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THE EFFECT OF WAVES ON THE MOTION OF THE TRIPLE-PHASE FRONT OF A DRY PATCH FORMED IN A THIN MOTIVATED LIQUID FILM

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Abstract—A theory which predicts the effect of surface waves on rewetting dry patches which are formed in thin motivated heated liquid films is introduced. The main parameters considered are mass velocity, the dimensionless wave amplitude, the surface heat-flux and the subcooling. The theory is applied to some available published experimental results on dry-out, and it reveals the importance of surface-wave phenomena on the rewetting process.

NOMENCLATURE

A, cross-sectional area of the liquid phase;
A', cross-sectional area of the vapour phase;
A_t, $A+A'$;
c, wave speed;
c_1, dimensionless wave amplitude, defined in equation (7);
f_{q_a}, heat-flux per unit area of tube between the tube wall and the fluid;
f_{q_l}, heat-flux per unit length of tube between the tube wall and the fluid;
g, gravitational acceleration;
g_0, gravitational dimensional constant;
h, specific enthalpy of saturated liquid;
h', specific enthalpy of saturated vapour;
k, conductivity of liquid;
$m(z, t)$, local liquid mass flow rate at time t;
$\dot{m}_1$, mass-flow rate of the fluid film which is free from waves;
$\dot{m}_2$, mass of excess liquid supplied by the wave at time t;
M, $\dot{m}_1$;
N_{Re}, Reynolds number;
N_{We}, Weber number;
R, tube radius;
S, B, Z, Y, parameters defined in equation (13);
t, time;
T, temperature;
w, average film velocity;
x, flow quality;
z, direction of motion of the triple-phase point.

Greek symbols

$\alpha(z, t)$, local void fraction at time t;
$\bar{\alpha}$, mean void fraction;
β, coefficient of thermal expansion;
δ, film thickness at time t;
δ_c, critical film thickness;
δ_r, $\delta-\delta_c$;
θ, contact angle at the triple-phase front;
λ, wave length;
ϕ, free surface deformation;
ρ, ρ', density of liquid and vapour respectively;
$\eta(t)$, distance travelled by the triple-phase point at t;
σ, surface tension;
ν, kinematic viscosity;
ξ, dimensionless wave celerity;
Φ, a parameter defined by equation (20);
μ, μ', dynamic viscosity of liquid and vapour respectively.

1. INTRODUCTION

WHEN thin films of liquid flow over a solid surface, there is always a possibility that a dry patch could develop. In the present work, we are interested in the study of the motion of the triple-phase front as this determines if the dry patch could be re-wetted, enlarged or become stable. The heated solid surface is the internal surface of a horizontal tube and the thin film is motivated by vapour of the same substance. The film flow is under the influence of the shear which is applied by an interface vapour stream, the gravity force being neglected.

Experimental evidence [1, 2] has established the presence of waves on such free thin film surfaces and we shall assume that harmonic waves exist on the liquid surface.

2. THE MODEL

Assume that the triple-phase stagnation point of a dry patch of a shape similar to that suggested by Hartley and Murgatroyd [3] and later photographed by Thompson [1] would behave in a similar way to the edge of the annular liquid film at the end of the region of two-phase flow in a straight tubular steam generator. Figure 1(a) shows the cross section of the film and the triple-phase front where θ is the contact angle. According to Hartley and Murgatroyd [3] for each contact angle there is a unique value of the critical thickness δ_c; when the film becomes thicker than δ_c, the kinetic head overcomes the capillary force at the stagnation point and this point advances to re-wet the dry patch.

Assume a film front, Fig. 1(a) which, in the absence of waves, is just stable and of thickness δ_c, the heat supplied being just sufficient to evaporate the incoming liquid at the triple-phase front. Now, if we assume that harmonic waves exist on the film surface, as shown in Fig. 1(b), the film thickness will increase at the triple-phase point when the waves reach it. The static and dynamic forces will overcome the capillary forces and the triple-phase front will move forward over the heated surface. The subsequent advance and retreat of the front will depend on whether the excess liquid is evaporated before the next wave arrives. In the proper circumstances the front will, on average, move forward and re-wet the surface.

The objectives of the present work were to find the effect of surface waves on the triple-phase front motion, hence, to find the rewetting speed at different values of heat-flux, mass velocity, subcooling and dimensionless wave amplitude. The thermal inertia of the solid surface has for the moment been neglected.

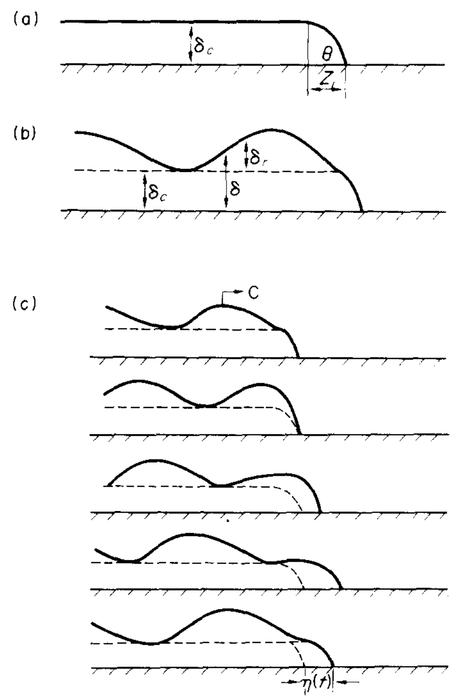

FIG. 1. Schematic motion of triple-phase front during one wave period.

3. GOVERNING EQUATIONS

The distance, $\eta(t)$, travelled by the triple-phase front at time t is proportional to $m_2'(t)/f_{q_i}$, where $m_2'(t)$ is the mass of excess liquid supplied by the wave at time t and f_{q_i} is the heat-flux between the tube wall and the fluid.

The continuity equation describing the two-phase flow (see Fig. 1) is

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_{z=0}^{z=\eta(t)} [\rho+(\rho'-\rho)\alpha]A_t\,\mathrm{d}z = m(z,t)_{z=0}-m(z,t)_{z=\eta(t)} \quad (1)$$

where $\alpha = A'(z,t)/A_t$.

Applying Leibnitz theorem to equation (1) and multiplying both sides by h', (the specific enthalpy of the vapour phase)

$$\int_{z=0}^{z=\eta}\frac{\mathrm{d}}{\mathrm{d}t}[\rho h'+h'(\rho'-\rho)\alpha]A_t\,\mathrm{d}z+[h'\rho+h'(\rho'-\rho)\alpha]A_t\frac{\mathrm{d}\eta}{\mathrm{d}t} = h'm(z,t)_{z=0}-h'm(z,t). \quad (2)$$

To write the energy equation, we neglect the changes in kinetic energy and viscous dissipation and consider that the average surface heat-flux f_{q_i} is the only heat to be transferred from the solid surface to the fluid, then

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_{z=0}^{z=\eta}[\rho h+(\rho'h'-\rho h)\alpha]A_t\,\mathrm{d}z = \int_{z=0}^{z=\eta} f_{q_i}\,\mathrm{d}z + [\{h+(h'-h)x\}m(z,t)_{z=0}]-[h'm(z,t)]. \quad (3)$$

Applying Leibnitz theorem to equation (3) we get

$$\int_{z=0}^{z=\eta}\frac{\mathrm{d}}{\mathrm{d}t}[\rho h+(\rho'h'-\rho h)\alpha]A_t\,\mathrm{d}z + [\rho h+(\rho'h'-\rho h)\alpha]A_t\frac{\mathrm{d}\eta}{\mathrm{d}t} = \int_{z=0}^{z=\eta} f_{q_i}\,\mathrm{d}z+[\{h+(h'-h)x\}m(z,t)_{z=0}] - [h'm(z,t)_{z=\eta}]. \quad (4)$$

Subtract equation (2) from (4) and re-arrange

$$\rho(h-h')A_t\left[\int_0^{z=\eta}\frac{\mathrm{d}}{\mathrm{d}t}(-\alpha)\,\mathrm{d}z+(-\alpha)\frac{\mathrm{d}\eta}{\mathrm{d}t}+\frac{\mathrm{d}\eta}{\mathrm{d}t}\right]$$
$$=\int_0^{\eta} f_{q_t}\,\mathrm{d}z+m(z,t)(h-h')(1-x). \quad (5)$$

Applying Leibnitz theorem to equation (5) and putting

$$\bar{\alpha}=\frac{1}{\eta}\int_0^{\eta}\alpha\,\mathrm{d}z,$$

we get

$$\frac{\mathrm{d}\eta}{\mathrm{d}t}+\frac{f_{q_t}}{\rho A_t(h'-h)(1-\bar{\alpha})}\;\eta=\frac{1-x}{\rho(1-\bar{\alpha})A_t}m(z,t)_{z=0}. \quad (6)$$

The m(z, t) function

The assumed harmonic wave [4] is given by

$$\varphi=c_1\sin\frac{2\pi}{\lambda}z_1 \quad (7)$$

where φ is a function of film thickness.

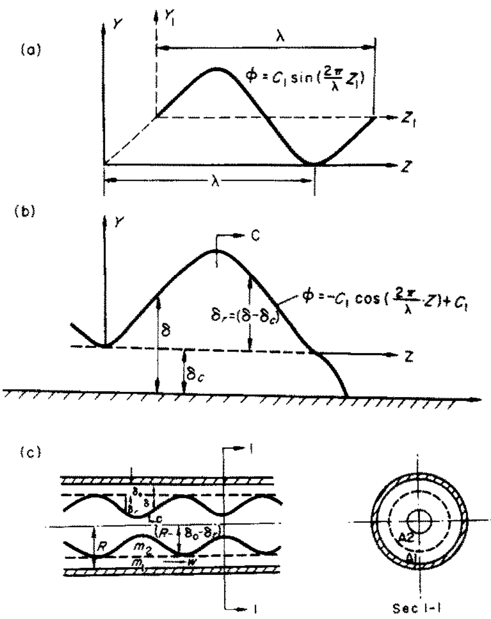

FIG. 2.

As shown in Fig. 2(a) by shifting the z_1, y_1 axes to z, y, equation (7) becomes

$$\varphi=c_1\sin\frac{2\pi}{\lambda}\left(z-\frac{\lambda}{4}\right)+c_1$$

or

$$\varphi=-c_1\cos\left(\frac{2\pi}{\lambda}z\right)+c_1 \quad (8)$$

also

$$\varphi\equiv\frac{\delta_r}{\delta_c}=\frac{\delta-\delta_c}{\delta_c}\quad\text{(see Fig. 2b).} \quad (9)$$

From equations (8) and (9) and by putting $\delta_c c_1=a$ and $z=ct$

$$\delta_r=-a\cos\left(\frac{2\pi}{\lambda}ct\right)+a. \quad (10)$$

With reference to Fig. 2(c), $\dot{m}_1$ is the mass-flow rate of the fluid film which is free from waves while $\dot{m}_2$ is the excess mass-flow rate due to the presence of the waves. The total mass-flow rate of the fluid $\dot{m}_t=\dot{m}_1+\dot{m}_2$

$$=\dot{m}_1+\rho c[-\pi\delta_r^2+2\pi\delta_r(R-\delta_c)] \quad (11)$$

and from (10) and (11)

$$\dot{m}_t=\dot{m}_1+\rho c\left[2\pi(R-\delta_c)\left(-a\cos\frac{2\pi ct}{\lambda}+a\right)\right.$$
$$\left.-\pi\left(a^2\cos^2\frac{2\pi ct}{\lambda}+a^2-2a^2\cos\frac{2\pi ct}{\lambda}\right)\right]. \quad (12)$$

Let

$$\left.\begin{aligned}S&=\frac{f_{q_t}}{\rho(1-\bar{\alpha})(h'-h)A_t}\\ B&=\frac{(1-x)}{\rho(1-\bar{\alpha})A_t}\\ M&=\dot{m}_1\\ Z&=2\pi\rho ca(R-\delta_c)\\ Y&=\pi\rho ca^2.\end{aligned}\right\} \quad (13)$$

Substitute (12) and (13) in (6)

$$\frac{\mathrm{d}\eta}{\mathrm{d}t}+S\eta=B\left[M+Z\left(-\cos\frac{2\pi ct}{\lambda}+1\right)\right.$$
$$\left.-Y\left(\cos^2\frac{2\pi ct}{\lambda}+1-2\cos\frac{2\pi ct}{\lambda}\right)\right]. \quad (14)$$

The temperature profile in the neighbourhood of the triple-phase front shows that there is an appreciable temperature rise on its dry side and the temperature of the solid surface under the wet part is reduced considerably [5]. The triple-phase front being nearer to the higher temperature surface undergoes a higher rate of evaporation which in turn decreases the film thickness for a distance z_i before which the film attains the critical thickness, Fig. 1. In order to calculate $z_i=\eta(0)$ we have from Fig. 1(a)

$$M=\rho w\pi[R^2-(R-\delta_C)^2]=[2\pi R\delta_C-\pi\delta_C^2]\rho w. \quad (15)$$

Assuming that the film is free of surface waves and the triple-phase front is stationary

$$\frac{d\eta}{dt} = 0. \tag{16}$$

From equations (14)–(16)

$$z_i = \eta_0 = \frac{BM}{S} \tag{17}$$

which is the initial boundary condition at $t = 0$.

4. SOLUTION

We recognize that equation (14) can be solved analytically. However we have chosen to apply Runge–Kutta method, so as to take advantage of the available computer facility in processing and plotting extensive results in a rather convenient way and also to establish this method for further developments of the present theory. The relation between the triple-phase front position during the time of two wave periods and the average rewetting speed for different values of surface heat-flux, mass velocity, flow quality and dimensionless wave amplitude has been found, the following being the major steps:

(i) The surface tension is calculated from the following equation (reference [6])

$$\sigma = 2{\cdot}204 \times 10^{-3} p_c^{2/3} T_c^{1/3} (0{\cdot}133\,\alpha_c - 0{\cdot}281) \times (1 - T_r)^{11/9} \tag{18}$$

where

p_c: critical pressure of the fluid substance (atmosphere);
T_c: critical temperature of the fluid substance (°K);
α_c: Riedel factor (dimensionless);
T_r: T/T_c.

(ii) The film thickness δ_c which is the minimum undisturbed film thickness (a film free of waves) is calculated from the equation derived by Zuber and Staub [7] for minimum film thickness with heat transfer,

$$\frac{\rho}{15}\left[\frac{g(\rho' - \rho)}{\rho v}\right]^2 \delta_c^4 = \frac{\sigma(1 - \cos\theta)}{\delta_c} + \frac{d\sigma}{dT}\frac{f_{q_a}}{k}\cos\theta + \rho'\left[\frac{f_{q_a}}{\rho'(h' - h)}\right]^2 \frac{\rho' - \rho}{\rho}\cos^2\theta. \tag{19}$$

Equation (18) is used to calculate the thermocapillary term in equation (19). However, it should be mentioned here that the minimum film thickness δ_c when calculated from Hartley and Murgatroyd [3] equation for isothermal flow shows that it has a lower value than obtained from equation (19).

(iii) The contact angle is calculated from the equation in reference [8]

$$\cos\theta = 1 - \frac{\delta_c^2 g \rho}{2 g_0 \sigma}.$$

(iv) The mean void fraction is calculated from the following equation, [9]

$$\bar{\alpha} = \left\{1 + \frac{0{\cdot}4\,\rho'}{\rho}\left(\frac{1}{x} - 1\right) + \frac{0{\cdot}6\,\rho'}{\rho}\left(\frac{1}{x} - 1\right) \cdot \left[\frac{\frac{\rho}{\rho'} + 0{\cdot}4\left(\frac{1}{x} - 1\right)}{1 + 0{\cdot}4\left(\frac{1}{x} - 1\right)}\right]^{1/2}\right\}^{-1}.$$

The calculated $\bar{\alpha}$ is in agreement with values found by Levy [10] and Fujie [11].

(v) The relation between flow quality x, surface heat-flux f_{q_a}, the mass velocity G_a and subcooling ΔH is given by

$$x = \frac{4L}{2R} \cdot \frac{f_{q_a}}{G_a(h' - h)} - \frac{\Delta H}{(h' - h)} \qquad [12]$$

(vi) The wave length λ and the dimensionless wave amplitude c_1 are calculated from the equations derived in [4]

$$\lambda = 2\pi\delta_c \sqrt{\left(\frac{1}{N_{We}(\xi^2 - 12/5\,\xi + 6/5)}\right)}$$

where

$$N_{We} = \frac{6(3 - \xi + (1/30)N_{Re}/N_{Fr}^2\Phi)}{(7\xi - 9)(\xi^2 - (12/5)\xi + (6/5))}$$

and

$$\Phi = \frac{f_{q_a}\delta_c}{k}\beta. \tag{20}$$

(vii) Results on burn out in uniformly heated round tubes by Barnett *et al.* [13] and Thompson and Macbeth [14] are used in our calculations. Although we applied the results of different runs, nevertheless, the results of one run from each of the references [13] and [14] are reported here as demonstrative examples of the application of the present theory as follows:

Reference	[13]	[14]
Run No.	29·001	205·03
substance	Freon 12	water
pressure (lb/in^2)	155	1000
temperature (°F)	112	545
ρ (lb$_m$/ft^3)	77·18	46·3
ρ (lb$_m$/ft^3)	3·714	2·244
$h' - h$ (Btu/lb$_m$)	55·43	649·4
k Btu/h.ft°F	0·046	0·358
μ lb/h.ft	0·571	0·233
μ' (lb/h.ft)	0·0316	0·0493
β 1/°R	0·00025	0·000416
inside diameter (in)	0·303	0·22
heated length (in)	47·4	68
G_a lb/h.ft^2	784000	690000
ΔH Btu/lb	13·6	11·3
f_{q_a} Btu/h.ft^2	44090	349200

5. RESULTS AND DISCUSSION

The main parameters considered in the present work which are thought to affect the motion of the triple-phase front are the mass velocity, the dimensionless wave amplitude, the surface heat-flux and the sub-cooling. To demonstrate the effect of these, three were kept constant while different values of the fourth were considered.

velocity is relatively small the triple-phase front moves backward initially at higher speed, then it slows down and then afterwards the motion accelerates again. When the mass velocity is relatively large the forward movement of the triple-phase front is such that it starts with slower speed and then accelerates, and then it decelerates. This phenomenon could be explained by considering the mass of fluid fed to the triple-phase

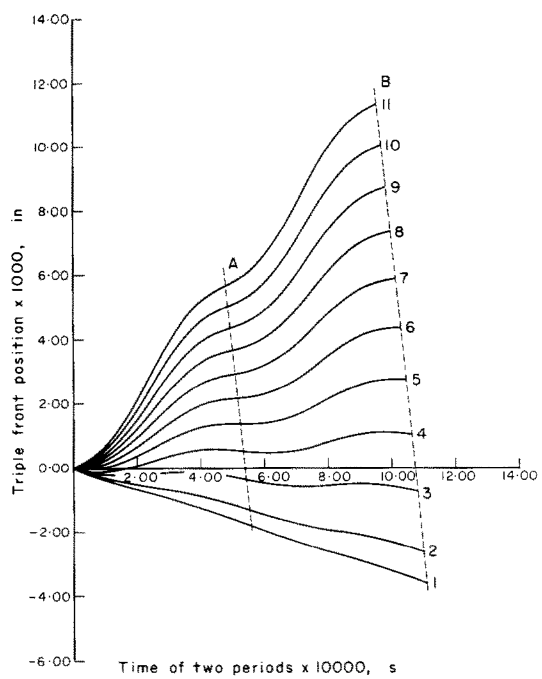

FIG. 3. Interface triple front position during two waves for different values of ($G_a^{\cdot}$). Water at pressure = 1000 lb/in^2. Constant parameters: $f_{q_a} = 0{\cdot}349 \times 10^6$ Btu/h ft^2; $\Delta H = 11{\cdot}30$ Btu/lb; $c_1 = 0{\cdot}4$. Contour line of: A—one wave period; B—two waves period.
1. $G_a^{\cdot} = 0{\cdot}652 \times 10^6$ lb/h ft^2. 2. $G_a^{\cdot} = 0{\cdot}658 \times 10^6$ lb/h ft^2. 3. $G_a^{\cdot} = 0{\cdot}668 \times 10^6$ lb/h ft^2. 4. $G_a^{\cdot} = 0{\cdot}678 \times 10^6$ lb/h ft^2. 5. $G_a^{\cdot} = 0{\cdot}689 \times 10^6$ lb/h ft^2. 6. $G_a^{\cdot} = 0{\cdot}699 \times 10^6$ lb/h ft^2. 7. $G_a^{\cdot} = 0{\cdot}709 \times 10^6$ lb/h ft^2. 8. $G_a^{\cdot} = 0{\cdot}721 \times 10^6$ lb/h ft^2. 9. $G_a^{\cdot} = 0{\cdot}730 \times 10^6$ lb/h ft^2. 10. $G_a^{\cdot} = 0{\cdot}741 \times 10^6$ lb/h ft^2. 11. $G_a^{\cdot} = 0{\cdot}751 \times 10^6$ lb/h ft^2.

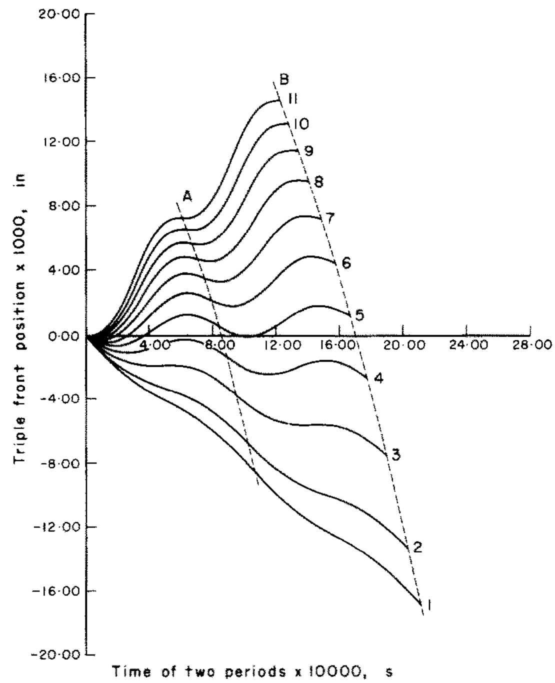

FIG. 4. Interface triple front position during two waves for different values of ($G_a^{\cdot}$). Freon 12 at pressure = 155 lb/in^2. Constant parameters: $f_{q_a} = 0{\cdot}441 \times 10^5$ Btu/h ft^2; $\Delta H = 13{\cdot}6$ Btu/lb; $c_1 = 0{\cdot}4$. Contour line of: A—one wave period; B—two waves period.
1. $G_a^{\cdot} = 0{\cdot}486 \times 10^6$ lb/h ft^2. 2. $G_a^{\cdot} = 0{\cdot}503 \times 10^6$ lb/h ft^2. 3. $G_a^{\cdot} = 0{\cdot}536 \times 10^6$ lb/h ft^2. 4. $G_a^{\cdot} = 0{\cdot}569 \times 10^6$ lb/h ft^2. 5. $G_a^{\cdot} = 0{\cdot}602 \times 10^6$ lb/h ft^2. 6. $G_a^{\cdot} = 0{\cdot}636 \times 10^6$ lb/h ft^2. 7. $G_a^{\cdot} = 0{\cdot}669 \times 10^6$ lb/h ft^2. 8. $G_a^{\cdot} = 0{\cdot}702 \times 10^6$ lb/h ft^2. 9. $G_a^{\cdot} = 0{\cdot}735 \times 10^6$ lb/h ft^2. 10. $G_a^{\cdot} = 0{\cdot}768 \times 10^6$ lb/h ft^2. 11. $G_a^{\cdot} = 0{\cdot}802 \times 10^6$ lb/h ft^2.

Figures 3 and 4 show the triple-phase front position during the period of two successive waves. Eleven different mass velocities are taken, for run No. 29·001 reference [13] where $0{\cdot}486 \times 10^6 \leqslant G_a^{\cdot} \leqslant 0{\cdot}802 \times 10^6$ and for run No. 205·03 reference [14] where $0{\cdot}652 \times 10^6 \leqslant G_a^{\cdot} \leqslant 0{\cdot}751 \times 10^6$ Btu/h.ft^2.

The triple-phase front moves either forward or backward depending on the mass-flow rate. When the mass front region by the incoming harmonic liquid waves. It is shown also that an increase in mass velocity results in a decrease in the wave period. The forward displacement of the liquid front after two waves increases with the increase of mass velocity while the reverse occurs when the motion is backward. It is obvious that at a particular value of mass velocity the triple front oscillates around its original position.

Figures 5 and 6 show the position of the triple-phase front during the motion of two waves this time, the dimensionless wave amplitude c_1 is considered and eleven different values for each run are taken; $0{\cdot}02 \geqslant c_1 \geqslant 0{\cdot}571$. From the figures, it is obvious that the change of the dimensionless wave amplitude does not affect the time needed for the triple front point to go to its outermost position, but significantly affects the distance moved by the triple front during the period of one wave. As c_1 increases the maximum distance moved by the triple-phase front increases. The motion of the triple front is slower at both the beginning and near the end.

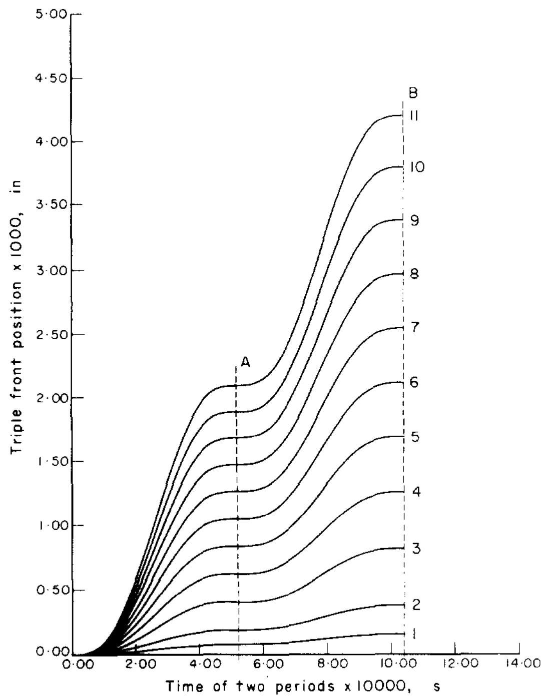

FIG. 5. Interface triple front position during two waves for different values of (c_1). Water at pressure = 1000 lb/in^2. Constant parameters: $f_{q_a} = 0{\cdot}349 \times 10^6$ Btu/h ft^2. $G_a = 0{\cdot}690 \times 10^6$ lb/h ft^2; $\Delta H = 11{\cdot}3$ Btu/lb. Contour line of: A—one wave period; B—two waves period. 1. $c_1 = 0{\cdot}020$. 2. $c_1 = 0{\cdot}049$. 3. $c_1 = 0{\cdot}107$. 4. $c_1 = 0{\cdot}165$. 5. $c_1 = 0{\cdot}223$. 6. $c_1 = 0{\cdot}281$. 7. $c_1 = 0{\cdot}339$. 8. $c_1 = 0{\cdot}397$. 9. $c_1 = 0{\cdot}455$. 10. $c_1 = 0{\cdot}513$. 11. $c_1 = 0{\cdot}571$.

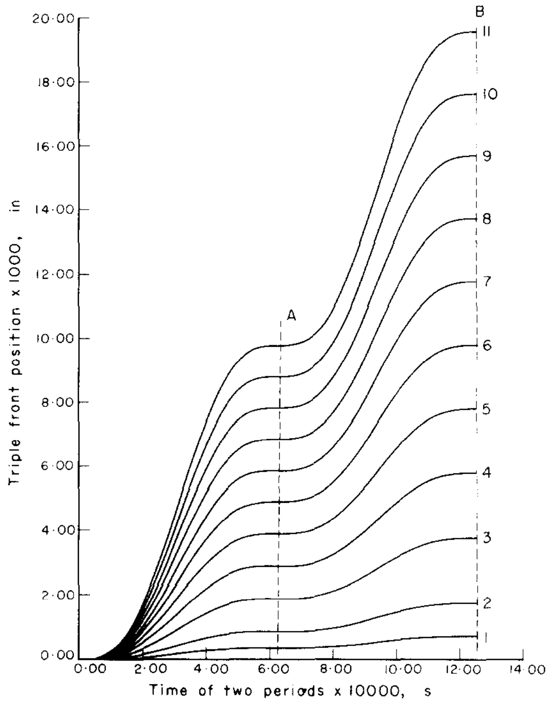

FIG. 6. Interface triple front position during two waves for different values of (c_1). Freon 12 at pressure = 155 lb/in^2. Constant parameters: $f_{q_a} = 0{\cdot}441 \times 10^5$ Btu/h ft^2; $G_a = 0{\cdot}784 \times 10^6$ lb/h ft^2; $\Delta H = 13{\cdot}6$ Btu/lb. Contour line of: A—one wave period; B—two waves period. 1. $c_1 = 0{\cdot}020$. 2. $c_1 = 0{\cdot}049$. 3. $c_1 = 0{\cdot}107$. 4. $c_1 = 0{\cdot}165$. 5. $c_1 = 0{\cdot}223$. 6. $c_1 = 0{\cdot}281$. 7. $c_1 = 0{\cdot}339$. 8. $c_1 = 0{\cdot}397$. 9. $c_1 = 0{\cdot}455$. 10. $c_1 = 0{\cdot}513$. 11. $c_1 = 0{\cdot}571$.

Figures 7 and 8 show the relation between the triple-phase front position and the period of wave travel at different subcooling values; for Freon 12 $0{\cdot}952 \leqslant \Delta H \leqslant 19{\cdot}04$ and for water $0{\cdot}791 \leqslant \Delta H \leqslant 15{\cdot}82$. The trend is that the maximum travel of the triple-phase front is proportional to the subcooling.

The shape of the curves is typical of the results of the present study, insofar as motion is slower at the start and end of the wave period when the net motion is forward, except for the case of lower subcooling where the triple-phase front starts with backward motion and then advances afterwards.

Figures 9 and 10 show the effect of surface heat-flux f_{q_a} on the motion of the triple-phase front. For Freon 12 $0{\cdot}425 \times 10^5 \leqslant f_{q_a} \leqslant 0{\cdot}616 \times 10^5$ and for water $0{\cdot}317 \times 10^6 \leqslant f_{q_a} \leqslant 0{\cdot}367 \times 10^6$. As expected, at relatively high surface heat-flux, the triple-phase front moves backwards. A decrease in f_{q_a} is reached at which the triple-phase front oscillates about its original position. A further decrease in the surface heat-flux results in re-wetting the dry area.

Examination of Figs. 11 and 12 shows that the re-wetting average velocity per wave period increases with the increase of c_1 or G_a or ΔH and decreases with the increase of f_{q_a}. f_{q_a} and G_a have a greater effect on the rewetting average velocity than the effect of both ΔH and c_1.

Hewitt [15] processed the experimental results of Shires [16] and Bennett *et al.* [17] for water. He found that at constant pressure, when the average tube temperature increased, the rewetting velocity decreased. He mentioned that Shires and Bennett have found no significant effect of water flow-rate changes on the rate of advance of the triple-phase front, though this conclusion is based on relatively few results. This is not in agreement with our theory which predicts that the mass velocity affects the advance of the triple-phase front. It should be mentioned here that although Shires [16] and Bennett [17] reported the presence of waves on the surface, they did not emphasize the important role of such waves in the rewetting process.

We would like to record that during an earlier stage of the present work we found that neglecting both the thermocapillary term in the film thickness equation (19) and the existance of a relation between flow quality, surface heat-flux, mass velocity and subcooling equation (references [13, 18]) resulted in the surface heat-flux having no significant effect on the average velocity of the triple-phase front, Fig. 13. This time the results of Stevens *et al.* [18] were processed.

At present, work is in progress to develop the model by the introduction of more realistic wave forms and other factors.

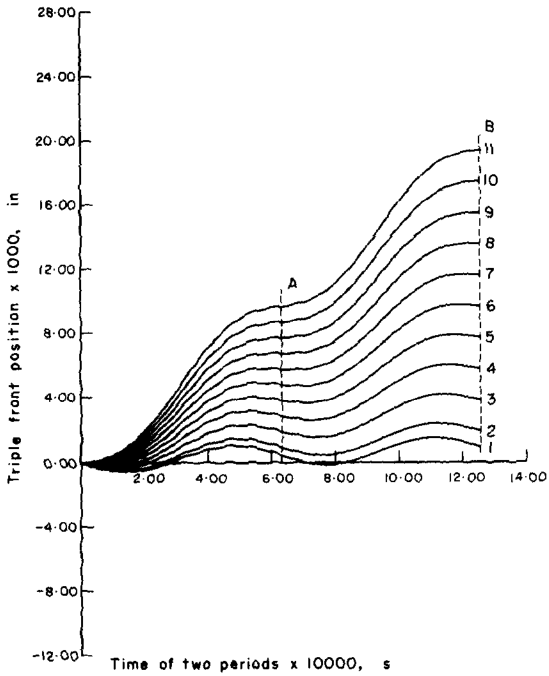

FIG. 7. Interface triple front position during two waves for different values of (ΔH). Freon 12 at pressure = 155 lb/in^2. Constant parameters: $f_{q_a} = 0{\cdot}441 \times 10^5$ Btu/h ft^2; $G_a' = 0{\cdot}784 \times 10^6$ lb/h ft^2; $c_1 = 0{\cdot}4$. Contour line of: A—one wave period; B—two waves period.
1. $\Delta H = 0{\cdot}952$ Btu/lb. 2. $\Delta H = 1{\cdot}904$ Btu/lb.
3. $\Delta H = 3{\cdot}808$ Btu/lb. 4. $\Delta H = 5{\cdot}712$ Btu/lb.
5. $\Delta H = 7{\cdot}616$ Btu/lb. 6. $\Delta H = 9{\cdot}520$ Btu/lb.
7. $\Delta H = 11{\cdot}424$ Btu/lb. 8. $\Delta H = 13{\cdot}328$ Btu/lb.
9. $\Delta H = 15{\cdot}232$ Btu/lb. 10. $\Delta H = 17{\cdot}136$ Btu/lb.
11. $\Delta H = 19{\cdot}040$ Btu/lb.

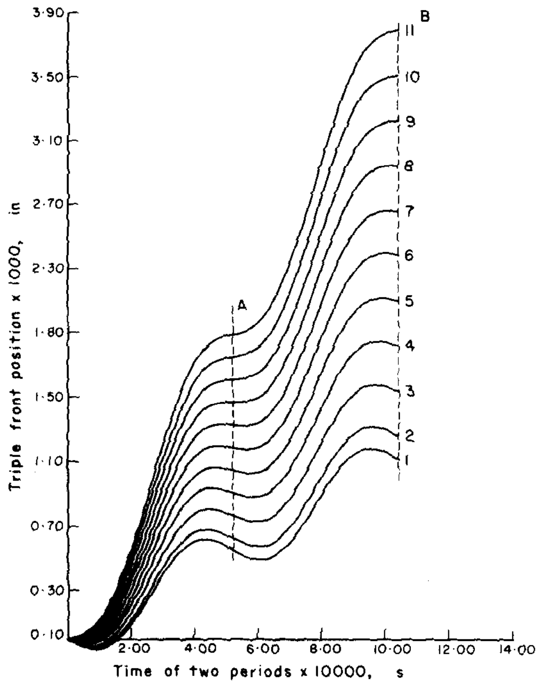

FIG. 8. Interface triple front position during two waves for different values of (ΔH). Water at pressure = 1000 lb/in^2. Constant parameters: $f_{q_a} = 0{\cdot}349 \times 10^6$ Btu/h ft^2; $G_a' = 0{\cdot}690 \times 10^6$ lb/h ft^2; $c_1 = 0{\cdot}4$. Contour line of: A—one wave period; B—two waves period.
1. $\Delta H = 0{\cdot}791$ Btu/lb. 2. $\Delta H = 1{\cdot}582$ Btu/lb.
3. $\Delta H = 3{\cdot}164$ Btu/lb. 4. $\Delta H = 4{\cdot}746$ Btu/lb.
5. $\Delta H = 6{\cdot}328$ Btu/lb. 6. $\Delta H = 7{\cdot}910$ Btu/lb.
7. $\Delta H = 9{\cdot}492$ Btu/lb. 8. $\Delta H = 11{\cdot}074$ Btu/lb.
9. $\Delta H = 12{\cdot}656$ Btu/lb. 10. $\Delta H = 14{\cdot}238$ Btu/lb.
11. $\Delta H = 15{\cdot}820$ Btu/lb.

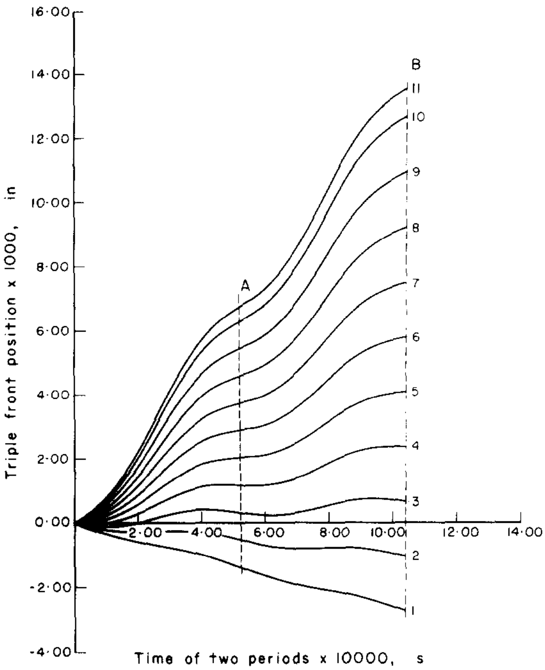

FIG. 9. Interface triple front position during two waves for different values of (f_{q_a}). Water at pressure = 1000 lb/in^2. Constant parameters: G_a = 0·690 × 10^6 lb/h ft^2; ΔH = 11·3 Btu/lb; c_1 = 0·4. Contour line of: A—one wave period; B—two waves period.
1. f_{q_a} = 0·367 × 10^6 Btu/h ft^2. 2. f_{q_a} = 0·362 × 10^6 Btu/h ft^2. 3. f_{q_a} = 0·356 × 10^6 Btu/h ft^2. 4. f_{q_a} = 0·351 × 10^6 Btu/h ft^2. 5. f_{q_a} = 0·346 × 10^6 Btu/h ft^2. 6. f_{q_a} = 0·341 × 10^6 Btu/h ft^2. 7. f_{q_a} = 0·336 × 10^6 Btu/h ft^2. 8. f_{q_a} = 0·330 × 10^6 Btu/h ft^2. 9. f_{q_a} = 0·325 × 10^6 Btu/h ft^2. 10. f_{q_a} = 0·320 × 10^6 Btu/h ft^2. 11. f_{q_a} = 0·317 × 10^6 Btu/h ft^2.

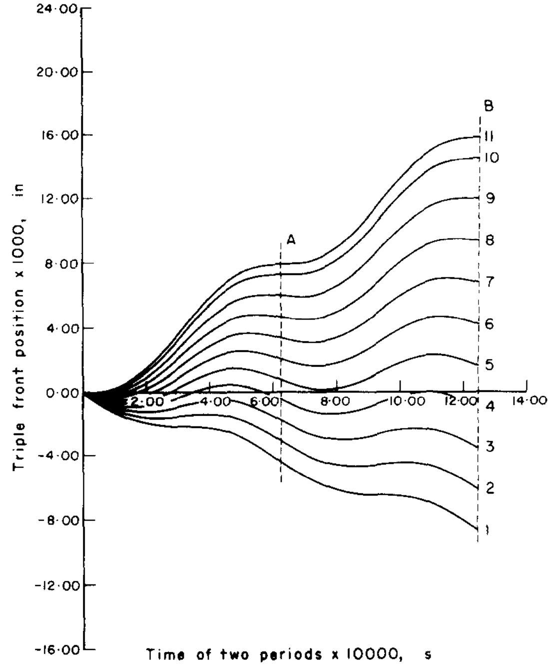

FIG. 10. Interface triple front position during two waves for different values of (f_{q_a}). Freon 12 at pressure = 155 lb/in^2. Constant parameters: G_a = 0·784 × 10^6 lb/h ft^2; ΔH = 13·6 Btu/lb; c_1 = 0·4. Contour line of: A—one wave period; B—two waves period.
1. f_{q_a} = 0·616 × 10^5 Btu/h ft^2. 2. f_{q_a} = 0·596 × 10^5 Btu/h ft^2. 3. f_{q_a} = 0·576 × 10^5 Btu/h ft^2. 4. f_{q_a} = 0·556 × 10^5 Btu/h ft^2. 5. f_{q_a} = 0·536 × 10^5 Btu/h ft^2. 6. f_{q_a} = 0·516 × 10^5 Btu/h ft^2. 7. f_{q_a} = 0·496 × 10^5 Btu/h ft^2. 8. f_{q_a} = 0·476 × 10^5 Btu/h ft^2. 9. f_{q_a} = 0·455 × 10^5 Btu/h ft^2. 10. f_{q_a} = 0·435 × 10^5 Btu/h ft^2. 11. f_{q_a} = 0·425 × 10^5 Btu/h ft^2.

A Freon simulating rig is in its final stages of preparation to verify the effect of waves on the movement of the triple-phase front of a dry patch.

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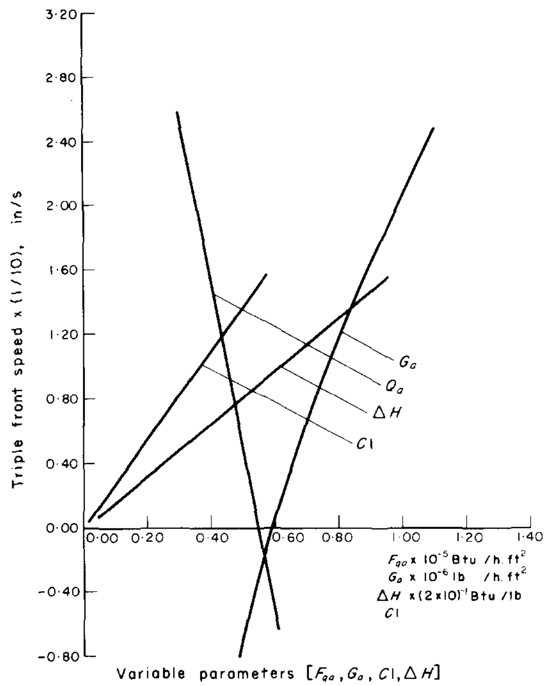

FIG. 11. Interface triple front speed vs (f_{q_a}, $G_a^{\cdot}$, c_1, ΔH). Freon 12 at pressure = 155 lb/in^2.

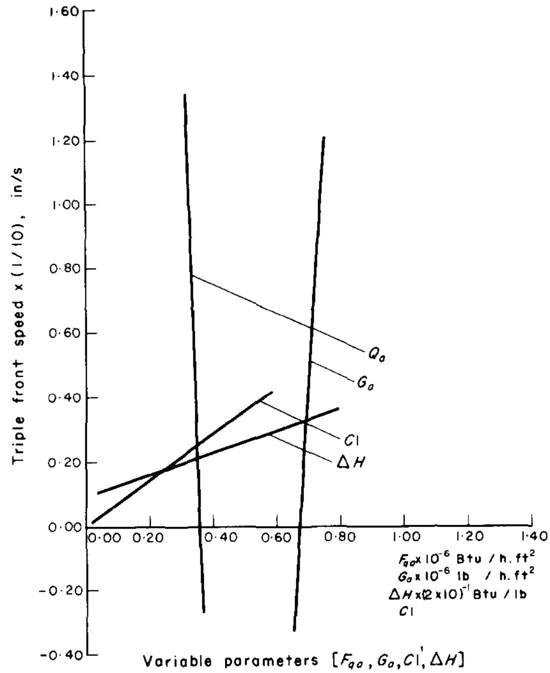

FIG. 12. Interface triple front speed vs (f_{q_a}, $G_a^{\cdot}$, c_1, ΔH). Water at pressure 1000 lb/in^2.

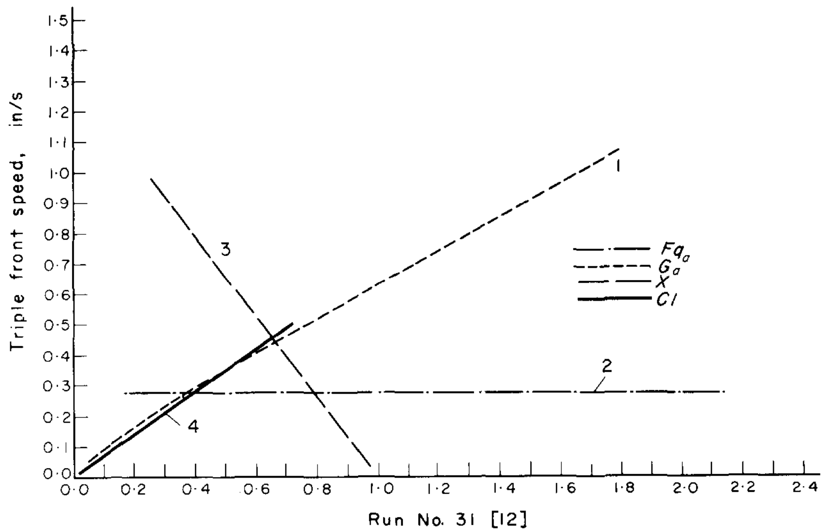

FIG. 13. (1) Triple front speed vs mass velocity ($G_a^{\cdot}$) at a constant $f_{q_a} = 2{\cdot}03 \times 10^4$ Btu/h ft^2; $c_1 = 0{\cdot}4$; $x = 0{\cdot}79$. (2) Triple front speed vs surface heat flux (f_{q_a}) at a constant $G_a^{\cdot} = 3{\cdot}75 \times 10^5$ lb/h ft^2; $c_1 = 0{\cdot}4$; $x = 0{\cdot}79$. (3) Triple front speed vs flow quality (x) at a constant $G_a^{\cdot} = 3{\cdot}75 \times 10^5$ lb/h ft^2; $c_1 = 0{\cdot}4$; $f_{q_a} = 2{\cdot}03 \times 10^4$ Btu/h ft^2. (4) Triple front speed vs dimensionless wave $A(c_1)$ at a constant $G_a^{\cdot} = 3{\cdot}75 \times 10^5$ lb/h ft^2, $x = 0{\cdot}79$, $f_{q_a} = 2{\cdot}03 \times 10^4$ Btu/h ft^2.

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EFFET DES ONDES SUR LE MOUVEMENT DU FRONT A TROIS PHASES D'UNE TACHE SECHE FORMEE DANS UN FILM LIQUIDE MINCE

Résumé—On présente une théorie qui prédit l'effet des ondes de surface sur le remouillage des taches sèches qui sont formées dans des minces films liquides chauffés. Les principaux paramètres considérés sont la vitesse massique, l'amplitude adimensionnelle de l'onde, le flux de chaleur et le sous-refroidissement. La théorie est appliquée à quelques résultats expérimentaux publiés sur l'assèchement et elle montre l'importance du phénomène d'ondes de surface sur le processus de remouillage.

DER EINFLUSS VON WELLEN AUF DIE BEWEGUNG DER DREI-PHASEN-GRENZFLÄCHE EINER TROCKENEN STELLE IN EINEM BEWEGTEN FLÜSSIGKEITSFILM

Zusammenfassung—Es wird eine Theorie eingeführt, nach der der Einfluß von Oberflächenwellen auf das Wiederbefeuchten trockener Stellen, die sich in dünnen, bewegten und beheizten Flüssigkeitsfilmen gebildet haben, vorherbestimmt werden kann. Die wichtigsten betrachteten Parameter sind die Geschwindigkeit des Massenstroms, die dimensionslose Wellenamplitude, der Wärmestrom an der Oberfläche und die Unterkühlung. Die Theorie wird auf einige verfügbare veröffentlichte experimentelle Ergebnisse beim Austrocken angewandt, wobei sich die Bedeutung des Phänomens der Oberflächenwellen auf den Prozeß der Wiederbenetzung zeigt.

ВЛИЯНИЕ ВОЛН НА ДВИЖЕНИЕ ТРЕХФАЗНОГО ФРОНТА СУХОГО ПЯТНА, ОБРАЗОВАННОГО В ТОНКОЙ ДВИЖУЩЕЙСЯ ЖИДКОЙ ПЛЕНКЕ

Аннотация — Предлагается теория, которая учитывает влияние поверхностных волн на смачивание сухих участков, образующихся в тонких движущихся жидких пленках при нагревании. В качестве основных параметров рассматриваются скорость, безразмерная амплитуда волны, тепловой поток на поверхности и переохлаждение. Результаты теории, показывающие влияние поверхностных волн в процессе смачивания, сопоставлены с некоторыми известными экспериментальными данными по высушиванию.