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FORMATION OF A DRY SPOT IN A HORIZONTAL LIQUID FILM HEATED FROM BELOW

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Abstract—This study deals with the formation of a dry spot in a non-boiling thin film of ethanol on a horizontal surface upon slowly increasing the heat flux from an embedded nichrome strip. Appreciable thinning of the film occurred prior to rupture, and is associated with the appearance of Bénard-type convective cells. The threshold heat flux for appearance of a dry spot is greater than for disappearance, presumably due to contact angle hysteresis and/or the temperature gradients in the heater strip in the vicinity of the triple interface. A quasi-static stability analysis is given, based upon the equilibrium shape of a semi-infinite drop on a heated surface.

NOMENCLATURE

a, rate of change of surface tension with temperature;
b, slope of the film temperature profile;
g_c, conversion factor;
k, thermal conductivity;
m, dimensionless ratio, defined in connection with equations (8) and (15);
M, molecular weight;
q, heat flux;
R_s, radius of curvature;
R, gas constant;
s, arc length;
T, temperature;
Z, distance below the free surface at infinity.

Greek symbols

α, angle of inclination of a tangent to the liquid surface with the horizontal;
γ_1, γ_2, dimensionless quantities, equation (6);
γ_s, γ_w, dimensionless quantities, equation (14);
δ_f, film thickness far away from a dry spot;
δ_i, film thickness of the curved liquid surface;
ε, accommodation coefficient;
θ, contact angle;
η, dimensionless vertical distance;
λ, latent heat of vaporization;
ρ, density;
σ, surface tension;
σ_0, surface tension at zero temperature;
ξ, dimensionless horizontal distance.

Subscripts

f, film;
i, liquid interface;
L, l, liquid;
s, saturation;
v, vapor;
w, wall.

I. INTRODUCTION

THE DISRUPTION and dryout of flowing thin liquid films in contact with a heated wall is of central importance in connection with the burnout phenomenon in boiling channels and in a number of other applications. Previous work has dealt with the formation of dry spots due to gradual increase of the wall temperature

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above the saturation temperature of the liquid at constant film flowrates [1–4], gradual decrease of the liquid flowrate at a constant wall temperature [5–7], or quenching of electrically-heated tubes in a pool of liquid [8].

The stability of a dry patch, once it is formed, has been analyzed by several investigators [9–13] in order to predict the conditions under which the dry spot becomes stable. These criteria are usually obtained by a force balance in which the pressure force developed at the upstream stagnation point of the dry patch; the thermocapillary force developed as a result of the variation of surface tension with surface temperature and other forces are considered.

A detailed solution of the flow and temperature fields around the dry spot is indeed formidable, and, in fact, has not yet become available. A simpler problem, consisting of the formation of a dry spot in a liquid film flowing at low velocities on a horizontal heated surface, is therefore of interest. Apart from its inherently greater simplicity, it is of some intrinsic importance in its own right. For example, in fast reactor safety studies, the expulsion rate of sodium from a blocked channel depends critically upon whether a continuous liquid film is left at the wall as the slug of vapor develops and grows, but the time scale may be so short that drainage of the film can be neglected.

II. EXPERIMENTAL

The formation of a dry spot in a non-boiling thin film of absolute ethyl alcohol on the surface of a 0·022 in. thick nichrome heater strip, embedded in a horizontal transite plate, was studied. The heated zone was a 1 in. × 4·5 in. rectangle whose upper surface was highly polished in order to prevent bubble nucleation during the heat transfer runs. A heavy-duty 6V battery was used as a power source. The voltage was regulated with two water-cooled rheostats in parallel.

The film thickness was controlled by the height of an overflow tube and measured by means of a micrometer to within 10^{-4} in. at several points along the major axis of the strip. The nominal film thickness was varied from 0·032 to 0·052 in. Because of surface tension and evaporation effects, a small upstream flow of 4 cm^3/min of ethanol at ambient temperature was supplied from a dropping funnel, corresponding to a mean film velocity of 0·1 cm/s. The temperature of the strip was measured at five locations by means of spot-welded 30-gauge iron–constantan thermocouples.

Film thicknesses and dry spot temperatures were measured under quasi-steady conditions upon increasing the heat flux in steps of about 200 Btu/ft^2 h. Smaller steps were used in the neighbourhood of incipient formation of a dry patch, and conversely, in the reverse process of rewetting the dried area.

III. RESULTS

Some representative results on the formation and disappearance of dry spots by rewetting the surface, for three nominal film thicknesses, are given in Table 1.

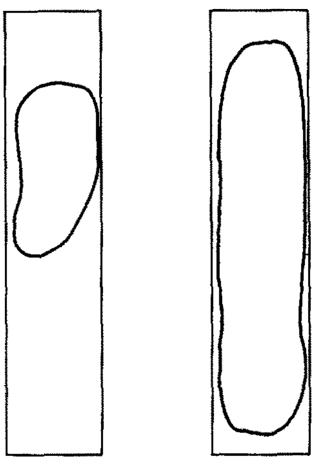
Prior to the formation of a dry spot the liquid film at a random location on the heating strip started thinning, forming a recessed circular region. As the heat flux approached the threshold value for formation of a dry spot a distinct Bénard-type flow cell pattern appeared in the thinned region. At the threshold heat flux a dry spot originated as a pinhole within the circular, thinned region of the film. After reaching steady state conditions the triple interface position became stable with, however, a small, but noticeable, advancing and receding motion.

Figure 1 gives free-hand sketches of the typical shape of a dry spot at two different film thicknesses. As the film thickness increased, the size of the spot increased also, covering almost the entire heating surface at a film thickness of 0·052 in.

In several runs at high heat fluxes, as the strip temperature exceeded the saturation temperature, the liquid started to boil from nucleation sites in the cement that bonded the heating

Table 1. Effect of film thickness on minimum heat flux for appearance and disappearance of dry spot
(T_{sat} = 173°F; *Flow rate*: 4 cm³/min)

Initial film thickness (in. × 10³)	Heat flux for appearance (Btu/ft² h)	Strip temperature (°F)	Average film thickness around dry spot (in. × 10³)		Heat flux for disappearance (Btu/ft² h)	Strip temperature after rewetting (°F)	Maximum wall temp under a dry spot (°F)
			Upstream	Downstream			
34	1020	124	24	18	770	125	149
43	2080	146	30	24	1700	147	186
52	4680	186	39	26	3000	186	269



(A) (B)

FIG. 1. Typical shapes of a stable dry spot.
(A) 0·034 in. thick film.
(B) 0·052 in. thick film.

strip to the transite sheet. Extremely small vapor bubbles, emerging from the transite–strip boundary, served as flow tracers, indicating a transverse liquid motion towards the triple boundary of the dry spot.

Table 1 shows that dry spots may occur when the wall temperature is below or above the liquid saturation point at the ambient pressure (173°F). In the latter case no ebullition was observed from the heating surface.

The threshold heat flux required for the formation of a dry spot increased with the nominal film thickness, within the range studied here. A similar trend was noted for the threshold flux required for closing the dry spot. Moreover, the wall temperatures at closure were, within experimental error, the same as at rupture. On the other hand, the closure heat fluxes were roughly lower by 30 per cent than those at which a stable dry patch had formed, indicating a hysteresis effect. The marked hysteresis for rewetting the surface may be ascribed partly to contact angle hysteresis and partly to the increased heater wall temperature in the dry region.

The maximum observed temperature of the bare heating strip within the dry spot appreciably exceeded the strip temperature in regions covered by liquid. A difference as high as 83°F was observed with 0·052 in. thick films. Once the dry spot closed, though, the strip temperature decreased to a level at which the dry spot appeared first.

The threshold heat flux for formation of a dry spot at wall temperatures exceeding the saturation temperature was substantially lower than that reported for initiation of pool boiling of ethanol [15, 16]. In one sense, this is not surprising, in view of the considerably smaller radii of curvature which the liquid–vapor interface must assume in order to initiate the formation of a bubble [17].

Although the effect of flow rate on the formation of a dry spot was not investigated formally in this study, it became apparent that the threshold heat flux was quite sensitive to the liquid flow rate. Upon increasing the flow rate from 3 to 5 ml/s the heat flux increased from 760 to 1560 Btu/h ft^2 for a 0·034 in. film.

Representative film thickness profiles along the major axis of the strip at various heat flux levels are given in Figs. 2 and 3. The highest

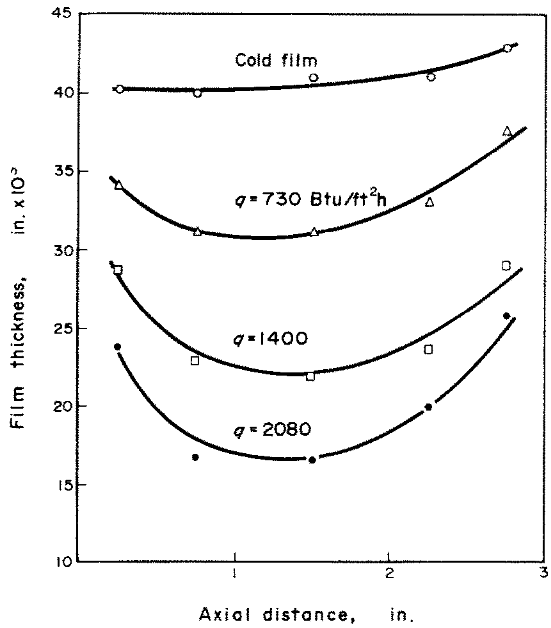


FIG. 2. The effect of heat flux on film thickness profile. Initial film thickness—0·043 in.

heat flux in Fig. 2, represents the last observed level before film rupture. A pronounced thinning of the film, especially in the neighbourhood of the strip mid-point, occurred prior to rupture. The mechanism of this preliminary thinning is not clear at present. A likely explanation is the existence of a secondary circulation, symmetric about the strip centerline, induced by the transverse gradients in density and surface tension. Once rupture occurred, there was a pronounced thickening of the film upstream and downstream of the dry spots as might be expected.

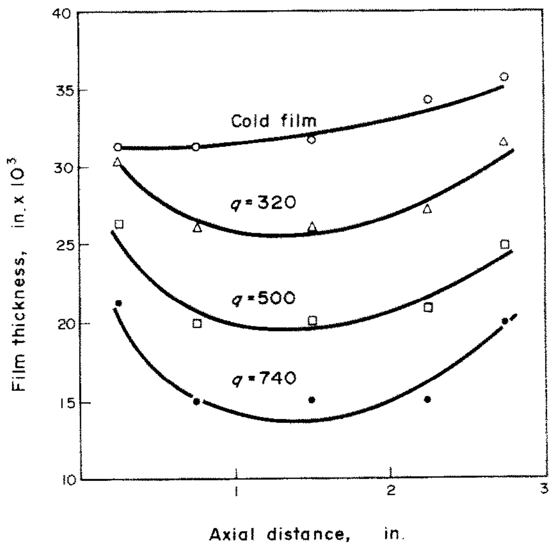


FIG. 3. The effect of heat flux on film thickness profile. Initial film thickness—0·034 in.

The apparent thickening of liquid film in the axial direction at normal ambient temperatures shown in Figs. 2 and 3 resulted from slight deviations from horizontal of the downstream end of the embedded nichrome strip.

IV. ANALYSIS

Despite the low average velocity head in the unbroken film ($\sim 2 \times 10^{-6}$ cm), the film upstream of the dry spot was markedly thicker than downstream (Table 1). Viscous and inertial effects in the vicinity of the upstream stagnation point would thus seem to be of some importance. Nevertheless, a quasi-static analysis, based upon the equilibrium shape of a semi-infinite liquid drop on a heated horizontal surface, is instructive.

We seek an equation for the shape of the free surface extending from the triple interface outward. This shape is approximated by considering a semi-infinite drop resting on a heated horizontal wall. An analysis is given in the Appendix by which the liquid surface shape may be calculated once the wall heat flux, the liquid contact angle, and the liquid film thickness at infinity, are specified.

Two assumptions are made concerning the liquid surface temperature, T_i:

(1) T_i is determined by the local film thickness, δ_i, and the surface heat flux, q, assuming a straight-line temperature distribution through the film.

(2) T_i is determined by the non-equilibrium surface transport equations, assuming that the local surface flux is equal to the local wall flux.

Equations (9) and (15) in the Appendix were used to calculate the upstream and downstream liquid contact angles, using the data in Table 1. Computed contact angles, given in Table 2, for three typical runs appear to be reasonable, based upon visual observation. A direct measurement at the contact angle at the periphery of an irregular dry spot is not at present experimentally feasible. Note that the upstream contact angle in a stable dry patch increases materially with the strip wall temperature.

It is of considerable interest to note that the invocation of the non-equilibrium surface transport conditions gives only minor changes in the calculated contact angle. A more elaborate calculation would incorporate the Laplace equation for the temperature distribution in the liquid, but this hardly seems to be justified, in view of the neglect of convective effects.

Equations (9) and (15) may also be considered as criteria for the stability of dry patches once the contact angle is specified. Given the heater wall temperature and heat flux, the equations predict the maximum film thickness for which a dry patch can be supported on a horizontal heating surface.

Table 2. Calculated values of contact angles

Initial film thickness (in. × 10^3)	Contact angle at dry spot			
	Upstream		Downstream	
	Method I	Method II	I	II
34	22°	23°	17°	18°
43	28°	30°	24°	25°
52	37°	39°	25°	26°

V. CONCLUSIONS

1. Dry patches may form during creeping flow of thin films of ethanol over a horizontal heating surface, without boiling, when the wall temperature is either below or above the liquid saturation temperature.

2. The appearance of a dry spot is preceded by formation of Bénard-type convection cells, indicating that a thermocapillary mechanism may be responsible for its formation.

3. The threshold heat flux required for the formation of dry spots is appreciably lower than that for incipience of pool boiling of ethanol.

4. Due to a hysteresis effect a dry spot closes at a heat flux which is lower by 30 per cent from its threshold value at a given film thickness.

5. Reasonable values of liquid contact angles may be calculated using a quasi-static stability analysis of a dry spot.

VI. ACKNOWLEDGEMENTS

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APPENDIX

We consider here the equation for the shape of a semi-infinite drop on a uniformly-heated horizontal surface. The force balance follows that given in [18], with the exception that the variation of surface tension with temperature must now be taken into account. To avoid the solution of the difficult free-boundary potential problem with mixed boundary conditions, we assume that the heat flow is everywhere normal to the solid surface. This is reasonable for thin films, except in a small region near the triple interface. Even with this assumption, which avoids the two-dimensional potential problem in the liquid, a complete solution cannot be obtained without considering the heat flow in the supporting solid region. Two limiting cases are possible:

(1) The heat flux from the solid surface is everywhere constant, corresponding to the limiting case of uniform heat flow in the solid. This is the assumption made by Zuber and Staub [12], which, when coupled with straight-line heat flow in the liquid film, makes the difference between the solid and liquid surface temperatures proportional to the local film thickness. This ignores the non-equilibrium transport condition at the liquid surface [14] which must be satisfied at every point.

(2) Alternatively, one can satisfy the surface transport requirement by relaxing the condition of uniform surface heat flux. This is clearly a more realistic assumption physically, particularly near the singularity. We shall consider both cases.

Let (X, Z) be the two-dimensional coordinate system, with the X-axis being the horizontal asymptote to the free liquid surface, the positive Z-axis is pointing downwards and intersecting the triple interface at $Z = \delta_f$ (Fig. 4). The Gibbs equation for the equilibrium of a curved interface

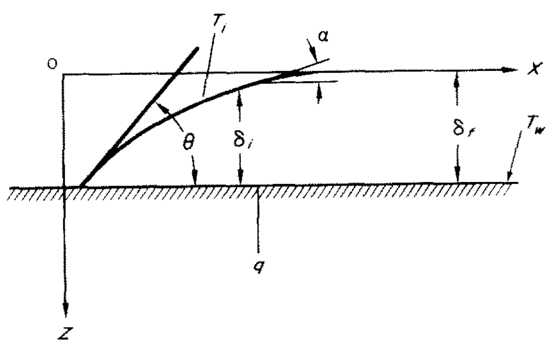

FIG. 4. The shape of the liquid surface near a dry spot.

becomes in this case:

$$(\rho_l - \rho_v) g_c Z = \frac{\sigma}{R_s} \quad (1)$$

where σ is the surface tension, and R_s the radius of curvature of the liquid surface.

Approximating the variation of the surface tension over a small temperature range by:

$$\sigma = \sigma_0 - aT \quad (2)$$

and assuming a linear variation of temperature through the liquid film, one has

$$T = T_w - b(\delta_f - Z) \quad (3)$$

$$\sigma = \sigma_w + ab(\delta_f - Z) \quad (4)$$

where σ_w is the surface tension of the liquid at the wall temperature, T_w, and $b = q/k_L$.

Here (Method I), q is considered to be a constant, according to the assumption of uniform heat flux. Noting that

$$ds = -R_s\, d\alpha = -\frac{dZ}{\sin\alpha} = -\frac{\delta_f\, d\eta}{\sin\alpha} \quad (5)$$

where s is the arc length, α is the angle of inclination of the tangent with the horizontal, and $\eta = Z/\delta_f$, and defining the dimensionless quantities

$$\gamma_1 = \frac{\sigma_w}{\delta_f^2(\rho_l - \rho_v) g_c}; \qquad \gamma_2 = \frac{ab}{\delta_f^2(\rho_l - \rho_v) g_c} \quad (6)$$

one obtains from equations (1), (4)–(6):

$$\frac{\eta}{\gamma_1 + \gamma_2(1-\eta)} = \sin\alpha \frac{d\alpha}{d\eta} \quad (7)$$

subject to the initial condition: $\alpha = 0$ when $\eta = 0$. This leads to

$$\cos\alpha = 1 + \frac{\eta}{\gamma_2} + \frac{m+1}{\gamma_2} \ln\left(\frac{m+1-\eta}{m+1}\right) \quad (8)$$

where $m \equiv \gamma_1/\gamma_2$. Finally, defining $\xi = X/\delta_f$,

$$\tan\alpha = \frac{d\eta}{d\xi} = \frac{\left\{1 - \left[1 + \frac{\eta}{\gamma_2} + \frac{m+1}{\gamma_2}\ln\left(\frac{m+1-\eta}{m+1}\right)\right]^2\right\}^{\frac{1}{2}}}{1 + \frac{\eta}{\gamma_2} + \frac{m+1}{\gamma_2}\ln\left(\frac{m+1-\eta}{m+1}\right)} \quad (9)$$

which is an equation for the slope of the tangent at any point on the curved surface of the liquid. For $\eta = 1$, α calculated from equation (9) is the contact angle θ measured through the liquid.

Alternatively (Method II), the heat flux, q, is given by:

$$q = \frac{k_L(T_w - T_i)}{\delta_i} \quad (10)$$

where T_i is the local interface temperature, and δ_i is the local film thickness.

An approximate expression for the surface flux in non-equilibrium transport, based upon the theory of absolute evaporation rates, is given by (14):

$$q = \varepsilon\lambda \sqrt{\left(\frac{Mg_c}{2\pi RT_s}\right)} \frac{\rho_v \lambda}{T_s} (T_i - T_s) \quad (11)$$

where ε is the accommodation coefficient, and the other symbols have their usual significance. From equations (10) and (11) one obtains,

$$T_i = \left\{\frac{T_w}{\delta_i} + \frac{\lambda^2 \varepsilon \rho_v}{k_L}\sqrt{\left(\frac{Mg_c}{2\pi RT_s}\right)}\right\} \Big/ \left\{\frac{1}{\delta_i} + \frac{\lambda^2 \varepsilon \rho_v}{k_L T_s}\sqrt{\left(\frac{Mg_c}{2\pi RT_s}\right)}\right\}. \quad (12)$$

Letting

$$b' = \frac{\lambda^2 \varepsilon \rho_v}{k_L T_s}\sqrt{\left(\frac{Mg_c}{2\pi RT_s}\right)}$$

the equation for the interface temperature reduces to:

$$T_i = \frac{T_w + b'\delta_i T_s}{1 + b'\delta_i}. \quad (13)$$

Proceeding in a similar manner, and defining the dimensionless groups

$$\gamma_s = \frac{\sigma_s}{(\rho_l - \rho_v) g_c \delta_f^2}; \qquad b_1 = b'\delta_f; \qquad \gamma_w = \frac{\gamma_s \sigma_w}{\sigma_s} \quad (14)$$

one obtains, in place of equation (8), the formula:

$$\cos\alpha = 1 + \frac{1+b_1}{b_1\gamma_s}\left\{m' \ln\left(\frac{m'-\eta}{m'}\right) + \eta\right\} - \frac{1}{\gamma_s}\left\{m'^2 \ln\left(\frac{m'-\eta}{m'}\right) + m'\eta + \frac{\eta^2}{2}\right\} \quad (15)$$

where m' is now the dimensionless ratio, $m' = (\gamma_w + b_1\gamma_s)/b_1\gamma_s$. Equation (15) leads directly to expressions for $\tan\alpha$ and for the contact angle for this case.

FORMATION D'UNE ZONE D'ASSECHEMENT DANS UN FILM LIQUIDE HORIZONTAL CHAUFFE PAR LE BAS

Résumé—Cette étude concerne la formation d'une région d'assèchement dans un film mince non-bouillant d'éthanol sur une surface horizontale soumise à un accroissement lent de flux thermique depuis un ruban de nichrome inclus. Un amincissement appréciable du film se produit avant la rupture et est associée avec des cellules de convection du type Bénard. Le flux de chaleur relatif à l'apparition du spot sec est supérieur à celui relatif à la disparition, ce qui peut être lié à un hystérèse de l'angle de contact et/ou à des gradients de température dans le ruban chauffant au voisinage du triple interface. On donne une analyse de stabilité quasi-statique basée sur la forme d'équilibre d'une goutte semi-infinie sur une surface chauffée.

BILDUNG VON TROCKENSTELLEN IN EINEM HORIZONTALEN, VON UNTEN BEHEIZTEN FLÜSSIGKEITSFILM.

Zusammenfassung—Diese Untersuchung behandelt die Bildung einer Trockenstelle in einem nicht siedenden, dünnen Film aus Äthanol auf einer waagrechten Oberfläche. Sie entsteht, wenn man die Heizleistung von einem eingebetteten Streifen aus Nickelchrom langsam erhöht. Vor dem Aufreissen wird der Film merklich dünner. Dabei entstehen Benard-Konvektionszellen. Die Wärmestromdichte, bei der eine Trockenstelle auftritt, ist grösser als die, bei der die Trockenstelle verschwindet. Der Grund für diese Erscheinung ist wahrscheinlich in einer Hysterese des Randwinkels und/oder in den Temperaturgradienten des Heizstreifens in der Nähe der 3 zusammentreffenden Oberflächen zu suchen. Auf der Grundlage der Gleichgewichtskontur eines halbunendlichen Tropfens auf einer geheizten Oberfläche

ОБРАЗОВАНИЕ ВЫСОХШЕГО УЧАСТКА В ГОРИЗОНТАЛЬНОЙ ПЛЕНКЕ ЖИДКОСТИ, НАГРЕВАЕМОЙ СНИЗУ

Аннотация—Это исследование связано с образованием сухого участка в пленке этанола при отсутствии кипения на горизонтальной поверхности при медленном возрастании теплового потока от заделанной нихромовой пластины. Перед отрывом происходило значительное утончение пленки, связанное с появлением конвективных ячеек типа Бенарда. Критический тепловой поток, необходимый для появления сухого участка превышает критический тепловой поток, необходимый для исчезновения, вероятно, из-за гистерезиса угла смачивания или температурных градиентов в нагретой пластине вблизи тройной поверхности раздела. Проведен квазистатический анализ устойчивости, основанный на равновесной форме полубесконечной капли на поверхности нагрева.