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STABILITY OF CONDENSATE FLOW DOWN A VERTICAL WALL

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Abstract—The linear stability theory is used to study stability characteristics of condensate film flow down a vertical wall. A critical Reynolds number exists above which disturbances will be amplified. The magnitude of the critical Reynolds number is so small that in all technical situations a laminar gravity-induced, vertical condensate film is unstable. The condensation mass transfer has a stabilizing effect if the temperature drop across the film is constant. For locally constant heat flux across the condensate film no stabilizing effect of the condensation mass transfer can be found.

NOMENCLATURE

c, c^*/u_0, complex wave velocity, celerity [dimensionless];
c^*, $c_r^* + ic_i^*$, complex wave velocity, celerity [dimensional];
c_p, specific heat at constant pressure;
f, dimensionless stream function;
F, dimensionless stream function, equation (5);
g, gravitational acceleration;
h_{fg}, latent heat;
k, thermal conductivity of liquid;
p^*, pressure;
p, $p^*/\rho u_0^2$, dimensionless pressure;
Pe, $Pr\, Re$, Péclét number;
Pr, Prandtl number;
Re, $u_0\delta/\nu$, Reynolds number;
S, temperature perturbation amplitude;
t^*, time;
t, t^*u_0/δ, dimensionless time;
T, temperature;
T_s, saturation temperature;
T_w, wall temperature;
ΔT, $T_s - T_w$, temperature drop across liquid film;
u^*, v^*, velocity components;
u, u^*/u_0; v, v^*/u_0 dimensionless velocity components;
u_0, surface velocity of undisturbed film flow, [dimensional];
v_g^*, vapor velocity;
x^*, y^*, coordinates;
x, x^*/δ; y, y^*/δ, dimensionless coordinates.

Greek symbols

α, $\alpha^*\delta$, wave number [dimensionless];
α^*, $2\pi/\lambda^*$, wave number [dimensional];
λ^*, wave length [dimensional];
λ, λ^*/δ wave length [dimensionless];
δ, local thickness of undisturbed condensate film;
η, similarity variable, equation (2);
θ, temperature variable, equation (7);
ν, kinematic viscosity, liquid;
ρ, density, liquid;
ρ_g, density, vapor;
σ, surface tension;
ε, $\delta(1 + \tau)$, film thickness of disturbed film, Fig. 1;
ϕ, stream function perturbation amplitude;
ψ, stream function, equation (5);
Ω, temperature variable, equation (2).

Base flow quantities are denoted by $^{-}$, disturbance quantities are denoted by $\hat{}$.

INTRODUCTION

THE ORIGINAL theory of gravity induced laminar film condensation was developed by Nusselt in 1916 [1]. Since then, the condensation process has been reexamined many times. Presently, the most advanced theory of laminar film condensation is based on the thorough investigations carried out by Sparrow *et al.* [2–4]. In this theory, in accordance with all former theories, it is assumed that the condensate film is undisturbed. Consequently, the film flow is taken to be free of waves, ripples, or other time dependent phenomena. There does not appear to be a predictive theory for laminar film condensation which includes the wavy character of disturbed film flow. As a first step in the formulation of such a theory the stability of condensate films has to be examined. While to the knowledge of the authors the stability characteristics of condensate films have never been investigated, much research has been done on the stability of falling films. Benjamin [5] proved that vertical free-surface flow with constant flowrate is unstable for all Reynolds numbers. Whether a disturbance superimposed on the undisturbed flow is damped or amplified depends according to this theory on the wavelength of the disturbance and the surface tension of the liquid.

It is of interest to investigate whether this result also applies to condensate film flow down a vertical plate. Therefore, in this report the linear stability theory will be used to study the stability characteristics of condensate films. In the formulation of the problem, infinitesimal disturbances will be considered as amplified or damped in time. The wave number will be taken to be real and the frequency will be taken to be complex. The existence of a critical Reynolds number will be established. A condensate film is stable, for all Reynolds numbers small er than the critical Reynolds number. It will be shown that this critical Reynolds number is so small that in all practical condensation problems the film can be assumed to be unstable.

FORMULATION OF THE PROBLEM

The present study relates to laminar film condensation on a cooled, isothermal, vertical plate. The physical situation and some nomenclature are shown in Fig. 1. The plate is suspended in a large volume of a pure vapor which for

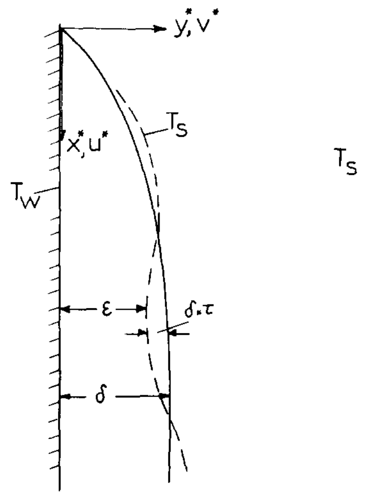

FIG. 1. Schematic of condensation problem.

simplicity will later on be assumed to be saturated. As shown in [3, 4], for undisturbed flow a similarity transformation of the equations expressing conservation of mass, momentum and energy leads to the following ordinary differential equations:

Momentum:

$$f''' + 3ff'' - 2f'^2 + 1 = 0 \tag{1}$$

Energy:

$$\Omega'' + 3Prf\Omega' = 0. \tag{2}$$

In equations (1) and (2) f and Ω are functions of η alone and given by

$$\psi = 4\nu c_L (x^*)^{\frac{3}{4}} f(\eta); \qquad \Omega(\eta) = \frac{T - T_s}{T_w - T_s}$$

with

$$\eta = \frac{c_L y^*}{(x^*)^{\frac{1}{4}}}; \qquad c_L = \left[\frac{g(\rho - \rho_g)}{4\nu^2 \rho}\right]^{\frac{1}{4}}.$$

Assuming a negligibly small shear force acting on the condensate at the interface between the liquid and vapor, the boundary conditions to equations (1) and (2) are, at the wall:

$$f(0) = f'(0) = 0; \qquad \Omega(0) = 1 \tag{3}$$

at the liquid–vapor interface:

$$f''(\eta_\delta) = 0; \qquad \Omega(\eta_\delta) = 0;$$

$$-3\frac{f(\eta_\delta)}{\Omega'(\eta_\delta)} = \frac{1}{Pr}\frac{c_p \Delta T}{h_{fg}}.$$

For mathematical convenience in the further development, the following similarity transformation is defined:

$$y = \frac{c_L}{\eta_\delta}\frac{y^*}{(x^*)^{\frac{1}{4}}} = \frac{y^*}{\delta}. \tag{4}$$

By this definition $y = 0$ at the wall and $y = 1$ at the liquid–vapor interface. Then a dimensionless stream function F is introduced

$$\psi = 4\nu c_L (\eta_\delta f'(\eta_\delta))(x^*)^{\frac{3}{4}} F(y) \tag{5}$$

where $F(y)$ is a function of y alone and η_δ and $f(\eta)$ satisfy the differential equations (1) and (2). With this, momentum and energy equations become

$$F''' + \eta_\delta^2 f'(\eta_\delta)[3FF'' - 2(F')^2] + \frac{\eta_\delta^2}{f'(\eta_\delta)} = 0 \tag{6}$$

and

$$\theta'' + 3\eta_\delta^2 f'(\eta_\delta) Pr F\theta' = 0 \tag{7}$$

where $\theta(y) = (T - T_s)/(T_w - T_s)$ is a function of y alone. The boundary conditions are, at the wall:

$$F(0) = F'(0) = 0; \qquad \theta(0) = 1 \tag{8}$$

at the liquid–vapor interface:

$$F'(1) = 1; \qquad \theta(1) = 0. \tag{9}$$

The advantage of this transformation is that

$$F' = \frac{u^*}{u_0} = \bar{u} \tag{10}$$

is equal to zero at the wall and equal to one at the liquid–vapor interface. Therefore

$$\bar{u}(0) = 0 \qquad \text{and} \qquad \bar{u}(1) = 1 \tag{11}$$

where u_0, the velocity at the surface, is obtained from the solution of equation (1),

$$u_0 = 4\nu\, c_L^2 f'(\eta_\delta)(x^*)^{\frac{1}{2}}.$$

The function $\bar{u}$ will be used as base flow in the stability analysis.

A further inspection of equation (6) reveals that for small values of $\eta_\delta^2 f'(\eta_\delta)$ and for $\eta_\delta^2/f'(\eta_\delta) = 2$ the classical Nusselt solution is a valid approximation. The approximation can be regarded as a sufficiently accurate representation of the undisturbed condensate film flow for a broad range of condensation problems.

The physical question now asked is the following. Would a disturbance of frequency f_w superimposed on the undisturbed (base) flow be amplified, damped, or remain neutral with respect to time? Can conditions be found under which disturbance of arbitrary frequency are damped, that is, can a condensate film be stable at all?

To answer this question a disturbance of the Tollmien–Schlichting type is considered with a complex celerity $c = c_r + ic_i$, and the conditions are determined under which the disturbance is amplified ($c_i > 0$), damped ($c_i < 0$) or remains unchanged ($c_i = 0$; neutral). According to the linear stability theory, the instantaneous velocity components, temperature and pressure can be expressed in terms of base flow and disturbance quantities.

$$\begin{aligned} u &= \bar{u}(y) + \hat{u}(x, y, t) \\ v &= \bar{v}(y) + \hat{v}(x, y, t) \\ p &= \bar{p}(y) + \hat{p}(x, y, t) \\ \theta &= \bar{\theta}(y) + \hat{\theta}(x, y, t). \end{aligned} \tag{12}$$

All quantities in equations (12) are dimensionless as indicated in the nomenclature. As one usually does in stability studies, $\bar{v}$ is taken to be zero and x-derivatives of $\bar{u}$ and $\bar{\theta}$ are neglected. This approximation is, in particular, valid when the base flow can be closely predicted by the Nusselt theory. In the following development the variation of the fluid properties will be neglected. Hence, the Reynolds number Re and the Péclét number Pe have to be evaluated at a reasonable reference state, for instance, at $T = T_w + \frac{1}{3}(T_s - T_w)$ as indicated in [6].

Next, the disturbance is expressed by defining disturbance stream function and temperature as follows:

$$\hat{\psi}(x, y, t) = \phi(y)\, e^{i\alpha(x-ct)} \tag{13}$$

and

$$\hat{\theta}(x, y, t) = S(y)\, e^{i\alpha(x-ct)} \tag{14}$$

with the understanding that the real part of the solution represents the physical quantity as shown in [7]. The disturbance velocity components in terms of the stream function (13) are

$$\hat{u} = \frac{\partial \hat{\psi}}{\partial y} = \phi'(y)\, e^{i\alpha(x-ct)} \tag{15}$$

and

$$\hat{v} = -\frac{\partial \hat{\psi}}{\partial x} = -\, i\alpha\phi(y)\, e^{i\alpha(x-ct)}. \tag{16}$$

Substituting equations (13)–(16) into the conservation equations, the following differential equations are obtained:

$$\phi'''' - 2\alpha^2\phi'' + \alpha^4\phi = i\alpha Re \times [(\bar{u} - c)(\phi'' - \alpha^2\phi) - \bar{u}''\phi] \tag{17}$$

and

$$S'' - \alpha^2 S = i\alpha Pe[(\bar{u} - c)S - \phi\bar{\theta}']. \tag{18}$$

In order to complete the formulation of the problem, it is necessary to provide the appropriate boundary conditions.

At the wall, perturbations of velocity components and temperature are equal to zero. Therefore:

$$\phi = 0 \tag{19}$$

$$y = 0 \quad \phi' = 0 \tag{20}$$

$$S = 0. \tag{21}$$

At the film surface, the boundary conditions can be obtained from the equations for the kinematic surface condition, the vanishing of the shear stress, and the continuity of normal stress as shown, for example, in [5]. An additional boundary condition can be specified by noting that the film surface is at saturation temperature T_s.

The kinematic surface condition is

$$v(1 + \tau) = \frac{\partial \tau}{\partial t} + u(1 + \tau)\frac{\partial \tau}{\partial x}.$$

Expressing the displacement τ by

$$\tau = d\, e^{i\alpha(x-ct)}$$

d being the amplitude, a straightforward calculation leads to

$$\phi(1) = (c - 1)d \tag{22}$$

where d can be taken equal to one, which can easily be shown. At the free surface the shear stress is vanishing. Hence it is

$$\frac{\partial(\bar{u} + \hat{u})}{\partial y} + \frac{\partial \hat{v}}{\partial x} = 0 \qquad \text{at} \qquad y = 1 + \tau$$

which in terms of the disturbance amplitude may be written as

$$\phi''(1) + \left(\alpha^2 + \frac{\bar{u}''(1)}{c - 1}\right)\phi(1) = 0. \tag{23}$$

The continuity in the normal stress component at the liquid–vapor interface yields:

$$-\left(\frac{\partial p}{\partial x}\right) - \frac{2}{Re}\left(\frac{\partial^2 u}{\partial x^2}\right) = \frac{\sigma}{\rho}\frac{1}{u_0^2\delta}\frac{\partial^3 \tau}{\partial x^3} + \frac{1}{2}\frac{\rho_g}{\rho}\frac{\partial}{\partial x}\left(\frac{v_g^*}{u_0}\right)^2$$

at $y = 1 + \tau$. Ignoring terms of smaller order, the following relationship between the disturbance characteristics is obtained

$$\phi'''(1) - [i\alpha Re(1-c) + 3\alpha^2]\,\phi'(1) - \frac{\sigma}{\rho u_0^2 \delta} Re\, i\alpha^3 \frac{\phi(1)}{c-1} = -\frac{1}{2} Re \frac{\rho_g}{\rho} \frac{\partial}{\partial x}\left(\frac{v_g^*}{u_0}\right)^2 e^{-i\alpha(x-ct)}. \quad (24)$$

The term

$$\frac{1}{2} Re \frac{\rho_g}{\rho} \frac{\partial}{\partial x}\left(\frac{v_g^*}{u_0}\right)^2$$

can be evaluated by noting that the vapor velocity v_g^* and the heat flux at the condensate surface are related by

$$\rho_g v_g^* h_{fg} = -k\left(\frac{\partial T}{\partial y^*}\right); \quad \text{at} \quad y^* = \delta(1+\tau).$$

Introducing the dimensionless group

$$Nd = \left(\frac{1}{Pr}\frac{c_p \Delta T}{h_{fg}}\right)^2 \left(\frac{\rho}{\rho_g}\right)$$

one obtains

$$\frac{1}{2} Re \frac{\rho_g}{\rho} \frac{\partial}{\partial x}\left(\frac{v_g^*}{u_0}\right)^2 = i\alpha \frac{Nd}{Re} \bar{\theta}'(1) \left[S'(1) + \bar{\theta}''(1)\frac{\phi(1)}{c-1}\right] e^{i\alpha(x-ct)}.$$

Hence equation (24) may be written as:

$$\phi'''(1) - \alpha[(3\alpha - iRe(c-1)]\,\phi'(1) - \frac{i\alpha^3}{c-1} N_c N_\xi Re^{-\frac{1}{3}} \phi(1) + i\alpha \frac{Nd}{Re} \bar{\theta}'(1)\left[S'(1) + \bar{\theta}''(1)\frac{\phi(1)}{c-1}\right] = 0 \quad (25)$$

where

$$N_\xi = \left(\frac{\sigma}{\rho}\right) \nu^{-\frac{4}{3}} \left(\frac{g(\rho - \rho_g)}{2\rho}\right)^{-\frac{1}{3}}$$

and

$$N_c = \left(\frac{\eta_\delta^2}{2f'(\eta_\delta)}\right)^{\frac{1}{3}}$$

and therefore

$$\frac{\sigma}{\rho u_0^2 \delta} = N_\xi N_c Re^{-\frac{1}{3}}.$$

The remaining condition, that the temperature at the condensate surface is the saturation temperature can be expressed by

$$\theta(1+\tau) = 0 = \theta(1) + \left(\frac{\partial \theta}{\partial y}\right)_1 \tau.$$

In terms of disturbance parameters this equations reads

$$S(1) + \frac{\bar{\theta}'(1)}{c-1}\phi(1) = 0. \quad (26)$$

The equations (17) and (18) with the boundary conditions (19)–(23), (25) and (26), constitute an eigenvalue problem leading to functions of the form $c = c(Re; \alpha)$, and can be solved with help of a variety of computer-aided methods. Since the objective of this study is to find out whether there exist conditions under which a laminar, vertical condensate film is stable, a computer solution can be circumvented.

SOLUTIONS AND RESULTS

As stated before, the classical Nusselt solution is a good approximation for the description of laminar gravity induced, undisturbed film condensation. For example, for condensing steam at 1 atm and $\eta = 0{\cdot}2$ one finds $\eta_\delta^2 f'(\eta_\delta) = 0{\cdot}7997 \times 10^{-3}$ and $\eta_\delta^2/f'(\eta_\delta) = 2$. Therefore, the Nusselt model is taken to be appropriate for the determination of base flow and base temperature. Then from equation (6) and (7) it follows:

$$\bar{u} = 2y - y^2$$
$$\bar{\theta} = 1 - y \quad (27)$$
$$N_c = 1.$$

For very small values of α the solutions of equations (17) and (18) can be expanded in terms of

$$\phi = \phi_0 + \alpha\phi_1 + \alpha^2\phi_2 + \ldots$$
$$S = S_0 + \alpha S_1 + \alpha^2 S_2 + \ldots \quad (28)$$
$$c = c_0 + \alpha c_1 + \alpha^2 c_2 + \ldots$$

Substituting equations (28) into equations (17) and (18), one finds along with the appropriate boundary conditions for the zeroth order solution

$$\phi_0 = y^2; \qquad c_0 = 2; \qquad S_0 = y. \tag{29}$$

With this and the boundary conditions of the first order equations, the following solutions for ϕ_1, c_1 and S_1 can be obtained:

$$\phi_1 = 4i\,Re\left[\frac{y^5}{120} - \frac{y^4}{24} + \frac{y^3}{24Re}\left(\frac{Nd}{Re}\right) + \frac{y^2}{6} - \frac{y^2}{8Re}\left(\frac{Nd}{Re}\right)\right] \tag{30}$$

$$c_1 = i\left[\frac{8}{15}Re - \frac{1}{3}\frac{Nd}{Re}\right] \tag{31}$$

and

$$S_1 = i\,Pe\left(-\frac{y^5}{20} + \frac{y^4}{4} - \frac{y^3}{3} + \frac{2y}{15}\right). \tag{32}$$

For the purpose of this study only the celerity c is of interest.

$$c = 2 + i\alpha\left[\frac{8}{15}Re - \frac{1}{3}\frac{Nd}{Re}\right]. \tag{33}$$

For a disturbance to be damped, the imaginary part of c must be negative. Therefore, it follows from equation (33) for every value of $\alpha > 0$:

$$\frac{8}{15}Re - \frac{1}{3}\frac{Nd}{Re} < 0$$

hence

$$Re < \left(\tfrac{5}{8}Nd\right)^{\frac{1}{2}} = Re_{cr}. \tag{34}$$

Thus, it has been established that for a vertical, laminar condensate film a critical Reynolds number Re_{cr} exists, above which some disturbances will be amplified. The value of this critical Reynolds number is a function of thermodynamic properties of liquid and vapor as well as the temperature drop across the condensate film.

It is of interest to solve equation (24) for the distance $x = x_{cr}$ up to which a laminar condensate film can be considered to be stable.

$$Re = \frac{u_0\delta}{\nu} = 2\left(\frac{g}{4\nu^2}\right)^{\frac{1}{4}}\left(\frac{1}{Pr}\frac{c_p\Delta T}{h_{fg}}\right)^{\frac{3}{4}} x^{\frac{3}{4}} = \frac{5}{8}\frac{\rho}{\rho_g}\left(\frac{1}{Pr}\frac{c_p\Delta T}{h_{fg}}\right).$$

From this it follows that

$$x_{cr} = \left[\left(\frac{5}{16}\frac{\rho}{\rho_g}\nu\right)^2 \frac{1}{g}\frac{1}{Pr}\frac{c_p\Delta T}{h_{fg}}\right]^{\frac{4}{3}}. \tag{35}$$

An inspection of equation (35) reveals that for all practical situations the distance from the leading edge to $x = x_{cr}$ is negligibly small. For instance, for saturated steam at atmospheric pressure, condensing at a vertical wall this distance is about $1{\cdot}7 \times 10^{-4}$ m for $\Delta T = T_s - T_w = 2$°C and about 5×10^{-4} m for a temperature drop of $\Delta T = 50$°C. Consequently one has to assume that in every practical condensation process waves may be present because some disturbance will be amplified.

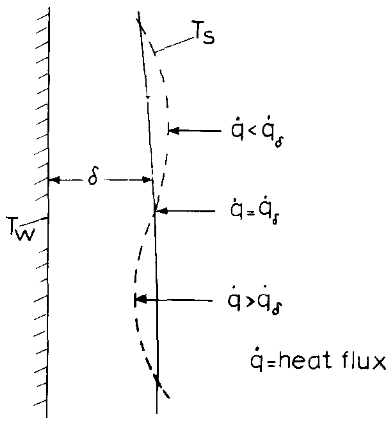

FIG. 2. Condensation at constant ΔT.

Although the critical Reynolds number Re_{cr} is of no practical value, it indicates a stabilizing effect of the condensation mass transfer on the film flow. The result $Re_{cr} > 0$ has been found assuming constant temperatures at the wall and the liquid–vapor interface. At a constant temperature drop across the condensate film the local transfer rates and therefore the local mass-transfer rates are higher for negative values of τ than for positive values, as indicated in Fig. 2. Therefore the condensation rate is so distributed along x that the wavy film surface is smoothed out.

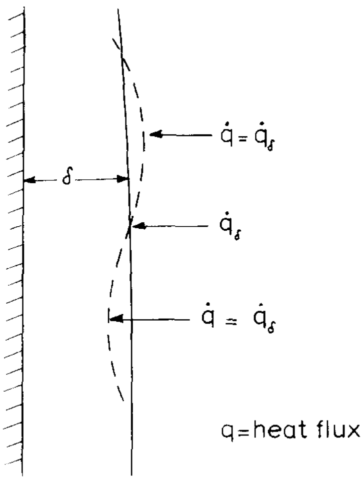

FIG. 3. Condensation at locally constant heat flux.

If a constant local heat flux across the film is assumed, which is tantamount to assuming zero heat flux disturbance at the wall, then equation (21) must be replaced by

$$S'(0) = 0.$$

The celerity c for this case becomes

$$c = 2 + i\alpha\tfrac{8}{15}Re \qquad (36)$$

and the critical Reynolds number for every positive α is equal to zero. There is apparently no stabilizing effect of the condensation mass transfer on the film flow. The reason for this result is that for a constant local heat flux the local condensation rate is constant and does not depend on the value of τ as shown in Fig. 3. Therefore, at the troughs as much vapor condenses as at the crest which does not alter the wavy film surface. For this case, the condensate film behaves like a falling film with constant mass flow rate.

Since (for physical reasons) a constant temperature drop across the film is more likely than a locally constant condensation rate, there will be a stabilizing effect of the mass transfer on the condensate film. The intensive study of this effect will be the subject of future research.

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STABILITE DE L'ECOULEMENT D'UN CONDENSAT DESCENDANT LE LONG D'UNE PAROI VERTICALE

Résumé— On utilise une théorie de la stabilité linéaire afin d'étudier les caractéristiques de stabilité de l'écoulement en film d'un condensat le long d'une paroi verticale. Il existe un nombre critique de Reynolds au-dessus duquel les perturbations sont amplifiées. La grandeur de ce nombre critique de Reynolds est si petite que dans toutes les situations techniques, un mouvement laminaire par gravité étant induit, le film vertical condensé est instable. Le transfert massique par condensation a une effet stabilisateur si l'abaissement de température au travers du film est constant. Pour un flux thermique local constant au travers du film condensé on ne peut trouver aucun effet stabilisateur du transfert massique par condensation.

DIE STABILITÄT EINER KONDENSATSTRÖMUNG AN EINER VERTIKALEN WAND

Zusammenfassung—Die lineare Stabilitätstheorie wird für die Untersuchung des Stabilitätsverhaltens eines Kondensatfilms herangezogen, der an einer senkrechten Wand herabströmt. Es existiert eine kritische Reynolds-Zahl, jenseits der die Störungen verstärkt werden.

Diese Kritische Reynolds-Zahl ist so klein, dass in allen technischen Fällen der laminare, durch die Schwerkraft bedingte, vertikale Kondensatfilm instabil ist. Der Stofftransport durch Kondensation hat stabilisiderende Wirkung, wenn der Temperaturabfall im Film konstant ist. Bei örtlich konstanter Wärmestromdichte durch den Kondensatfilm konnte keine stabilisierende Wirkung des Stofftransportes gefunden werden.

УСТОЙЧИВОСТЬ ПОТОКА КОНДЕНСАТА НЕ ВЕРТИКАЛЬНОЙ СТЕНКЕ

Аннотация—В статье исследуются характеристики потока пленки конденсата на вертикальной стенке на основе линейной теории устойчивости. Поскольку величина критического числа Рейнольдса мала, то практически во всех технических ситуациях ламинарная вертикальная пленка конденсата, образующаяся под действием силы тяжести, является нестабильной. Показывается, что конденсационный массообмен оказывает стабилизирующее влияние в случае постоянного перепада температур по ширине пленки. Для постоянного локального теплового потока по ширине пленки не обнаружено стабилизирующего влияния конденсационного массообмена.