MATHEMATICAL DESCRIPTION OF THE PROCESS OF FILM CONDENSATION OF VAPORS FROM STEAM-GAS MIXTURES

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ABSTRACT

This article presents an analysis of the mathematical description of the process of film condensation of vapors from vapor-gas mixtures. Taking into account the considerable variety of effects that occur during the flow of films in processes in which phase transformations occur, the complexity of the mathematical description of the flow of condensate films becomes obvious. This complexity of describing the process is aggravated by the combination of heat and mass transfer, non-isothermal, and changes in such properties as surface tension, viscosity, and density. To describe the flow rate and film thickness during film condensation, a fundamental system of equations is used, and the equations of dynamics and continuity in the long-wave approximation are also taken into account. The estimation of the propagation length of nonlinear waves in condensate films with varying flow rates showed that with an increase in the condensation intensity, the role of the proposed corrections increases, but within the limits of the validity of the thin-film approximation does not become decisive and significant. During the description of the process of film condensation of vapors from steam-gas mixtures, it was found that when the basic conditions are met, the influence of undulation manifests itself mainly through an increase in the heat exchange surface, and the contribution of surface forces to the intensification of the process, i.e., an increase in condensate consumption, is no more than 10-12%.

Keywords: Mathematical Description, Fundamental Equations, Film Condensation, Phase Transformations, Process, Steam-Gas Mixture, Heat Power Engineering.

INTRODUCTION

Steam condensation from steam-gas mixtures is widely used in various processes of the chemical industry, metallurgy, thermal power engineering, cement production, and other related fields.\textsuperscript{1-43}

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Condensation can be organized directly in the volume of the device, for example, on drops of sprayed liquid, or on cooled surfaces. The second method of conducting the process has advantages in terms of better controllability, as well as the possibility of reducing the amount of contaminated production waste since the steam-gas mixture entering the condensation system often contains dust, which is captured by the condensate and contributes to the formation of a difficult-to-separate sludge. This problem is typical for the production of phosphorus and sulfur, for electric-thermal and other heat and mass transfer processes, characterized by simultaneous condensation of vapors in the volume of the apparatus filled with a dusty vapor gas mixture and on cooled surfaces. However, there is still practically no description of the process of film flow over curved surfaces. When vapors from vapor-gas mixtures condense on the cooled surfaces, even a small addition of a non-condensable component in the gas phase creates an additional diffusion resistance near the surface of the condensate film, which increases the probability of condensation in the volume of the vapor-gas mixture on the surface of solid particles. In connection with the above, studies aimed at revealing the regularities of the process of film condensation from a mixture containing a finely dispersed solid phase and a large number of non-condensing gases are becoming particularly relevant.

**EXPERIMENTAL**

The fundamental system of equations for describing the flow rate and film thickness during film condensation, represented by the equations of dynamics and continuity in the long-wave approximation, is critically analyzed and generalized. The obtained equations are the main ones for calculating the flow rate and the thickness of the condensate film. They form a basic system for the film thickness and condensate flow rate for the development of the device and allow taking into account the development of wave disturbances of the condensate film profile. In this case, methods of the secular perturbation theory, taking into account the temperature dependence of viscosity and taking into account surface forces are used. Based on the basic principles of the mathematical description of the film condensation process and taking into account the significant variety of effects that occur during the expiration of films in processes in which phase transformations occur, the complexity of the mathematical description of the flow of condensate films becomes obvious, even taking into account the results of. The complexity of studying the process is compounded by the combination of heat and mass transfer, and non-isothermic, changes in such properties as surface tension, viscosity, density, and much more.

**RESULTS AND DISCUSSION**

The fundamental system of equations for describing the flow rate and film thickness during film condensation is given in. The equations of dynamics and continuity in the long-wave approximation are described in. The equation of the material balance of condensate:

\[ \frac{\partial h}{\partial t} + \frac{\partial}{\partial x} \left( \rho \frac{\partial U}{\partial y} \right) = I_m, \]  

(4)

Where is true for the mass source:

\[ I_{m, \text{con}} = \frac{\lambda}{r \rho} \frac{\partial T}{\partial y} \bigg|_{y=b}. \]  

(5)

The following equation is obtained for the condensate flow rate in.\[ \frac{\partial U}{\partial t} + \frac{\partial}{\partial x} \left( \rho U \right) = 0. \]  

(2)
The presented equations are the main ones for calculating the flow rate and the thickness of the condensate film. If the heat exchange surface is non-isothermal, then the dependences on the film thickness are used as a parameter, including it in the expression for the self-similar velocity profile. \( U = U_S f(\eta); \ \eta = \frac{y}{h}; \ f(1) = 1 \)

Based on the above equation (6), we can write this equation in the following form:

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} \left( \frac{f^2}{f_1^2} h \right) + \frac{h}{f_1} \left( f_3 v_w - I_m h \right) = g_{ef} h + \frac{\sigma h}{\rho} \frac{dK_S}{dx}.
\]

Where the following designations are accepted: \( \int_0^1 f d\eta = f_1; \ \int_0^1 f^2 d\eta = f_2; \ \int_\eta \left| \frac{\partial}{\partial \eta} \right|_{\eta=0} = f_3 \).

The resulting equations form a basic system for the film thickness and flow rate. If the temperature of the reference surface is not constant, then it is necessary to include in the expression for the self-similar velocity profile a dependence on the film thickness as a parameter, that is, \( U = U_S f(\eta, x, h) \).

Then we get a more general form of the evolutionary equation:\(^{62,63}\)

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} \left( \frac{f^2}{f_1^2} h \right) + \frac{h}{f_1^2} \left( f_3 v_w - I_m h \right) = g_{ef} h + \frac{\sigma h}{\rho} \frac{dK_S}{dx}.
\]

Usually, the intensity of the mass source at a certain distance from the starting point during film condensation is insignificant. This allows us to use a small parameter \( \varepsilon = \lambda \Delta T / r \rho \) \( j_0(\varepsilon = \lambda \Delta T / r \rho) \), where \( j_0 \) is the average condensate flow rate in an undisturbed film in the considered area. In favor of this argument, the essential value of the heat generation value during the phase transformation also plays a role. In this case, you can use the balance equation: \( \frac{\partial h}{\partial t} + \frac{\partial}{\partial x} = \varepsilon \frac{j_0}{h} \).

You can also enter stretched slow variables \( \tau = \alpha t \ \ \ z = \alpha x \) and a fast phase variable \( \eta = \theta(z, \tau) / \varepsilon \).\(^{64}\)

Then the system of basic equations takes the form:\(^{62}\)

\[
\varepsilon \frac{\partial^2}{\partial \tau^2} + \frac{\partial}{\partial \tau} \left( \frac{f^2}{f_1^2} h \right) + (B + \varepsilon B_1) \frac{j}{h^2} = g_{ef} h + \varepsilon^2 K_R h \frac{\partial^3}{\partial \tau^3} h.
\]

Where the following designations are accepted: \( A = \frac{f^2}{f_1^2} j_0; \ B = \frac{v_w f_3}{f_1} \)

The coefficients in the obtained equations are disclosed as follows:\(^{59}\)

\[
K_1 = \frac{\sigma}{\rho}
\]

As a result, a system of evolutionary equations is obtained.\(^{65}\) In the future, for the solution of this system, the recurrent relations are obtained by asymptotic expansions.\(^{64-67}\) Moreover, all systems with the exception of the first one obey a linear law with respect to the desired functions and they are uncoupled. A quasi-linear relationship has been established between the thicknesses and the flow rates for different orders of decomposition between the functions of fast and slow variables.\(^{67}\) Taking into account the surface pressure gradient formed due to the variable curvature of the film and which is responsible for the dispersion of waves, appears as a complex indicator only in the zero-order. The amplitudes of waves of higher orders increase but are not decisive.\(^{67-73}\) Methods for calculating the main parameters of a moving condensate film, taking into account additional restrictions on the coefficients of the main equations, are presented in.\(^{74}\) However, in real processes, taking into account such restrictions is not always mandatory and fulfilled. Therefore, to develop an apparatus that allows taking into account the development of wave
perturbations of the condensate film profile, we use the methods of the secular perturbation theory. The apparatus of this theory is used by researchers in the description of nonlinear waves and solutions. Moreover, the quasi-stationary process is in the immediate vicinity of the stability boundary of the stationary flow regime. In this case, taking into account the slowness of the function \( j_0 \) and \( h_0 \), used to describe stationary solutions, it can be assumed with a certain assumption that \( j_1 = L(h_1) \), where \( j_1 << j_0 \) and \( h_1 << h_0 \) are perturbations of the stationary solution of the film vapor condensation problem, \( L \) is a slow function. Using by analogy a system of equations describing the change in the thickness and flow rate of the film for a cylindrical surface, we can proceed to a system of equations for a flat wall.\(^{75,76}\) However, in this case, nonlinear terms appear in the equations caused by the addition of the mass and energy of the condensate flow in the film. The next source that feeds the system is the forces of gravity. The system obtained in this way can be uncoupled using the results of the analysis of the linearized problem in the range of an adequate description of the qualitative behavior of small perturbations of the stationary solution.\(^{77}\) The authors obtained an equation structurally characterizing the Korteweg-de Vries equation.\(^{78}\) It has slowly changing coefficients and a nonlinear perturbation of the right side. The presence of this perturbation contributes to the fact that the undamped wave solution exists only in the region of amplitude growth and only on the neutral line, and the dispersion relation of the last equation contains a zero imaginary part. The equation presented in has the form: \(^{79,80}\)

\[
\frac{\partial h_1}{\partial t} + R_1 h_1 \frac{\partial h_1}{\partial \xi} + R_2 (h_1^3 \frac{\partial h_1}{\partial \xi}^3) = R_3 h_1 + R_4 h_1^2 .
\]

In accordance with the recommendations proposed in solutions to this problem can be attributed to the category of dissipative instability.\(^{75-79}\) By transformation, it is possible to obtain an amplitude equation of the form Landau-Ginzburg.\(^{79-81}\)

\[
\frac{\partial^2 A}{\partial t^2} + i \gamma_1(k,v) \frac{\partial^2 A}{\partial \xi^2} = i \gamma_2(k,v) A^2 A' + \gamma_3(k,v) B A .
\]

In the presented equation, there is an additional nonlinearity, the appearance of which is associated with the presence of an average background flow. The presence of the flow is due to the additional condensate flow rate during the phase transformation. As a result, the obtained equations form a mathematical model that characterizes the mechanism of propagation of weakly nonlinear waves in a condensate film. Moreover, the nature of these equations does not depend on the type and type of boundary conditions. At the same time, through the coefficients of the derived equations, which are components of functions and depend on stationary solutions, the structure of the equations describing the change in perturbations is affected. The effect of the temperature dependence of the condensate viscosity on the wave propagation conditions is described in a similar way. So, an estimate of the propagation length of nonlinear waves in condensate films with a varying flow rate is given equations for calculating the measurement of wave characteristics are obtained, and the conditions for the propagation of single nonlinear waves in condensate films are clarified, the dependence of an insignificant mass source on the characteristics of nonlinear waves is determined.\(^{75-81}\) Of particular interest are the studies devoted to the simulation of condensation on surfaces of variable curvature. Profiled surfaces are widely used in heat and mass transfer devices to intensify the processes of heat and mass transfer in liquid films. Therefore, the issues of calculating and optimizing their form constantly attract the attention of researchers. Paper describes the flow of a thin film of a viscous liquid over a wavy surface, i.e. a wall of variable curvature, with sufficiently weak restrictions on the shape of the surface, but using the assumption of a constant flow rate and a constant surface velocity of the film.\(^{81}\) However, the assumption about the constancy of the surface velocity is artificial and can be approximately fulfilled only for a film of constant flow rate in flow sections of constant thickness. This is due to the fact that with a self-similar film profile, the ratio must be fulfilled \( \frac{j}{U_S h} = \text{const} \). At the same time, as follows from the equations for the film flow, with a variable curvature of the reference surface and, accordingly, the film surface, the film thickness cannot be constant. Since there are no estimates of the rate of change in the film thickness in it is difficult to judge the reliability of the conclusions obtained in this work.\(^{82}\) Moreover, the assumption of a constant surface

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velocity for films of variable flow, in particular, condensate films, is incorrect. In addition, even for a thin film, the difference between the curvature of the film surface and the curvature of the reference surface in some cases introduces disturbances in the flow pattern. These considerations encourage us to return to the analysis of the problem of the flow of a viscous film over a wavy surface. When talking about a thin film, it should be borne in mind that it implies a small thickness in comparison with the characteristic dimensions of inhomogeneities, as well as in comparison with the radius of curvature of the reference surface at any point.

Next, we will mainly follow the presentation of the problem in the work. A plane problem is considered and two coordinate systems are introduced: a reference system \((X,Z)\), in which an equation is given that determines the shape of the reference surface in the form of an unambiguous function, \(Z = Z(X)\) and the current coordinate system \((x,y)\), where the axis \(x\) at each point is directed tangentially to the reference surface, and the axis \(y\) is normal to it. In this case, \(y\) it is counted from the wall surface, and \(x\) - from the starting point, that is:

\[
x = \frac{\zeta}{\sqrt{1 + \left(\frac{dZ}{dX}\right)^2}} \frac{1 + \left(\frac{dZ}{dX}\right)^2}{dX}.
\] (14)

Let us further consider both the flow of a film with a constant flow rate and a condensate film.

1) Constant flow film.

From the equation of motion:

\[
f \frac{d^2U}{dx^2} = -g_s - \frac{\sigma}{\rho} \frac{dK_s}{dx} = -\frac{dP}{dx}.
\] (15)

And boundary conditions in the Nusselt approximation: \(U \big|_{y=0} = 0\) \(u = \frac{\partial U}{\partial y} \big|_{y=h} = \frac{\tau}{\mu}\) and we get an expression for the film consumption:

\[
j = \frac{dP}{dx} \frac{h^2}{3\nu} + \frac{\theta^2}{2\mu}.
\] (16)

The surface of an isothermal film is less strong than the assumption of a constant surface velocity. If the velocity of the gas washing the film is small, it is possible to accept the condition without significant errors at all \(\tau = 0\); at a sufficiently high gas velocity, it can be assumed that the value of the tangential stress \(\tau\) is determined by the velocity in the core of the gas flow.

With a constant flow rate, you can rewrite (16) as:

\[
\frac{\sigma}{\rho} \frac{dK_s}{dx} = \frac{3\nu j}{h^2} - \frac{3\tau}{2\rho h} - g_s.
\] (17)

If, in the first approximation, for a sufficiently thin film, we assume that the curvature of its surface differs slightly from the curvature of the reference surface, that is \(K_s = K_w\), and, thereby, we assume \(K_s\) independent of the thickness of the film, then when \(\tau > 0\) it is easy to get an inequality:

\[
\frac{dK_s}{dx} \geq -\frac{\rho}{\sigma} \left[ \frac{2\tau}{\rho} \frac{\sqrt{6\mu j}}{g_s} + \frac{\tau}{\rho} \right]
\] (18)

Moving on to the reference coordinate system, we get:

\[
\frac{dK_s}{dx} \geq -\frac{\rho}{\sigma} \left[ 1 + \left(\frac{dZ}{dX}\right)^2 \right]^{\frac{1}{2}} \left[ \frac{2\tau}{\rho} \left( \frac{\tau}{6\mu j} + g_s \right) \right]^\frac{1}{2} + g \cos \beta + \arctg \left( \frac{dZ}{dX} \right)
\] (19)

The fulfillment of conditions (18) and (19) is necessary for the correctness of the approximation of a thin film when it is possible to neglect the difference between the radii of curvature of the reference surface and the surface of the film. However, for a thin film, you can also get an adjustment for this difference by taking \(R_s \equiv R + h\) and the resulting relation:

\[
K_s \approx K_w + K_s^2 h.
\] (20)
Moreover, for the approximation to be fair $K_S \equiv K_w$ a strong inequality must be fulfilled $h \ll 1/K_w$. Thus, for the possibility of smooth flow of a thin film over a reference surface of variable curvature, both the condition (19) and the inequality limiting the rate of change in the curvature of the reference surface must be fulfilled, which is qualitatively consistent with the conclusions.\textsuperscript{82}

2) Condensate film. In this case, the system is added to the equation of motion:

\[
\frac{\rho^2 T}{\partial y^2} = 0, \quad (21)
\]

\[
\frac{dj}{dx} = \frac{l}{h} g_T, \quad (22)
\]

Where, \( I = \frac{\lambda \Delta T}{r \rho} \) - boundary conditions for the thermal problem: \( T|_{y=0} = T_w \) and \( T|_{y=h} = T_s \).

During the condensation of pure saturated steam, the surface temperature of the film is constant \( T_s = \) const and at a constant wall temperature, the equality is also valid: \( \Delta T = T_s - T_w = \) const taking this into account, we obtain the following system of equations for the condensate flow rate and the film thickness:

\[
j = \frac{dP}{dx} \frac{h^3}{3 \nu} + \frac{\mu h^2}{2 \mu}, \quad (23)
\]

\[
\frac{dj}{dx} = \frac{l}{h}. \quad (24)
\]

After a number of transformations, we get from here:

\[
\frac{d}{dx} \left[ \left( \frac{dP}{dx} \right)^{\frac{3}{2}} \right] + \frac{4 \tau}{3 \rho} \left( \frac{dP}{dx} \right)^{\frac{3}{2}} \frac{d}{dx} = 4 \eta \left( \frac{dP}{dx} \right)^{\frac{3}{2}}. \quad (25)
\]

Analyzing the obtained expressions, just as it was done for a constant flow film, but taking into account the change in flow rate and film thickness, we obtain a condition limiting the rate of change in the curvature of the wall in the case of film condensation:

\[
\frac{dK_S}{dx} \geq -\frac{\rho}{\sigma} \left[ \frac{1}{\rho} \left( \frac{r \tau^3}{6 \nu} \right)^{\frac{1}{2}} + g_s \right]. \quad (26)
\]

Taking into account the temperature dependence of the viscosity, instead of (26), we can obtain:

\[
j = \left[ \frac{\rho g_x}{\mu_w} + \frac{\sigma}{\mu_w} \frac{dK_S}{dx} \right] \frac{h^3}{\omega^3} \frac{\omega^2 + 2 \omega - 2 \exp(\omega) + 2}{\omega^2 + 2 \omega - 2 \exp(\omega) + 2} + \frac{\mu h^2}{\omega^3 \mu_w} (\exp(\omega) - \omega - 1). \quad (27)
\]

Hence it follows:

\[
\frac{\sigma}{\mu_w} \frac{dK_S}{dx} = \frac{j \omega^3}{h^3} \frac{\omega^2 + 2 \omega - 2 \exp(\omega) + 2}{\omega^2 + 2 \omega - 2 \exp(\omega) + 2} \frac{\tau (\exp(\omega) - \omega - 1) \omega}{\mu_w h (\omega^2 + 2 \omega - 2 \exp(\omega) + 2)} + \frac{\rho g_x}{\mu_w}. \quad (28)
\]

We introduce the following notation: \( m = \frac{\nu_w \omega^3}{\omega^2 + 2 \omega - 2 \exp(\omega) + 2} \); \( n = \frac{\omega (\exp(\omega) - \omega - 1)}{\rho (\omega^2 + 2 \omega - 2 \exp(\omega) + 2)} \).

Then we can write the following relation:

\[
\frac{\sigma}{\rho} \frac{dK_S}{dx} = \frac{jm}{h^3} \frac{m}{h} - g_s, \quad (29)
\]

From which the inequality follows:\textsuperscript{82}

\[
\frac{dK_S}{dx} \geq -\frac{\rho}{\sigma} \left[ \left( \frac{m^3}{jm} \right)^{\frac{1}{2}} \frac{2 \sqrt{3}}{9} + g_s \right]. \quad (30)
\]

At the same time \( \tau \leq 0 \) the situation looks much simpler:

\[
\frac{dK_S}{dx} \geq -\frac{\rho}{\sigma} g_s. \quad (31)
\]
This condition is the same for a condensate film and for a film with a constant flow rate, regardless of the temperature dependence of the viscosity. For the condensation of stationary steam, the neglect of tangential stresses at the liquid-vapor boundary is quite acceptable. In this case, we obtain a solution of the equation in the form similar to the Nusseltovian:

\[ h^4 = \frac{4\pi}{(dP/dx)^{1/3}} \int_0^\infty \left( \frac{dP}{dx} \right)^{1/3} dx. \]  

(32)

If we accept \( K_S = K_w \), then the expression (32) can be considered as a calculation formula. At the same time, the expression (32) remains valid even under the condition (20), but it turns out that it is no longer a calculation formula, but an integrodifferential equation that requires a solution. The surface was used as a reference for the numerical experiment: \( Z = A[1 + \sin(\frac{X}{L})] \), \( \beta = 0 \), where \( A \) и \( L \) - characteristic dimensions of undulation. The experimental results show that at a low condensation intensity, the role of correction \( K_S^2 h \) is small and its value increases with the increase in the characteristic size of the waviness, especially its amplitude. At very small characteristic sizes (\( A < 0.001; L \leq 0.005 \)), and also, when \( A \approx O(L) \) the calculation according to the described method becomes impossible, since both the condition of the smallness of the film thickness in comparison with the size of inhomogeneity the condition (20) are violated. With an increase in the condensation intensity, the role of the correction (20) increases, but it does not become decisive within the validity of the thin-film approximation. Note that when the above conditions are met, the influence of undulation is manifested mainly through an increase in the heat exchange surface, and the contribution of surface forces to the intensification of the process, i.e., an increase in condensate consumption, is no more than 10-12%. Therefore, in our opinion, the estimates (20) and (32) should be kept in mind in those cases, when designing and optimizing the heat exchange surface but also by using effects due to surface forces. Further studies showed the prospects of the obtained data.83-91

CONCLUSION

Based on the analysis of the mathematical description and transformations of the process of film condensation of vapors from vapor-gas mixtures, the following conclusions can be drawn:

- A fundamental system of equations is used to describe the flow rate and thickness of the film during film condensation, and the equations of dynamics and continuity in the long-wave approximation are also taken into account.
- An estimate of the propagation length of nonlinear waves in condensate films with varying flow rate has been established, which showed that with an increase in the condensation intensity, the role of the proposed corrections increases, but does not become decisive within the validity of the thin-film approximation.
- When the above conditions are met, the effect of undulation is manifested mainly through an increase in the heat exchange surface, and the increase in condensate consumption is in the comparable range from 10 to 12%.

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