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THEORETICAL STUDIES OF THE HEAT TRANSFER PROCESS AND THE HYDRODYNAMICS OF A CONDENSATE FILM BY NUMERICAL EXPERIMENT

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ABSTRACT

The paper presents an analysis of the mathematical description of the process of film condensation of vapors from steam-gas mixtures, taking into account the dependence of the processes of heat transfer and the hydrodynamics of the condensate film. It is established that the presence of an insignificant fraction of non-condensing gases sharply reduces the surface temperature of the condensate film. The numerical experiment has confirmed that the loss of stability of the film and its deceleration are associated with the temperature gradient on its surface. It is established that the influence of non-isothermicity on the characteristics of transfer processes can significantly change their flow mode even with small fluctuations in functional parameters. The influence of temperature on the condensate density leads to a certain increase in the average and local Nusselt numbers. As a result of the conducted studies, it was found that the dependence of the condensate density on temperature contributes to an increase in the average and local Nusselt number. This is confirmed by its fundamentally small effect on heat exchange under condensation conditions for liquids in the following range $\gamma \sim 10^{-4} - 10^{-2}$.

Keywords: Diffusion Flow, Condensate, Temperature Gradient, Interphase Thermal Resistance, Heat Transfer and Hydrodynamics, Numerical Experiment.

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INTRODUCTION

The use of the vapor condensation process has become widespread in many industrial sectors, which include heat and power engineering, metallurgy, chemistry, construction, medicine, and several other industries.[1-10] The process of vapor condensation from dusty steam-gas mixtures has become even more widespread. It is the relevance of these processes that force scientists and production workers to study them. However, conducting these studies is associated with great complexity, both theoretical and implementation in industrial conditions. This can include the simultaneous flow of heat and mass transfer processes that affect the formation of a film flow or homogeneous (heterogeneous) condensation, the presence of heterogeneous particles in the volume of the apparatus, the amount of non-condensing gas, and much more inherent in similar environments and conditions of these processes.[5,10-20] These nuances have a very significant impact on both the process itself and the quality of the products obtained. This problem is typical for heat-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.[1,2,7] However, it is the characteristics of the film flow that determine the intensity of the heat and mass transfer processes during condensation. Taking into account the influence of non-condensable components of the vapor-gas mixture and its dustiness is necessary when calculating and designing vapor condensation systems in the processes of gas purification and production of many valuable products in the chemical and metallurgical industries. Despite the mentioned aspects of the problem, there is still practically no description of the influence of the main indicators, as well as viscosity and surface tension on temperature and other parameters, the influence of non-isothermicity on the characteristics of transfer processes can significantly change their flow mode even with small fluctuations in functional parameters. In connection with the above, studies aimed at revealing the regularities of the condensation process from a three-phase mixture containing a finely dispersed solid phase and a large number of non-condensing gases are becoming particularly relevant.

EXPERIMENTAL

The essence of the method was to evaluate the influence of the main factors on the intensity of the film process. For this purpose, the information on the study of the dependence of the heat transfer processes and the hydrodynamics of the condensate film was critically analyzed and summarized. The role of the Stephan flow, non isothermicity, Prandtl, and Marangoni numbers are noted, and the dependence of the condensate film thickness on the longitudinal coordinate obtained numerically is analyzed, and it is established that the loss of stability of the film and its deceleration are associated with the temperature gradient on its surface. The effects caused by the dependence of viscosity on temperature are analyzed, and the appearance of thermocapillary stresses affecting the decrease in the film thickness in the upper part of the cylinder is noted.

RESULTS AND DISCUSSION

In order to study the dependence of heat transfer processes and the hydrodynamics of a condensate film, several authors use the following model.[21,22]

Stefan's formula describes the process of diffusion of the condensed component from the center of the mixture to the heat exchange surface:[21]

$$\frac{\rho_l}{M_n}\frac{dj}{dx} = \beta\frac{P_0}{R_g T_0}\ln\left(\frac{P_0 - P_S}{P_0 - P_n}\right), \tag{1}$$

Where: β- the mass transfer coefficient, R_g- the universal gas constant, and the other designations are clear.

The equilibrium pressure (P_S), to the surface temperature (T_S), is determined from the Claiperon-Clausius ratio:

$$P_S = P_W \exp\left(\frac{rM_n}{R_g}\left(\frac{1}{T_S} - \frac{1}{T_W}\right)\right). \tag{2}$$

For the dimensionalization on the scale of length *l,* which is characteristic, and also using the dimensionless condensate flow rate $\bar{j} = \frac{j\rho}{\mu}$, we come to a system of equations:

$$\bar{j} = \frac{H^3}{\mathrm{F}r} + \frac{\mathrm{Ma}}{2\,\mathrm{Pr}}H^2\frac{d\theta_S}{dX}\ ; \tag{3}$$

$$\frac{d\bar{j}}{dX} = const_1 \mathrm{St} \ln\left[\frac{1-\frac{P_C}{P_0}\exp\left[const_2 \mathrm{Sf}\left(\frac{1}{\theta_S-\theta_C}-\frac{1}{\theta_C}\right)\right]}{1-\frac{P_C}{P_0}}\right]; \quad (4)$$

$$\theta_S = H\left[\mathrm{Sf}\,\mathrm{Pr}\frac{d\bar{j}}{dX}+\mathrm{Bi}(1-\theta_S)\right]. \quad (5)$$

In the resulting system: $H=\frac{h}{l}$- the dimensionless thickness of the condensate film; $\theta=\frac{T-T_W}{T_0-T_W}$- dimensionless temperature; $\mathrm{Pr}=\frac{\nu}{a}$; $\mathrm{Ma}=\frac{d\sigma/dt(T_0-T_W)l}{\mu a}$; $\mathrm{Fr}=\frac{\nu^2}{gl^3}$; $\mathrm{St}=\frac{\beta l}{\nu}$; $\mathrm{Sf}=\frac{r}{C_P(T_0-T_W)}$; $\mathrm{Bi}=\frac{\alpha l}{\lambda}$; α - heat transfer coefficient in the gas phase; $a=\frac{\lambda}{C_P\rho}$.

It should be noted that in this case, the influence of the main indicators, as well as viscosity and surface tension on temperature and other parameters cannot be taken into account with the help of additions in the solution that do not take into account such dependencies. However, it is precisely the non-isothermicity that can significantly affect the characteristics of the transfer processes even with small changes in the decisive factors.[22] Under normal conditions, in films with a surface of zero curvature, the presence of additional tangential stresses at the interface is associated with the appearance of a surface tension gradient. In addition, when condensation occurs on a cylindrical surface under the influence of the same factor, a surface pressure gradient occurs. The listed additional voltages have approximately the same value. In order to determine them, the Prandtl and Marangoni numbers are used. Taking into account the influence of the thermal resistance of the interfacial surface in their mathematical model, the authors of the work performed numerical experiments.[22] The result of the experiments was to obtain the characteristic dependences of the dimensionless thickness of the film H on the dimensionless longitudinal coordinate X (Fig.-1).

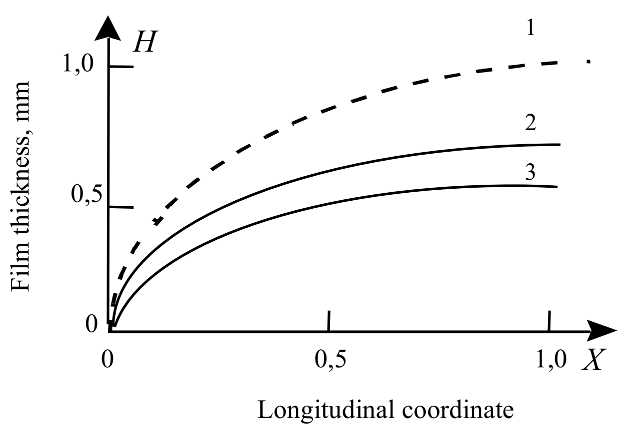


Fig.-1: Dependence of the Condensate Film Thickness on the Longitudinal Coordinate

Attention is drawn to the dependence in Fig.-1, constructed without the influence of thermocapillary stresses caused by interphase thermal resistance and surface tension. The dependence 2 of this figure is constructed taking into account the influence of only the thermal resistance at the phase interface. Dependence 3 is constructed taking into account the influence of interphase thermal resistance and surface tension. As a result of the conducted numerical experiments, results were obtained that characterize the effects caused by the dependence of viscosity on temperature, as insignificant. At the same time, the presence of an insignificant fraction of non-condensing gases sharply reduces the surface temperatures of the condensate film. Similar results were obtained by the authors of the work.[23] However, with an increase in the thickness of the condensate film, the temperature of its surface increases. This leads to the appearance of thermo capillary stresses that affect the reduction of the film thickness in the upper part of the cylinder. But this part of the cylinder is most influential when taking into account the heat exchange during the condensation of vapors from steam-gas mixtures. Note that the influence of the shape and curvature of the condensation surface has usually been studied in relation to a specific heat exchanger. Depending on the change in the curvature of the condensate film for small cylinder diameters $R \leq$ 0,5 cm, the influence of the surface pressure gradient on both the heat transfer coefficients and its thickness becomes significant. The mutual effect of these effects is expressed in the presence of a zone with negative values, a dimensionless condensate flow below the coordinate of the point *X*=0, 35. Thus, the numerical experiment confirmed that the loss of stability of the film and its deceleration are associated with the temperature gradient on its surface. A more detailed analysis of stability confirms this in the following works.[24-28] Consequently, a change in the flow regime of the condensate film occurs only at certain critical values of the Marangoni number. In this mode, wave structures of the type of nonlinear individual waves are observed. In cases when the vapor content in the vapor-gas mixture is 0.4 -0.6 of the volume, then the Stefan flow, which has a stabilizing effect, most effectively affects the driving force of the process. In this mode, no transient action is observed, that is, the gradient of the condensate flow $\frac{d\bar{j}}{dX}$ it does not change and is stable. Thus, the following correlation is possible between the film thickness and the dimensionless surface temperature:

$$H = \theta_H \Big/ \left[\mathrm{Sf\ Pr} \frac{dQ}{dX}\bigg|_0 + \mathrm{Bi}\left(1 - \theta_{\mathrm{H}}\right) \right], \tag{6}$$

Here T_S - the surface temperature of the film; T_W - the wall temperature; T_0 - the temperature in the core of the vapor-gas mixture; r - the heat of condensation; C_p - the specific heat capacity of the condensate; λ and χ - respectively, the coefficients of thermal conductivity and thermal conductivity of the condensate; ν - kinematic viscosity; q - specific heat flux. In the well-known work, the vapor density is introduced in the core of the gas flow ρ_0^n and on the surface of the film ρ_h^n. Therefore, it is necessary to add the diffusion equation of the condensed component to the equations of motion.[29]

$$m' = -k\left(\rho_0^n - \rho_h^n\right), \tag{7}$$

and the equation relating the surface temperature of the film $T_h = T_H(x)$ to the density ρ_h using the Clapeyron - Clausius equation and the equation of state of ideal gases:

$$\rho_h^n = C_1 \frac{\exp\left(-\frac{C}{T_H}\right)}{T_H}, \tag{8}$$

Where $C = \frac{\mu\lambda}{R_g}$, $C_1 = \frac{C}{\lambda} P_0 \exp\left(\frac{C}{T_0}\right)$.

Hence follows a system of ordinary differential equations with respect to T_h and h:

$$T_H - T_1 = \frac{r}{\lambda}\rho h \frac{d}{dx}\left(\frac{g_{eff} h^2}{3\nu} + \frac{\sigma_t h}{2\mu}\frac{dT_H}{dx}\right) + \frac{qh}{\lambda}\left(T_0 - T_H\right), \tag{9}$$

$$\rho\frac{d}{dx}\left(\frac{g_{eff}h^2}{3\nu}+\frac{\sigma_t h}{2\mu}\frac{dT_H}{dx}\right)=k\frac{C_1}{T_H}\exp\left(-\frac{C}{T_H}\right)-k\rho_0^n. \quad (10)$$

As observed in the literature.[29]

$$h=\frac{\lambda(T_H-T_1)}{rk\left(\frac{C_1}{T_H}\exp\left(-\frac{C}{T_H}\right)-\rho_0^n\right)-q(T_H-T_0)}. \quad (11)$$

If we determine the thermal Nusselt number at each point $\mathrm{Nu}_L=Q/Q_\lambda$, where Q -s the total heat flow taking into account the heat of condensation, Q_λ - is the heat flow due only to heat transfer, we get: [29]

$$\mathrm{Nu}_L=\frac{1+B}{H^{-1}+B}\left[\frac{T_H-T_1}{T_0-T_1}+\frac{T_0-T_H}{H(T_0-T_1)}\right]. \quad (12)$$

To overheat the film surface $\Delta_h=\frac{T_h-T_H}{T_H-T_1}$ we have:[29]

$$\Delta_h=\frac{1+B}{H^{-1}+B}-1. \quad (13)$$

For the condensation plane of length L, then we can write:

$$\mathrm{Nu}=\frac{1}{L}\int_0^L \mathrm{Nu}_L dX. \quad (14)$$

The effect of increasing surface activity on the decrease in the thickness of the condensate film is reflected.[30] In this case, a zone with negative data of a dimensionless hydrodynamic flow $V<0$ is observed on the functional dependence of the flow on the longitudinal coordinate. The above is commented as follows: the flow of the condensate film in the opposite direction with respect to the effective gravitational acceleration occurs under the influence of the thermocapillary effect and the temperature gradient on the surface of the film. When studying the change in the condensate density from the temperature during film condensation, the authors of established a non-parabolic velocity distribution in the condensate film.[22, 28] For this case, an equation for calculating the film thickness is proposed:

$$\delta\frac{\partial}{\partial\varphi}\left(\delta^3\sin\varphi\right)=\frac{3\lambda\nu R}{\rho_S g q}\Delta T f(\gamma), \quad (15)$$

Where $f(\gamma)=\frac{1}{1+0{,}75\gamma+0{,}15\gamma^2}$.

The solution of (1.15) is the following expression:

$$\delta=\frac{1}{\sin^{1/3}\varphi}\left[\frac{4}{3}\alpha'\int_0^\varphi \sin^{1/3}\varphi d\varphi\right]^{1/4}, \quad (16)$$

где $\alpha'=\frac{3\lambda\nu R}{\rho_S g q}\Delta T f(\gamma)$.

The dependence of the condensate film thickness on the angle, taking into account the dependence of the condensate density on the temperature, differs by a multiplier $[f(\gamma)]^{1/4}$ from the Nusselt dependence. In this case, the relative deviation of the local Nusselt number as a function of the dependence of the condensate density on temperature is determined by the expression:

$$\frac{\mathrm{Nu}-\mathrm{Nu}_0}{\mathrm{Nu}_0}=\frac{1-f^{\frac{1}{4}}(\gamma)}{f^{\frac{1}{4}}(\gamma)}\approx 0{,}1875\gamma \cdot \qquad (17)$$

An expression for the relative deviation of the average Nusselt number over the cylinder surface is also obtained: [29]

$$\frac{\overline{\mathrm{Nu}}-\overline{\mathrm{Nu}_0}}{\overline{\mathrm{Nu}_0}}=f^{-\frac{1}{4}}(\gamma)\approx 0{,}1875\gamma \cdot \qquad (18)$$

Therefore, based on the analysis of expressions (16) and (18), it can be concluded that the influence of temperature on the condensate density leads to a certain increase in the average and local Nusselt numbers. Nevertheless, this conclusion confirms that in these cases there is a slight influence on the heat exchange during condensation for liquids with a range of $\gamma \sim 10^{-4}-10^{-2}$. Evaluating the Marangoni effect on the film condensation process, it was shown that the local Nusselt number increases in the upper part of the cylinder, and it decreases at the diametrically opposite point.[14-20] The explanation of this fact is due to the fact that when $\varphi = \pi/2$ the pressure is minimal, it means that the interfacial tension of the film is maximum. Thus, a decrease in the film flow velocity and an increase in its thickness in the lower part of the cylinder, a decrease in the thickness, and an increase in the local Nusselt number in the upper part are due to the presence of additional tangential stresses due to the Marangoni effect. The effect of the effect increases with a decrease in the radius of the cylinder, an increase in the Reynold number, and the rate of change of the surface tension. Moreover, it is most noticeable in liquids with a high boiling point, low specific heat of evaporation, and low molecular weight. The main role in the heat exchange process is played by the upper part of the cylinder, on which the value of the local Nusselt number is very significant. At the same time, its increase on the lower part of the cylinder does not dramatically affect the change in the average Nusselt number over the entire surface. The Marangoni effect increases the average Nusselt number as a whole, and it increases with increasing speed of the incoming flow. In cases where the viscosity of the condensate film has an instantaneous dependence on temperature, with significant temperature changes, significant changes in the processes of heat and mass transfer and hydrodynamic regimes are also possible.[21] This is explained by the fact that a significant deviation from the parabolic profile of the longitudinal component of the film velocity is possible. In this case, it will be incorrect to mention the average wall temperature when taking it into account in the mathematical model of the process. But the main parameter is $\omega = \beta_1 \Delta T$, where β_1- is the coefficient of the steepness of the viscogram.[22-26] In a particular case, for example, for a liquid such as glycerin $\Delta T = 20^{\circ}\mathrm{C}$ the longitudinal velocity profile deviates from the parabola by 16%, as much $\Delta T = 60^{\circ}\mathrm{C}$ and at this deviation already reaches 56%.[23] In addition, the values of the surface velocity of the condensate film, determined by the dependence of viscosity on temperature on the basis of the parabolic law, differ significantly.[31] The main equations describing the thermal conductivity, the equations of motion, continuity, and the thermal balance condition taking into account the Nusselt theory, taking into account the boundary conditions for pure steam: $u|_{y=0}=0$, $\left.\frac{\partial u}{\partial y}\right|_{y=\delta}=0$, $T|_{y=0}=T_w=\mathrm{var}$, $T|_{y=\delta}=T_S=\mathrm{const}$ allow you to get the expression:

$$u=C\left[1-\exp(ay)\right]+\frac{b}{a}y\exp(ay) \cdot \qquad (19)$$

$a=\beta\frac{(T_S-T_w)}{\delta}$, $b=-\frac{\rho g}{\mu_S}$, $C=\frac{b(a\delta+1)}{a^2}$.

The paper estimates the contribution of heat released during supercooling of a glycerol condensate film, in which the viscosity significantly depends on the temperature within a wide range of changes in the latter.[22] So, for example, when $(T_S-T_w)=80-200°\,C$ rating received: $[C_p(T_S-T_w)F_2]/(rF_1)=0{,}065-0{,}077$, that is, on average, about 0,074.[22] Thus, the temperature variability of the outer surface of the heat exchange pipe depends on the change in the thickness of the condensate film. Hence, dependency accounting $T_w=T_w(\varphi)$ when calculating the heat transfer coefficient during condensation, it is necessary for the case of a significant dependence of viscosity on temperature.[22-25] Comparing the known methods and the Labuntsov method, it should be noted that in the latter, the known average temperature of the condensation surface is used as the base.[22,25] A similar remark applies to the work.[32] In the same cases, when there are significant temperature differences corresponding to a large value of the parameter ω_0, the results differ significantly if the temperature of the refrigerant or the average temperature of the cooling pipe wall is used as the determining one. However, there are no specific tips in these calculations on how to calculate the average temperature of the cooling wall. The advantages and advantages of this technique, which does not have these disadvantages, are given in the works.[23,30-33] In order to intensify the processes of heat and mass transfer in the appropriate equipment, developed surfaces of various profiles are used to break liquid films. At the same time, there are still questions of optimizing their form and calculation. In particular, in the well-known work, when describing the flow of a viscous liquid in the form of a thin film over a profiled surface, it is assumed as an assumption that the surface velocity and flow rate are constant.[8] But such a proposal for films with variable condensate flow is not real. The authors conducted a study of the effect of the thermocapillary effect on the condensation process on surfaces of various geometric profiles.[25] It was found that with an increase in the number of Marangoni, i.e., surface forces, the stability of the system increases.[25-33] This can be described in a linear approximation as the stabilization of small perturbations with an insignificant wavelength. The growth of the wave amplitude contributes to the stabilization and occurrence of stationary surface waves. This effect is explained by an increase in the amplitude of perturbations and the Marangoni number. Similarly, there is a decrease in the phase velocities of surface waves with an increase in the number of Marangoni. These results were obtained using the compatibility equation, and they were identified with the effect of insoluble surfactants on the stability of the flowing film.[34] Thus, long stable waves can be formed with an increase in the surface tension gradient, and the influence of the thermocapillary effect in the processes of vapor condensation from vapor-gas mixtures affects the characteristics of surface waves. At the final stage of the conducted numerical studies, characteristic graphs of the dependence of the maximum size of dust particles entrained by the Stefan flow on the partial vapor pressure of a condensing substance in a vapor-gas mixture are presented.[35-40] It is obvious that for larger dust particles, the main role in the process of their drift to the surface of the film will be played by the lateral force.[41-47] Indeed, the greatest gradient of the gas velocity is observed in the immediate vicinity of the interface between the liquid film and the vapor-gas phase. For the time of migration of the particle to the surface of the film, we can approximately assume S equal to the thickness of the boundary layer δ .[40-52] Then we get the following estimate:

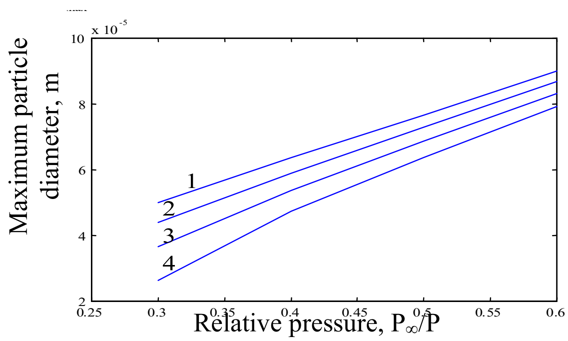
$$\tau \sim \mathrm{Re}_{rel}^{3/8}/d^{1/2} \tag{20}$$

Figure-2 shows some results of a numerical experiment carried out to determine the maximum size of dust particles entrained by a Stefan flow.

Fig.-3 shows some results of a numerical experiment carried out to determine the relative migration time of dust particles in a vapor-gas mixture. It should be noted that particles with a diameter of 1 to 2 microns require more time for migration than larger particles. This conclusion is quite natural and fits into the physics of the process.

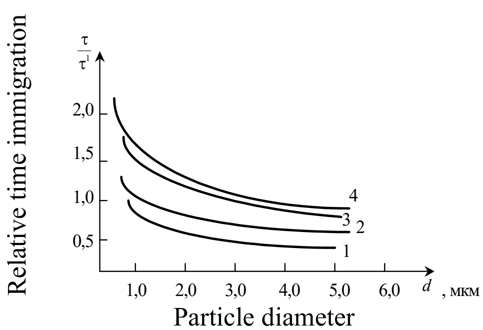
τ^1 - The migration time of a particle with a diameter of 1 microns at the relative Reynolds number of the gas in the boundary layer Re_{rel}=5.

In the works further studies of the heat and mass transfer of dispersed media formed during complex transformations were continued.[1,2,4,7,46-58] The obtained theoretical results satisfactorily coincide with the theoretical and experimental data of other authors.[59-62]



1- P_S/P=0,1; 2- P_S/P=0,15; 3- P_S/P=0,2; 4- P_S/P=0,25

Fig.-2: The Maximum Size of Dust Particles Entrained by the Stefan Flow



1- Re_{rel}=5; 2- Re_{rel}= 10; 3- Re_{rel}= 20; 4- Re_{rel}= 40

Fig.-3: Relative Migration Time of Dust Particles

CONCLUSION

Thus, in the course of theoretical studies of the heat transfer process and the hydrodynamics of a condensate film, it was established by numerical experiment that:

- The presence of an insignificant fraction of non-condensing gases sharply reduces the surface temperature of the condensate film.
- The loss of stability of the film and its braking are associated with the temperature gradient on its surface. A change in the flow regime of the condensate film occurs only at certain critical values of the Marangoni number. In this mode, wave structures of the type of nonlinear individual waves are observed.
- The influence of non-isothermicity on the characteristics of transfer processes can significantly change their flow mode even with small fluctuations in functional parameters. The presence of additional tangential stresses at the phase interface is expressed in the influence of the surface tension gradient only for films with a surface of zero curvature.
- The influence of temperature on the condensate density leads to a certain increase in the average and local Nusselt number, which is confirmed by its insignificant effect on heat exchange during condensation for liquids with a range of $\gamma \sim 10^{-4} - 10^{-2}$.
- The film thickness and the dimensionless surface temperature are correlated in the form of the expression-

$$H = \theta_H \Big/ \left[\mathrm{Sf}\,\mathrm{Pr} \frac{dQ}{dX}\bigg|_0 + \mathrm{Bi}(1-\theta_H) \right].$$

- The parabolic profile of the longitudinal component of the film velocity depends on the steepness of the viscogram for viscous liquids.
- Long stable waves can be formed with an increase in the surface tension gradient, and the influence of the thermocapillary effect in the processes of vapor condensation from vapor-gas mixtures affects the characteristics of surface waves.
- Particles with a diameter of 1 to 2 microns require more time for migration than larger particles.

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[RJC-6741/2021]