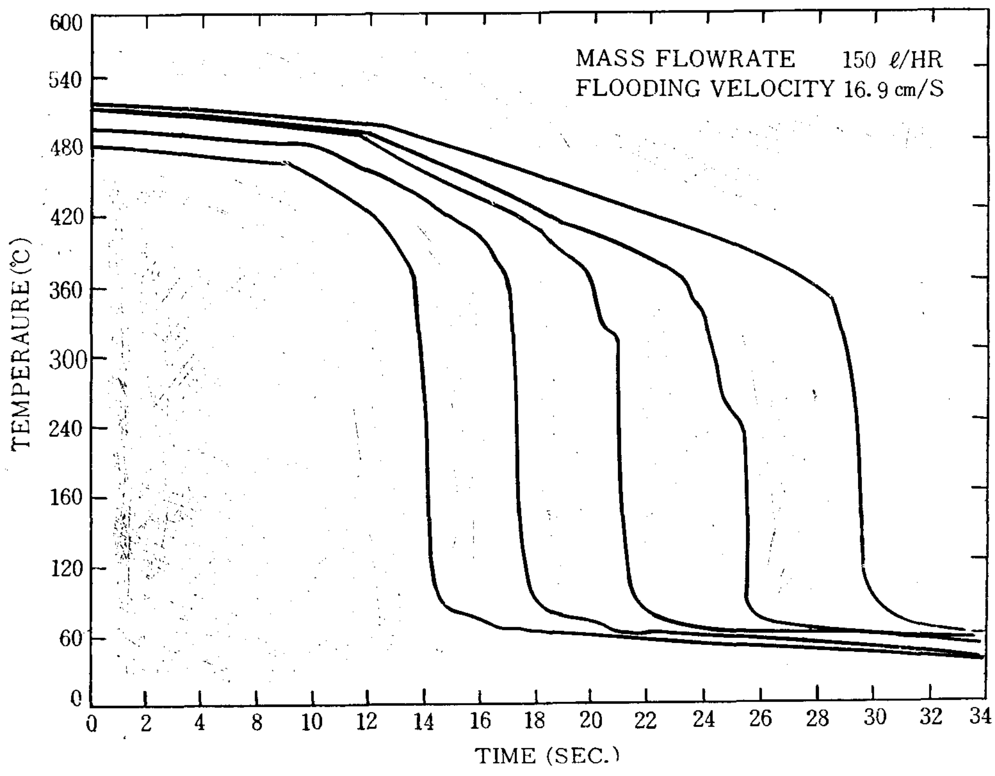

Fig. 4. Temperature-time Traces

decide the point, where the actual rewetting front passes the particular thermocouples. However it is almost impossible. For the calculation of rewetting velocities, it suffices to determine only a reference point for a given temperature-time trace. This is done by taking the intersection of the gradients of the traces before and after the region, where the rapid fall in temperature is recognized as shown in Fig. 5. This method is also generally used by other workers[1].

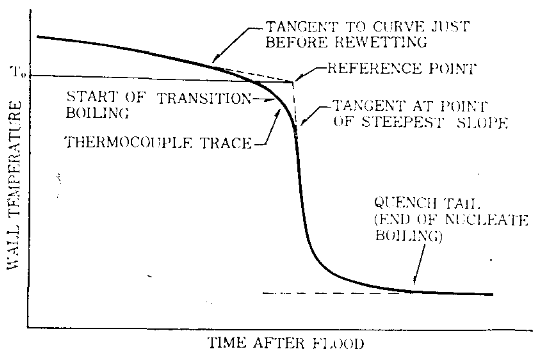

Fig. 5. Definition of Rewetting Temperature Reference Point

Since the thermocouples were welded onto the outside wall of the test section, it is required to have the solution of the inverse heat conduction equation[14] to obtain the transient wall temperature on the inside surface where the actural rewetting phenomena take place. This calculation method of the conduction problem is described in appendix.

Ⅳ. Results and Discussion

According to the results of the theoretical and experimental analysis the parameters which affect the rewetting velocity are material of test tube, reproducibility of test results, system pressure, rewetting temperature, initial temperature of test tube, injected coolant temperature, coolant flow rate, thickness of test tube, and two-phase heat transfer mechanism during reflooding. Since the experiment has been carried out with S.S. 304 tube with the given thickness under atmospheric pressure, above parameters except system pressure, material of test tube and thickness of test tube are discussed here and, if possible, compared with experimental results.

1. Reproducibility of the Test Results

It is already known that the surface condition affects the boiling heat transfer mechanism involved[2].

Elliot et al.[3),4] reported that rewetting velocity showed progressive improvement with time and that the results of later experiments were 2-4 times faster than those of initial test runs. This tendency was backuped by the experiments of Piggot et al.[5]. These investigators concluded that the effect was due to the initial surface oxidation.

Contrary to this, Lee et al.[1] reported that during their early test runs rewetting velocity was gradually decreased with time and that after 7 days it remained constant. But it was not reported that how many times the experiments were conducted.

In the present study we conducted preliminary tests to investigate the effects of the surface conditions. The temperature-time traces resulted from the 4th preliminary test and 14th preliminary test are shown in Fig. 6. And the result shows the coincidence of the two, so the experimental data are reproducible.

It can be considered that the effects of surface conditions on rewetting are due to the change of thermal properties and the change of characteristics of active nuclea-

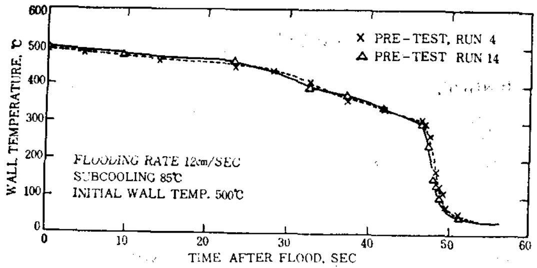

Fig. 6. Reproducibility of Test Restlts

tion sites of the surface, but it is not easy to predict how they would affect the rewetting velocity itself.

All the experimental results reported here are those obtained from the experiments after 15 preliminary tests during 5 days.

2. Rewetting Temperature

Rewetting temperature is generally considered to be dependent on the coolant physical properties, material properties of fuel cladding, surface conditions of fuel cladding, system pressure, coolant flow rate, initial coolant temperature, flow regime of coolant, and the impact angles of droplets onto the surface of the fuel cladding. But it is not well known yet that how each of these parameters affects the rewetting temperature because of their simultaneous effects on rewetting temperature. Also, it is very difficult to obtain rewetting temperature experimentally because the rewetting phenomena are highly transient and show very steep temperature gradient at rewetting front.

Many investigators assume the rewetting temperature of their own, but those are different from one another very significantly, i.e., 280-540°C in FLECHT experiment[6], 150°C under the atmospheric pressure by Yamanouchi[7], 260°C by Elias and Yadigaroglu[8], 190-250°C by Duffey and Porthouse[9], 260°C by Blair[10], and 200°C by Thompson[11].

In the present experimental study, the temperature which is the intersection of the tangent of the curve just before the steep gradient and the tangent of the curve just after the steep gradient is considered to be the reference temperature (not to be a rewetting temperature) as shown in Fig. 5.

It is very difficult to obtain the actual rewetting temperature, and so, it will belong to the future research work.

3. Effect of Initial Wall Temperature

A linear relationship between the inverse rewetting velocity and the initial wall temperature was proposed by Yamanouchi[7] who delivered the analytical one-dimensional solution and by Duffey and Porthouse who delivered the analytical two-dimensional solution on rewetting and was confirmed by experiments[12].

But according to the PWR-FLECHT expe-

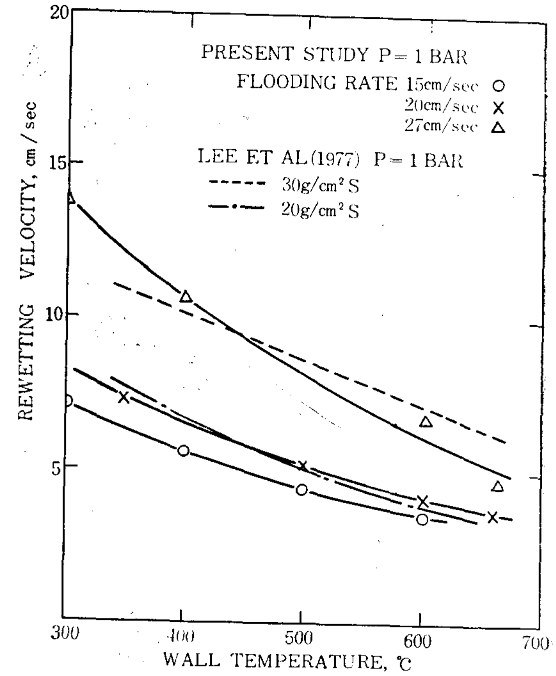

Fig. 7. Effects of Initial Wall Temperature and Flooding Rate on Rewetting Velocity

riment[6], there's a tendency that the rewetting velocity is almost independent of the initial wall temperature. And this is due to the fact that the decrease of subcooling counteracts the increase of initial wall temperature.

In the present study, the rewetting velcoity is decreased with the initial wall temperature increase as shown in Fig. 7. The result is in good agreement with the experimental result of Lee et al.[1] and with the theories of Yamanouchi[7] and Duffey[9].

4. Effect of Subcooling

It was observed by experiments[5),13] that the rewetting velocity increases as subcooling increases. It was pointed out that this result was caused by the increase in heat transfer coefficient due to the increase in subcooling.

On the contrary, however, Thompson[11] insisted that increase in subcooling contribute the increase in rewetting temperature. Further work should be necessary for better understanding of the effect of subcooling on rewetting velocity.

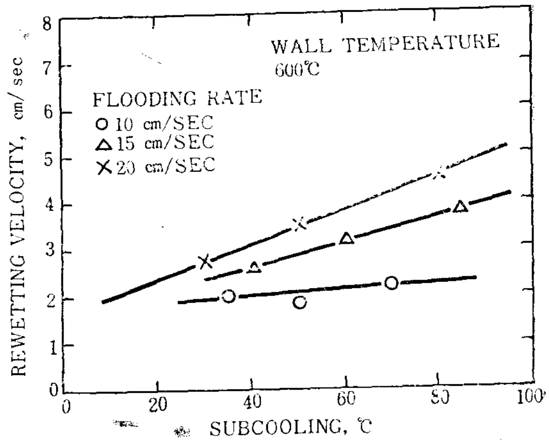

Fig. 8. Effect of Inlet Coolant Subcooling

Fig. 8 shows the experimental results. Rewetting velocity is plotted as a function of subcooling, with a parameter of flooding rate. This shows that the increase in subcooling brings the increase in rewetting velocity.

In Fig. 9, the effects of subcooling of 70°C and 85°C are compared. Rewetting

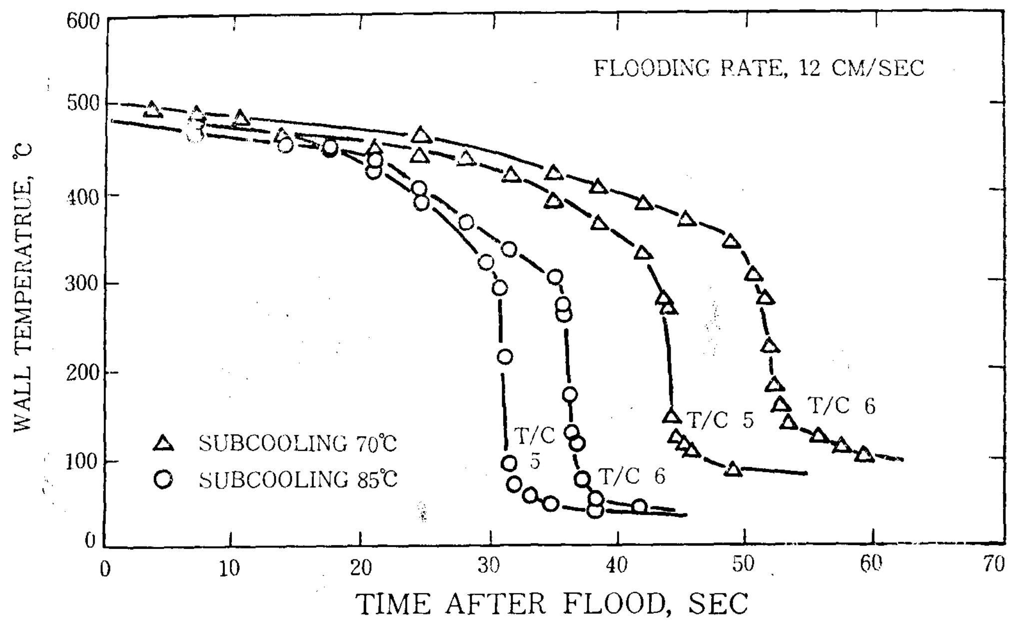

Fig. 9. Effect of Coolant Temperature on Rewetting Time and Rewetting Temperature

time is longer in the case of subcooling of 70°C than that of 85°C.

In both cases, rewetting temperature are almost equal, but the temperatures where nucleate boiling ends are different, i.e, about 100°C for subcooling of 70°C and about 50°C for subcooling of 85°C.

5. Coolant Flow Rate

Elliot et al.[3,4] reported that rewetting velocity is independent of coolant flow rate under higher pressure than that of atmosphere. But Yamanouchi[7], Duffey et al[9], and Lee et al.[1] reported by their experimental study under atmospheric pressure that the increase in coolant flow rate increases the rewetting velocity.

Fig. 10 shows the effects of coolant flow rate on the rewetting velocity with a parameter of initial wall temperature.

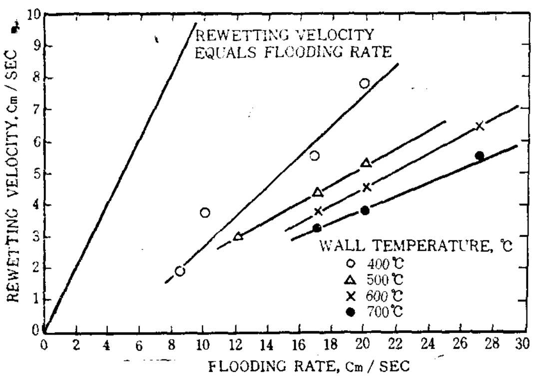

Fig. 10. Effect of Flooding Rate on Rewetting Velocity

For all cases of the wall temperatures the rewetting velocity increases linearly as the coolant flow rate increases. This is because the increase in coolant flow rate may increase the heat transfer coefficient and precursory cooling of the unrewetted region of the tubes. However, the relations between heat transfer coefficient and rewetting temperature are not known and have to be investigated continuously.

6. Heat Transfer Coefficient

Heat transfer coefficient of rewetting for the test tube is defined as follows.

$$h=\frac{-k\left.\frac{\partial T}{\partial R}\right|_{R_o}}{T_o-T_s} \quad \cdots\cdots\cdots\cdots (1)$$

where k : thermal condnctivity of the tube

$\left.\frac{\partial T}{\partial R}\right|_{R_o}$: Radial temperature gradient of the tube outside surface at the rewetting front

T_s : Saturated temperature

T_o : Rewetting temperature

As shown in equation (1), heat transfer coefficient includes the rewetting temperature, T_o. Since the assuming of rewetting temperature T_o is very different from one researcher to another, it is very difficult to determine a real heat transfer coefficient.

Furthermore, difficulty for the assumption of heat transfer coefficient is that the heat transfer coefficient changes with local conditions. In the determination of heat transfer coefficient there exist a large difference between the phenomena in top-spray and bottom-flooding condition.

The radiation heat transfer phenomena play an important role in top-spray, whereas the cooling effect of vapor on the unrewetted region of the tube has to be taken into account in bottom flooding.

Yamanouchi equation for one-dimensional analysis[7] and Duffey equation for two-dimensional analysis[9] are based on the same assumption, that is, heat transfer coefficient of the unrewetted region is zero. This assumption could meet the case of top-spray but not meet the case of bottom-flooding under the negligible radiation heat transfer conditions.

To insert the effects of vapor cooling on the heat transfer coefficient in bottom-flooding still remains a future research work.

CONCLUSIONS

(1) Experimental studies for the rewetting phenomena are carried out under atmospheric pressure with the vertical single tube.
(2) Effects of the parameters, which play a role in the rewetting phenomena are observed and discussed.
(3) It is known that the study for the determination of the rewetting temperature remains a future work.
(4) In bottom-flooding the cooling effect of vapor on the unrewetted region of the test tube should be taken into account in the future work.

APPENDIX

Solution of Inverse Heat Conduction Problem

In the present experiments, it is required to predict the inside surface temperature of tube wall, since the thermocouples are attached onto the outside tube wall.

To predict the inside surface temperature of tube wall we could proceed by solving the inverse heat transfer problem[14] as follows. The governing equation is Fourier's unsteady state conduction equation, i.e

$$\Delta^2 T = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

where α is the thermal diffusivity of the material

Neglecting the temperature variation in θ-and Z-direction for cylindrical coordinates yields

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \frac{1}{\alpha}\frac{\partial T}{\partial r} \qquad (1)'$$

with boundary conditions

$$T(R_o, t) = T_o(t) \qquad (2)$$

$$\left.\frac{\partial T}{\partial r}\right|_{R_o, t} = O \qquad (3)$$

where R_o is outside radius and T_o is the outside wall temperature.

$T_o(t)$ is measured by thermocouples and boundary condition (3) is valid because the outside of the tube wall is insulated.

Assuming the solution of equation (1) to be

$$T(r,t) = \sum_{i=o}^{\infty}\frac{1}{\alpha^i}f_i(r)g_i(t) \qquad (4)$$

And inserting the equation (4) into (1)', (2), (3) yields

$$\sum_{i=o}^{\infty}\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\frac{\partial f_i}{\partial r}\right)g_i = \sum_{i=o}^{\infty}\frac{1}{\alpha^{i+1}}f_i(r)\cdot g_i'(t) \qquad (5)$$

$$\sum_{i=o}^{\infty}\frac{1}{\alpha^i}f_i g_i = T_o \qquad (6)$$

$$\sum_{i=o}^{\infty}\frac{1}{\alpha^i}f_i' g_i = O \qquad (7)$$

Arranging these equations with respect to α^{-1} and integrating $f_i(r)$, $g_i(t)$ sequencially yields

$$f_o(r) = 1$$

$$f_1(r) = \frac{R_o^2}{4}\left[\left(\frac{r}{R_o}\right)^2 - 1 - 2ln\left(\frac{r}{R_o}\right)\right]$$

$$f_2(r) = \frac{1}{64}(r^4 - 5R_o^4) - \frac{R_o^2 r^2}{8}ln\left(\frac{r}{R_o}\right) - \frac{R_o^4}{16}ln\left(\frac{r}{R_o}\right) + \frac{R_o^2 r^2}{16}$$

$$g_o(t) = T_o(t), \quad g_1(t) = T_o'(t), \quad g_2(t) = T_o''(t), \cdots\cdots\cdots\cdots$$

Therefore

$$T(r,t) = T_o(t) + \frac{1}{\alpha}\frac{R_o^2}{4}\left[\left(\frac{r}{R_o}\right)^2 - 2ln\left(\frac{r}{R_o}\right) - 1\right]T_o'(t) + \frac{1}{\alpha^2}\left\{\frac{1}{64}(r^4 - 5R_o^4) - \frac{R_o^2 r^2}{8}ln\left(\frac{r}{R_o}\right) - \frac{R_o^4}{16}ln\left(\frac{r}{R_o}\right) + \frac{R_o^2 r^2}{16}\right\}T_o''(t) + \qquad (8)$$

Substituting r with inside radius R_i in equation (8) yields

$$T(R_i,t)=T_o(t)+\frac{1}{\alpha}\frac{R_o^2}{4}\left[\left(\frac{R_i}{R_o}\right)^2-1-2ln\left(\frac{R_i}{R_o}\right)\right]T_o'(t)+\frac{1}{\alpha^2}\left[\frac{1}{64}(R_i^4-5R_o^4)-\frac{R_o^2R_i^2}{8}ln\left(\frac{R_i}{R_o}\right)-\frac{R_o^4}{16}ln\left(\frac{R_i}{R_o}\right)+\frac{R_o^2R_i^2}{16}\right]\cdot T_o''(t)+\cdots \qquad (9)$$

So we can predict the inside surface temperature of tube wall using equation (9) if temperature is expressed as a function of time.

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