Int. J. Heat Mass Transfer. Vol. 9, pp. 897–905. Pergamon Press 1966. Printed in Great Britain

STABILITY OF DRY PATCHES FORMING IN LIQUID FILMS FLOWING OVER HEATED SURFACES

NOVAK ZUBER and FRED W. STAUB

Research and Development Center, General Electric Company, Schenectady, New York

(*Received* 21 *October* 1965)

Abstract—Criteria are derived which predict the stability of dry patches forming in thin liquid films flowing over a heated surface. The analysis of Hartley and Murgatroyd [1, 2], applicable to isothermal films, is extended to include the effects of vapor thrust and of thermocapillarity.

Numerical evaluations are carried out that indicate the relative importance of the various effects in conjunction with typical heated water and liquid metal films. The results show that for liquids of high wettability (for example for liquid metals) the thermal effects become dominant in determining the stability of dry patches.

NOMENCLATURE

$[MLT\theta]$ systems of units with H defined by $H = ML^2T^{-2}$

- C_1, dimensionless constant;
- C_2, dimensionless constant;
- F, force per unit perimeter $(M\theta^{-2})$;
- g, acceleration due to gravity (LT^{-2});
- h_{fg}, latent heat of vaporization (HM^{-1});
- k, coefficient of thermal conductivity $(HT^{-1}\theta^{-1}L^{-1})$;
- n, normal to interface (L);
- P, pressure $(ML^{-1}\theta^{-2})$;
- s, length (L);
- $\dot{Q}/A$, heat flux density $(H\theta^{-1}L^{-2})$;
- T, temperature (T);
- u_f, velocity of liquid $(L\theta^{-1})$;
- u_{vn}, vapor velocity normal to interface $(L\theta^{-1})$;
- u_{fn}, liquid velocity normal to interface $(L\theta^{-1})$;
- x, y, z, coordinates (L);

Greek symbols

- α, angle;
- δ_{av}, average film thickness (L);
- δ_c, superheated film thickness (L);
- θ, contact angle;
- ρ, density (ML^{-3});
- μ, viscosity $(ML^{-1}\theta^{-1})$;
- ν, kinematic viscosity (L^2T^{-1});
- τ, shear stress $(ML^{-1}\theta^{-2})$;
- σ, surface tension $(M\theta^{-2})$;
- Γ, mass flow rate per unit perimeter $(M\theta^{-1}L^{-1})$.

Subscripts

- av, average;
- f, liquid;
- v, vapor;
- w, wall;
- s, saturation.

1. INTRODUCTION

THE APPEARANCE of large dry patches in liquid films flowing over surfaces heated or unheated have been recently observed and reported by several researchers [1–6 and others]. The appearance and the behavior of these vapor patches in two-phase systems with heat addition is important for several reasons. First, the sudden formation and expansion of patches may induce pressure pulsation and flow oscillation in the mixture and influence thereby the stability of the flow. Second, the appearance of patches and the attendant break-up of the liquid film may mark a change in the flow regime from annular to drop flow. A change of flow regime will affect not only the steady-state characteristics but it will affect also the transient response of the system. Finally, the appearance and the persistence of dry patches on the surface result in an abrupt decrease of the heat transfer coefficient and attendant overheating of the surface which may cause the "burnout" of the heated duct.

The various possible mechanisms which may generate large vapor patches on a heated surface are discussed elsewhere [7]. The problem which we consider here is as follows: assume that a large vapor patch has been formed (by any of the various possible mechanisms) in a flowing, heated liquid film which is thereby broken up; we wish to determine under what conditions such a liquid rupture will persist, i.e. under what conditions will the dry patch remain attached to the surface? We consider therefore the stability of a dry patch and we seek the value of the minimum flow in the liquid which is necessary to remove (sweep) the dry patch from the heating surface.

Questions similar to those raised above were posed also by Hartley and Murgatroyd [1, 2] in their analysis of dry patches forming in isothermal liquid films flowing over *unheated* surfaces. For this condition they derived several stability criteria which predict the minimum film thickness and minimum liquid flow rate recessary to maintain complete wetting of an unheated surface. Although these criteria were derived for isothermal films they were used in reference [4] to predict the minimum film thickness for the stability of a dry patch on a heated surface. Neither Hartley and Murgatroyd [1, 2] nor Hsu *et al.* [4] considered the thermal effects on the stability of a dry patch.

In this paper we shall extend the analysis of Hartley and Murgatroyd [1, 2] to take into account the thermal effects.* These effects become important in liquid films flowing over heated surfaces because they give rise to these forces: a nonuniform temperature of the interface gives rise to thermocapillary force whereas the evaporation at the interface gives rise to a vapor thrust. It will be seen that for liquid of high wettability (for example for liquid metals) the thermal effects become dominant.

* An extension was originally put forward by the authors [6].

2. THE FORCE BALANCE

Consider Fig. 1 which shows two views of a dry patch formed in a flowing liquid film over a heated plate. The geometry of the flow shown on this figure is similar to that considered by Hartley and Murgatroyd; both are identical with the geometry of patches shown in the photographs reported in reference [3].

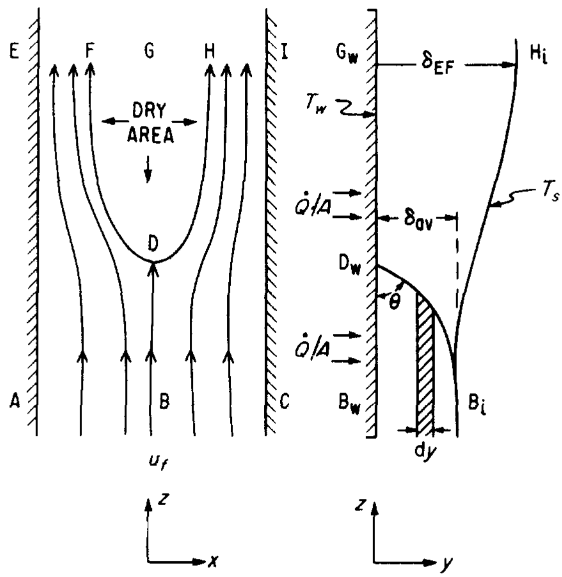

FIG. 1. Formation of a dry patch in a thin liquid film flowing over a heated surface.

A uniform film of an average thickness δ_{av}, flows with a mean velocity u_f; a dry patch with the vertex at point D is formed in this film. As the liquid approaches this vertex the film thickness changes and the flow separates. The geometry of liquid interface past the vertex point will depend on the surface forces, as well as on the hydrodynamic forces. With heat addition the liquid may also roll up to form two jets which become detached from the heating surface [3].

In order to evaluate whether the patch will remain stationary it is necessary to consider the forces acting on the interface. The exact formulation of the problem requires detailed information on the shape of the interface, on the dynamic effects of the surface forces, on the flow, on the heat transfer mechanism, etc. It can be expected that the result of such an analysis would be rather complex and difficult to come by. An approximate analysis, however, can be easily performed by considering a force balance at the stagnation point. The forces which act at this point arise from the stagnation pressure, from the surface tension, from the nonuniform surface tension (the thermocapillary force) and from evaporation (the vapor thrust). The first two are also present in adiabatic flow and have already been considered [1, 2], the last two arise because of thermal effects and are present in systems with heat addition and vaporization.

Consider the forces acting on an interfacial area of unit perimeter along the dividing stream line. On this area the stagnation pressure exerts a force per unit perimeter whose component is given by:

$$F_P = \frac{\rho_f}{2}\int_0^{\delta_{av}} u_f^2(y)\,\mathrm{d}y. \tag{1}$$

The force per unit perimeter due to surface tension is given by:

$$F_\sigma = \sigma(1 - \cos\theta) \tag{2}$$

where θ is the contact angle. In equation (2) we neglected the effect of curvature in the z–x plane, which seems reasonable if one considers the dimensions of the patch compared to the thickness of the film.

Since the temperature of the interface along the dividing stream line may not be constant, a shear stress will be generated because of the nonuniform surface tension, thus

$$\tau = \frac{\partial\sigma}{\partial s}. \tag{3}$$

Considering again the unit perimeter along the dividing stream line we obtain from equation (3) the z-component of the force per unit perimeter caused by the thermocapillary effect, thus

$$F_s = \int_0^s \frac{\partial\sigma}{\partial s}\cos\alpha\,\mathrm{d}s \tag{4}$$

where s is the length of the arc and α is the angle between the tangent to the interface and the z-axis as illustrated in Fig. 2(a).

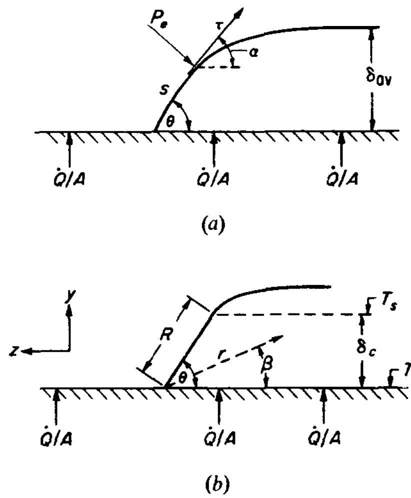

FIG. 2. The leading edge of the liquid film.
(a) The true geometry.
(b) The wedge approximation.

The vaporization at the interface gives rise to a pressure given by:

$$P_e = \rho_v\left(\frac{-k\partial T/\partial n}{\rho_v h_{fg}}\right)^2 \frac{\rho_f - \rho_v}{\rho_f} \tag{5}$$

where $-k\partial T/\partial n$, is the heat flux density normal to the interface. The z-component of the force per unit perimeter acting along the dividing stream line is then given by:

$$F_e = \int_0^s \rho_v\left(\frac{-k\partial T/\partial n}{\rho_v h_{fg}}\right)^2 \frac{\Delta\rho}{\rho_f}\sin\alpha\,\mathrm{d}s. \tag{6}$$

The effect of the flow is to sweep the patch downstream whereas the other forces act in the opposite direction and tend to spread the patch upstream. For a stationary case these forces must be in equilibrium. It follows then from equations (6), (4), (2) and (1) that the condition for a dry patch to be stationary is given by:

$$\frac{\rho_f}{2}\int_0^{\delta_{av}} u_f^2(y)\,\mathrm{d}y = \sigma(1-\cos\theta) + \int_0^s \frac{\partial\sigma}{\partial s}\cos\alpha\,\mathrm{d}s + \int_0^s \rho_v\left(\frac{-k\partial T/\partial n}{\rho_v h_{fg}}\right)^2 \frac{\Delta\rho}{\rho_f}\sin\alpha\,\mathrm{d}s. \quad (7)$$

If the left-hand side of equation (7) is larger than the right-hand side the patch will be removed. Consequently, equation (7) gives the minimum liquid velocity which, under given conditions, can maintain complete wetting of the solid surface. The value of this flow can be evaluated if the liquid velocity distribution and the values of the derivatives under the integrals are known. These quantities can be determined by the simultaneous solution of the fluid dynamic equations for the vapor and the liquid together with the three energy equations: for the liquid, vapor and the solid. One must consider the solid because of the heat transfer process at the triple interface shown as point D_w on Fig. 1. The dynamics and the geometry of the interface will be determined by the simultaneous solution of these equations together with the appropriate boundary conditions. An exact solution of such a complex problem is not warranted for an evaluation of the thermal effects. In order to determine the *form* of the solution and to *estimate* the effect of the thermocapillary force and of the vapor thrust one can make some reasonable assumptions concerning the geometry of the interface, the value of the heat flux density and determine then the equilibrium conditions by considering various flow regimes, for example: laminar or turbulent flow in the film. Such an approach was adapted in this work, the results are presented in sections that follow.

3. THE THERMOCAPILLARY EFFECT

The force caused by the nonuniform surface tension [see equation (4)] can be evaluated if the variation of σ along the dividing stream line is known. Since this variation is caused by temperature variations along the interface, we can write:

$$\frac{\partial\sigma}{\partial s} = \frac{\partial\sigma}{\partial T}\frac{\partial T}{\partial s}. \quad (8)$$

Thus, the problem is reduced to determining the temperature gradient along the stream line which necessitates a knowledge of the temperature field in the film. As noted in the preceding section, this field will be determined by the simultaneous solution of the fluid dynamic equations together with the energy equations for the fluid and the solid. For the present problem, however, it will be assumed that the temperature change in the liquid film is linear, thus:

$$T(y) - T_s = (T_w - T_s)\left(1 - \frac{y}{\delta_c}\right). \quad (9)$$

This distribution not only considerably simplifies the problem, but it is also a realistic approximation valid for thin films.

In what follows we shall approximate the leading edge of the film by a wedge making an angle θ (equal to the contact angle) with the heated surface [see Fig. 2(b)]. Introducing polar coordinates r, β we have:

$$y = r\sin\beta, \qquad z = r\cos\beta \quad (10)$$

whence the thickness of the superheated liquid film becomes:

$$\delta_c = R\sin\theta. \quad (11)$$

Substituting equations (11) and (10) in equation (9), we obtain for the temperature distribution in the wedge:

$$T(r,\beta) - T_s = (T_w - T_s)\left(1 - \frac{r\sin\beta}{R\sin\theta}\right). \quad (12)$$

We note that at the heated surface $\beta = 0$ and $T(r, 0) = T_w$ from equation (12); whereas along the interface $\beta = \theta$ and the temperature variation becomes:

$$T(r, \theta) - T_s = (T_w - T_s)\left(1 - \frac{r}{R}\right). \quad (13)$$

In view of these two approximations, the variation of surface tension can be expressed as:

$$\frac{\partial \sigma}{\partial s} = \frac{\partial \sigma}{\partial T}\left(\frac{\partial T}{\partial r}\right)_{\beta=\theta} \quad (14)$$

whence from equation (13):

$$\frac{\partial \sigma}{\partial s} = -\frac{\partial \sigma}{\partial T}\frac{T_w - T_s}{R} = -\frac{\partial \sigma}{\partial T}\frac{T_w - T_s}{\delta_c}\sin\theta \quad (15)$$

which can be expressed also in terms of the heat flux density, thus:

$$\frac{\partial \sigma}{\partial s} = \frac{\partial \sigma}{\partial T}\frac{\dot{Q}/A}{k}\sin\theta. \quad (16)$$

Substituting equation (16) in equation (4), we obtain for the thermocapillary force:

$$F_s = \int_0^R \frac{\partial \sigma}{\partial T}\frac{\dot{Q}/A}{k}\sin\theta\cos\theta\,\mathrm{d}r \quad (17)$$

which, in view of equation (11), can be written as

$$F_s = \frac{\partial \sigma}{\partial T}\frac{\dot{Q}/A}{k}\delta_c\cos\theta. \quad (18)$$

Equation (18) indicates that for a given δ_c the thermocapillary force increases with increasing heat flux density and wettability, i.e. with decreasing contact angle θ.

4. THE VAPOR-THRUST EFFECT

In order to evaluate the effect of the vapor thrust given by equation (5), we note that, for the wedge approximation, the temperature gradient normal to the interface is given by:

$$\frac{\partial T}{\partial n} = \frac{1}{r}\left(\frac{\partial T}{\partial \beta}\right)_{\beta=\theta} \quad (19)$$

which, for the temperature distribution given by equation (12), reduces to:

$$\frac{\partial T}{\partial n} = -\frac{T_w - T_s}{R\sin\theta}\cos\theta = -\frac{\dot{Q}/A}{k}\cos\theta. \quad (20)$$

Substituting equation (20) in equation (5), we obtain for the evaporation pressure:

$$P_e = \rho_v\left[\frac{\dot{Q}/A}{\rho_v h_{fg}}\right]^2\frac{\Delta\rho}{\rho_f}\cos^2\theta. \quad (21)$$

This pressure gives rise to a force per unit perimeter given by equation (6). Upon integration it follows from equation (6) and equation (21) that this force can be expressed as:

$$F_e = \rho_v\left[\frac{\dot{Q}/A}{\rho_v h_{fg}}\right]^2\frac{\Delta\rho}{\rho_f}\delta_c\cos^2\theta \quad (22)$$

where we have taken into account equation (11).

With the thermocapillary and the vapor thrust forces given by equations (18) and (22) respectively, the stability criterion can be evaluated if the velocity distribution appearing in the integral term of equation (7) is known. In the two sections that follow it will be assumed that the film is in laminar flow motivated by gravity and by surface shear respectively; these two flow regimes specify the velocity distribution to be used in equation (7).

5. LAMINAR FILM MOTIVATED BY GRAVITY

For a laminar film flowing under the action of gravity the velocity distribution is given by:

$$u_f(y) = -\frac{g\,\Delta\rho}{2\mu}(y^2 - 2y\,\delta_c). \quad (23)$$

Inserting this distribution in equation (1) we obtain:

$$F_p = \tfrac{8}{15}\left[\frac{g\,\Delta\rho}{2\mu}\right]^2\delta_c^5. \quad (24)$$

Substituting equations (24), (22), and (18) in equation (7), we obtain for the stability criterion:

$$\frac{\rho_f}{15}\left[\frac{g\,\Delta\rho}{\rho_f\nu}\right]^2\delta_c^4 = \frac{\sigma(1-\cos\theta)}{\delta_c} + \frac{\partial\sigma}{\partial T}\frac{\dot{Q}/A}{k}\cos\theta + \rho_v\left[\frac{\dot{Q}/A}{\rho_v h_{fg}}\right]^2\frac{\Delta\rho}{\rho_f}\cos^2\theta. \quad (25)$$

This equation predicts the minimum film thickness in laminar flow motivated by gravity which will permit the wetting of the entire surface. For film thicknesses smaller than that given by equation (25), dry patches can be established on the heating surface.

Recalling that in laminar flow the average film thickness is related to the mass flow rate per unit wetted perimeter Γ by:

$$\delta_c = \left[\frac{3\Gamma\nu}{g\Delta\rho}\right]^{\frac{1}{3}}. \quad (26)$$

Equation (25) can be expressed also in terms of Γ, thus:

$$\frac{\rho_f}{15}\left[\frac{g\,\Delta\rho}{\rho_f\nu}\right]^2\left[\frac{3\Gamma\nu}{g\,\Delta\rho}\right]^{\frac{4}{3}} = \frac{\sigma(1-\cos\theta)}{[3\Gamma\nu/g\,\Delta\rho]^{\frac{1}{3}}} + \frac{\partial\sigma}{\partial T}\frac{\dot{Q}/A}{k}\cos\theta + \rho_v\left[\frac{\dot{Q}/A}{\rho_v h_{fg}}\right]^2\frac{\Delta\rho}{\rho_f}\cos^2\theta. \quad (27)$$

For a given fluid and for a given operating pressure and power density, this equation can be used to evaluate the minimum mass flow rate per unit perimeter which will permit the wetting of the entire surface. Alternately for a given Γ this equation predicts the maximum value of the power density which can be maintained without establishing a stationary dry patch in a laminar liquid film flowing under the action of gravity.

6. LAMINAR FILM MOTIVATED BY SURFACE SHEAR

For a laminar film motivated by surface shear the velocity distribution is given by:

$$u_f(y) = u_{f\,\max}\left(\frac{y}{\delta}\right). \quad (28)$$

It follows then from equations (28) and (1) that:

$$F_p = \frac{\rho_f}{6}u_{f\,\max}^2\delta_c. \quad (29)$$

Inserting this equation in equation (7), we obtain for the stability criterion:

$$\frac{\rho_f}{6}u_{f\,\max}^2 = \frac{\sigma(1-\cos\theta)}{\delta_c} + \frac{\partial\sigma}{\partial T}\frac{\dot{Q}/A}{k}\cos\theta + \rho_v\left[\frac{\dot{Q}/A}{\rho_v h_{fg}}\right]^2\frac{\Delta\rho}{\rho_f}\cos^2\theta. \quad (30)$$

Since the velocity $u_{f\,\max}$ at the interface is related to the surface shear τ_s and to Γ by the following expressions:

$$\Gamma = \rho_f u_{f\,\mathrm{av}}\delta_c = \rho_f\frac{u_{f\,\max}}{2}\delta_c \quad (31)$$

$$\tau_s = \mu\frac{u_{f\,\max}}{\delta_c}. \quad (32)$$

Equation (30) can be also expressed by:

$$\frac{\rho_f}{6}\left[\frac{2\Gamma}{\rho_f\delta_c}\right]^2 = \left(\frac{\tau_s\delta_c}{\rho_f\nu}\right)^2 = \frac{\sigma(1-\cos\theta)}{\delta_c} + \frac{\partial\sigma}{\partial T}\frac{\dot{Q}/A}{k}\cos\theta + \rho_v\left[\frac{\dot{Q}/A}{\rho_v h_{fg}}\right]^2\frac{\Delta\rho}{\rho_f}\cos^2\theta. \quad (33)$$

Thus equation (33) predicts either the value of the minimum mass flow rate or the value of the surface shear required to maintain a wet surface in laminar film flow motivated by surface shear.

7. SIGNIFICANCE OF GOVERNING FORCES

For a given fluid, heat transfer rate and flow regime, equation (7) or more specifically equations (25), (27) or (33) can be used to estimate the minimum flow, minimum film thickness or minimum surface shear which will permit complete wetting of the surface. Or, alternately, for a given mass flow rate these equations can be used to estimate the highest heat flux which can be attained without establishing stationary dry patches in the film. The results predicted by the analysis have not been tested against experiments because quantitative data are not available yet. However, several observations can be made.

By substituting equations (18) and (22) in equation (7), we obtain:

$$\frac{\rho_f}{2}\int_0^{\delta_c} u_f^2(y)\,\mathrm{d}y = \sigma(1-\cos\theta) + \frac{\partial\sigma}{\partial T}\frac{\dot{Q}/A}{k}\delta_c\cos\theta + \rho_v\left(\frac{\dot{Q}/A}{\rho_v h_{fg}}\right)\frac{\Delta\rho}{\rho_f}\delta_c\cos^2\theta. \quad (34)$$

As noted before the effect of the flow, given by the integral in equation (34), is to sweep the dry patch downstream and reestablish the liquid film adjacent to the heating surface. The effect of surface wetting, thermocapillarity and of the vapor thrust is to spread the dry patch. The preceding equation can be used therefore to determine and compare the importance of the various effects on the speading tendency of a dry patch as a function of the thermodynamic properties of the fluid and of the operating conditions of the system. For this purpose the analysis provides three dimensionless groups:

The relative importance of the various effects on the spreading tendency of the dry patch can be evaluated by taking the ratio of the dimensionless groups, thus

$$\frac{\pi_2}{\pi_1} = \pi_4 = \frac{\frac{\partial\sigma}{\partial T}\frac{\dot{Q}/A}{k}\delta_c\cos\theta}{\sigma(1-\cos\theta)} \quad (38)$$

$$\frac{\pi_3}{\pi_4} = \pi_5 = \frac{\rho_v\left(\frac{\dot{Q}/A}{\rho_v h_{fg}}\right)^2\frac{\Delta\rho}{\rho_f}\delta_c\cos^2\theta}{\sigma(1-\cos\theta)}. \quad (39)$$

The dimensionless groups π_4 and π_5 compare the thermal to the surface wetting effect, whereas the relative importance of the vapor thrust to the thermocapillary effect is given by:

$$\frac{\pi_3}{\pi_2} = \pi_6 = \frac{\partial T}{\partial\sigma}\rho_v\left[\frac{\dot{Q}/A}{\rho_v h_{fg}}\right]\frac{\Delta\rho}{\rho_f}\cos\theta. \quad (40)$$

The values of the dimensionless groups π_4, π_5 and π_6 are listed in Table 1 for several conditions of practical interest employing water and liquid-metal films.

Table 1 indicates the importance of the thermocapillary and of the vapor thrust forces relative to the surface wetting force. It can be

$$\pi_1 = \frac{\sigma(1-\cos\theta)}{\frac{\rho_f}{2}\int_0^{\delta} u_f^2(y)\,\mathrm{d}y} \quad : \frac{\text{Surface wetting}}{\text{Inertia}} \quad (35)$$

$$\pi_2 = \frac{\frac{\partial\sigma}{\partial T}\frac{\dot{Q}/A}{k}\delta_c\cos\theta}{\frac{\rho_f}{2}\int_0^{\delta} u_f^2(y)\,\mathrm{d}y} \quad : \frac{\text{Thermocapillary}}{\text{Inertia}} \quad (36)$$

$$\pi_3 = \frac{\rho_v\left(\frac{\dot{Q}/A}{\rho_v h_{fg}}\right)^2\frac{\Delta\rho}{\rho_f}\delta_c\cos^2\theta}{\frac{\rho_f}{2}\int_0^{\delta} u_f^2(y)\,\mathrm{d}y} \quad : \frac{\text{Vapor thrust}}{\text{Inertia}}. \quad (37)$$

Table 1. Importance of surface wetting and of thermal effects

Liquid	Saturation temperature	$\dot{Q}/A$	δ_c	ΔT	π_4 equation (38)		π_5 equation (39)		π_6 equation (40)	
	(°F)	(Btu/h ft²)	(in)	(degF)*	$\theta = 10°$	$\theta = 60°$	$\theta = 10°$	$\theta = 60°$	$\theta = 10°$	$\theta = 60°$
Water	212	$0{\cdot}5 \times 10^6$	0·0004	45	0·55	0·01	0·017	<0·001	0·03	0·015
Water	635	$0{\cdot}5 \times 10^6$	0·0004	50	3·6	0·06	0·003	<0·001	0·001	<0·001
Sodium	1200	10^6	0·004	8·5	0·217	0·003	2·3	0·018	10·5	6·0
Sodium	1700	10^6	0·004	11	0·18	0·003	0·1	0·001	0·82	0·4
Potassium	1500	10^6	0·004	17	0·55	0·01	0·53	0·004	0·96	0·5

* Temperature difference across film.

seen that entirely different conclusions can be drawn from experiments where the surface conditions are not closely controlled.

It can be seen either from this table or from equation (34) that with liquid metals or with other liquid of high wettability the effect of the surface wetting force in maintaining a dry patch will be small since the value of the contact angle θ is close to zero, i.e. $(1 - \cos\theta) \approx 0$. Consequently, for these liquids whether or not a dry patch remains stationary will depend entirely on the thermal effects; which confirms the statement made in the introduction concerning the importance of the thermocapillary and of the vapor thrust forces in a system with heat addition and evaporation. It can be seen also, that for large contact angles, i.e. when the wetting is poor, the surface forces will be dominant. For this condition a dry patch could be maintained at very low heat flux densities.

Table 1 indicates also that whether or not the vapor thrust is important when compared to the thermocapillary force depends on the fluid properties and on the operating conditions. Thus, whereas for liquid metals the vapor thrust is equally or more imporant than the thermocapillary force, the opposite is true for water.

8. CONCLUSIONS

(1) An analysis is presented which predicts the conditions that will permit a dry patch to form and remain stationary in a liquid film flowing over a heated surface.

The analysis takes into account the effect of the thermocapillary and of the vapor thrust forces as well as the effect of forces due to flow and to surface wetting.

(2) Criteria are presented, in terms of the thermodynamic properties of the fluid, which predict the minimum film thickness, the minimum flow rate, the minimum surface shear or the maximum heat flux density which can be attained without establishing a stationary dry patch in the flowing liquid film.

(3) The results indicate that for liquids of high wettability (liquid metals for example) the effect of the surface wetting force in maintaining a dry patch is small. Consequently, for these liquids, whether or not a dry patch remains stationary depends on the thermocapillary and on the vapor thrust forces which, in turn, depend on the thermodynamic properties and on the heat flux density.

(4) For liquids of poor wettability, the surface force is dominant in maintaining the dry patch. For these liquids such a patch can be maintained at very low heat flux densities.

(5) Whether or not the effect of evaporation thrust is important when compared to the

effect of the thermocapillary force depends on the fluid properties and on the operating conditions. Whereas for liquid metals the evaporation thrust is equally or more important than the thermocapillary force, the opposite is true for water.

(6) The results of the analysis show that a significant error can be made in estimating the minimum film thickness, flow rate and surface shear (that can be attained without establishing a stationary dry patch in a liquid film flowing over a *heated* surface) if the thermal effects due to the thermocapillary force and to the evaporation thrust are not taken into account.

ACKNOWLEDGEMENT

This work was performed under the U.S. Atomic Energy Commission Contract No. AT(04-3)-189, Project Agreement 35 for the Joint U.S.A.E.C.–Euratom Research and Development Program.

REFERENCES

1. D. E. Hartley and W. Murgatroyd, Criteria for the break-up of thin liquid layers flowing isothermally over solid surfaces, Nuclear Research Memo. Q5 Nuclear Engr. Lab., Queen Mary College, University of London, September, 1961.
2. D. E. Hartley and W. Murgatroyd, Criteria for the break-up of thin liquid layers flowing isothermally over a solid surface, *Int. J. Heat Mass Transfer* **7**, 1003 (1964).
3. W. Leidenfrost, Strömungs- und Wärmeubergang verhaltnisse bei frei fallenden Rieselfilmen in Zustand der Verdampfung, *Naturwissenschaften* **43**, 465 (1956).
4. Y. Y. Hsu, F. T. Simon and J. F. Lad, Destruction of a thin liquid film flowing over a heating surface, NASA Report E 2144 (1963).
5. W. S. Norman and V. McIntyre, Heat transfer to a film on a vertical surface, *Trans. Instn Chem. Engrs* **38**, 301 (1960).
6. F. W. Staub and N. Zuber, A program of two-phase flow investigation, Second Quarterly Report, GEAP 4367, EURAEC Report No. 866 (October, 1963) (available from the O.T.S., Washington 25, D.C.).
7. N. Zuber and F. W. Staub, Thermal effects on the stability of liquid films flowing over a heated surface. Submitted for publication in the *Int. J. Heat Mass Transfer*.

Résumé—On obtient les critères de stabilité des taches sèches qui se forment dans les films liquides minces s'écoulant sur une paroi chauffée. La théorie de Hartley et Murgatroyd [1, 2], qui s'applique aux films isothermes, est étendue pour tenir compte des effets de la poussée de la vapeur et de la thermocapillarité.

Les résultats des calculs numériques montrent l'importance relative des divers effets en relation avec l'eau ordinaire chauffée et les films de métaux liquides très mouillants (par exemple, pour les métaux liquides), les effets thermiques deviennent prépondérants pour la stabilité des taches sèches.

Zusammenfassung—Es werden Kriterien abgeleitet für die Stabilität von Trockenzonen, die sich in dünnen Flüssigkeitsfilmen bilden, wenn sie über eine beheizte Fläche fliessen. Die Analyse von Hartley und Murgatroyd [1, 2] für isotherme Filme wird auf die Einflüsse von Dampfschub und Thermokapillarität erweitert.

Die durchgeführten numerischen Auswertungen zeigen den wechselseitigen Einfluss bei typischen Heisswasser- und Flüssigmetallfilmen. Die Ergebnisse zeigen, dass für Flüssigkeiten mit hoher Benetzbarkeit (zum Beispiel für Flüssigmetalle) die thermischen Effekte bei der Bestimmung der Stabilität der Trockenzonen dominieren.

Аннотация—Выведены критерии для расчета устойчивости сухих участков, возникающих при течении жидкой пленки на поверхности нагрева. Метод анализа, развитый Хартли и Мургатройдом (1,2) применительно к течению изотермических пленок, обобщен на случай учета влияния давления пара и термокапиллярности.

Приведены численные расчеты, выявившие относительную роль и вклад различных эффектов при течении типичных пленок нагретой воды и жидкого металла. Результаты показывают, что при течении жидкостей с высокой смачиваемостью (напрмер, жидких металлов) термические эффекты становятся доминирующими при определении стабильности сухих участков.