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AN EXPERIMENTAL INVESTIGATION OF FALLING-FILM REWETTING

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Abstract—The present experimental study of rewetting of a copper tube by a falling film of liquid nitrogen indicates the variations of the surface heat flux behind the wet front to be similar to those observed in the nucleate and film pool boiling of liquid nitrogen. The heat flux variation ahead of the wet front, representing the precursory cooling, is also presented. The maximum heat flux in rewetting occurs at the location of the wet front and its magnitude is comparable to the average of the maximum and the minimum heat fluxes of nucleate and film pool boiling. The measured rewetting temperature is found to be very close to the Leidenfrost temperature of liquid nitrogen on a copper surface. It is also demonstrated that the rewetting temperature and the heat-transfer characteristics behind the wet front are very sensitive to the surface conditions. The experimental data on the wet-front velocity obtained on a smooth surface are compared to that on a rough surface, and are successfully correlated by the earlier analytical model of rewetting with precursory cooling.

NOMENCLATURE

a, exponential power, Fig. 1;
b, dimensionless exponent, $a\delta$;
B, Biot number, $h\delta/k$;
c, specific heat of solid;
h, wet-side heat-transfer coefficient in the two-region model;
h_1, convective heat-transfer coefficient for the continuous film region in the three-regions model;
h_2, average boiling heat-transfer coefficient for the sputtering region in the three-regions model;
k, thermal conductivity of solid;
N, constant;
P, Peclet number, $\rho cu\delta k$;
Q_0, heat flux at the wet front, $h(T_0 - T_s)$;
Q, heat flux at any point on the surface;
t, time;
T, temperature;
T_a, ambient temperature of the droplet-vapor mixture, Fig. 1;
T_n, incipient boiling temperature;
T_0, rewetting or sputtering temperature;
T_s, saturation temperature;
T_w, initial dry-wall temperature;
u, wet-front velocity;
$\tilde{x}$, axial coordinate, Fig. 1;
x, dimensionless axial coordinate, $\tilde{x}/\delta$;
$\tilde{y}$, transverse coordinate, Fig. 1;
y, dimensionless transverse coordinate, $\tilde{y}/\delta$;
Y, constant, equation (4).

Greek Symbols

δ, one-half slab thickness, Fig. 1;
θ, dimensionless temperature, $(T_w - T)/(T_w - T_s)$;
$\bar{\theta}$, dimensionless temperature, $(T - T_s)/(T_0 - T_s)$;
θ_0, dimensionless rewetting temperature, $(T_w - T_0)/(T_w - T_s)$;
θ_1, dimensionless wall temperature, $(T_w - T_0)/(T_0 - T_s)$;
ρ, density of solid;
ψ, mass flow rate of coolant per unit perimeter.

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1. INTRODUCTION

SURFACE rewetting refers to the establishing of liquid contact with a solid surface whose initial temperature is higher than the sputtering temperature, the temperature up to which a surface may wet. Due to its importance to the emergency core cooling of water reactors in the event of postulated loss-of-coolant accidents, the problem of surface rewetting has gained much attention in recent years. For conduction-controlled rewetting, several one and two-dimensional analytical and numerical studies [1–9] have appeared in the literature and are summarized in the recent review reports [10–12].

The most commonly employed physical model to describe falling-film rewetting characterizes the wet region behind the moving film-front by a constant heat-transfer coefficient and the dry region ahead of the wet front as adiabatic. Such a physical model has been quite successful in correlating the experimental data at low coolant flow rates. The effect of precursory cooling ahead of the wet front becomes very significant at high coolant flow rates and a recent two-dimensional analytical study by Dua and Tien [13] characterizes the precursory cooling by an exponentially decaying heat flux and successfully correlates the experimental data at high coolant (water) flow rates in atmospheric steam environment [1, 14]. All the existing rewetting analyses provide explicit or implicit relationships between a normalized wet-front velocity, a dimensionless wall temperature (which contains the sputtering temperature) and a Biot number characteristic of the heat transfer in the wet region.

The prediction of the wet-front velocity by existing analytical models thus requires the knowledge of the sputtering temperature and the surface heat transfer in the wet region behind the film-front and in the dry region ahead. The measurement of both the sputtering temperature and the surface heat-transfer coefficient in the sputtering zone present acute experimental difficulties and no direct measurements have been reported to date. For this reason, the rewetting (or sputtering) temperature, T_0, and the wet-side heat-transfer coefficient, h, are currently used as matching parameters for correlating the experimental data on the wet-front velocity [10–12]. For lack of direct measurements of T_0 and h, it has not so far been possible either to fully understand the boiling phenomenon in the sputtering region or to check directly the validity of the different rewetting models.

The present experimental study aims at several different aspects of the problem of falling-film rewetting. The major objective, however, is to measure the surface temperature and the heat flux behind a moving wet front and thereby to reveal the true nature of the boiling phenomenon encountered in a falling-film rewetting. This understanding of the state of boiling in the sputtering region is, in turn, utilized to devise an empirical methodology to extract reasonable estimates of the system parameters, T_0 and h, as applicable to rewetting, from the more rapidly available information on the nucleate and film pool boiling experiments. In view of very little experimental information available on precursory cooling, the present study serves another important purpose in providing the necessary information to check the validity of the analytical model of precursory cooling [13]. Another essential feature of the present work is to explore the effect of surface conditions on the rewetting rate. Existing experimental studies provide little information on this aspect, although some investigators [10, 15–17] have suggested the significant effect of surface conditions on the measured rewetting rates. By artificially changing the surface condition, the present work explores the influence of such changes on the rewetting temperature and the heat-transfer characteristics in the sputtering region.

2. PHYSICAL MODEL OF PRECURSORY COOLING

In order to achieve a better understanding of the experiments and the data reduction scheme, it is essential to discuss briefly the analytical physical model of conduction-controlled rewetting with precursory cooling [13] as shown in Fig. 1. When the liquid film progresses downward on a vertical hot surface, the surface is cooled down from its initial wall temperature, T_w, to the rewetting temperature, T_0, at which the surface begins to wet. Behind the wet front, the surface temperature drops sharply to the saturation temperature, T_s. To simplify the heat-transfer characteristics outside the slab, it is a common practice to assume

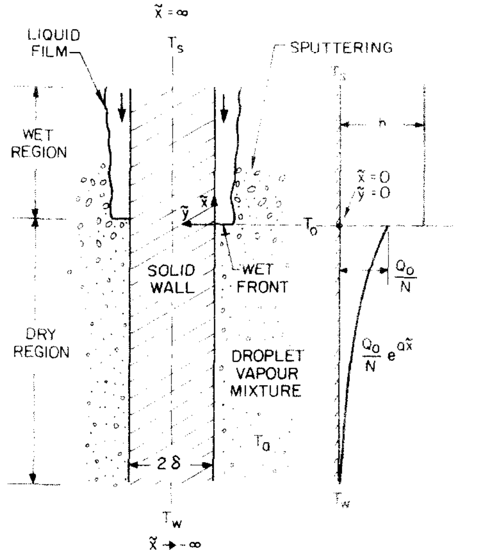

FIG. 1. Falling-film rewetting of a slab and the analytical model with precursory cooling ahead of the wet front.

the region behind the wet front ($\tilde{x}>0$) associated with a constant sputtering heat-transfer coefficient, h. The mechanism of precursory cooling ahead of the wet front ($x<0$) is rather complex and is modelled by an exponentially decaying heat flux. The precursory cooling is thus mathematically described by two constants, a and N (Fig. 1). While the exponent a characterizes the effective region of precursory cooling, the constant N represents a fractional step decrease in heat flux just ahead of the wet front and thus illustrates the magnitude of precursory cooling. The value of N depends on the coolant mass flow rate. For increasing coolant flow rates, the precursory cooling is enhanced resulting in a smaller N. Apart from these two constants, the physical problem is characterized by three dimensional groups: the Peclet number (or the dimensionless wetting velocity), the Biot number and a dimensionless temperature. The analytical solution for this physical model [13] will be compared with the experimental data obtained in the present study in order to check directly the validity of the rewetting model with precursory cooling.

3. EXPERIMENTAL SETUP

The present experiments involve a falling film of liquid nitrogen rewetting a copper tube initially at room temperature. Since the Leidenfrost temperature of liquid nitrogen is about 100–104 K [18], much lower than the room temperature, there is no need to heat the copper tube, thus simplifying considerably the experimental system.

The experimental setup consists essentially of two components, the liquid nitrogen container and the test section, as shown in Fig. 2. The container is an insulated double-walled vessel made out of stainless steel tubes and is provided with a manual valve to adjust the flow rate of liquid nitrogen passing over the test tube. A graduated circular scale is provided at the

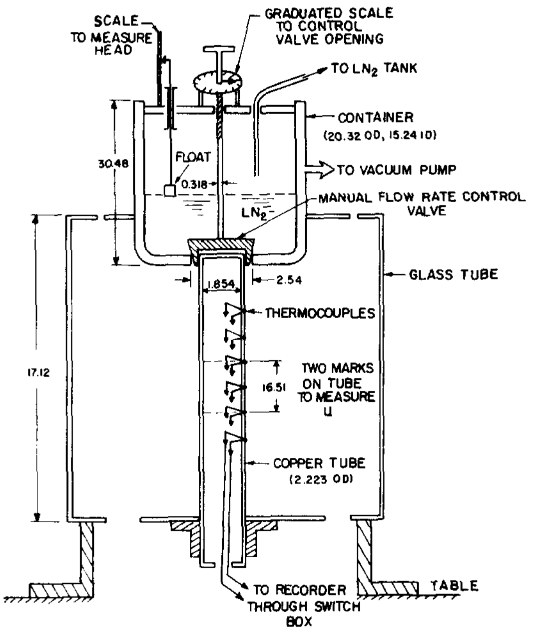

FIG. 2. Schematic diagram of the test section and the liquid nitrogen container (all dimensions in 10^{-2} m).

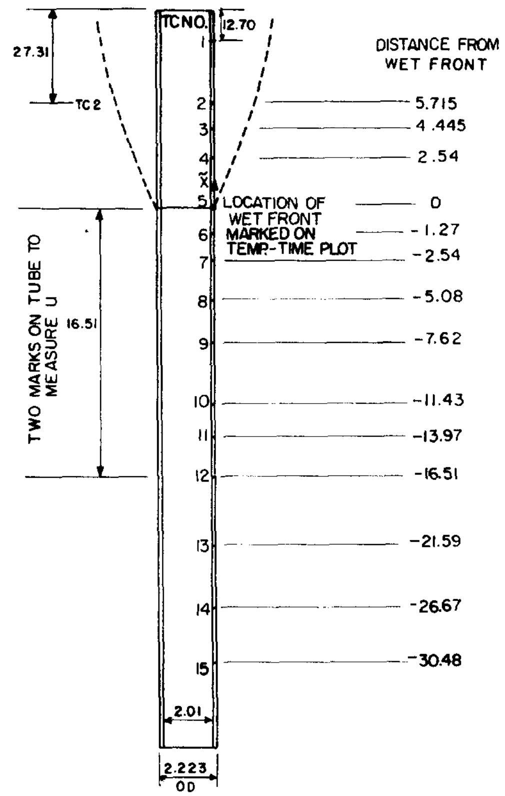

FIG. 3. Arrangement of thermocouples on the surface of the tube (all distances in 10^{-2} m).

top of the container to control the valve opening. The level of liquid nitrogen in the container is measured by a float, and the attached scale provides a direct level reading at any time.

The test section consists of a 0.01905 m N.B. copper tube inside a large circular glass section. The falling film of liquid nitrogen rewets the outside of the copper tube and the rewetting phenomenon can be viewed directly through the surrounding glass section. This allows visualization of the wet-front motion and careful examination and control of the surface conditions during the experiment. Due to the small wall thickness (0.00108 m) of the copper tube, the conduction in the solid wall is essentially one-dimensional. The copper tube is provided with fifteen iron–constanton thermocouples which are flushed with the outside surface of the tube. The leads of these thermocouples are taken, through the inside of the tube, to the chart recorder. These thermocouples are located at pre-determined distances on the surface and the details of the spacings between different thermocouples are shown in Fig. 3. The chart recorder has six channels to record the temperature–time history at six different locations on the surface of the tube in any given experimental run. This is done through a switch box which permits an appropriate choice of any six thermocouples in order to record the complete surface temperature distribution.

4. EXPERIMENTAL PROCEDURE

In order to check the validity of the physical model, it is necessary to measure the rewetting velocity at different initial wall temperatures of the copper tube, keeping the mass flow rate of the coolant constant. Four such sets of experimental data were obtained at four different mass flow rates of the coolant. At the start of the experiment, the container is filled with liquid nitrogen with the manual valve closed. The copper tube which touches the bottom of the manual valve in the closed position (Fig. 2) starts to cool down due to conduction. The initial tube-wall temperature is determined by the time period of this conduction cooling before opening the manual valve and thus letting the liquid nitrogen pass over the tube. The thermocouple No. 1, which is located 0.127 m from the top end of the tube (Fig. 3) is always connected to the potentiometer and the temperature read by this thermocouple indicates as to when to open the manual valve. It must be emphasized, however, that the thermocouple No. 1 does not give the initial wall temperature, T_w, which is instead deduced from the temperature–time plot of a thermocouple placed sufficiently ahead of the wet front. Corresponding to each run, the temperature–time (abbreviated as T–t) history of six thermocouples located on the surface is recorded by the chart recorder. One of the channels on the chart recorder is connected to an electronic marker which is used to mark the time when the moving wet front reaches any given location on the tube.

When the manual valve is opened, liquid nitrogen starts to fall down onto the copper tube. The tube temperature initially being higher than the rewetting temperature, liquid nitrogen does not wet the surface and is violently sputtered away from the copper tube. When the surface temperature locally drops to the rewetting temperature, a film of liquid nitrogen now begins to wet the surface and a wet front is formed which moves down the tube at approximately a constant speed. The sputtering phenomenon is now seen only near the location of the wet front and the tube surface behind the wet front is covered with a continuous liquid film. The wet-front velocity is calculated by measuring the time taken for the wet front to pass between the two marked locations, 0.1651 m apart, on the tube surface. The time taken by the wet front to traverse this distance is measured directly by a stop watch and also by the chart recorder with the aid of an electronic marker which is pressed to mark, on the T–t plot, both the times when the wet front passes through two specified locations on the tube.

During an experimental run, the liquid nitrogen level in the container is kept constant by maintaining a continuous supply of liquid nitrogen. When the liquid film covers the entire tube, the supply of liquid nitrogen is cut off and the time is noted for the liquid nitrogen level in the container to drop by a known amount (one or two in). With this information, the mass flow rate, $\dot{m}$, (or the mass flow rate per unit perimeter of the copper tube, ψ) is calculated.

5. REDUCTION OF EXPERIMENTAL DATA

A temperature–time plot such as shown in Fig. 4, is obtained by the chart recorder for each of the 26 experimental data points reported subsequently in Fig. 7. The six thermocouples connected to the recorder for the run shown in Fig. 4 are numbered as 2, 4, 5, 6, 7 and 8. In order to clearly distinguish the temperature–time traverse of one thermocouple from the other, the zero positions (indicating 0 mV output) of these thermocouples have been separated from one another. Also the gain, measured as mV/cm, of the different channels on the recorder connected to these thermocouples are not exactly identical. In view of different zero positions and different temperature scales for each of the six thermocouples, no scales are shown in Fig. 4 which is included here only to illustrate the methology of data reduction. When the wet front reaches the location where the thermocouple No. 5 (abbreviated as TC5) is situated, the electronic marker is pressed to mark this time on the temperature-time plot. This is shown by an arrow (at $t = t_1$) in Fig. 4. Corresponding to this time, the temperature read by TC5 directly gives the rewetting temperature, T_0. The spacial positions of these thermocouples relative to the wet front are read from Fig. 3 and the temperatures reached by these thermocouples at the time ($t = t_1$) when the wet front reaches TC5 are read from Fig. 4. This directly yields the surface temperature distribution with respect to the wet front. It is to be observed from Fig. 4 that at $t = t_1$, the derivative $(\partial T/\partial t)$ at the location of TC8 is zero. This implies that the thermal effects of the wet front reaching TC5 are not felt at the location of TC8 which, therefore, gives the value of the initial wall temperature, T_w, to be used in theoretical calculations. The distance ahead of the wet front to which the effect of precursory cooling extends, is dependent upon the mass flow rate of the coolant. While in Fig. 4, $(\partial T/\partial t)$ is zero only about 0.05 m ahead of the wet front because of the low mass flow rate (ψ = 0.127 kg/ms) for this particular run, the region of precursory cooling increases to about 0.229 m at a higher flow rate of $\psi = 0.3556$ kg/ms, as is shown in Fig. 6.

It should be noted that the surface temperature behind the wet front very sharply drops to the saturation temperature. Figures 3 and 4 indicate that TC4 which is only 0.0254 m behind the wet front has already reached the saturation temperature, T_s, and hence TC2 which is further behind the wet front does not give any new information regarding the surface temperature distribution. It is extremely difficult to mount any two thermocouples closer than 0.0127 m apart, and for this reason a special technique was devised to obtain the surface temperature distribution behind the wet front. In the real situation the wet front reaches TC5 at $t = t_1$ and the sputtering region and the continuous film then pass over TC5 at the wet front speed u. An exact analog of this situation would be to consider the wet front and the film stationary and to consider TC5, instead, traversing the film at a constant rate u, starting from the location of the wet front at $t = t_1$. As shown in Fig. 4, several points such as, B', C', and D' are then marked at the temperature–time traverse of TC5 at known time intervals from the reference point $t = t_1$. The temperature at the point B', which is at $t = t_1 + \Delta t$, is measured from the $T-t$ plot and this gives the surface temperature at a point $u\Delta t$ behind the wet front ($\bar{x}$ =

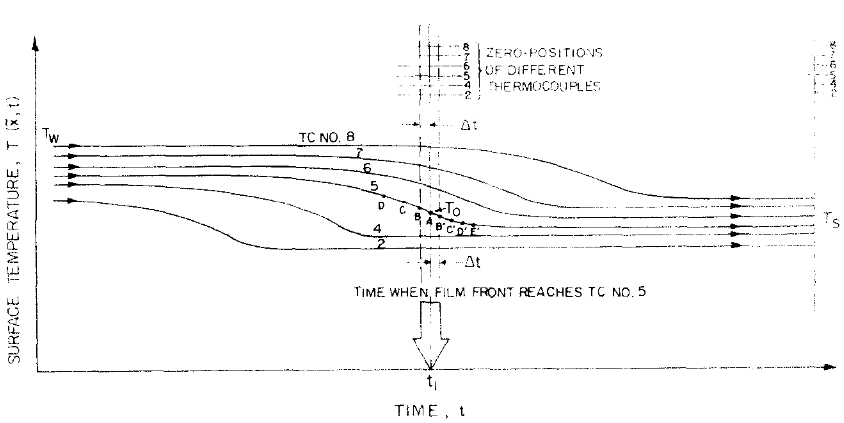

FIG. 4. Temperature–time plot at six different locations on the tube.

$+u\Delta t$). Similarly the temperature measured at point B, which is at $t = t_1 - \Delta t$, is considered to be the surface temperature at $x = -u\Delta t$. In this way the various points on the temperature–time traverse of one thermocouple (TC5) give the complete surface temperature distribution both ahead and behind the wet front. This procedure, however, implicitly assumes the invariance of the surface temperature profile with respect to the moving wet front. This assumption is justified as being reasonable by the fact that velocity of the wet front, u, was found to be fairly constant over the entire length of the copper tube. From the surface temperature distribution thus obtained, it is possible to calculate in theory both $(\mathrm{d}T/\mathrm{d}\tilde{x})$ and $(\mathrm{d}^2T/\mathrm{d}\tilde{x}^2)$ at any point relative to the wet front. Knowing these derivatives, the surface heat flux $Q(x)$ at any location on the tube is obtained by applying equation (1) which is easily derived from an energy balance on a small element of the tube:

$$Q(x) = -\rho c\delta u \frac{\mathrm{d}T}{\mathrm{d}\tilde{x}} + k\delta \frac{\mathrm{d}^2T}{\mathrm{d}\tilde{x}^2}. \quad (1)$$

Equation (1) is based on the assumption that the thickness of the tube is much smaller than its diameter. Although it is possible to determine $(\mathrm{d}T/\mathrm{d}\tilde{x})$ either by the finite-difference method or by drawing the tangent to the curve representing the surface temperature distribution, it is extremely difficult to calculate the second derivative, $(\mathrm{d}^2T)/\mathrm{d}\tilde{x}^2)$, accurately. For this reason, an approximate method based on the present physical model is developed in the following to estimate the second term in equation (1).

With the present physical model as shown in Fig. 1, a one-dimensional conduction analysis in the solid yields the following results for the surface temperature distribution [13]:

For $x \geqslant 0$,

$$\theta(x) = (\theta_0 - 1)\exp\left(\left\{\frac{P}{2} - [(P/2)^2 + B]^{1/2}\right\}x\right) + 1. \quad (2)$$

For $x \leqslant 0$,

$$\theta(x) = \frac{(B/N)(\theta_0 - 1)}{b(b-P)}[\exp(bx) - \exp(Px)] + \theta_0 \exp(Px). \quad (3)$$

Applying the condition of continuity of heat flux in the solid at $x = 0$ to equations (2) and (3), the following expression for the dimensionless wet-front velocity is obtained

$$P = [Y - (B/Y)] \quad (4)$$

where

$$Y = \frac{1}{2}\left\{\frac{B}{Nb}\left(\frac{1-\theta_0}{\theta_0}\right) + \left[\frac{B^2}{N^2b^2}\left(\frac{1-\theta_0}{\theta_0}\right)^2 + \frac{4B}{\theta_0}\right]^{1/2}\right\}.$$

Equation (4) can also be deduced as a special case of the two-dimensional analysis of precursory cooling [13]. The second term on the RHS. of equation (1) is directly obtained from equation (2) which gives:

$$k\delta\frac{\mathrm{d}^2T}{\mathrm{d}\tilde{x}^2} = \frac{k}{\delta}(T_0 - T_s)\{(P/2) - [(P/2)^2 + B]^{1/2}\}^2 \times \exp\{(P/2) - [(P/2)^2 + B]^{1/2}\}x. \quad (5)$$

The heat flux variation behind the wet front is first obtained from equation (1) neglecting the axial conduction term and, then, the results so obtained are corrected to account for the axial conduction with the aid of equation (5). It is clear from equation (5) that the term $k\delta\ (\mathrm{d}^2T/\mathrm{d}\tilde{x}^2) \to 0$ in the limit of $(P/2)^2 \gg B$, and the estimated correction to account for the axial conduction is, therefore, minimal for the experimental data at large Peclet numbers. Since equation (5) does not contain the parameters N or b, no assumptions need to be made with regard to the precursory cooling when making the axial conduction corrections behind the wet front. A relation similar to equation (5) is obtained from equation (3) which gives an estimate of the axial conduction term ahead of the wet front. For distances greater than 0.0254 m ahead of the wet front, the axial conduction constitutes a very small part (about 3–5%) of the total heat flux, and for this reason, the constants characterizing the precursory cooling, namely b and N, as obtained by neglecting the axial conduction term remain essentially unaltered by the subsequent inclusion of axial conduction in equation (1).

The constants a and N describing the precursory cooling are obtained by the curve fitting of the heat flux variations ahead of the wet front.

6. RESULTS AND DISCUSSION

The results reported and discussed here are based on 26 experimental runs performed at various different values of the initial wall temperature, T_w, of the copper tube and at four different values of the coolant mass flow rate. Before correlating the experimental data on the rewetting rate with the analytical results presented in equations (2)–(4), it is necessary to discuss the findings of the present experimental study with respect to the measurements made on the rewetting temperature, T_0, and the sputtering heat-transfer coefficient, h. Both of those quantities have so often been used as matching parameters that their real magnitude and physical significance have not been reported and discussed in the literature [10]. The rewetting temperature in most of the experimental runs was measured to be (102·34 ± 3) K with maximum uncertainty of ±5 K for some of the runs where locating the position of the wet front became very difficult either on account of very fast wet-front velocities or due to the large generation of vapor which prevents clear visibility of the wet front. The Leidenfrost temperature of liquid nitrogen on a copper surface is measured to be 100–104 K [18, 19] and this temperature agrees well with the rewetting temperature of (102·34 ± 3) K measured in the present work. It should also be pointed out here that the rewetting temperature, T_0, in the present experimental study was not found to depend on the mass flow rate or the initial wall temperature, T_w. This is contrary to the suggestions made in an earlier work [14] where the rewetting temperature, T_0, was characterized to be dependent on the mass flow rate in order to correlate the experimental data on rewetting velocities.

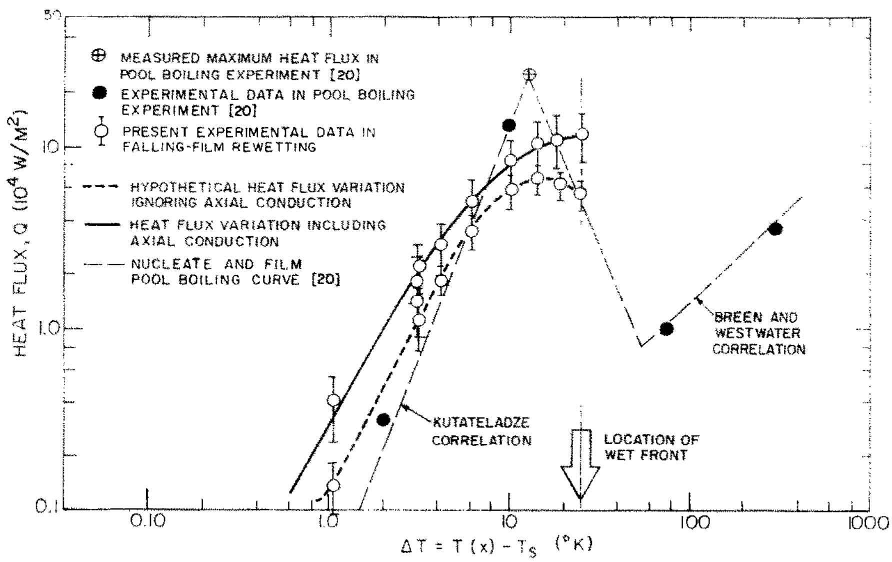

Fig. 5. Heat flux variation behind the wet front.

The variation of the surface heat flux behind the wet front for a typical experimental run is shown in Fig. 5 which reveals some very important aspects of the heat-transfer characteristics in falling-film rewetting in contrast to those observed in the nucleate and film pool boiling. Also shown in Fig. 5 is the boiling curve for liquid nitrogen [20]. In calculating the surface heat flux from equation (1), the axial conduction term was first neglected, thus rendering the calculational procedure similar to that employed in obtaining the heat flux in pool boiling type of experiments. The curve thus obtained (shown in Fig. 5) is only a hypothetical representation of the falling-film rewetting. This curve is then corrected by accounting for the axial conduction in the solid and the heat flux variation thus obtained (shown by solid line in Fig. 5) is a true representation of the rewetting phenomenon. The first important deduction from Fig. 5 is that the rewetting temperature, T_0, at the wet front corresponds to neither of the two temperatures at which the maximum (or critical) or the minimum heat fluxes of the pool boiling exist. The rewetting temperature, T_0, instead lies in the region of transition boiling which is indicative of the state of boiling at the location of the wet front. The heat flux variation behind the wet front is very similar to the conventional pool boiling curve. The second important aspect of the falling-film rewetting revealed by Fig. 5 is that the maximum heat flux occurs right at the location of the wet front ($\bar{x} = 0$) and its magnitude ($\simeq 1.1 \times 10^5\ \mathrm{W/m^2}$) is very close to the average ($\simeq 1.24 \times 10^5\ \mathrm{W/m^2}$) of the maximum and minimum heat fluxes of pool boiling. This further suggests that the state of boiling at the wet front being transitional in nature. It must be emphasized here that this deduction with respect to the magnitude of the heat flux at the wet front is confirmed by the entire data on 26 experimental runs taken at several different initial wall temperature, T_w, of the copper tube and at four different flow rates. The average heat flux at the wet front for all of these experimental runs was found to be $1.046 \times 10^5\ \mathrm{W/m^2}$, which gives the average heat-transfer coefficient of $4175\ \mathrm{W/m^2\,K}$.

A discussion of the findings of the present work with respect to the results of the experimental study by Howard, Linehan and Grolmes [21] is appropriate at this point. In their experimental study, they made the rewetting front stationary by supplying enough heat at the bottom of the rod and then conducted the measurement of the surface temperature behind the stationary wet front, but no measurements of heat flux were made. The successful correlation of the experimentally measured temperature profile by utilizing the nucleate pool boiling correlations for the surface heat-transfer coefficient led them to conclude that the heat flux variation behind the wet front in the rewetting phenomenon follows the pool boiling curve up to the point of the critical heat flux. It is, however, not clear if this steady-state experiment is an exact analog of the moving coordinate transformation which is permissible only due to the localized nature of the rewetting phenomenon demanding the existence of no temperature gradients far downstream of the wet front. It must be emphasized that the existence of the maximum heat flux at the wet front is on account of the fact that the axial conduction is the largest at the wet front. This is clearly seen from Fig. 5 wherein the maxima of the hypothetical curve, neglecting axial conduction, lies slightly behind the wet front where the state of boiling is nucleate due to the reduced surface temperature.

The experiments to measure the Liedenfrost temperature and the heat fluxes of pool boiling are generally much easier to conduct than the rewetting experiments. The deductions of the present experimental study suggest an empirical methodology to estimate the sputtering heat-transfer coefficient at the wet front in falling-film rewetting by approximating the heat flux at and immediately behind the wet front by the average of the maximum and minimum heat fluxes of pool boiling and by taking the rewetting

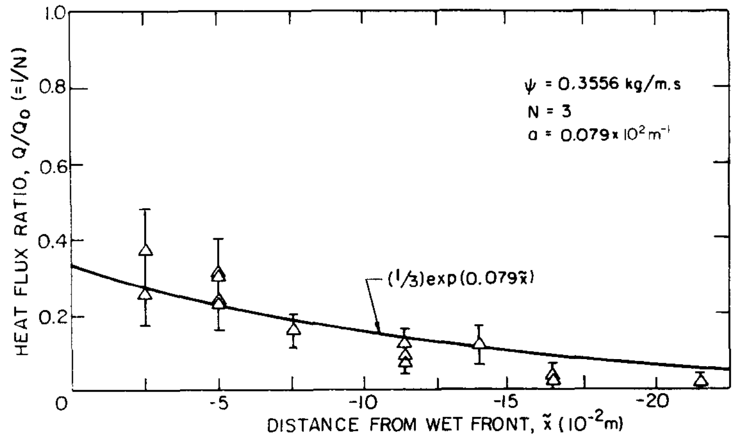

FIG. 6. The variation of heat flux ahead of the wet front.

temperature to be the same as the Liedenfrost temperature.

Figure 6 shows the typical variation of the surface heat flux ahead of the wet front for the experimental runs taken at a constant flow rate of $\psi = 0.3556$ kg/ms. The curve fitting of the experimental data shown here gives an estimate of the exponent a, in the description of precursory cooling, as $7.9\,m^{-1}$. This exponential curve when extrapolated to $\tilde{x} = 0$ gives approximately the value of N, measuring the magnitude of precursory cooling, as 3.0 at this flow rate ($\psi = 0.3556$ kg/ms). Consistent with the physical model presented in Fig. 1, the heat flux variations ahead of the wet front at other flow rates are similar to that shown in Fig. 5, except for the different values of N at different flow rates. Figures 5 and 6 together give the complete variation of the surface heat flux both behind ($\tilde{x} > 0$) and ahead ($\tilde{x} < 0$) of the wet front.

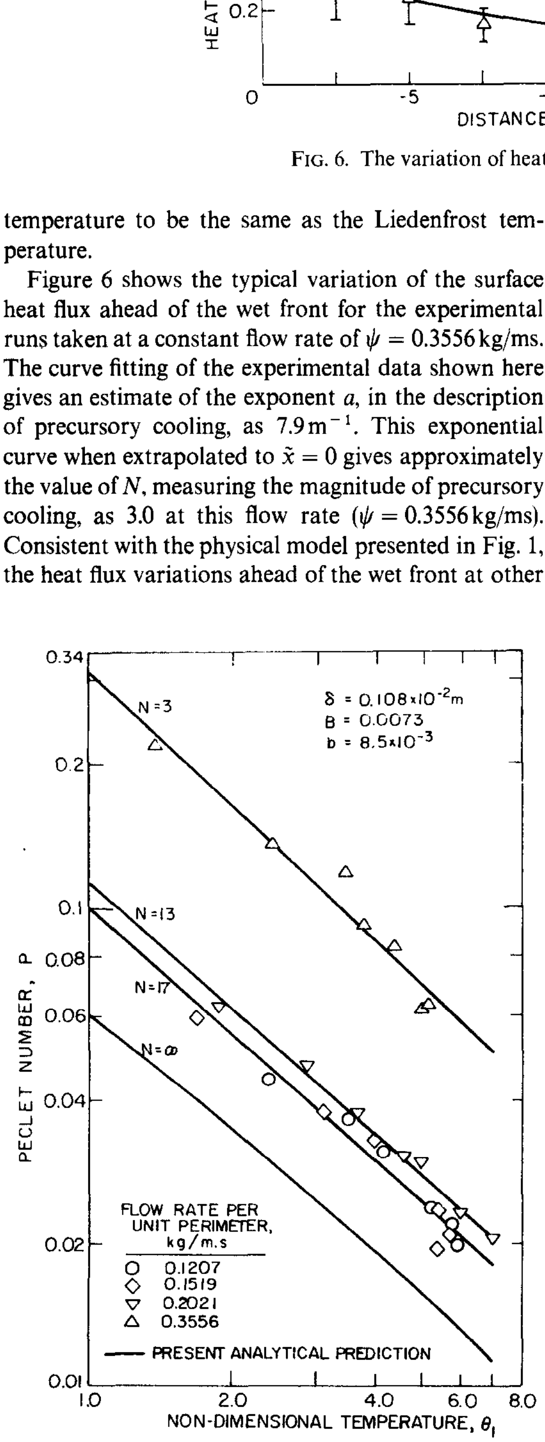

FIG. 7. Comparison of the predicted dimensionless wet front velocity with the present experimental results.

It must be emphasized here that with the known values of N, b, B and θ_0 (or θ_1), the validity of the present physical model can be unambiguously checked as there is no parameter being arbitrarily adjusted here to force the predicted results on the wet-front velocity to match the corresponding experimental data. Figure 7 depicts that the rewetting data taken on 26 experimental runs at different initial wall temperature and at four different flow rates are successfully correlated by the physical model [Fig. 1] of precursory cooling [13]. Also shown in Fig. 7 is the prediction curve neglecting precursory cooling ($N \to \infty$), which gives much too low values of the wet-front velocity corresponding to different initial wall temperatures. This further emphasizes the need to include the effect of precursory cooling in a rewetting model.

The comparison of the predicted surface temperature profile with that obtained experimentally for two experimental runs at the same initial wall temperature but at two different mass flow rates of the coolant is shown in Fig. 8. It is observed from Fig. 8 that the present predictions, equations (2) and (3), fairly well match the experimental data near the wet front, but this agreement becomes worse with increasing distance on either side of the wet front. The trend of the experimentally observed variation of the surface temperature remains, however, in close agreement with that predicted. The present physical model predicts the surface temperature to reach the saturation temperature, T_s, behind the wet front and the initial wall temperature, T_w, ahead of the wet front at much larger distances than are experimentally observed. This is, perhaps, a direct consequence of the boundary conditions imposed on the analytical solution [13], which demand the surface temperature to reach T_s and T_w, respectively at $+\infty$ and $-\infty$ (Fig. 1). Also it should be mentioned here that the experimental data reported in Fig. 8 are not directly recorded by the thermocouples which, for practical reasons, can not be installed so

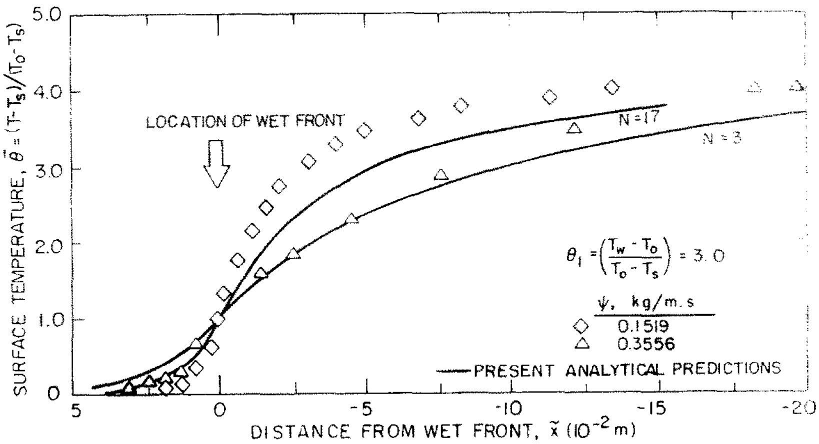

Fig. 8. Comparison of the predicted surface temperature with the present experimental results.

closely on the surface. The surface temperature variation, shown here, was instead deduced from the temperature–time transverse of one thermocouple as described before. In view of the fact that the wet-front velocity depends on the surface temperature immediately ahead of the wet front, which is well predicted, the present model nevertheless successfully correlates the experimental data on rewetting rates as already discussed. As anticipated, the surface temperature ahead of the wet front is lower at higher flow rate due to the increased precursory cooling (Fig. 8).

In order to study the effect of surface conditions on rewetting phenomenon, the surface of the copper tube in the present study was greased with Vaseline jelly. Before running the experiments, the surface of the tube was, however, wiped clean so that the effect of the grease enters only in changing the surface conditions, from a rough surface to a smooth one, without adding any additional surface thermal resistance. Figure 9 reveals some very important aspects of the effect of surface conditions on the heat flux variation behind the wet front. The two curves in Fig. 9 depict the heat flux variations for the greased (smooth) and the ungreased (rough) surfaces. Although the general qualitative characteristics of the heat flux

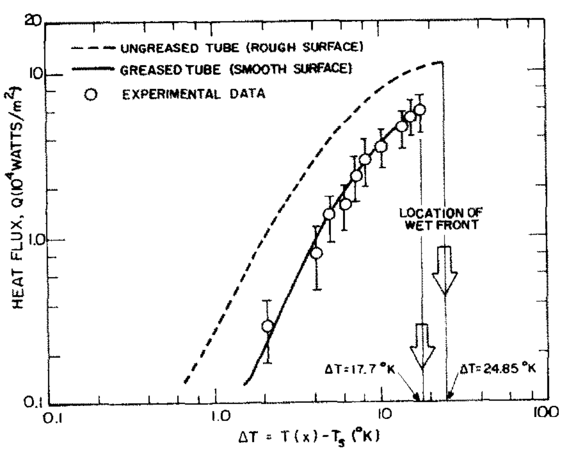

Fig. 9. The effect of the surface conditions on the rewetting temperature and the heat flux variation behind the wet front.

variation are very similar, there exists some significant quantitive differences between the two. The rewetting temperature, T_0, as seen from Fig. 9, for a smooth surface is lower than that for a rough surface. In the present experiments, the rewetting temperatures of the greased (smooth) surface was measured to be 94.90 K in contrast to a value of 102.34 K for an ungreased (rough) surface. A similar effect of the surface conditions is also observed in the measurement of Leidenfrost temperature with liquid droplets evaporating off a hot horizontal surface. Baumeister and Simon [18] reported that the Leidenfrost temperature increases with surface roughness. The increase of the wetting temperature with surface roughness implies that it is easier to wet a rough surface than it is to wet a smooth surface. A plausible physical explanation for this effect comes from the fact that a rough surface tends to break or destroy the vapor film and thus facilitate the direct contact between the liquid film and the hot surface.

The incipient boiling temperature, T_n, in the present experimental study, was measured to be 88.32 K for a greased (smooth) surface in contrast to a value of 83.50 K for an ungreased (rough) surface. The increase of T_n for a smooth surface is well anticipated in light of the higher superheat required for the nucleation of small-sized cavities present on such a surface. The nucleation cavities on a rough surface, on the other hand are larger in size and hence these require less superheat (small T_n) for the incipience of bubble generation.

Also seen from Fig. 9 is that the heat flux at the wet front and inside the sputtering region drops for a smooth surface. Compared to a heat flux of $11.0 \times 10^4\,W/m^2$ at the wet front of a rough surface, the corresponding heat flux for a smooth surface was measured to be only about $5.7 \times 10^4\,W/m^2$. This is also an anticipated result because the population of the nucleation cavities, contributing to the boiling heat flux, is smaller on a smooth surface than it is for a rough surface. The rewetting of a smooth surface requires the surface to be cooled to a lower temperature (smaller T_0) and furthermore, the effectiveness of this cooling is also reduced due to the smaller heat

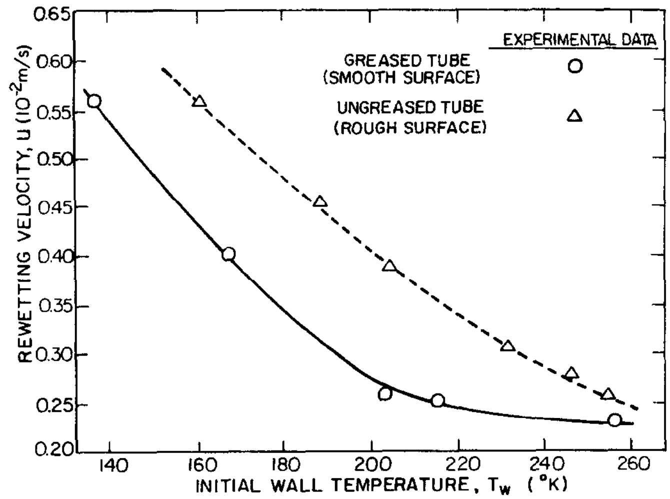

FIG. 10. The effect of the surface conditions on rewetting velocity.

fluxes of boiling in the sputtering region. Both factors lead to the deduction that the wet-front velocity on a smooth surface should be lower than that on a rough surface. This is indeed true as seen from Fig. 10 which depicts the effect of surface condition on the wet-front velocity. The present study also provides an explanation for the similar experimental observations of other research workers [10, 15–17, 22, 23] with respect to the effect of surface conditions on the rewetting rate. Piggot and Duffey [17] artificially changed the nature of the surface by shot blasting and by silver plating. The shot blasting caused the wet-front velocity to increase by a factor of three while the silver plating halved the wetting velocity. Elliot and Rose [15, 16] noted that the zircaloy tube became oxidized when heated to temperatures between 800 and 850°C, resulting in a substantial increase in the wetting rate. Yu [10] and Piggot and Porthouse [22, 23] have also observed a tendency for the wet-front velocity to increase with successive tests due to the build-up of surface deposits. A common explanation to all these observations lies in the fact that the surface roughness increases the wet-front velocity by manifesting its effect in the increased rewetting temperature and the enhanced cooling effectiveness in the sputtering region, as already explained with reference to Fig. 9. The foregoing discussion specifically refers to the effect of surface conditions, assuming that the surface deposits are so thin that no extra thermal resistance is added on the surface.

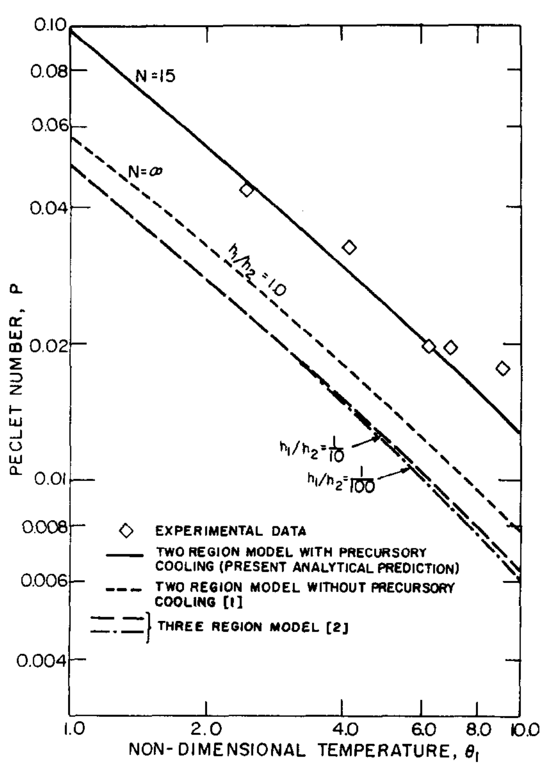

FIG. 11. Comparison of the predicted dimensionless wet-front velocity with the experimental data on the greased tube.

Finally, the rewetting velocities obtained on five experimental runs on a greased (smooth) tube shown in Fig. 11 are successfully correlated by the present model of precursory cooling, which indirectly provides a means to assess the quantitative effect of the surface conditions by incorporating the appropriate values of the rewetting temperature and the sputtering heat-transfer coefficient. Also shown in Fig. 11 are the predictions of the three-region model of Sun *et al.* [2] and of the two region model of Yamanouchi [1], both of which, due to the neglect of precursory cooling, predict lower values of the dimensionless wet-front velocity.

7. CONCLUSIONS

1. The experimental study presented here is fundamental to establishing the nature of the boiling phenomenon in the falling-film rewetting. The maximum heat flux in rewetting occurs at the wet front and its magnitude is very comparable to the average of the maximum and minimum heat fluxes of pool boiling. The measured rewetting temperature does not correspond to either of the two temperatures at which the maximum or the minimum heat fluxes of pool boiling

occur, but is instead represented by the Leidenfrost temperature of liquid nitrogen on a copper surface. This conclusion permits an empirical methodology to estimate the sputtering heat-transfer coefficient in a rewetting situation from the more readily available information of the corresponding pool boiling curve and the Leidenfrost temperatures.

2. Surface roughness increases the wet-front velocity by manifesting its effect in the increased rewetting temperature and the enhanced heat transfer in the sputtering region.

3. The rewetting rates measured both on the rough and the smooth surfaces are very successfully correlated by the present analytical model of rewetting with precursory cooling.

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UNE ETUDE EXPERIMENTALE SUR LE REMOUILLAGE DU FILM TOMBANT

Résumé—L'étude expérimentale du remouillage d'un tube de cuivre par un film tombant d'azote liquide montre que les variations du flux thermique pariétal derrière le front de mouillage sont semblables à celles observées dans l'ébullition nucléée et en film de l'azote liquide en réservoir. On présente aussi la variation de flux thermique en aval du front mouillé, représentant le refroidissement précurseur. Le flux maximal de remouillage apparait à l'emplacement du front mouillé et sa grandeur est comparable à la moyenne des flux maximaux et minimaux de l'ébullition nucléée et en film dans un réservoir. La température mesurée de remouillage est trouvée très proche de la température de Leidenfrost de l'azote liquide sur une surface de cuivre. On montre aussi que la température de remouillage et les caractéristiques de transfert thermique derrière le front mouillé sont très sensibles aux conditions des surfaces. Les résultats expérimentaux sur la vitesse du front mouillé obtenus sur une surface lisse sont comparés à ceux pour une surface rugueuse et ils sont convenablement représentés par un modèle analytique antérieur de remouillage avec refroidissement précurseur.

EINE EXPERIMENTELLE STUDIE DER WIEDERBENETZUNG DURCH EINEN FALLENDEN FILM

Zusammenfassung—Die vorliegende experimentelle Studie über das Wiederbenetzen eines Kupferrohres durch einen fallenden Film aus flüssigem Stickstoff zeigt, daß die Änderungen des Wärmestroms an der Oberfläche hinter der Flüssigkeitsfront denen ähnlich sind, die beim Blasensieden und Behälterfilmsieden von flüssigem Stickstoff beobachtet werden. Die Änderung des Wärmestroms vor der Flüssigkeitsfront, die die fortschreitende Kühlung darstellt, wird ebenfalls gezeigt. Der maximale Wärmestrom beim Wiederbenetzen tritt am Ort der Flüssigkeitsfront auf, und seine Größe ist vergleichbar dem Mittel aus maximalem und minimalem Wärmestrom beim Blasensieden und Behälterfilmsieden. Die gemessene Wiederbenetzungstemperatur liegt nahe bei der Leidenfrost-Temperatur von flüssigem Stickstoff auf einer Kupferoberfläche. Es wird ebenfalls gezeigt, daß die Wiederbenetzungstemperatur und die Kenngrößen des Wärmeübergangs hinter der Flüssigkeitsfront stark von den Oberflächenbedingungen abhängen. Die experimentellen Daten für die Geschwindigkeit der Flüssigkeitsfront für eine glatte Oberfläche werden mit denen für eine rauhe Oberfläche berglichen und durch ein früheres analytisches Modell für das Wiederbenetzen mit fortschreitender Kühlung erfolgreich korreliert.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПОВТОРНОГО СМАЧИВАНИЯ СТЕКАЮЩЕЙ ПЛЕНКОЙ ЖИДКОСТИ

Аннотация — Проведенное экспериментальное исследование повторного смачивания медной трубки стекающей пленкой жидкого азота свидетельствует о том, что изменения в величине теплового потока на поверхности за фронтом смачивания аналогичны изменениям, наблюдаемым при пузырьковом и пленочном кипении жидкого азота в большом объеме. Также получены данные об изменении плотности теплового потока перед фронтом смачивания, указывающие на предварительное охлаждение. Максимальный тепловой поток при повторном смачивании наблюдается в месте расположения фронта смачивания, и его величина сравнима с осредненным значением максимального и минимального тепловых потоков при пузырьковом и пленочном кипении в большом объеме. Найдено, что экспериментально полученное значение температуры смачивания очень близко к температуре Лейденфроста для жидкого азота на медной поверхности. Также показано, что температура смачивания и теплообменные характеристики за фронтом смачивания весьма чувствительны к условиям на поверхности. Экспериментальные данные по скорости движения фронта смачивания, полученные на гладкой поверхности, сравниваются со скоростью на шероховатой поверхности и хорошо обобщаются с помощью ранее разработанной аналитической модели смачивания при предварительном охлаждении.