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# The effect of plate temperature on the onset of wetting

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**Abstract**—The wetting front velocity of a thin liquid film flowing over a hot flat plate is investigated analytically. An exact solution is developed as a function of the Peclet number, the Jakob number, the Biot number, the heat capacity ratio, and the thickness ratio of plate and liquid film. The initial plate temperature affects only the time required for the onset of wetting, and the actual wetting front velocity is independent of the initial plate temperature. The experimental data obtained by other investigators are used to compute the onset time and actual wetting front velocity. The results provide further insight into the mechanism and help to clarify the fundamental phenomena.

## INTRODUCTION

THE WETTING and rewetting of thin films flowing over a hot flat plate are of significant importance in many applications, including the emergency cooling of fuel elements in water-cooled nuclear reactors during loss-of-coolant accidents (LOCA), thermal control systems for cooling high density electronic components [1], and two-phase heat rejection systems for spacecraft thermal control [2]. As a result, numerous investigations have been performed to better understand the parameters that govern this phenomenon.

Several experimental investigations [3–9] have been conducted to measure the wetting characteristics of thin liquid films on the outer surface of heated rods, the inner surfaces of heated tubes, and the horizontal surface of flat plates. In other analytical investigations [10–15] models have been developed to determine and better understand the fundamental mechanisms involved. Recently, Peng and Peterson [16] proposed a physical model to investigate the wetting behavior of heated plates. In this model, the evaporation of liquid at the wetting front was considered to be an important aspect of the wetting. Consequently, in the theoretical analysis, the wetting velocity was related to liquid flow velocity and an analytical solution was obtained for determining the wetting front velocity for a thin liquid film as a function of liquid flow velocity, fluid properties, film thickness, and the applied heat flux, for both grooved and flat plates. In another separate investigation, analytical expression for the surface tension induced flow of thin liquid films over flat plates was studied [17]. Because of the observations made during the experimental evaluation, this expression was modified to include a term to compensate for liquid sputtering. The correlation between the analytical expression and the available experimental data was quite good in both trend and magnitude [16, 17]. This technique was successfully extended to include the wetting in a flat porous layer [18], and was later verified by additional experimental data [19].

Although these investigations have resulted in a substantial amount of experimental data and several analytical models, it is clear from reviewing the literature that no physical model exists, which is capable of fully describing the governing physical phenomena. Several generally accepted conclusions have evolved, however. One of these conclusions is that the wetting velocity of a liquid flowing along a hot plate is strongly dependent upon the initial plate temperature. This conclusion appears to be supported by experimental data [3–9], and as a result, the initial plate temperatures are frequently included as a governing parameter in a majority of the recently developed analytical models [10, 12, 13]. In the present work, the validity of this conclusion was examined analytically by investigating the flow of thin liquid films over hot flat surfaces to determine how variations in the initial plate temperature affect the velocity of the wetting front.

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## NOMENCLATURE

| | |
|---|---|
| $A$ | non-dimensional number, equation (17) |
| $B$ | heat capacity ratio, equation (16) |
| $Bi$ | Biot number |
| $c$ | specific heat of plate |
| $C_p$ | specific heat at constant pressure |
| $h$ | heat transfer coefficient |
| $h_f$ | liquid latent heat |
| $h_w$ | heat transfer coefficient during wetting onset |
| $Ja$ | Jakob number |
| $k$ | conductivity of plate |
| $L$ | wetted distance |
| $P$ | Peclet number |
| $Q$ | total heat |
| $T$ | temperature |
| $T_f$ | initial liquid temperature |
| $T_0$ | plate edge temperature |
| $T_s$ | liquid saturation temperature |
| $T_w$ | surface temperature at the wetting front |
| $T_{wi}$ | initial wall temperature |
| $t$ | time |
| $U$ | average velocity of liquid flow |
| $U_w$ | rewetting velocity. |

Greek symbols

| | |
|---|---|
| $\alpha$ | thermal diffusivity |
| $\delta$ | thickness of plate |
| $\delta_l$ | thickness of liquid film |
| $\eta$ | non-dimensional length, equation (3) |
| $\Theta$ | non-dimensional temperature, equation (3) |
| $\rho$ | density |
| $\phi$ | variable of temperature difference. |

Subscripts

| | |
|---|---|
| i | initial |
| l | liquid |
| on | onset |
| w | wetting. |

## ANALYSIS

From the equation of continuity, it is clear that the wetting front velocity for a thin liquid film flowing over a flat horizontal surface will be equal to the film velocity if the plate is completely wettable and cool enough that no vaporization occurs. However, when the plate temperature at the wetting front is higher than the saturation temperature of the liquid, some of the liquid will be vaporized due to conduction from the dry hot zone immediately ahead of the advancing wetting front. As this vaporization reduces the liquid mass flow rate, the wetting front velocity, $U_w$, will be smaller than the film velocity, $U$.

This problem is illustrated schematically in Fig. 1, where a liquid film of thickness, $\delta_l$, advances in the $x$-direction over a hot plate of thickness $\delta$. The problem of interest in this particular investigation is to determine how the initial plate temperature affects the velocity with which the thin liquid film wets the flat surface. To solve this problem, several assumptions were made. These can be summarized as follows:

(1) conduction in the plate was assumed to be one-dimensional;

(2) the plate was assumed to be at some initial temperature and no additional heat was supplied;

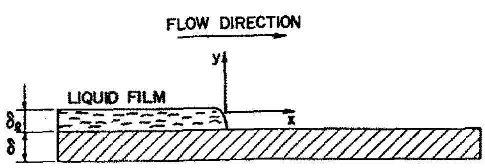


FIG. 1. Analytical model.

(3) the liquid temperature at the rewetting front, $T_l$, was assumed to be different from the rewetting temperature, $T_w$, which was assumed to be constant and equal to the saturation temperature, $T_s$;

(4) the thermophysical properties of the liquid and the plate were assumed to be constant;

(5) the convective heat transfer between the plate and air (or vapor) along with the radiation between the hot surface and the surroundings were assumed to be constant and included in the heat transfer coefficient.

In addition to these fundamental assumptions, the liquid was assumed to be supplied at a constant velocity, $U$, and the conduction equation for the plate was transformed to a coordinate system moving with the wetting front at a velocity, $U_w$, as illustrated in Fig. 1.

Utilizing these assumptions, the one-dimensional conduction equation for the plate yields

$$k\frac{\partial^2 T}{\partial x^2} - \frac{h(T-T_f)}{\delta} = \rho c\frac{\partial T}{\partial t} \tag{1}$$

or

$$k\frac{\mathrm{d}^2 T}{\mathrm{d}x^2} - \frac{h}{\delta}(T-T_f) = -\rho c U_w \frac{\mathrm{d}T}{\mathrm{d}x}. \tag{2}$$

Introducing the dimensionless temperature and distance

$$\Theta = \frac{T-T_f}{T_w-T_f} \quad \text{and} \quad \eta = \frac{x}{\delta} \tag{3}$$

and rearranging equation (2) can be expressed as

$$\frac{d^2\Theta}{d\eta^2}+P_w\frac{d\Theta}{d\eta}-Bi\,\Theta=0 \qquad (4)$$

where the Peclet number of the wetting front, $P_w$, and Biot number, $Bi$, are defined as

$$P_w=\frac{U_w\delta}{\alpha} \qquad (5)$$

$$Bi=\frac{h\delta}{k} \qquad (6)$$

respectively. The general solution for equation (4) has been shown to be

$$\Theta=\exp(-\tfrac{1}{2}P_w)[c_1\exp(\tfrac{1}{2}\eta\sqrt{(P_w^2+4Bi)})+c_2\exp(-\tfrac{1}{2}\eta\sqrt{(P_w^2+4Bi)})]. \qquad (7)$$

When $\eta\to\infty$ (i.e. $x\to\infty$), the second term in the square root bracket of equation (7) tends to approach infinity, hence $c_1\equiv 0$. Utilizing the boundary conditions $\eta=0$ (or $x=0$) and $\Theta=\Theta_w=1$, the other constant, $c_2$, can be determined and shown to be equal to one, i.e. $c_2\equiv 1$. The final solution of equation (4) is thus given by

$$\Theta=\exp(-\tfrac{1}{2}[P_w+\eta\sqrt{(P_w^2+4Bi)}]). \qquad (8)$$

Here it is important to note that at the wetting front, some of the heat conducted away from the dry hot region is partially absorbed by vaporization of the liquid. The remaining heat is transferred into the wet region. If the heat transferred into the wet region is assumed to be small compared to that absorbed by vaporization, the total heat conduction from the dry region should be approximately equal to the energy absorbed by vaporization of the liquid.

The total heat conduction at $x=0$ will be

$$Q=-\delta k\left.\frac{\partial T}{\partial x}\right|_{x=0}=-\delta k\frac{T_w-T_f}{\delta}\left.\frac{\partial\Theta}{\partial\eta}\right|_{\eta=0}. \qquad (9)$$

Substituting into equation (8) yields

$$Q=k(T_w-T_f)\tfrac{1}{2}[P_w+\sqrt{(P_w^2+4Bi)}]. \qquad (10)$$

The heat absorbed by vaporization of the liquid can be found as

$$Q=(U-U_w)\rho_l h_f\delta_l \qquad (11)$$

and combining equations (10) and (11) yields

$$\tfrac{1}{2}k(T_w-T_f)[P_w+\sqrt{(P_w^2+4Bi)}]=(U-U_w)\rho_l h_f\delta_l. \qquad (12)$$

Non-dimensionalizing equation (12) yields

$$P_w+\sqrt{(P_w^2+4Bi)}=2(P-P_w)\left(\frac{B}{Ja_l}\right)\left(\frac{\delta_l}{\delta}\right) \qquad (13)$$

where the Peclet number of the liquid, $P$, is defined as

$$P=\frac{U_l\delta}{\alpha}$$

the Jakob number is

$$Ja_l=\frac{C_{pl}(T_w-T_f)}{h_f} \qquad (14)$$

and the ratio of the liquid and plate heat capacities can be expressed as

$$B=\frac{\rho_l C_{pl}}{\rho C}. \qquad (15)$$

To further simplify, let

$$A=\frac{B}{Ja_l}\left(\frac{\delta_l}{\delta}\right). \qquad (16)$$

Substituting equation (16) into equation (13) and rearranging yields

$$P_w^2-\frac{2A+1}{A+1}PP_w+\frac{A^2P^2-Bi}{A(A+1)}=0 \qquad (17)$$

or

$$P_w=\frac{1}{2}\left[\frac{2A+1}{A+1}P\pm\sqrt{\left(\frac{AP^2+4Bi(A+1)}{A(A+1)^2}\right)}\right]. \qquad (18)$$

As the positive root would require that $P_w$ be greater than $P$, the correct solution is given by the negative root, or

$$P_w=\frac{1}{2}\left[\frac{2A+1}{A+1}P-\sqrt{\left(\frac{AP^2+4Bi(A+1)}{A(A+1)^2}\right)}\right]. \qquad (19)$$

The resulting expression, equation (19), is a non-dimensional relationship which describes the wetting velocity. Examining the relationship for $A$, given by equation (16), reveals that the wetting velocity Peclet number is related to the liquid velocity Peclet number, the liquid Jakob number, the heat capacity ratio, the ratio of the liquid film and plate thicknesses, and the Biot number. As noted by Peng and Peterson [17], the sputtering significantly affects the wetting velocity, hence this expression could also be modified to compensate for sputtering as described in ref. [17].

## DISCUSSION

Equation (19) indicates that since the Peclet number at the wetting front, $P_w$, is independent of the initial surface temperature, so too is the wetting front velocity. As noted previously, it has, in the past, been generally assumed that the wetting velocity is strongly affected by the initial surface temperature. Some experimental data, i.e. that shown in Figs. 2 and 3 obtained by Duffey and Porthouse [6] and Simopoulos *et al.* [7], respectively, appears to support this assumption. However, noting that $AP^2\gg 4Bi(A+1)$ for the general case, equation (19) can be simplified to

$$P_w=\frac{A}{A+1}P. \qquad (20)$$

For the experiments conducted by Duffey and Porthouse using water [6], the value $A$, given by equation (16), can be shown to be approximately 5.2. As

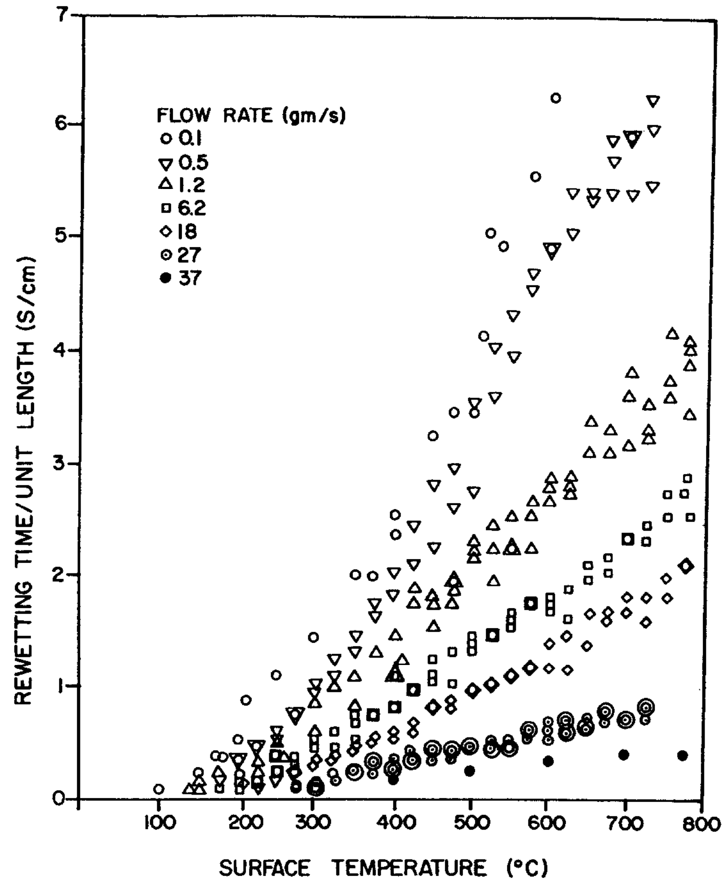


FIG. 2. Wetting velocity as a function of surface temperature [6].

a result, the relationship between $P_w$ and $P$ can be simplified to

$$P_w = 0.84P. \tag{21}$$

This relationship is illustrated in Fig. 4, and appears as a solid line. The experimental results of Duffey and Porthouse [6], shown as the triangles and squares, taken at wall temperatures of 200–250 and 600°C, respectively, are also illustrated. Clearly, the experimental data at a wall temperature of between 200 and 250°C, are in close agreement with results predicted by equation (21) and demonstrate a similar trend. The experimentally obtained data for the Peclet number at a wall temperature of 600°C, however, are significantly smaller than predicted, although the trend is similar.

If the wetting of a hot flat surface is examined in detail, several things are apparent. First, when the plate temperature at the wetting front is lower than the wetting temperature and the plate is wettable, a small amount of vaporization occurs and the liquid front advances with a velocity equal to the film velocity. Second and more importantly, when the plate surface temperature is greater than the wetting temperature, $T_w$, the liquid at the leading edge of the liquid is vaporized or sputtered away, as illustrated in Fig. 5. This causes the dry hot region immediately ahead of the leading edge to cool until the wetting temperature is reached and allows the wetting front to be established and advance continuously along the plate. As the wetting temperature is reached and the surface wets, a temperature distribution along the flow direction is established in the plate. This temperature distribution is steady relative to the coordinate system and moves with the front at a velocity equal to that of the wetting front. This implies that, as predicted by equation (8), the wetting is in fact independent of the initial wall temperature since the steady temperature profile does not vary in relation to this temperature. It should be true from the qualitative analysis presented above that the wetting velocity has little relation to the initial wall temperature. If this is true, it appears that the theoretical analysis presented here, and the experimental results of previous investigators are contradictory. However, it should be noted that the initial wall temperature will strongly affect the time required for the surface to reach the rewetting temperature, $T_w$. The higher the initial temperature, the longer the time required to reach the wetting temperature.

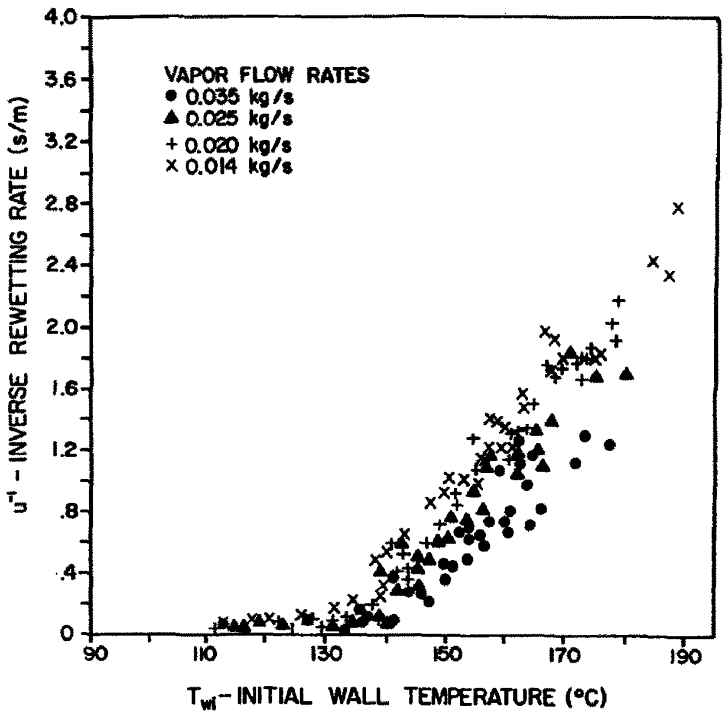


FIG. 3. Wetting velocity as a function of initial plate surface temperature [7].

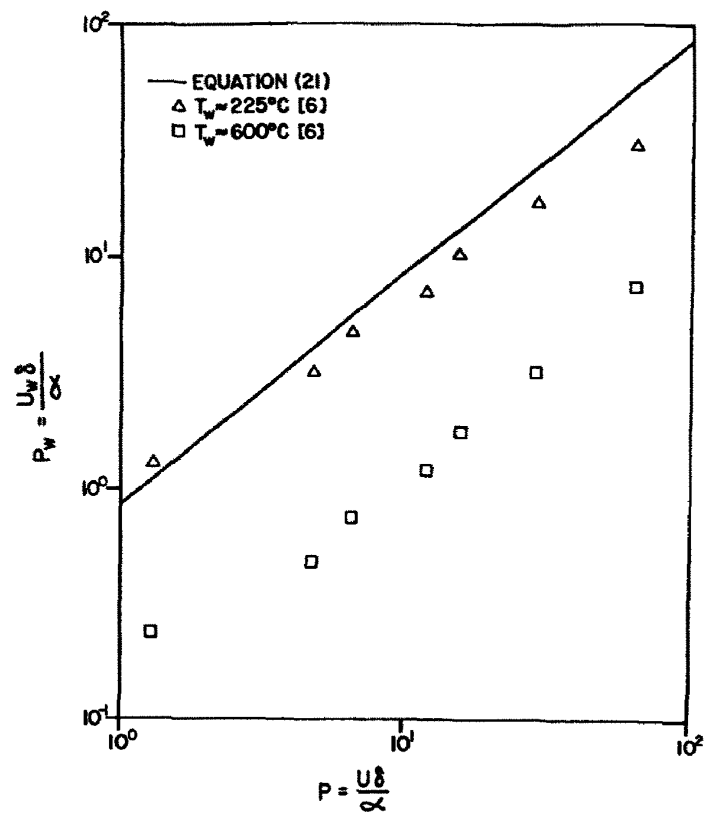


FIG. 4. Relationship between film velocity and wetting velocity Peclet numbers.

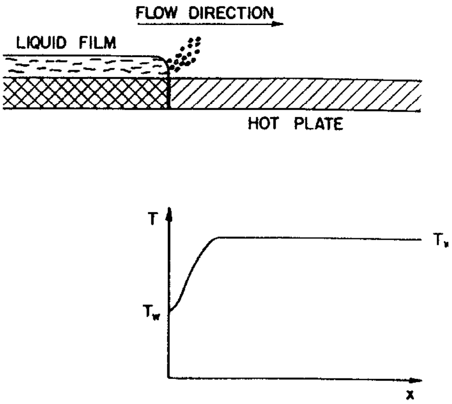


FIG. 5. Schematic of film leading edge and temperature profile.

Typically, the wetting front velocity is found by dividing the distance travelled by the time, i.e.

$$U_w = \frac{L}{\Delta t}. \quad (22)$$

In all of the previous experimental data the time, $\Delta t$, was measured from the instant the liquid first came into contact with the hot surface to the point when the liquid had travelled some distance $L$ along the plate. As explained earlier, when the liquid initially arrives at a surface whose temperature is greater than the wetting temperature, the liquid does not immediately wet the plate. As a result, the time in which the liquid actually travels and wets the plate, $\Delta t_w$, should be expressed as the difference between the actual measured time, $\Delta t$, and the time required for the liquid to cool the region immediately beyond the leading edge and begin to advance, i.e.

$$\Delta t_w = \Delta t - \Delta t_{on} \quad (23)$$

where $\Delta t_{on}$ is the time required to cool the hot surface to $T_w$, henceforth referred to as the onset time. Obviously, the higher the initial plate temperature, $T_w$, the greater the onset time, $\Delta t_{on}$, and also, the lower the previously presumed wetting velocity as shown in Figs. 2 and 3. Therefore, in order to validate equations (19) and (20), it is necessary to investigate $\Delta t_{on}$ to determine the real wetting time and the actual wetting velocity.

## THE EFFECT OF WETTING ONSET

For clarity, the process by which the liquid at the wetting front cools the hot surface to the wetting temperature and initiates the advance of the wetting front will be referred to as the onset process, or simply onset, and the time corresponding to this process as the onset time. To understand this process and the concept of onset time, assume a system similar to that shown in Fig. 5, where a liquid film flows over a hot plate. As mentioned previously, when the liquid arrives at the edge of the plate, it is vaporized or sputtered since the plate temperature is higher than the wetting temperature. Once the plate is cooled and the wetting temperature is reached, a wetting front similar to that shown in Fig. 5(a) will be formed. The resulting temperature profile in the plate can then be plotted as a function of position, as shown in Fig. 5(b). If no heat is lost from the two sides of the plate, and the temperature only varies along the flow direction, the onset can be approximated as a cooling process for a semi-infinite plate with liquid flowing over it, as shown in Fig. 6. This is a one-dimensional transient conduction problem. The temperature variation with respect to time at the plate edge, which is the same as the surface temperature variation of transient conduction in a semi-infinite medium, has been given previously by ref. [20] as

$$\frac{4}{3}\left(\frac{h_w}{k}\right)^2 \alpha t = \frac{1}{2}\left[\frac{1}{\left(1-\frac{\phi_{on}}{\phi_i}\right)^2} - 1\right] + \ln\left(1 - \frac{\phi_{on}}{\phi_i}\right) \quad (24)$$

where $\phi_{on} = T_{on} - T_{wi}$, $\phi_i = T_f - T_{wi}$, and $T_{on}$ is the temperature of the plate edge at any time $t$ ($t \leqslant t_{on}$). The onset time required for the plate edge temperature to reach the rewetting temperature, $T_w$, or $\phi_w$, is equal to the difference between the rewetting temperature and the initial plate temperature, i.e. $\phi_{on} = \phi_w = T_w - T_{wi}$. This time can be determined from equation (24) as

$$t_{on} = \frac{3}{4}\left(\frac{k}{h_w}\right)^2 \frac{1}{\alpha}\left\{\frac{1}{2}\left[\frac{1}{\left(1-\frac{\phi_w}{\phi_i}\right)^2} - 1\right] + \ln\left(1 - \frac{\phi_w}{\phi_i}\right)\right\}. \quad (25)$$

For a given system both the temperature of the liquid and the wetting temperature, $T_f$ and $T_w$, respectively, are nearly constant, thus the onset time, $t_{on}$, depends primarily on the initial wall temperature, $T_w$. If an appropriate value of $h_w$ ($h_w$ is related to the liquid velocity, temperature, and thermophysical properties) is chosen for the experimental data of Duffey and Porthouse [6], the variation of $t_{on}$ with $T_{wi}$ can be determined analytically from equation (25), as illustrated by the solid line in Fig. 7. The original experimental data obtained by Duffey and Porthouse are also shown for comparison in Fig. 7. As illustrated, the trend predicted by the analytical model is very similar to that of the actual experimental data. By combining equations (22) and (23), and rearranging, an expression for the rewetting velocity can be found as

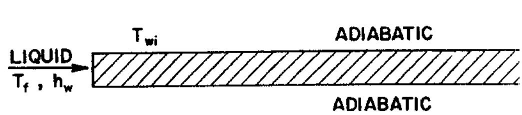


FIG. 6. Boundary conditions for the analytical model.

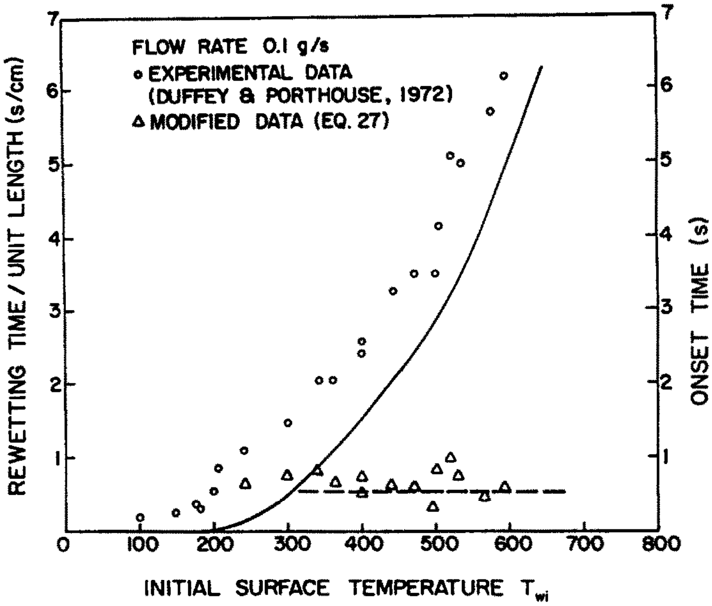


FIG. 7. Comparison of measured and modified data as a function of initial surface temperature.

$$\frac{1}{U_w} = \frac{\Delta t_{on} + \Delta t_w}{L} = \frac{\Delta t_{on}}{L} + \frac{\Delta t_w}{L}. \tag{26}$$

However, as previously discussed, the actual time used to determine the rewetting velocity, $U_w$, should not include the time required for onset, but only the actual wetting time, i.e.

$$\frac{1}{U_w} = \frac{\Delta t_w}{L}. \tag{27}$$

The experimental data in Fig. 7, therefore, should be modified to account for the time required for the onset of wetting. As a result, the actual wetting velocity should be determined by equation (27) rather than equation (26). When this is done, the experimental data fall in a narrow band around the broken line shown in Fig. 7. This helps to verify that the wetting velocity is in fact a constant and independent of the initial plate temperature.

This is a significant observation, which, with the exception of the work of Simopoulos *et al.* [7] who demonstrated, experimentally, that the actual wetting velocity in a range of surface temperatures near $T_w$ does not really depend on the initial temperature (see Fig. 3), has not been previously understood and/or verified. Recently, Peng *et al.* and Peng and Peterson [18, 19] showed, experimentally, that if the initial temperature of a plate covered with a porous cover layer was significantly higher than the wetting temperature, some sputtering would occur and would cause a slight delay in the rise of the liquid in the porous layer. It was also shown that the wetting temperature, $T_w$, increased with increases in liquid velocity or flow rate. The experimental data presented in Figs. 2 and 3 support this observation. In both of these cases, the data indicated that as the liquid velocity or flow rate increased, the onset time decreased. Also, as the liquid velocity increased, the dependence of onset time on the initial surface temperature decreased. This may partially explain why in the experimental results of Simopoulos *et al.* [7] there is a range of initial temperatures where the wetting velocity appears to be independent of the initial plate temperature. These observations, along with the re-evaluation of existing experimental data, support the theoretical analysis presented above and the existence of a wetting onset time.

## CONCLUSION

In this work, the wetting of a hot plate with liquid film flow was theoretically investigated and an exact solution was derived for the wetting velocity Peclet number as a function of the liquid velocity Peclet number, the Jakob number, the heat capacity ratio, the thickness ratio of liquid film and plate, and the Biot number. The analysis indicates that for the case of no heat addition, the initial plate temperature significantly affects the onset time, but does not affect the actual wetting front velocity.

The concept of an onset time for wetting has been proposed for the wetting of hot plates over which thin liquid films are flowing. The onset process, the effect of the initial surface temperature, and the onset time have all been examined analytically and it has been shown that the onset process and onset time are strongly dependent on the initial surface temperature but that the wetting front velocity has little relation to the surface temperature. In addition, if the onset time is not separated from the time in which the liquid front actually travels along the hot surface, the experimental data will indicate a significantly slower wetting velocity. This result is supported by the theoretical analysis and experimental results of Duffey and Porthouse [6] and Simopoulos [7]. The investigation of the wetting process and the existence of a wetting onset time not only clarifies the fundamental phenomena, but also provides further insight into the mechanism for the wetting of hot surfaces.

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## EFFET DE LA TEMPERATURE DE LA PLAQUE SUR LA NAISSANCE DU MOUILLAGE


**Résumé**—On étudie analytiquement la vitesse du front de mouillage d'un film liquide mince s'écoulant sur une plaque plane chauffée. On développe une solution exacte en fonction des nombres de Peclet, de Jakob et de Biot, du rapport des capacités thermiques, du rapport des épaisseurs de la plaque et du film liquide. La température initiale de la plaque affecte seulement le temps nécessaire pour l'apparition du mouillage et la vitesse du front de mouillage est indépendante de la température initiale de la plaque. Les données expérimentales sont utilisées pour calculer le temps de mouillage et la vitesse du front, et les résultats fournissent des renseignements sur le mécanisme et clarifient les phénomènes fondamentaux.


## DER EINFLUSS DER PLATTENTEMPERATUR AUF DAS EINSETZEN DER BENETZUNG


**Zusammenfassung**—Die Geschwindigkeit der Benetzungsfront bei der Strömung eines dünnen Flüssigkeitsfilms über eine heiße Platte wird analytisch untersucht. Eine exakte Lösung dieses Problems wird entwickelt und als Funktion der Peclet-Zahl, der Jakob-Zahl, der Biot-Zahl, des Verhältnisses der Wärmekapazitäten sowie des Dicken-Verhältnisses von Platte und Flüssigkeitsfilm dargestellt. Die anfängliche Plattentemperatur beeinflußt nur die Zeit, welche für das Einsetzen der Benetzung erforderlich ist. Die tatsäliche Geschwindigkeit der Benetzungsfront ist von der Anfangstemperatur der Platte unabhängig. Die von anderen Forschern ermittelten experimentellen Ergebnisse werden dazu verwendet, die Zeit bei Benetzungsbeginn und die tatsächliche Geschwindigkeit der Benetzungsfront zu berechnen. Die Ergebnisse erlauben weitere Einblicke in die Mechanismen und tragen zur Klärung des grundsätzlichen Phänomens bei.

## ВЛИЯНИЕ ТЕМПЕРАТУРЫ ПЛАСТИНЫ НА ВОЗНИКНОВЕНИЕ СМАЧИВАНИЯ

**Аннотация**—Анализируется скорость фронта смачивания при обтекании нагретой плоской пластины тонкой жидкой пленкой. Получено точное решение в виде функции чисел Пекле, Якоба и Био, а также отношения теплоемкостей и толщин пластины и жидкой пленки. Начальная температура пластины оказывает влияние только на время, необходимое для возникновения смачивания, тогда как реальная скорость фронта смачивания от нее не зависит. Имеющиеся в литературе экспериментальные данные используются для расчета времени возникновения и скорости фронта смачивания. Полученные результаты способствуют более глубокому пониманию механизма и характеристик этого процесса.