ANALYSIS OF LAMINAR FILM CONDENSATION FROM A MOVING VAPOR

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Correction functions are derived which permit extension of the results of the theory based on an asymptotic friction law for uniform suction of a boundary layer to low-intensity film condensation from a moving vapor.

Starting with the classical paper by Nusselt [1], the problem of film condensation from a moving vapor under strictly separate motion of the phases has been the subject of analysis in a whole series of studies [2-14]. The Nusselt paper, reflecting the level of development in hydrodynamics in his time, was based on an evaluation of interphase dynamic interactions by means of empirical relations characterizing the friction between the gas flow and a dry impermeable wall. The properties of interphase interactions in actual condensation processes, which depend on transverse mass flow through the frictional surface, have, on the other hand, determined the basic direction of subsequent development of the Nusselt theory. An important contribution to that direction was the paper of Chernyi [5] in which the concept of a two-phase boundary layer was first formulated for mass flow through a density discontinuity surface. A solution was obtained in the same paper for the problem of condensation from flow on an isothermal plate under weightless conditions. Unfortunately, the work of Chernyi escaped the attention of investigators in the field of condensation for a long time. It is only in this way that one can explain the fact that the concept of a two-phase boundary layer received recognition only at the beginning of the 1960's after foreign investigators [9, 10] once again proposed the concept and applied it to solve the very same problem of condensation under weightless conditions. It must also be regretted that the work [5] has not been reflected thus far in our own monographs and scientific manuscripts on heat transfer.

Another approach to the solution of the problem of condensation from a moving vapor was proposed in [11]; it was based on results from the hydrodynamics of sucked boundary layers which were well known as far back as the 1930's. Starting from the identity of condensation and suction, a frictional law typical of an asymptotic boundary layer with uniform suction [15] was taken in [11] as a basis for the analysis of condensation from a moving vapor. This approach, which is valid in the case of sufficiently intense condensation, is generally less rigorous than an analysis based on a two-phase boundary layer. On the other hand, the approach assumed made it possible to enlarge the group of analyzed problems considerably. In particular, a series of new solutions were obtained which were constructed for the first time with condensation of the existence of mass flow through the interphase surface (transverse flow over a cylinder under weightless conditions and in a gravitational field, a vertical plate, internal condensation problem under weightless conditions and in a gravitational field) [11, 16-18]. We have made an attempt to formulate the limits of applicability of the approach in [11] in terms of condensation parameters and to establish the form of the correction function permitting extension of the results of the analysis to the region of less intense condensation from a moving vapor.

The limits of applicability of this approach are determined by inequality (3) in [11]:

$$\frac{2C_Q}{C_f^*} \gg 1. \tag{1}$$

The upper limit of the coefficient C_f^* for the "dry" component of the total friction can be determined from the Blasius law for laminar flow over an impenetrable plate without suction:

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$$C_f^* = \frac{0.664}{\sqrt{\mathrm{Re}''}}. \tag{2}$$

The discharge coefficient for condensation from a moving vapor on an isothermal plate under weightless conditions is

$$C_Q = \frac{\alpha \Delta T}{r\rho'' U_\infty} = \frac{1}{2} N \sqrt{\frac{\mu'\rho'}{\rho''^2 x U_\infty}}. \tag{3}$$

The coefficient of heat transfer in the last relation was determined from the results of the analysis in [11] for nonmetallic fluids ($N \ll 1$).

After making the appropriate substitutions, the inequality (1) takes the following final form in terms of condensation parameters:

$$M = N\left[\frac{\rho'\mu'}{\rho''\mu''}\right]^{1/2} \gg 0.664. \tag{4}$$

As follows from the relation obtained, the limits of applicability of this approach are completely determined by the temperature head and the physical properties of the vapor and condensate. In addition, since the "dry" component of the friction in the presence of condensation is always less than according to the Blasius law, the conditions for the applicability of the approach in [11] must be somewhat less rigorous in the general case. It is possible to obtain more precise derivations on the basis of existing analytic results from investigations of the dynamic characteristics of sucked boundary layers.

A characteristic feature of condensation on an isothermal plate under weightless conditions is the change of the coefficient of heat transfer along the plate in inverse proportion to the square root of the distance from the leading edge. The corresponding problem of suction on a boundary layer ($C_Q \sim x^{-1/2}$) was studied by Schlichting and Bussman [15]. It was shown that this type of boundary layer is characterized by similar velocity profiles in contrast to the case of uniform suction. Detailed tables of the parameters for this type of flow were published somewhat later [19].

In general, the magnitude of the shear stress at the interphase surface during condensation on a plate from a vapor flow under weightless conditions can be determined from the expression

$$\tau = K j_x (U_\infty - U_s). \tag{5}$$

It is apparent that the coefficient K must satisfy the condition $K \geq 1$.

Similarity of velocity profiles in the vapor boundary layer for this case of an isothermal plate ensures the constancy of K along the plate.

When Eq. (5) is taken into consideration, it is easy to show that the solutions for local and average heat transfer on an isothermal plate (Eqs. (9) and (10) in [11]) will have the form

$$\alpha_x = \frac{1}{2}\sqrt{\frac{KN}{KN+1}\,\frac{r\rho' U_\infty \lambda}{\Delta T x}}, \tag{6}$$

$$\alpha = \sqrt{\frac{KN}{KN+1}\,\frac{r\rho' U_\infty \lambda}{\Delta T L}}. \tag{7}$$

Further, by determining K from the data of [20]† for the most varied possible hydrodynamic parameters of vapor flow, heat transfer can be calculated from Eqs. (6) and (7) for condensation of any intensity. The results of such calculations performed for a broad range of the parameter M for both local and average heat transfer are approximated with good accuracy by a relation of the following form:

$$\alpha = \alpha_j \left(1 + \frac{0.66}{M}\right)^{1/3}. \tag{8}$$

It should be noted that this solution for condensation of a laminar vapor flow on an isothermal plate under weightless conditions transforms in the limit both to the solution for intense processes [11] and to the solution corresponding to "dry" friction ($M \ll 1$) in accordance with Eq. (2).

†As in Russian original. There is no [20] given in Literature Cited — Publisher.

For condensation on an isothermal cylinder over which there is a nonseparating transverse flow of vapor under weightless conditions, the specific form of the analogous correction factor to the asymptotic solution of [11] (Eq. (20) in [11]) was obtained in [15]:

$$\alpha = \alpha_j \left(1 + \frac{1}{M}\right)^{1/3}. \tag{9}$$

Equations (8) and (9) make it possible to construct solutions which are valid for a broad range of the parameter M and for the occurrence of the processes discussed in a gravitational field (vertical plate and horizontal cylinder over which a descending vapor flows). It is most convenient to solve this problem by the representation of existing relations (Eqs. (19) and (20) of [16]; Eq. (22) in [11]) as a combination of two solutions of the same problem — separately under weightless conditions and separately in a gravitational field alone (according to Nusselt) — and through the introduction of solutions for weightless conditions in the form of Eqs. (8) and (9).

The relationship for the average coefficient of heat transfer during condensation of a descending vapor on a vertical plate under such a transformation takes the form

$$\alpha = \frac{\sqrt{2}}{3}\sqrt{\frac{\lambda^2\rho' U_\infty}{\mu' L}}\left(1 + \frac{0.66}{M}\right)^{1/3} \frac{2 + \sqrt{1 + \dfrac{16gL}{U_\infty^2 N\left(1 + \dfrac{0.66}{M}\right)^{4/3}}}}{\sqrt{1 + \sqrt{1 + \dfrac{16gL}{U_\infty^2 N\left(1 + \dfrac{0.66}{M}\right)^{1/3}}}}}. \tag{10}$$

For condensation during nonseparating flow of a descending vapor over a horizontal cylinder, the solution (22) of [11] for $N \ll 1$ transforms to

$$\bar{\alpha} = 0.64\sqrt{\frac{\lambda^2\rho' U_\infty}{\mu' D}}\left(1 + \frac{1}{M}\right)^{1/3} \sqrt{1 + \sqrt{1 + 1.69\,\frac{Dg}{U_\infty^2 N\left(1 + \dfrac{1}{M}\right)^{4/3}}}}. \tag{11}$$

On the whole, the results make it possible to expand the applicability of the theory of film condensation from a moving vapor, which is based on the classical results of hydrodynamics for sucked boundary layers, into the region of low-intensity condensation.

NOTATION

C_Q, discharge coefficient; C_f^*, coefficient of the "dry" component of total friction (not associated with interphase mass flow); U_s, U_∞, velocities at interphase surface and at a great distance from it; λ, thermal conductivity of condensate; r, latent heat of condensation; ρ', ρ'', densities of condensate and vapor; ν'', kinematic viscosity of vapor; μ', μ'', dynamic viscosities of condensate and vapor; α, coefficient of heat transfer; α_j, coefficient of heat transfer according to theory in [11]; ΔT, difference between temperatures of saturated vapor and condensation surface; j, mass flow through interphase surface; τ, interphase shear stress; g, acceleration of gravity; x, L, distance from leading edge and plate length; D, cylinder diameter;

$$\mathrm{Re}'' = \frac{U_\infty x}{\nu''};\quad N = \frac{\lambda\Delta T}{r\mu''};\quad M = N\left[\frac{\rho'\mu'}{\rho''\mu''}\right]^{1/2}.$$

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FLOW OF TWO-PHASE MIXTURES IN A ROTARY MIXER

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On the basis of a hydrodynamic model of a multivelocity continuum, the flow of miscible materials over the working surface of a multistage centrifugal (rotary) mixer is investigated, and the optimal dimensions of the working sections required to obtain a high-quality mixture are determined.

In the operation of a rotary mixer, a liquid and a highly disperse solid are supplied to the center of the rotating section of the first stage of the rotor, and layers of the liquid, the forming mixture, and the solid component flow over the surface of a conical channel. Under the action of centrifugal forces, the solid material tends to settle out into the liquid, and then at the edge of the section all this material is dispersed (Fig. 1). The two-phase medium flows on through successive stages of the rotor, which are similar in construction, where the final redistribution of the components occurs.

The motion of each layer of material over the surface of the spinning rotor is described by the equations of fluid mechanics; each layer has its corresponding rheological equation of state. The flow of pure liquid is described by the differential equations

$$\rho_1^0 \frac{d\mathbf{V}_0}{dt} = \rho_1^0 \mathbf{F}_0 + \operatorname{div} \mathbf{T}_0, \tag{1}$$

where ρ_1^0 and $\mathbf{V}_0$ are the density and velocity of the liquid; $\mathbf{T}_0$ is the stress tensor; and $\mathbf{F}_0$ is the mass force.

The mixture which forms constitutes a two-phase medium and can be described on the basis of the multivelocity Rakhmatulin model (if direct collisions and shear strains of the solid particles may be neglected in comparison with the carrier phase) by the equations [1, 2]

$$\frac{\partial \rho_1}{\partial t} + \nabla (\rho_1 \mathbf{V}_1) = 0, \tag{2}$$

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