WETTING OF A HOT VERTICAL SURFACE BY A FLOWING LIQUID FILM

B. G. Ganchev and A. E. Bokov

UDC 532.62:536.24

A planar two-dimensional problem of the wetting of a dry heated vertical surface by a flowing liquid film was experimentally investigated. A model of the process was developed and the problem was numerically solved.

The gravitational flow of a liquid film over a vertical surface is characterized by fairly high velocities even at low unit flow rates – spraying densities [1]. In connection with this and with the fact that a wave motion develops on the surface of the film, film cooling is characterized by a relatively high heat-transfer coefficient. For stable, continuous flow, it is necessary that the spraying density be greater than a certain minimum, this minimum being dependent on the heat flux. At $Re > 1150$, stable flow is seen at any heat flux – at least up to $q = 3 \cdot 10^5$ W/m^2 [2]. With the delivery of the liquid onto a dry cold surface, the rate of propagation of the wetting front is roughly the same as in steady-state film flow. If the liquid is delivered onto a surface previously heated to a temperature significantly in excess of the saturation temperature (above the Leidenfrost point), then the wetting rate, even at $Re > 1150$, will be one to two orders lower than in steady-state film flow [3]. The velocity of the wetting front – the boundary between the wetted and unwetted surfaces – is determined by the rate of cooling of the surface ahead of the front. Earlier studies have shown that the wetting rate depends significantly on the temperature of the dry surface, the temperature and flow rate of the liquid in the film, the condition of the surface, and the physical properties of the liquid and the body being cooled [3].

However, the data in the works published to date is inadequate to construct a substantial physical model of the process of the wetting of a preheated surface. The data on the effect of given parameters, such as the flow rate in the film, is contradictory.

The present work experimentally investigates the rate of wetting of vertical working sections represented by a tube made of stainless steel and a zirconium alloy 0.5 m long, 12 m in diameter, and 1 mm in wall thickness. The section was heated by the passage of an electrical current over the walls of the tube. After a certain wall temperature was reached, the load was either removed or reduced to a fixed level and liquid was supplied to a film-forming material installed in the top part of the working section. The main experiments were conducted with the load disconnected. A wetting front formed at the outlet of the film-forming material and descended over the outside surface of the section. The wetting rate was measured on a section 100 (200) mm long located 150 mm from the film-forming material. Three pairs of thermocouples were installed on the surface of the measurement section along three generatrices located uniformly about the perimeter. The distance between the top and bottom thermocouples of each pair was equal to the length of the measurement section. The signals from the thermocouples were sent to a loop oscillograph. There was a sudden change in the signal as the wetting fronts passed the points of thermocouple attachment, and the velocity of the front was determined along each of the generatrices from the distance between the jumps in the signals of the thermocouples on the respective generatrices on the oscillogram, as well from the speed of the light-sensitive tape. As the wetting rate in the experiments, we took the arithmetic mean of three velocities measured along the respective generatrices:

$$u_{\mathrm{f}} = \frac{1}{3}\sum_{i=1}^{3} u_{\mathrm{f}i} = \frac{1}{3}\sum_{i=1}^{3} \frac{L w_{\mathrm{tp}}}{l_i}. \tag{1}$$

The velocity of the front, particularly at high liquid flow rates in the film, is not constant along a given generatrix. The mean wetting rate about the perimeter, however, is nearly constant.

For the characteristic temperature of the surface, we took the temperature when the wetting front reached the middle of the measurement section. The temperature of the surface was measured with an additional thermocouple located in the lower half of the measurement section.

N. É. Bauman Moscow Higher Technical School. Translated from Izhenerno-Fizicheskii Zhurnal, Vol. 14, No. 5, pp. 773-780, November, 1981. Original article submitted August 8, 1980.

0022-0841/81/4105-1163 $07.50

The wetting rate was investigated in the following parameter ranges: temperature of dry wall 300-700°C; spraying density 0.21-1.6 kg/m • sec; temperature of liquid supplied 30-90°C; heat flux 0 and $1.7 \cdot 10^4$ W/m^2; pressure – atmospheric; working liquid – distilled water.

It was found during the experiments that the wetting rate increased significantly on one working section with long operation of the unit, a phenomenon connected with the effect of the layer of oxides formed on the surface of this section. The experiments were therefore conducted in short series, after each of which the section was ground to remove the oxide film. The results of tests with similar numbers of load cycles were compared.

Figure 1 shows typical results of the experiments in the form of dependences of the inverse wetting rate on the different parameters. It is apparent that a reduction in the temperature of the dry wall, an increase in the liquid flow rate in the film, and a decrease in the temperature of the liquid lead to a substantial increase in the velocity of the wetting front (Fig. 1a-c). The working section made of the zirconium alloy wets roughly twice as rapidly as the stainless-steel working section, which had the same dimensions and test conditions (Fig. 1d). Moderate heat flow through the walls of the section ($q = 1.7 \cdot 10^4$ W/m^2) did not lead to a change in the wetting rate compared to cooling of the section with the load disconnected and the same temperature of the dry surface of the wall ahead of the wetting front (Fig. 1e).

We also investigated the effect of the condition of the surface on the wetting rate. The surface condition changed during the tests due to the formation of oxide films as the number of load cycles increased. It was found that the lowest wetting rate corresponds to a purely metallic surface. The presence of the oxide layer on the surface of the working section increases the speed of the wetting front, although this effect is restricted to a certain range of parameter values (Fig. 1c). For example, with a temperature of the liquid equal to 50°C (initial temperature of the wall 400°C), there is a difference between the wetting rates on the purely metallic surface and on the oxide-coated surface when the spraying density $\Gamma < 1$ kg/m • sec, and this difference increases with a decrease in flow rate. At $\Gamma \geq 1$ kg/m • sec, all of the data in the present study agrees with the data in [4], regardless of the number of load cycles. At $t_l = 30$°C, the data for the purely metallic and oxide-coated surfaces agree over nearly the entire investigated range of spraying densities. At $t_l = 70$°C, the wetting rates on these two surfaces differ throughout the range, but the difference decreases with an increase in spraying density.

Wetting rate is quite dependent on spraying density at liquid temperatures up to 80-90°C. When these temperatures are reached, the wetting rate, on the one hand, decreases sharply as the spraying density remains constant and, on the other hand, becomes independent of the spraying density. The latter result is in agreement with the data in [5], obtained with the delivery of liquid to the working section at the saturation temperature. Thus, in film cooling on the same experimental unit, we observed a substantial change in the character of the effect of the liquid temperature and flow rate on the wetting rate at both high and low liquid temperatures below the saturation temperature. This is evidently connected with a change in the character of heat transfer to the liquid film in the zone directly adjacent to the wetting front.

Analysis of data from our experiments (Fig. 1c) and the data of other authors [4, 6] shows that, in the region up to boiling of the liquid, the flow rate of the liquid in the film has a strong effect on wetting rate. Also, as indicated above, there is a range of flow rates in which the condition of the surface has no effect on wetting rate, and this range is broader, the lower the temperature of the liquid. All this suggests that convective heat transfer plays the decisive role in cooling of the heated body (surface), at least in the regions in which the wetting rate is strongly influenced by the flow rate and unaffected by the condition of the surface. The effect of flow rate degenerates as temperatures close to the saturation temperature are reached. Then nucleate boiling close to the wetting front becomes decisive. The presence of the oxide layer causes boiling to begin at lower liquid temperatures. Here, heat is transferred both as a result of convection to the single-phase liquid and by nucleate boiling.

The main problem that has to be solved in developing theoretical methods of determining wetting rate is correct assignment of the boundary conditions defining the position of the wetting front. After this is done, the problem is reduced to the solution of the heat-conduction equation for a body with a wetted surface and the assigned boundary conditions. Nearly all of the analytical and numerical studies conducted thus far [6-8, etc.] have used arbitrarily assigned distribution laws for the heat-transfer coefficient on the surface (here generally assuming the absence of heat transfer on the dry surface and a constant or exponentially varying heat-transfer coefficient on the wetted surface) and arbitrarily assigned constant (independent of the experimental conditions) values of temperature at the boundary between the wetted and nonwetted surfaces – defined by most authors as

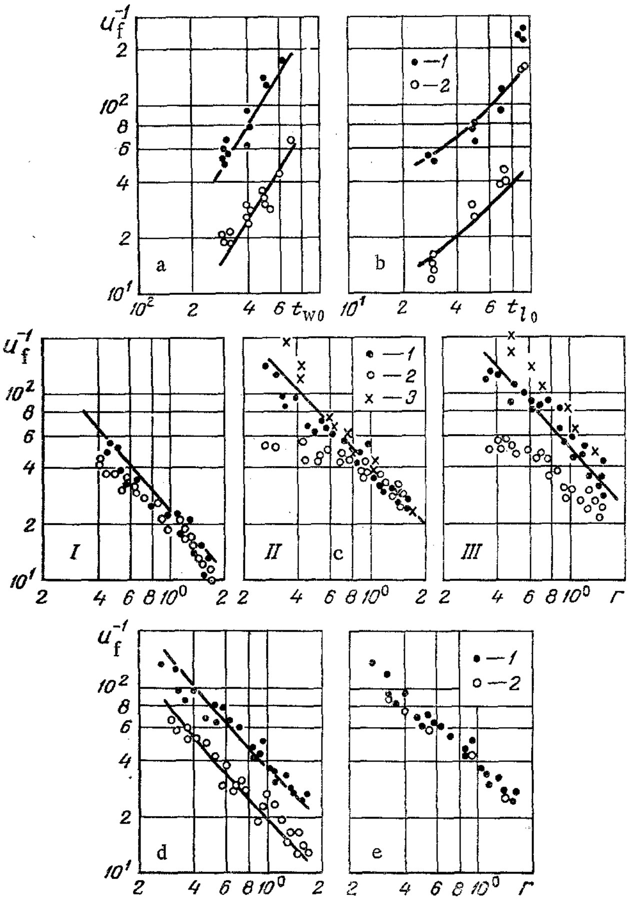

Fig. 1. Effect of different parameters on u_f^{-1} (a-c, e – stainless steel; a-d – $q = 0$); a) $t_{l0} = 50°C$ (1 – $\Gamma = 0.5$ kg/m • sec; 2 – 1.5); b) $t_{w0} = 400°C$ (1 – $\Gamma = 0.5$ kg/m • sec; 2 – 1.5); c) $T_{w0} = 400°C$ (1 – purely metallic surface; 2 – surface with oxide layer; 3 – data from [4]; I – $t_{l0} = 30°C$; II – 50; III – 70); d) $t_{w0} = 400°C$; $t_{l0} = 50°C$ (1 – stainless steel; 2 – zirconium alloy); e) $t_{w0} = 400°C$; $t_{l0} = 50°C$ (1 – $q = 1.7 \cdot 10^4$ W/m^2; 2 – 0). The solid lines denote calculated data. u_f^{-1}, m/sec; Γ, kg/m • sec.

the Leidenfrost point (and ranging from 150 to 260°C), depending on the author). Several authors compared theoretical formulas obtained with experimental results and come up with exaggerated values of the heat-transfer coefficient in the wetted region, reaching (10^5-10^6) W/m^2 • K [7]. Also, to describe the effect of the temperature and flow rate of the film liquid on the wetting rate, several authors found it necessary to introduce empirical relations for the heat-transfer coefficient in the wetted region – either behind [6] or ahead of [9] the front. In all of the studies conducted thus far, it has been assumed that heat is removed from the wetted surface directly behind the front as a result of nucleate boiling and that the intensity of this heat removal determines the rate of cooling of the body ahead of the wetting front, hence the speed of the front.

As a result of analysis of the experimental data, we propose a heat-transfer model based on the assumption of the predominance of convective heat transfer in the film directly behind the wetting front under the condition that the wall surface and the boundary layers of the liquid are heated to temperatures considerably in excess of the saturation temperature.

Boiling of the superheated boundary layer begins and the transition to nucleate boiling occurs directly in the wetting front, which is a vapor pocket moving over the surface of the body.

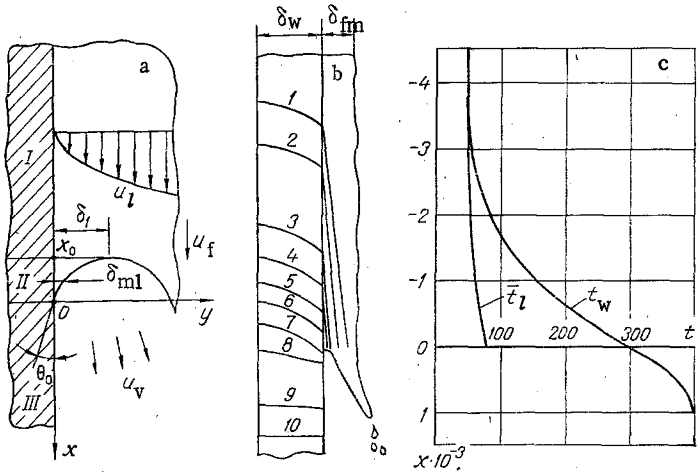

Fig. 2. Model of wetting process and results of calculation of temperature fields in the wall and the flowing film at $t_{w0} = 400°C$, $t_{l0} = 50°C$: 1) 51°C; 2) 55; 3) 100; 4) 150; 5) 200; 6) 250; 7) 300; 8) 350; 9) 390; 10) 399 (b). $x \cdot 10^{-3}$, m.

Let us examine the problem of determining the velocity of the wetting front of a liquid film over the vertical surface of a flat wall of thickness δ_w.

The entire surface of the body along the direction of movement of the wetting front is broken down into three zones with respect to heat-transfer conditions (Fig. 2a): zone I ($x < x_0$) – heat transfer by convection to the flowing film; zone II ($0 > x > x_0$) – heat transfer by conduction through a microscopic boundary layer located in the immediate vicinity of the front and determined by the contact angle θ_0; zone III ($x > 0$) – heat transfer by convection to the vapor.

In the wetted region, it is necessary to solve a quasistationary conjugate heat-conduction problem in the wall and a problem of the same type of convective heat transfer in the liquid film in a coordinate system which moves together with the wetting front:

$$\frac{\partial}{\partial x}\left(\lambda_w \frac{\partial t_w}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_w \frac{\partial t_w}{\partial y}\right) + (c\rho)_w u_f \frac{\partial t_w}{\partial x} = 0, \tag{2}$$

$$(u_l - u_f)\frac{\partial t_l}{x} = \frac{\partial}{\partial y}\left(a_{ef}\frac{\partial t_l}{\partial y}\right) \tag{3}$$

with the boundary conditions

$$\text{for } x \to -\infty \quad t_w \to t_{l\,0};\; t_l \to t_{l\,0}; \tag{4}$$

$$x \to \infty \quad t_w \to {}_{w\,0}; \tag{5}$$

$$y = \delta_{fm} \quad \frac{\partial t_l}{\partial y} = 0; \tag{6}$$

$$y = -\delta_w \quad \frac{\partial t_w}{\partial y} = 0; \tag{7}$$

$$y = 0 \begin{cases} x < x_0,\; t_l = t_w,\; \lambda_l \dfrac{\partial t_l}{\partial y} = \lambda_w \dfrac{\partial t_w}{\partial y}, & (8) \\ 0 > x > x_0,\; -\lambda_w \dfrac{\partial t_w}{\partial y} = \dfrac{\lambda_l}{\delta_{ml}}(t_w - t_{sat}), & (9) \\ x > 0,\; -\lambda_w \dfrac{\partial t_w}{\partial y} = \alpha_v (t_w - t_{sat}). & (10) \end{cases}$$

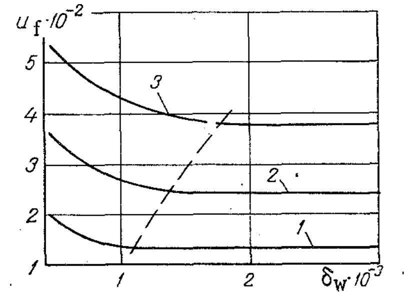

Fig. 3. Effect of wall thickness on the calculated wetting rate: t_{w0} = 400°C; t_{l0} = 50°C; 1) Γ = 0.5 kg/m • sec; 2) 1.0; 3) 1.5. $\delta_w \cdot 10^{-3}$, m.

To determine the position of the front, we will make use of the suggestion in [10] that it is determined by the condition of dynamic equilibrium between the inflowing liquid in the film and the reaction of the vapor generated in the front itself:

$$\int_0^{\delta_1} \frac{1}{2} \rho_l (u_l - u_f)^2 \, dy = \int_0^{\delta_1} \frac{1}{2} \rho_v (u_v + u_f)^2 \, dy. \tag{11}$$

In this equation, the thickness of the liquid boundary layer in which dynamic equilibrium is maintained δ_1 is determined from the empirical relation

$$\frac{\delta_1}{(\nu^2/g)^{1/3}} = \varphi \, \mathrm{Pe}, \tag{12}$$

where φ is a constant. The velocity of the vapor u_v is found on the basis of the assumption that a certain constant fraction (ψ) of the enthalpy of the liquid boundary layer (δ_1) associated with its overheating relative to saturation conditions is expended on vapor generation. The thus-formulated problem was solved numerically on a computer.

Comparison of the results of the computation with the empirical data for Γ = 1 kg/m • sec, t_{w0} = 400°C, and t_{l0} = 50°C allowed us to find the required values of the contants φ and ψ: $\varphi = 4.85 \cdot 10^{-5}$; $\psi = 0$ and 28. The solid lines in Fig. 1 show the results of calculation of the wetting rate with these coefficient values. There is good agreement between the theoretical and empirical data for the pure surfaces throughout the investigated parameter ranges and for any condition of the surfaces in the region where the surface condition has no effect. The cooling of the stainless steel and zirconium-alloy surfaces was calculated at the same contact angle $\theta_0 = 36°$.

Thus, the model, describing the predominant effect of convective heat transfer to the film in the region of the wetting front under the condition of dynamic equilibrium in the front, agrees satisfactorily with the empirical data.

Figure 2b shows the typical distribution of temperature over the cross section of the wall and liquid film. Figure 2c shows the change in the mean temperatures of the liquid and the cooling wall surface along the working section. There is a thin layer which is quite overheated in the boundary region ahead of the front, but the mean temperature of the liquid does not reach the saturation temperature. A rapid change occurs in the temperature of the liquid and wall surface within a narrow interval directly behind the wetting front – within a space of 2-3 mm in the figure. There is a substantial temperature gradient through the wall thickness.

Figure 3 shows the calculated dependence of the velocity of the wetting front on the thickness of the stainless steel wall for three different spraying densities. In the region of small wall thickness, the velocity of the front decreases with an increase in thickness. When the thickness of the wall exceeds a certain critical value (the dashed line in Fig. 3), the wetting rate becomes nearly independent of the thickness. The value of the critical thickness changes according to the test conditions. For example, at t_{w0} = 400°C and t_{l0} = 50°C (Fig. 3), the critical thickness increases with an increase in flow rate: $\delta_{cr} \simeq 1.1$ mm at Γ = 0.5 kg/m • sec and 1.7 mm at Γ = 1.5 kg/m • sec.

The results obtained here agree qualitatively with the conclusion reached in [11] on the presence of a critical wall thickness. However, the latter work examined the effect only of the physical properties of the wall material and heat release in the wall on the critical thickness. The method of calculation we propose allows for the effect of practically all regime parameters.

NOTATION

Γ, spraying density, kg/m • sec; a_{ef}, effective diffusivity, m^2/sec; c, heat capacity, J/kg • K; l_i, distance, on oscillogram, between jumps in signals of thermocouples located on the i-th generatrix, m; L, length of measurement section, m; q, heat flux, W/m^2; t, temperature, °C; u, velocity, m/sec; w_{tp}, velocity of light-sensitive tape, m/sec; α_v, coefficient of heat transfer from dry wall to vapor, W/m^2 • K; δ, thickness, m; λ, thermal conductivity, W/m • K; ν, kinematic viscosity, m^2/sec; ρ, density, kg/m^3; $Re = \Gamma/\mu$, Reynolds number; $Pe = \Gamma/\rho a$, Peclet number; indices: f, wetting front; l, liquid; v, vapor; fm, film; w, wall; sat, saturation conditions; ml, microlayer.

LITERATURE CITED

1. B. G. Ganchev, V. M. Kozlov, and V. V. Lozovetskii, "Investigation of a descending flow of a liquid film over a vertical surface and heat transfer to the film," Inzh.-Fiz. Zh., 20, No. 4, 674-682 (1971).
2. B. G. Ganchev and A. E. Bokov, "Study of thermocapillary stability in the gravitational flow of a liquid film," Inzh.-Fiz. Zh., 39, No. 4 (1980).
3. M. E. Sawan and M. W. Carbon, "A review of spray cooling and bottom flooding works for LWR cores," Nucl. Eng. Des., 32, 191-207 (1975).
4. K. Ioshioka and S. Hasegawa, "A correlation in displace velocity of liquid film boundary formed on a heated vertical surface in emergency cooling," J. Nucl. Sci. Technol., 7, 418-425 (1970).
5. A. W. Bennett, G. F. Hewitt, and H. A. Kearsey, "The wetting of hot dry surface by water in steam environment at high pressures," UKAEA, Report AERE-R5146 (1966).
6. R. B. Duffey and D. T. G. Porthouse, "The physics of rewetting in water reactor emergency core cooling," Nucl. Des. Eng., 25, 379-394 (1973).
7. A. Yamanouchi, "Effect of core spray cooling in transient state after loss of coolant accident," J. Nucl. Sci. Technol., 5, No. 11, 547-558 (1968).
8. T. S. Thompson, "An analysis of the wet-side heat transfer coefficient during rewetting of a hot dry patch," Nucl. Design Eng., 22, 212-224 (1972).
9. San, Dix, Tyep, "Effect of preliminary cooling on the wetting of a surface by a flowing liquid film," Teploperedacha, No. 3, 44-50 (1975).
10. B. G. Ganchev, "Study of motion and heat transfer in descending film flow and two-phase gas–liquid flows in vertical channels," Sb. Nauch. Tr. Mosk. Vyssh. Tekhn. Uchilishche, 4, No. 307, 21-54 (1979).
11. T. S. Thompson, "On the process of rewetting of a hot surface by a falling liquid film," Nucl. Design Eng., 31, 234-245 (1974).