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Numerical modeling of absorption process on a liquid film at nonuniform heat flux on the wall

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Abstract. Conjugated heat and mass transfer during nonisothermal absorption on a liquid film, flowing over nonuniformly cooled wall under the action of gas flow, is numerically investigated in this paper. The intensity of the tangential stress and that of the wall cooling were varied. The absorption efficiency was determined by the conjugation of two factors: the intensity of heat removal and the action of shear stress.

1. Introduction

The absorption process takes place in various energy devices [1]. The application of thin liquid falling films is widespread in absorption systems. The first theoretical description of combined heat and mass transfer processes at vapor absorption in a laminar falling liquid film was made in [2-4]. The overview of works on film flows with absorption is presented in [5]. The heat and mass transfer in the processes of absorption, desorption, evaporation and condensation in the initial part of semi-infinite axisymmetric film falling under the pressure is studied in [6]. The absorption and desorption processes under the conditions, corresponding to the operating modes of thermal transformers are described in [7]. The analytical solution to the problem of conjugate heat and mass transfer in a laminar falling liquid film with a linear velocity profile is presented in [8]. Data of numerical simulation of absorption are compared with experimental data in [9]. In [10] it is suggested that droplet size reduction and solution sub-cooling can improve the absorption rate, and an analytical tool to study the vapor absorption for a forming droplet is described. In [11] a model for solving simultaneous heat, mass and momentum transfer in a laminar falling film is introduced taking in account longitudinal and transversal velocities. Both, the influence of mass transfer on hydrodynamics and the inverse effect have been investigated. Moreover, such effects as sub-cooling at the inlet and high viscosity of the absorbing fluid have been discussed. The wavy films are known to have advantages over the laminar films. However, the purpose of this paper is to understand some characteristics of the laminar liquid film under the conjugated heat and mass transfer. This paper focuses on the dependence of absorption intensity on the conjugation of two factors: the intensity of heat removal and the action of shear stress.

2. Problem statement

Let us consider the two-dimensional stationary flow of a laminar liquid film (water solution of lithium bromide with constant thickness h) over a plate, inclined at an angle α to the horizon. The liquid surface contacts the stationary steam. Absorption is considered in the framework of conventional assumptions [1]. The vapor phase is single-component, and vapor pressure does not change during absorption. Thermophysical properties of solution are considered constant. The absorption heat is supposed to release at the interface and to be spent only on solution heating. For small ranges of concentrations and temperatures, according to [1], the dependence of absorbed substance concentration on temperature is approximated by the linear function $C_i = k_1 - k_2 T_i$, where coefficients

k_1 and k_2 are determined by the pressure. The values of $C_i(x), T_i(x)$ are interrelated, unknown and should be determined.

Let us introduce the Cartesian coordinate system with axis *Ox* along the flow and axis *Oy* normal to the plate. The velocity profile in the film takes the form:

$$u = 3\bar{u}\left(2y/h - y^2/h^2\right)/2 + \tau y/\mu,$$

where $\bar{u} = g\sin\alpha h^2/(3\nu)$ is the average velocity of liquid motion in the film. The process of heat and mass transfer at film absorption is described by the equation of heat conductivity and diffusion:

$$u\,\partial T/\partial x = a\,\partial^2 T/\partial y^2\,, \tag{1}$$

$$u\,\partial C/\partial x = D\,\partial^2 C/\partial y^2\,, \tag{2}$$

with the following boundary conditions. At the inlet:

$$x = 0 \quad T = T_0,\ \ C = C_0\,.$$

Here $C_e = k_1 - k_2 T_0$ is the equilibrium concentration, corresponding to initial temperature of the solution T_0, T_e is the equilibrium temperature, corresponding to initial concentration C_0 ($C_0 = k_1 - k_2 T_e$), similar to [1]. At the interface for $y = h$, similar to [1,4] there is the equilibrium "solution-vapor" system:

$$C_i = k_1 - k_2 T_i\,,\ -\lambda\,\partial T/\partial y = -r_a(\rho D/(1-C_0))\,\partial C/\partial y\,.$$

This equilibrium condition relates the equilibrium temperature to concentration. On the wall at $y = 0$, we set:

$$\lambda\,\partial T/\partial y\big|_{y=0} = q_w(x),\quad \partial C/\partial y\big|_{y=0} = 0\,,$$

where $q_w(x)$ is the nonuniform heat flux on the wall, characterizing the wall cooling. The integral characteristic of the process is the bulk temperature of liquid film $T_{av}(x) = \int_0^h u(x)T(x)dy \Big/ \int_0^h u(x)dy$.

Let us use dimensionless variables $\xi = x/(Peh)$, $\eta = y/h$, $v = u/\bar{u} = 3\left((2+r)\eta - \eta^2\right)/2$, $r = 2\tau/(\rho g h \sin\alpha)$, $\theta = (T - T_0)/(T_e - T_0)$, and $\gamma = (C - C_0)/(C_e - C_0)$. $\mathrm{Pe} = \bar{u}h/a$ is the Peclet number. The system of equations (1) – (2), reduced to the dimensionless form, is written as:

$$v\,\partial\theta/\partial\xi = \partial^2\theta/\partial\eta^2\,, \tag{3}$$

$$v\,\partial\gamma/\partial\xi = \mathrm{Le}\,\partial^2\gamma/\partial\eta^2\,, \tag{4}$$

here $\mathrm{Le} = D/a$ is the Lewis number. The boundary conditions at the inlet for $\xi = 0$:

$$\theta = 0\,,\ \gamma = 0\,.$$

At the interface for $\eta = 1$, similar to [1]:

$$\theta = \theta_i, \gamma = \gamma_i\,,$$

$$\theta_i + \gamma_i = 1,\ \mathrm{KaLe}\,\partial\gamma/\partial\eta = \partial\theta/\partial\eta\,. \tag{5}$$

Here, Ka = $r_a(C_e - C_0)/\left(C_P(T_e - T_0)(1 - C_0)\right)$ is the modified Kutateladze number. On the wall at $\eta = 0$, we obtain:

$$\partial\theta/\partial\eta\Big|_{\eta=0} = \varphi(\xi), \partial\gamma/\partial\eta\Big|_{\eta=0} = 0, \tag{6}$$

where $\varphi(\xi) = q_W h/(\lambda\Delta T)$ is the nonuniform dimensionless heat flux, $\Delta T = T_e - T_0$. In our numerical calculations we consider the regime of cooling when $\varphi(\xi)$ decreases downstream linearly from initial value φ_0 to zero.

3. Numerical calculations

The numerical calculations were performed by the finite-difference method. The relationship of temperature and concentration along the interface was calculated by conjugating the modified coefficients, taking into account the conditions at the interface. Equations (3) and (4) will take the difference form with approximation of the order of $O\left(\Delta\xi, \Delta\eta^2\right)$:

$$v_{i,j}\frac{\theta_{i,j} - \theta_{i-1,j}}{\Delta\xi} = \frac{\theta_{i,j+1} - 2\theta_{i,j} + \theta_{i,j-1}}{\Delta\eta^2}, \tag{7}$$

$$v_{i,j}\frac{\gamma_{i,j} - \gamma_{i-1,j}}{\Delta\xi} = Le\frac{\gamma_{i,j+1} - 2\gamma_{i,j} + \gamma_{i,j-1}}{\Delta\eta^2}. \tag{8}$$

Here, $\theta_{i,j}$ and $\gamma_{i,j}$ are the temperature and concentration values in the node (ξ_i, η_j). The values of the grid step $\Delta\xi = 1.\cdot 10^{-3}$ and $\Delta\eta = 2.\cdot 10^{-3}$ are rather small, so the results of calculations practically do not change with further decrease in the grid step. For every ξ_i Eq. (7) – (8) are solved by a sweep method on coordinate η_j using boundary conditions (5) – (6). The interfacial values of the temperature and concentration are found from the conjugated calculations of the sweep coefficients.

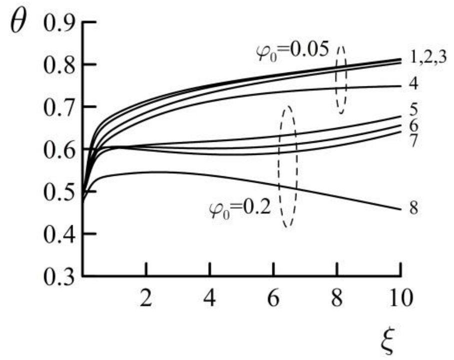

Figure 1. Dimensionless temperature on the film surface. 1-4 –initial heat flux φ_0 = 0.05 ; 5-8 – initial heat flux φ_0 = 0.2; 4,8 – corresponding to uniform cooling downstream ; **1** – r = -0.2 ; **2** – r =0.0 ; **3** – r = 0.5 ; **4** – r = 0.5 ; **5** – r = 0.5 ; **6** – r = 0.0 ; **7** – r = -0.2 ; **8** – r = 0.5

The calculations were carried out at Ka = 10, Le = 0.01. The calculated distributions of dimensionless temperature and concentration along the film surface are shown in Fig. 1 and Fig.2 for different initial heat fluxes on the wall φ_0. The dimensionless bulk temperature of the solution is shown in Fig.3. The calculations were carried out for different values of the tangential stress on the surface of the film, including negative values. Moreover, the values of heat flux on the wall were regarded constant (φ_0 = 0.05, φ_0 = 0.2) or decreasing (from φ_0 to 0). The absorption was determined by the conjugation of these two mechanisms.

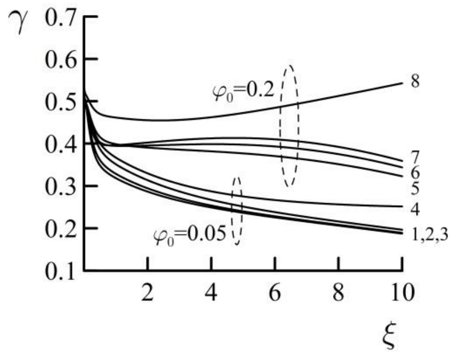

Figure 2. Dimensionless concentration on the film surface. 1-4 –initial heat flux $\varphi_0 = 0.05$; 5-8 – initial heat flux φ_0 = 0.2; 4,8 – corresponding to uniform cooling downstream ; **1** – r =-0.2 ; **2** – r =0.0 ; **3** – r = 0.5 ; **4** – r = 0.5 ; **5** – r = 0.5 ; **6** – r = 0.0 ; **7** – r = -0.2 ; **8** – r = 0.5

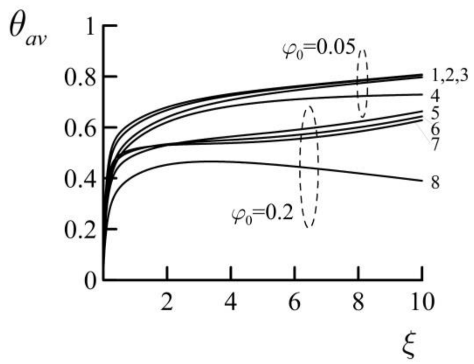

Figure 3. Dimensionless bulk temperature of liquid film. 1-4 –initial heat flux $\varphi_0 = 0.05$; 5-8 – initial heat flux φ_0 = 0.2; 4,8 – corresponding to uniform cooling downstream ; **1** – r =-0.2 ; **2** – r =0.0 ; **3** – r = 0.5 ; **4** – r = 0.5 ; **5** – r = 0.5 ; **6** – r = 0.0 ; **7** – r = -0.2 ; **8** – r = 0.5

4. Conclusions

The problem of conjugated heat and mass transfer at absorption on the film on a cooled wall with the given nonuniform heat flux has been studied numerically. The numerical calculations were carried out by the finite-difference method. The intensity of absorption was determined by combining two factors: the intensity of heat removal and the action of shear stress. The countercurrent shear stress and the absence of heat removal from the wall were found to contribute to the film heating due to heat released at absorption. While with a more intensive heat dissipation from the wall, the deceleration of the film, on the contrary, contributes to the overall cooling, and the acceleration of the film results in heating along the flow. In general, it may be concluded that the lesser intensity of cooling along the flow suppresses the absorption process, while the uniform cooling intensifies absorption.

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