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REWETTING OF A HOT SURFACE BY A FALLING LIQUID FILM—EFFECTS OF LIQUID SUBCOOLING

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Abstract—The wet front velocity and the surface heat flux distribution are investigated with a system of hot stainless steel and a subcooled Freon 113 liquid film at atmospheric pressure. For high subcoolings and flow rates, the wet front velocity increases with the product of the inlet subcooling and flow rate. A two-dimensional analysis is used for deriving the surface heat flux. The result shows that, arising from the fact that the subcooled film front is irregular, the heat flux at the surface ahead of the quench front increases with increasing liquid subcooling.

NOMENCLATURE

a	thermal diffusivity
c_p	specific heat
h	heat transfer coefficient
k	thermal conductivity
q	heat flux
R_i	inside radius of the tube
r	radial coordinate
T	temperature
T_s	saturation temperature
T_{wet}	rewetting temperature
T_{wi}	initial wall temperature
ΔT_s	wall superheat, $T_w - T_s$
ΔT_{sub}	inlet liquid subcooling, $T_s - T_{lin}$
ΔT_{wet}	wall superheat at rewet point, $T_{wet} - T_s$
ΔT_{wi}	initial wall superheat, $T_{wi} - T_s$
t	time
Δt	time interval
U	wet front velocity
Z	axial coordinate moving with the wet front
z	fixed axial coordinate.

Greek symbols

Γ	liquid film flow rate per unit periphery
δ	wall thickness
ρ	density.

Subscripts

l	liquid phase
w	tube wall.

1. INTRODUCTION

IN THE falling liquid film cooling of hot vertical surfaces, the wet front of the film with violent boiling and sputtering flows down slowly as the surface ahead of it is cooled to the rewetting temperature. This phenomenon has been extensively investigated with particular reference to the emergency core cooling of water reactors.

In the cooling process, the surface heat transfer rate by boiling is so high that a steep gradient in wall temperature takes place across the wet front. Therefore, the axial heat conduction in the wall takes an important part in this process. Various 1- and 2-D heat conduction models have been proposed to describe the wet front velocity analytically, and they are summarized by Elias and Yadigaroglu [1]. For predicting the wet front velocity by these analytical models, knowledge on two parameters, the surface temperature at the rewet point which is called the rewetting or sputtering temperature and the surface heat transfer coefficient, is required. However, data on these two parameters are limited and there seems to be considerable uncertainty in the literature as to the boiling heat transfer in the rewetting process.

The wet front velocity obtained with liquid preheated near the saturation temperature and the relations between the surface heat flux and the wall superheat behind the wet front have been investigated in the previous paper [2]. This paper describes the experimental results obtained with subcooled liquid films. It has been known from experimental investigations presented so far [3–7] for subcooled liquid films that the wet front velocity increases with increasing liquid subcooling. This trend is thought to be a consequence of the fact that the surface heat flux in the wet front region increases with liquid subcooling.

In this study, measurements are made of the wet front velocity in a range of liquid subcoolings and film flow rates using the same system of a hot stainless steel tube and a R-113 liquid film as that mentioned in the previous paper. The surface heat flux distributions are also derived by solving the 2-D conduction equation in the wall numerically, and the effects of liquid subcooling on the boiling heat transfer in the wet front region are discussed.

2. APPARATUS AND PROCEDURE

The experimental apparatus consists of a test section, a liquid supply system and an electrical circuit for heating, as shown in Fig. 1. The test section is composed of a heating tube (SUS 304) of 16 mm O.D., 12 mm I.D. and 400 mm long, and copper parts silver-soldered to both ends of the heating tube. The test liquid passes

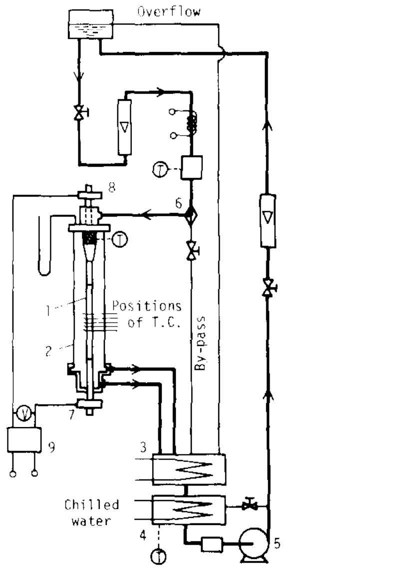

FIG. 1. Schematic diagram of the experimental apparatus: (1) heating section; (2) Pyrex tube; (3) condenser; (4) cooler; (5) pump; (6) three-way cock; (7), (8) electrodes; (9) transformer.

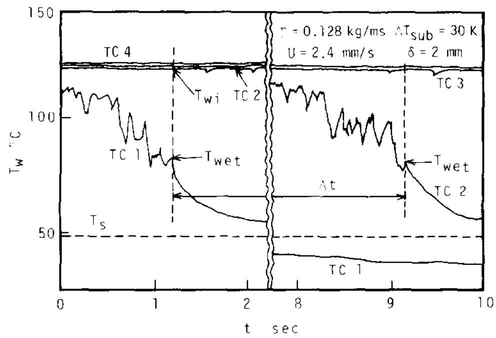

FIG. 2. Temperature–time history of thermocouples located on the tube surface.

through the wall of a porous sintered tube provided at the upper end of the test section, and flows down the outer surface of the heating tube. When the heating tube reached a desired temperature by passing an electric current through it, the current was shut off and then the liquid was supplied to the test section. The test liquid used was R-113 at atmospheric pressure, the saturation temperature being 47.6°C.

For measuring the surface temperature of the heated tube, as with the test section of the previous study, five C–A thermocouples were spot-welded to the outer surface at axial intervals of 20 mm. The top thermocouple (TC No. 1) was located at the position 160 mm down from the upper end of the heating tube. The thermocouple outputs were recorded on an oscillograph chart. Experimental ranges covered are: liquid film flow rate per unit periphery $\Gamma = 0.128 \sim 0.64$ kg m^{-1} s^{-1}, inlet liquid subcooling $\Delta T_{sub} = 3 \sim 40$ K, and initial wall temperature $T_{wi} = 140 \sim 220$°C. Besides this series, another test is also performed to find a lower boundary of the initial wall superheats for which the sputtering is maintained.

3. COOLING CURVE

In the falling film rewetting, the wet front with sputtering proceeds down the surface at approximately a constant velocity. Figure 2 shows a record of the temperature–time history (cooling curve) of TC Nos. 1–4 located on the tube surface. Fairly large temperature fluctuations are observed in the dry-wall, high-temperature region. However, a sharp drop in temperature and its fluctuation takes place when the wet front reaches the thermocouple location. In the same way as in the previous paper, the temperature at a starting point of the sharp drop was defined as the rewetting temperature T_{wet}, and the output of the thermocouple located 20 mm below (TC No. 2) at this moment was regarded as the initial wall temperature T_{wi}. The time interval Δt taken for the wet front to travel the distance $L = 20$ mm between the location of TC No. 1 and that of TC No. 2 was determined from the recorded chart as shown in Fig. 2. The wet front velocity was then derived by

$$U = L/\Delta t. \tag{1}$$

Figure 3 shows observed flow states of the liquid film. For low subcooled films, the wet front configuration was even and relatively uniform around the circumference of the heating tube, and the surface temperature was less fluctuated in the dry-wall region. However, the wet front of highly subcooled films was irregular, inclined or disturbed to form rivulets, as is seen in Figs. 3(b) and (c). The temperature fluctuation in the dry-wall region increased with increasing inlet liquid subcooling. The wet front disturbance due to liquid subcooling has also been observed by Yu *et al.* [7] in their experiments performed with water films. Cumo *et al.* [8] have shown that, in the rewetting of flat vertical surfaces by subcooled films, the dominating wet front configuration is a rivulet mode.

Figure 4 shows the wall superheat at the rewet point $\Delta T_{wet} = T_{wet} - T_s$ plotted against the inlet liquid subcooling. Although the rewetting temperature T_{wet} is extensively used as a matching parameter for correlating the wet front velocity measured, the experimentally determined data on T_{wet} are limited. Dua and Tien [9] have reported the value $\Delta T_{wet} = 25 \pm 3$ K for a copper and liquid nitrogen system. Linehan *et al.* [10] have measured ΔT_{wet} with a copper and water system and shown that, although the data are scattered in a range from 20 to 50 K, the value is not sensitive to the liquid subcooling. The data shown in Fig. 4 are also scattered, showing slightly lower values than those of the previous paper which were obtained with saturated films. It may be possible, however, to assume that the average of the wall superheat at the rewet point in this experiment is about $\Delta T_{wet} = 35$ K independent of the liquid subcooling and flow rate.

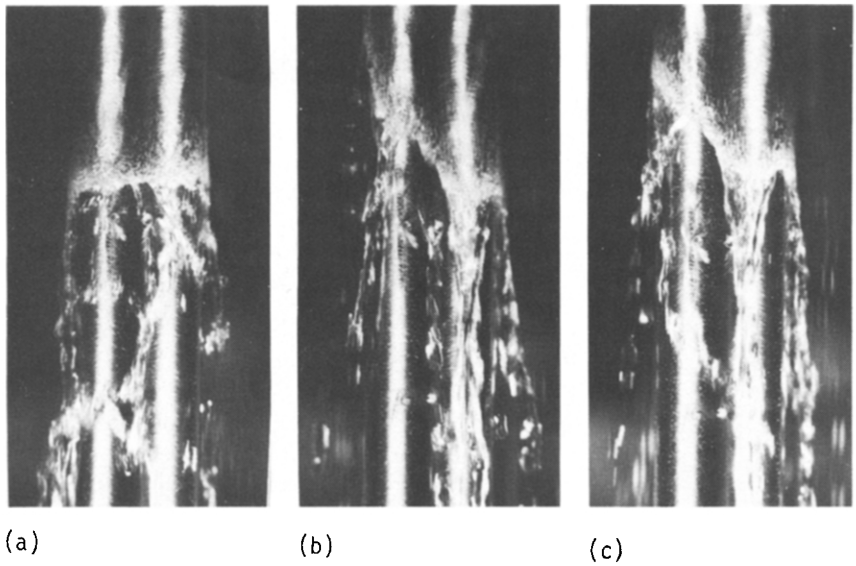

FIG. 3. Flow state of liquid film in the wet front region: (a) $T_{wi} = 170°C$, $\Gamma = 0.25\ kg\ m^{-1}\ s^{-1}$, $\Delta T_{sub} = 9\ K$; (b) $T_{wi} = 170°C$, $\Gamma = 0.25\ kg\ m^{-1}\ s^{-1}$, $\Delta T_{sub} = 37\ K$; (c) $T_{wi} = 210°C$, $\Gamma = 0.25\ kg\ m^{-1}\ s^{-1}$, $\Delta T_{sub} = 37\ K$.

4. WET FRONT VELOCITY

A number of analytical models for predicting the wet front velocity have been proposed. All of them have taken a method to solve the heat conduction equation in the wall coupled with appropriate boundary conditions for heat transfer at the wall surface. The 2-D solutions have been presented by Duffey and Porthouse [5], Coney [11], Tien and Yao [12] among others based on the assumptions that the wet front velocity is constant along the surface, and that the heat transfer coefficient h is constant in the wet region behind the wet front and zero in the dry region ahead of the wet front. These solutions show that the nondimensional parameter involving the wet front velocity $Pe = U\delta/a_w$ can be expressed in terms of the Biot number $Bi = h\delta/k_w$ and the dimensionless temperature ratio $\theta_w = (T_{wi}-T_s)/(T_{wet}-T_s)$. These solutions are complicated. However, for small Biot numbers, these solutions reduce to a simple relation as

$$Bi^{1/2}/Pe = [\theta_w(\theta_w-1)]^{1/2}. \tag{2}$$

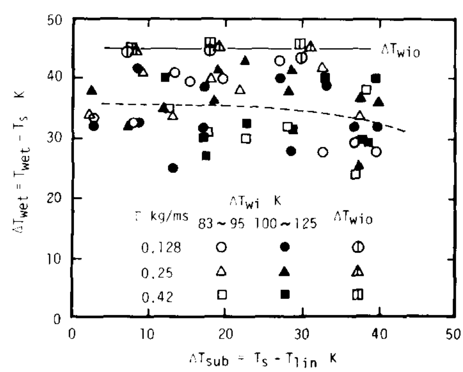

FIG. 4. Wall superheat at the rewet point.

This relation coincides strictly with the following Yamanouchi's 1-D solution [3] derived by assuming the temperature is uniform across the wall thickness

$$U = \frac{1}{\rho_w c_{pw}}\left(\frac{hk_w}{\delta}\right)^{1/2} \Big/ F(\Delta T) = \frac{a_w}{\delta}\left(\frac{h\delta}{k_w}\right)^{1/2} \Big/ F(\Delta T), \tag{3}$$

where

$$F(\Delta T) = [(T_{wi}-T_s)(T_{wi}-T_{wet})]^{1/2}/(T_{wet}-T_s).$$

For predicting the wet front velocity by the above-mentioned models, we have to assume the value of h or Bi. It has been known experimentally that the actual heat transfer coefficient changes sharply in a short axial distance behind the wet front. Therefore, there exists a difficulty in finding an appropriate value of h to substitute into the analytical solutions. However, the analytical results suggest the qualitative effects of the variables involved in the rewetting systems.

Here, the effects of initial wall temperature and inlet liquid subcooling on the wet front velocity are examined, based on the experimental results obtained by the present test.

4.1. *Effect of initial wall temperature*

Since the Biot number is usually not small in practical cases, it requires the use of 2-D analyses for evaluating the heat conduction in the wall accurately. However, the experimental results presented in the previous paper [2] were well correlated with equation (3) so far as the effect of the initial wall temperature T_{wi} on the wet front velocity U is concerned. Figure 5 shows the present data of U plotted against the temperature term $F(\Delta T)$ obtained by substituting the rewet point superheat $T_{wet}-T_s = 35$ K. Although the velocity U shows a trend to increase with increasing liquid subcooling ΔT_{sub} and film flow rate Γ, the data for given

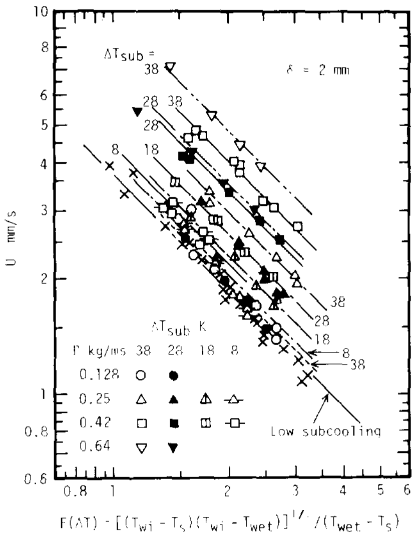

FIG. 5. Variation of the wet front velocity with the initial wall temperature.

ΔT_{sub} and Γ are well correlated with a form of $U \propto 1/F(\Delta T)$ as is indicated in equation (3). The previous data obtained with low subcoolings (shown by crosses in Fig. 5) are also in the relation of $U \propto 1/F(\Delta T)$ for $F(\Delta T)$ derived by substituting $T_{wet} - T_s = 35$ K.

In the present study, measurements were also made to examine a lower limit of the initial wall superheats where the sputtering took place at the wet front. The results are shown in Fig. 6. As the initial wall superheat ΔT_{wi} becomes less than a certain value, the wet front velocity starts to deviate from the linear relation for $1/F(\Delta T)$, along with an increase in inclination or disturbance of the wet front, and a point is reached where the sputtering ceases, while the nucleate boiling is still occurring at the wet front, and a sharp increase in the wet front velocity takes place. The wall superheat denoted by ΔT_{wio} in Fig. 6 represents the lower boundary of the sputtering. The values of ΔT_{wio} thus obtained were in a range of 43–46 K, and less affected by the liquid subcooling and flow rate, as shown in Fig. 4. Although ΔT_{wio} has been approximated as the rewet point superheat ΔT_{wet} in some investigations [13, 14], the present results show that ΔT_{wio} is slightly higher than ΔT_{wet}.

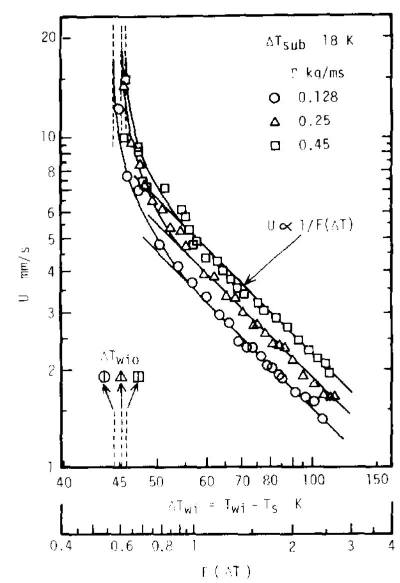

FIG. 6. Relation between the wet front velocity and the initial wall superheat.

4.2. *Effect of liquid subcooling*

Some experimental results have been presented on the effects of liquid subcooling. Yu *et al.* [7] have shown for subcooled water films that the wet front velocity is strongly affected by the film flow rate and increases with increasing liquid subcooling. Experimental results of water films by Piggott and Porthouse [6] have shown that, for high flow rates and subcoolings, the wet front velocity is proportional to the product of the flow rate and the inlet subcooling. However, since the wet front velocity is affected by many factors concerning the process, further studies are still required to make clear the effects of liquid subcooling.

As is seen in Fig. 5, the present data show a similar trend to that mentioned above. Taking into account this fact, the present data were plotted against the product $\Gamma\Delta T_{sub}$. Figure 7 shows the result, where the ordinate represents a nondimensional parameter $(U\delta/a_w)F(\Delta T)$ which appeared in equation (3). This figure shows that the wet front velocity is approximately constant for low values of $\sqrt{(\Gamma\Delta T_{sub})}$, and increases as the product $\Gamma\Delta T_{sub}$ increases over a value $\sqrt{(\Gamma\Delta T_{sub})} = 1.6\,\mathrm{kg}^{0.5}\,\mathrm{K}^{0.5}\,\mathrm{m}^{-0.5}\,\mathrm{s}^{-0.5}$. In the range of high values of $\sqrt{(\Gamma\Delta T_{sub})}$, the present data are correlated by the following equation

$$(U\delta/a_w)F(\Delta T) = 1.24(\Gamma\Delta T_{sub})^{0.4}. \quad (4)$$

Such an increase of the wet front velocity seems to be caused by the disturbance of the wet front which is enlarged with the liquid subcooling and flow rate as mentioned before.

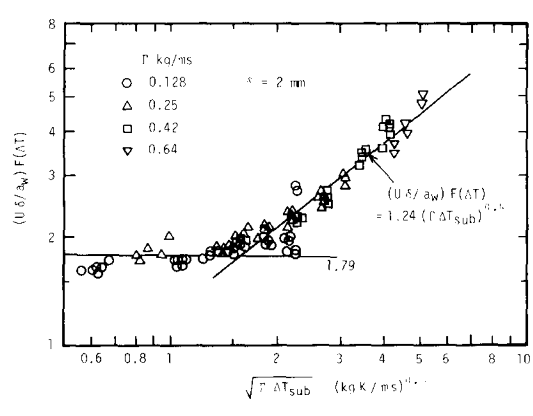

FIG. 7. Effect of liquid subcooling.

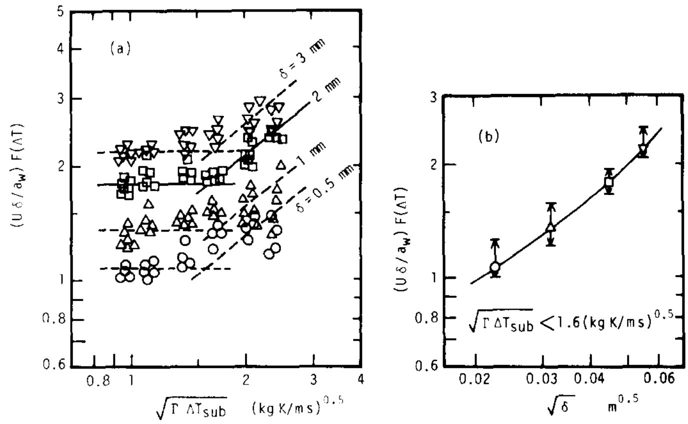

FIG. 8. Effects of liquid subcooling and wall thickness.

Figure 8 shows correlations of the wet front velocity data presented in the previous paper [2]. It is suggested from Fig. 8(a) that, irrespective of the tube wall thickness δ, the wet front velocity increases as $\sqrt{(\Gamma\Delta T_{sub})}$ becomes higher than a certain fixed value. It is interesting to note that the data of the velocity U presented by Piggott *et al.* [6] for water films show a trend to increase as $\sqrt{(\Gamma\Delta T_{sub})}$ increases over about 2.0 $kg^{0.5}$ $K^{0.5}$ $m^{-0.5}$ $s^{-0.5}$. Figure 8(b) shows the effect of wall thickness on the parameter $(U\delta/a_w)F(\Delta T)$ for low values of $\sqrt{(\Gamma\Delta T_{sub})}$. This curve is somewhat different from the relation given in equation (3) by the reasons mentioned in the previous paper. As is expected from equation (3), the parameter $(U\delta/a_w)F(\Delta T)$ is thought to be related to the surface heat transfer coefficient and so to the liquid properties.

5. SURFACE HEAT FLUX

Since the wet front of the film proceeds down at a constant velocity U, the surface temperature profile along the tube length can be derived from the recorded temperature–time history. Considering a coordinate Z which moves with the wet front and has its origin at the wet front point

$$Z = z - Ut, \tag{5}$$

the 2-D conduction equation in the tube wall is reduced to

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial Z^2} = -\frac{U}{a_w}\frac{\partial T}{\partial Z}. \tag{6}$$

The boundary conditions are

$$\begin{aligned} r = R_i: &\qquad \partial T/\partial r = 0, \\ r = R_i + \delta: &\qquad T = T_w(Z), \end{aligned} \tag{7}$$

where R_i is the inside radius of the tube and $T_w(Z)$ is the surface temperature obtained by reducing the recorded temperature–time history to the Z coordinate. In this paper, equations (6) and (7) were solved numerically as described in the previous paper, and the surface heat flux was derived from the computed temperature distribution in the tube wall.

The axial distributions of the wall surface superheat ΔT_s and the surface heat flux q thus derived are shown in Fig. 9, where $Z = 0$ denotes the location of the wet front. This figure represents the result of the test runs performed at a flow rate $\Gamma = 0.42$ kg m^{-1} s^{-1}, the test conditions and the wet front velocity measured are listed in Table 1.

The present result shows that the wet front velocity

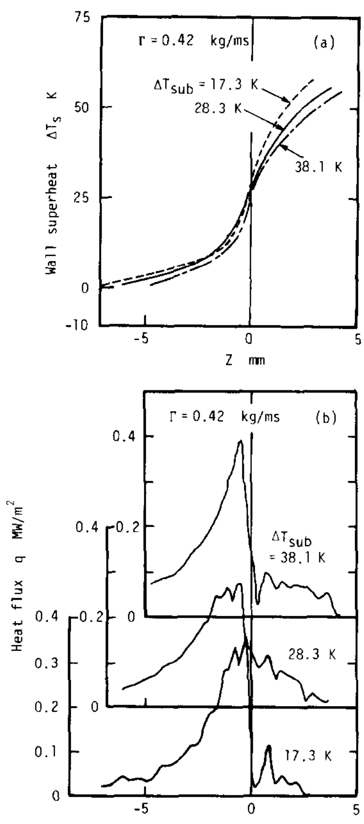

FIG. 9. Distributions of wall superheat and surface heat flux.

Table 1. Experimental conditions and the wet front velocity of the data shown in Fig. 9

Γ ($kg\ m^{-1}\ s^{-1}$)	ΔT_{sub} (K)	ΔT_{wi} (K)	ΔT_{wet} (K)	U ($mm\ s^{-1}$)
0.42	38.1	110.8	29	3.14
0.42	28.3	104.3	32	2.83
0.42	17.3	96.3	30	2.32

increases with liquid subcooling. This fact must come out from an increase of surface heat flux near the wet front. Figure 9(b) shows this trend clearly. In two regions: (a) the low superheat region at a distance behind the quench front, and (b) the dry-wall region ahead of the quench front, the heat fluxes are increased with increasing inlet liquid subcooling. The heat flux in the latter region is remarkable. This corresponds to the precursory cooling supposed by Sun *et al.* [15] and Dua and Tien [16] to take place at high film flow rates. Considering the states of the liquid film front observed, it seems to be that the heat flux ahead of the quench front is caused by the tips of the disturbed wet front being ahead of the quench front, i.e. the circumferentially averaged wet front, as shown in Fig. 3.

The heat flux distribution along the tube length is affected in a complicated manner by the boiling state and the wet front configuration. For discussing the heat transfer characteristics, it is convenient to examine the relations between the surface heat flux and the wall superheat (the boiling curves). Figure 10 shows the boiling curves of the test runs shown in Fig. 9. The heat fluxes in both low and high superheat regions are increased with liquid subcooling, however, the peak value is little affected. The peak heat flux shows a somewhat higher value than the critical heat flux

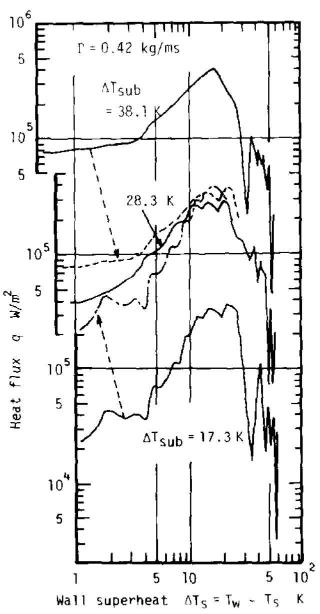

FIG. 10. Boiling curves.

$q_c = 2.47 \times 10^5\ W\ m^{-2}$ predicted from Kutateladze's equation for pool boiling [17]. This difference is probably ascribed to that in the present case the liquid is supplied to the wet front with a relatively high approaching velocity. Several empirical correlations for the falling liquid film thickness [18] have been presented. The mean velocities of the falling film calculated from these correlations are about $0.7\ m\ s^{-1}$ for the present condition of $\Gamma = 0.42\ kg\ m^{-1}\ s^{-1}$. The heat flux in the high superheat region is sharply fluctuated and shows a trend to decrease with increasing wall superheat, i.e. a different trend from that expected by film boiling. Therefore, it may be concluded that the heat flux at the surface ahead of the quench front is caused by the wet front disturbance, and is closely related to the effect of liquid subcooling on the wet front velocity.

6. CONCLUSIONS

Rewetting of a hot surface by a R-113 subcooled liquid film was studied experimentally, and the effects of the liquid subcooling were examined on the wet front velocity and the surface heat flux distribution. The conclusions derived from the present study are as follows:

(1) The effect of the initial wall temperature on the wet front velocity is well expressed by the analytical solution for the 1-D equation [equation (3)]. The wet front velocity increases with increasing the product of the liquid subcooling and flow rate, when the product is higher than a fixed value.

(2) The wall superheat at the rewet point is found to be about 35 K for the present stainless steel and R-113 liquid system, and this value is a little lower than the lower boundary of the initial wall superheat for which the sputtering is maintained.

(3) The surface heat fluxes in the low superheat region of the wet-wall and the dry-wall region ahead of the quench front increase with increasing liquid subcooling, however, the peak value is little affected. The heat flux in the dry-wall region is caused by the wet front disturbance and is closely related to an increase of the wet front velocity with liquid subcooling.

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REMOUILLAGE D'UNE SURFACE CHAUDE PAR UN FILM TOMBANT LIQUIDE—EFFETS DU REFROIDISSEMENT DU LIQUIDE

Résumé—La vitesse du front mouillé et la distribution du flux de chaleur pariétal sont étudiés avec un système acier inoxydable et Freon 113 sous-refroidi à pression atmosphérique. Pour les grands sous-refroidissements et débits, la vitesse du front mouillé croît avec le produit du sous-refroidissement à l'entrée par le débit. Une analyse bidimensionnelle est utilisée pour obtenir le flux de chaleur à la paroi. Le résultat montre que, du fait que le front de film sous-refroidi est irrégulier, le flux thermique à la surface derrière le front de trempe augmente quand le sous-refroidissement du liquide croît.

WIEDERBENETZUNG EINER HEISSEN OBERFLÄCHE DURCH EINEN FLÜSSIGKEITS-FALLFILM—EINFLUSS DER FLÜSSIGKEITS-UNTERKÜHLUNG

Zusammenfassung—Die Geschwindigkeit der Benetzungsfront und die Wärmestromdichte-Verteilung in der Oberfläche werden für ein System aus heißem rostfreien Stahl und einem unterkühlten Freon 113-Flüssigkeitsfilm bei Atmosphärendruck untersucht. Für große Unterkühlungen und Strömungsmengen nimmt die Geschwindigkeit der Benetzungsfront mit dem Produkt der Entrittsunterkühlung und der Strömungsmenge zu. Die Oberflächen-Wärmestromdichte wird mit einer zweidimensionalen Analyse ermittelt. Das Ergebnis zeigt, daß die Wärmestromdichte an der Oberfläche vor der Abschreckfront mit zunehmender Flüssigkeits-Unterkühlung zunimmt—dies aufgrund der Tatsache, daß die Front des unterkühlten Films unregelmäßig ist.

ПОВТОРНОЕ СМАЧИВАНИЕ НАГРЕТОЙ ПОВЕРХНОСТИ СТЕКАЮЩЕЙ ПЛЕНКОЙ ЖИДКОСТИ. ЭФФЕКТЫ НЕДОГРЕВА ЖИДКОСТИ

Аннотация—Исследуются скорость продвижения фронта смачивания и распределение теплового потока по поверхности тела из нержавеющей стали в случае течения пленки недогретого жидкого фреона-113 при атмосферном давлении. При больших недогреве и скорости течения скорость фронта смачивания возрастает с увеличением произведения указанных величин. Показано, что так как фронт пленки недогретой жидкости имеет неровную форму, то плотность теплового потока на поверхности перед фронтом закалки увеличивается с ростом недогрева жидкости.