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# CONJUGATE HEAT EXCHANGE OF COOLED POLYMER FILMS IN JET PRESSING OF THEM AGAINST A DRUM

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*Conditions of heat exchange on the surface of a polymer film cooled on a drum in jet pressing of the film against the drum surface have been studied. The integral methods of thermal calculation of boundary layers have been employed and the contact thermal resistance between the film and the drum has been taken into account in developing a mathematical model. The local thermal characteristics of the films have been obtained. The influence of different parameters on heat-exchange conditions has been investigated. Comparison of experimental and calculated data has shown their good agreement.*

Drum cooling of a polymer film is one of the well-known and efficient methods which has found a wide application in designing devices for production of polymer films. The basic principle of cooling of such devices is the intense removal of heat from a polymer film which is pulled from an extruder due to the contact with a drum having a low surface temperature. In the initial region of contact of the polymer film with the drum surface, to press the film against the surface one uses either a pressure roll or an air jet flowing out of the slot channel. In what follows, we will consider the latter scheme of cooling.

In thermal calculation of polymer films, one usually applies engineering procedures which are based on the assumption of ideal thermal contact between the polymer film and the drum and uses criterial dependences for the averaged coefficients of heat transfer on the portions of convective heat exchange of the polymer film [1]. However, such rough assumptions in the calculations can lead to considerable errors in determining the temperature regimes of a polymer film, which makes it impossible to design cooling systems and to determine means of intensifying heat exchange with a sufficient degree of accuracy [2].

We have analyzed thermophysical processes occurring on different portions of the film surface and developed a mathematical model of heat transfer in a polymer film with allowance for the contact thermal resistance between the film and the drum. We have calculated numerically heat transfer in polymer films and obtained recommendations on intensification of the processes of heat exchange for the devices in question.

Let us analyze the conditions of transfer of heat in the case of drum cooling of a polymer film in jet pressing of the film against the drum surface. A diagram of the cooling device is presented in Fig. 1. The polymer melt is fed to a metal drum from a spinneret. On the initial portion of contact of the film with the drum, a plane air jet arriving from a slot hole flows onto the film surface. It is assumed that the direction of the jet is perpendicular to the flowing surface and coincides with the line of contact of the film and the drum. The jet flow is used for two purposes: 1) to create higher-than-average pressure in the region of flowing and decrease the contact thermal resistance between the drum and the film; 2) to cool the polymer film on the outside.

The spreading of the jet on the exterior surface of the film results in the formation of boundary layers. One layer is formed near the flowing point and grows as the spinneret is approached, while the other has the opposite direction. In Fig. 1, the indicated regions of heat transfer are denoted as *I* and *III* respectively. On the interior surface of the film, one can single out three portions of the film surface on which the mechanism of heat exchange has distinctions. In region *I*, the boundary layer is formed due to the motion of the polymer film; it has its beginning near the spinneret and terminates at the drum. In zone *II*, heat is drawn from the film in contact with the drum. On this portion, the contact thermal resistance between them is of importance. In region *III*, the boundary layer appears near the point of separation of the film from the drum and develops as the winding roll is approached.

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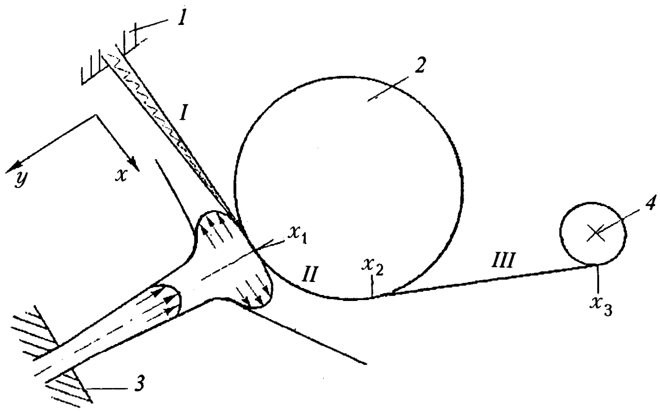



Fig. 1. Scheme of cooling of a polymer film: 1) spinneret; 2) drum; 3) slot hole; 4) winding roll.

In developing the mathematical model, we made the following assumptions: 1) the polymer film is considered as a thermally thin body; 2) the film curvature exerts no substantial influence on heat-exchange conditions; 3) the influence of the spinneret, the drum, and the winding roll on the conditions of formation of a boundary layer is insignificant. To determine heat exchange in the regions of formation of a boundary layer we used the integral method of calculation [3, 4]. According to such an approach, a general functional relationship between the density of the removed heat flux and the temperature head on the surface is established for an arbitrary nonisothermal surface; this relationship can be represented in both integral form and differential form. In the first case it has the form

$$q\,(x, T) = \alpha^*\,(x)\left[T\,(x = x_{\rm f}) - T_\infty + \int\limits_{x = x_{\rm f}}^{x} f\,(x, x')\,\frac{dT}{dx'}\,dx'\right], \tag{1}$$

and in the second case

$$q\,(x, T) = \alpha^*\,(x, T)\left[T\,(x) - T_\infty + \sum_{n=1}^{\infty} g_n x^n\,\frac{d^n T}{dx^n}\right], \tag{2}$$

where $f(x', x) = [1 - (x'/x)^{M_1}]^{-M_2}$ is the influence function of the unheated portion. The parameters $M_1$, $M_2$, and $g_n$ depend on the type of boundary layer, the regime of flow (laminar or turbulent), the change in the pressure gradient in the external flow, and other factors [3, 4].

In deriving the equation of transfer of heat in a polymer film, we proceed from the assumption that by virtue of the low conductivity of the film material the conductive heat transfer in the longitudinal direction is substantially smaller than the component of the heat transfer due to the motion of the film. The equation of transfer of heat in the film has the form

$$c_p\,(T)\,\rho\,(T)\,U_{\rm s}\,(x)\,\frac{\partial T}{\partial x} = \frac{\partial}{\partial y}\left[\lambda\,(T)\,\frac{\partial T}{\partial y}\right]. \tag{3}$$

The condition of constancy of the polymer flow rate in any cross section is determined by the equation [1]

$$\rho\,(T)\,U_{\rm s}\,(x)\,\delta\,(x) = \text{const}\,. \tag{4}$$

From the initial prerequisites, since the Biot number is $\text{Bi} = \alpha\delta/\lambda << 1$ we consider the polymer film as a thermally thin body for which the temperature drop in the transverse direction in insignificant and with a small error we can use in the calculations the film temperature averaged over the cross section:

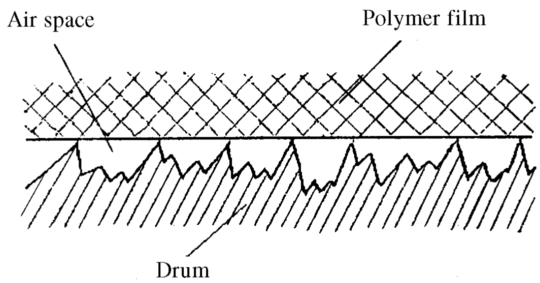



Fig. 2. Scheme of contact of the rough surface of the drum with the polymer film.

$$\bar{T} = \frac{1}{\delta} \int_{-\delta/2}^{\delta/2} T dy \,. \tag{5}$$

Upon integration of Eq. (3) with respect to the variable $y$ with account for the relations

$$-\lambda \frac{\partial T}{\partial y}\bigg|_{y=\delta(x)/2} = q_{1r} \,, \quad \lambda \frac{\partial T}{\partial y}\bigg|_{y=-\delta(x)/2} = q_{2r} \tag{6}$$

it is reduced to the following:

$$\frac{\partial \bar{T}}{\partial x} = -\frac{1}{\gamma(\bar{T})\, c_{pc}\, \rho_c U_{s.c} \delta_c} (q_{1r} + q_{2r}) \,, \tag{7}$$

where $\gamma(\bar{T}) = c_p \bar{T}/c_p\ (\bar{T} = T_c)$. Equation (7) is written with account for relation (4), which is fulfilled for any cross section of the polymer film, including the case after crystallization.

Assuming that the temperature of the molten polymer at the exit from the spinneret changes little over the film thickness, we write the boundary condition

$$\bar{T}\,(x = 0) = T_0 \,. \tag{8}$$

The densities of the removed heat fluxes $q_{1r}$ and $q_{2r}$ have different values for the regions of the film surface where the conditions of heat exchange differ. Let us consider these conditions in each region.

In region *I*, there are two mechanisms of formation of a boundary layer on the outside: one is caused by the jet flow of air onto the surface while the other is related to the formation of a boundary layer due to the motion of the film, i.e., superposition of two boundary layers having dissimilar mechanisms of formation is observed on portion *I*. For actual devices the velocity of the jet flow is $U_j \sim 1$–5 m/sec, while the velocity of motion of the film is $U_s \sim 1$–5 m/min. The evaluations show that the heat exchange due to the jet flow is predominant for such conditions and the expression for the heat flux $q_{11}(x, \bar{T})$ can be represented in the form (1) or (2); $x_f = x_1$ and the quantity $x_1 - x$ should be used instead of the coordinate $x$. The methods to determine the coefficients $M_1$, $M_2$, and $g_n$ for the boundary layer in the case of flow of a jet onto the surface for the laminar and turbulent regimes of flow have been developed in [5].

In region *III*, the heat exchange on the exterior surface of the film is determined by the jet flow, just as in region *I*; however the directions of the jet flow and of the film motion coincide on this portion. In determining the heat flux $q_{12}(x, \bar{T})$ in region *III*, we use relations (1) and (2), where $x_f = x_1$ and the coordinate $x$ is replaced by $x - x_1$.

On the inside of the film from the spinneret to the line of contact with the drum the density of the removed heat flux $q_{21}(x, \bar{T})$ in the region of formation of the boundary layer due to the motion of the film (region *I* in Fig. 1) is determined by expressions (1) and (2). The indicated relations and the values of the coefficients $M_1$, $M_2$, and $g_n$ for the laminar and turbulent regimes of flow have been obtained in [6].

In zone *II*, the heat transfer on the inside of the film is carried out in its contact with the surface of the cooled drum. On this portion, the leading part is played by the contact thermal resistance in which the degree of roughness of the drum is of primary importance and the film surface can be considered to be ideally smooth in the first approximation (Fig. 2). The methods to calculate contact thermal resistance are based either on theoretical prerequisites or employ empirical dependences [7]. For nearly ideal surfaces where the height of the roughness tips is comparable to the mean free path of the molecules of air the molecular mechanism of transfer of heat from wall to wall is decisive; this mechanism is characteristic of rarefied media (the so-called Smolukhowski effect). In considering the contact thermal resistance, one uses the relation [7]

$$\frac{1}{R_t} = \frac{1}{R_{con}} + \frac{1}{R_{mat}} , \tag{9}$$

where $R_t$ is the total thermal resistance, $R_{con}$ is the thermal resistance that is determined by the thermal conductivity of the heat-transfer agent filling cavities between the contacting bodies, the size of the gap, and other factors, and $R_{mat}$ is caused by the thermal resistance of the asperities themselves and is related to their conductivity, the pressure at the sites of contact, the properties of materials, and other factors. In composing the mathematical model, we used both theoretical models and empirical dependences, which yield insignificant differences in calculation results. For the surfaces with low roughness we also took account the effects which are characteristic of media with a high degree of rarefaction.

The density of the removed heat flux in the region of contact of the film and the drum is determined by the relation

$$q_{22} (x, \overline{T}) = \alpha_t (\overline{T} - T_d) , \tag{10}$$

where $\alpha_t = 1/R_t$.

In region *III*, on the interior film surface there is heat transfer to the boundary layer formed due to the motion of the film, and for this zone we have used the same relations for $q_{23}$ as for zone *I*. The quantity $x - x_2$ is used instead of the variable $x$.

Thus, for the assumptions given above heat transfer in the polymer film is reduced to solution of Eq. (7) with boundary condition (8); the quantities $q_{1r}$ and $q_{2r}$ take on different values depending on the mechanism of heat transfer on different portions of the film surface. For a numerical calculation of Eq. (7) with boundary condition (8) we used the Runge–Kutta scheme [8]. Since the initial equation involves the integral expression with the quantity $\partial\overline{T}/\partial x$ whose value at the running step is not known in advance, we organized an iteration computational scheme. In the numerical calculations, the indicated values were refined until the differences for the running and previous iterations decreased to 1%. To compute the integrals involved in Eq. (7) we used the Simpson method [8].

In view of the fact that the specific heat of the polymer $c_p(\overline{T})$ substantially depends on the temperature $\overline{T}$, the quantity $\gamma(\overline{T})$ was approximated by a third-degree polynomial according to the method of spline interpolation [8]:

$$\gamma (T) = A_i + B_i (T - T_{i-1}) + C_i (T - T_{i-1})^2 + D_i (T - T_{i-1})^3 , \quad T_{i-1} \le T \le T_i , \tag{11}$$

where $i = 1, ..., N$, $i$ is the running subscripts and $N$ is the number of intervals in the considered range of variation of the temperature. The values of the heat capacities tabulated in [9] are selected as the interpolation nodes $y_i = \gamma(T_i)$. The coefficients $A_i$, $B_i$, and $D_i$ satisfy the relations

$$A_i = y_{i-1} , \quad 1 \le i \le N ; \quad B_i = [(y_i - y_{i-1})/h_i] - \frac{1}{3} h_i (C_{i+1} - 2C_i) , \quad 1 \le i \le N - 1 ;$$

$$B_N = [(y_N - y_{N-1})/h_N] - \frac{2}{3} h_N C_N ; \quad D_i = (C_{i+1} - C_i)/3h_i , \quad 1 \le i \le N - 1 ;$$

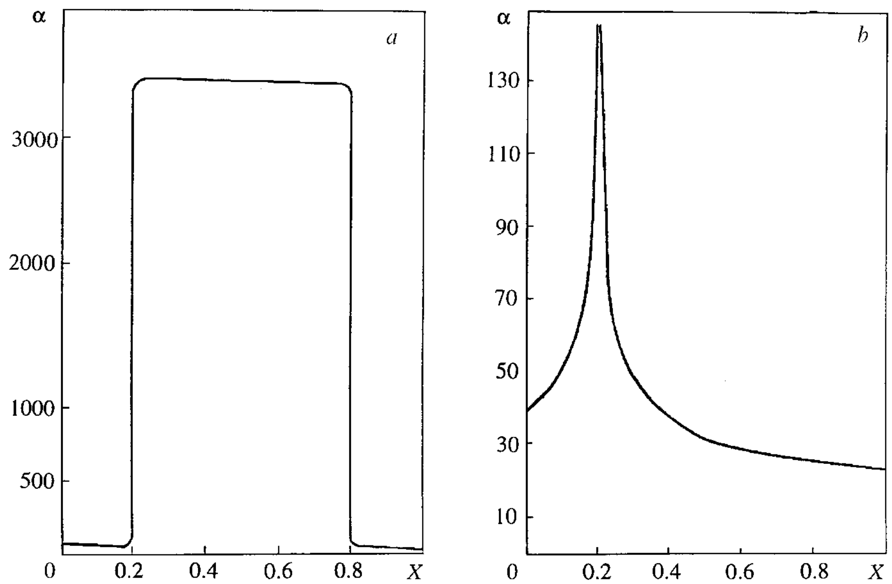
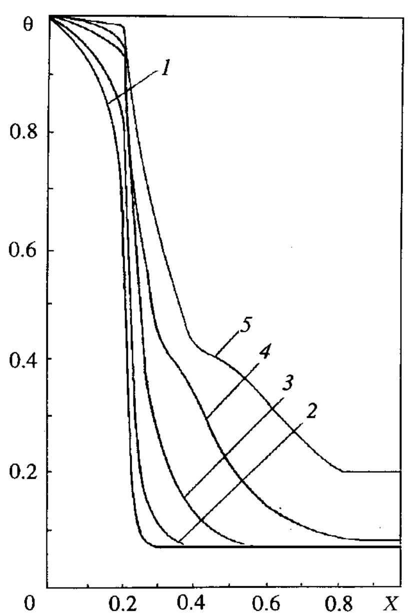



Fig. 3. Local values of the coefficients of heat transfer α (W/(m·K)) on the film surface: a) on the source side of the drum; b) on the source side of jet blowing.



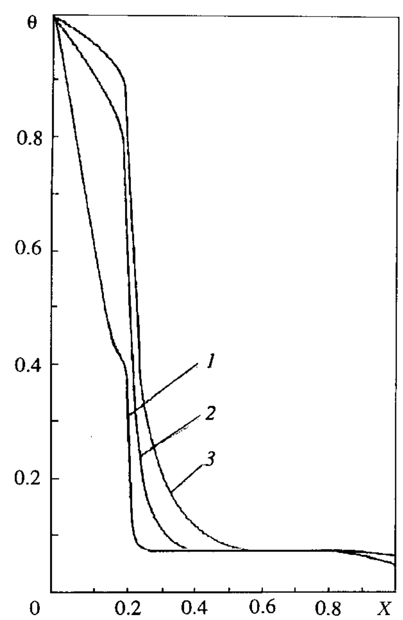



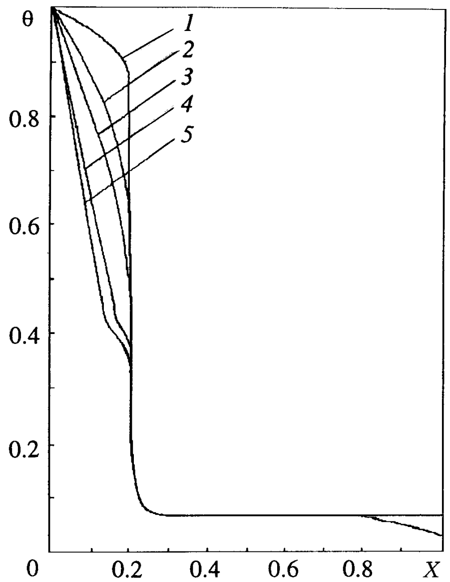

Fig. 4. Temperature distribution over the length of the film for different velocities of its motion $U_{s.c}$ (m/sec): 1) 0.05; 2) 0.1; 3) 0.25; 4) 0.5; 5) 1.0 ($\delta_c = 0.5$ mm, $T_d = 40^oC$, $T_0 = 225^oC$, and $U_j = 8$ m/sec).

Fig. 5. Influence of the thickness of the film $\delta_c$ (mm) on the temperature distributions over its length: 1) 0.2; 2) 1.0; 3) 2.0.

$$D_N = - C_N / 3h_N \,, \tag{12}$$

while $C_i$ are determined from the system of linear equations

$$C_1 = 0 \,; \quad h_{i-1}C_{i-1} + 2\,(h_{i-1} + h_i)\,C_i + h_iC_{i+1} = 3\,[(y_i - y_{i-1})/h_i - (y_{i-1} - y_{i-2})/h_i] \,,$$



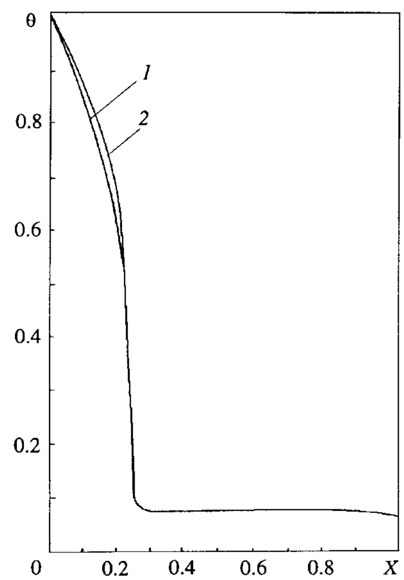




Fig. 6. Temperature distributions over the length of a polymer film for different values of the velocity of jet flowing of the air $U_j$ (m/sec) onto the film surface: 1) 1; 2) 5; 3) 10; 4) 20; 5) 30.

Fig. 7. Influence of the distance from the slot to the film surface $h$ (m) on cooling conditions: 1) 0.1; 2) 0.02.

$$2 \le i \le N\,; \quad C_{N+1} = 0\,. \tag{13}$$

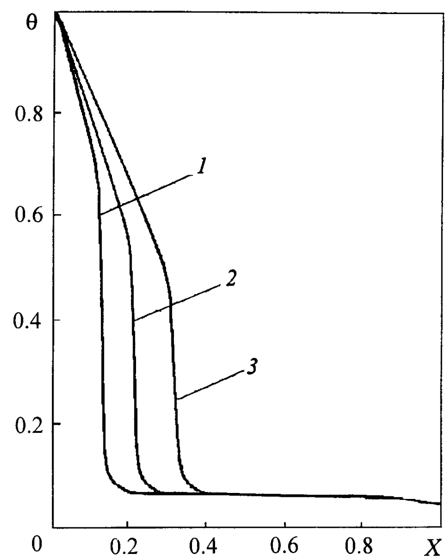
Solution of the system of equations (12) and (13) makes it possible to determine the coefficients $A_i$, $B_i$, $C_i$, and $D_i$ and hence the parameter $\gamma(\overline{T})$ for the arbitrary value of $\overline{T}$ in the considered interval of variation of the film temperature.

In the calculations, we took the values of dynamic and geometric parameters which are characteristic for cooling devices used for production of polymer films. In particular, the drum surface was considered as being smooth and polished, and the degree of roughness for such surfaces was selected accordingly.

The results of the numerical calculation are presented in Figs. 3–11. The influence of different parameters on the conditions of cooling of a polymer film has been investigated. As follows from Fig. 3, heat transfer on the drum surface where the coefficients of heat transfer are substantially higher than on other portions of the film surface is determining in the process of cooling. The region of flowing of a jet onto the film surface is characterized by the maximum values of heat-transfer coefficients, and the film is sharply cooled precisely on these portions (see Figs. 4–11). An important parameter determining the capacity of a device is the velocity of motion of the film. As follows from Fig. 4, for low velocities of motion of the film $U_{s.c}$ its temperature approaches the temperature of the drum surface; however with increase in $U_{s.c}$ the temperature drop in the film becomes not so sharp. It is characteristic that for low velocities of motion of the film crystallization occurs on the initial portions of its contact with the drum. At the same time, an increase in the values of $U_{s.c}$ causes the crystallization region to be displaced from the point of the film with the drum to the portions located closer to the point of its separation from the drum surface. By varying $U_{s.c}$ one can determine the maximum capacity which is attained for the prescribed dynamic and geometric parameters of the device.

Since in practice one produces films of different thicknesses, we investigate the influence of the thickness $\delta_c$ on cooling conditions. As follows from Fig. 5, cooling is less intense for thicker films and the crystallization region is displaced downward from the point of contact of the film and the drum. This has a natural physical explanation: from a thicker film, one must remove more heat to cool it down to the prescribed temperature.

Next we consider the influence of the dynamic and geometric parameters of a jet-blowing system on the conditions of heat exchange of a polymer film. The basic parameters are the blowing rate and the distance from the nozzle slot to the film surface. Figure 6 shows the temperature distributions over the film length as a function of the



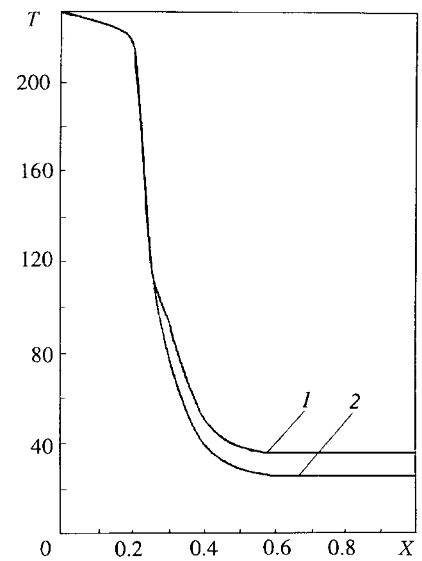
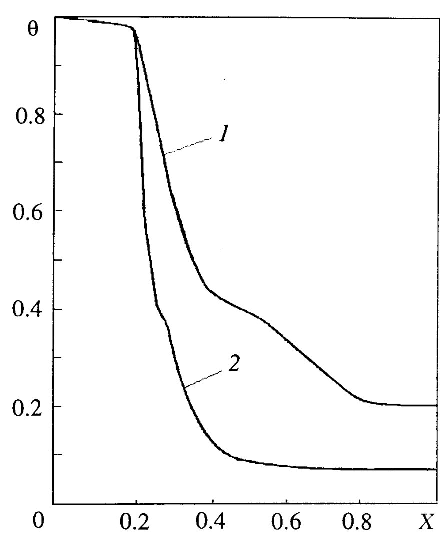




Fig. 8. Influence of the distance from the spinneret to the drum $X_1 = x_1/L$ on the temperature characteristics of the film: 1) $X_1 = 0.1$, 2) 0.2, and 3) 0.03.

Fig. 9. Influence of the surface temperature of the drum $T_d$ ($^o$C) on the conditions of cooling of the polymer film: 1) 35; 2) 25.



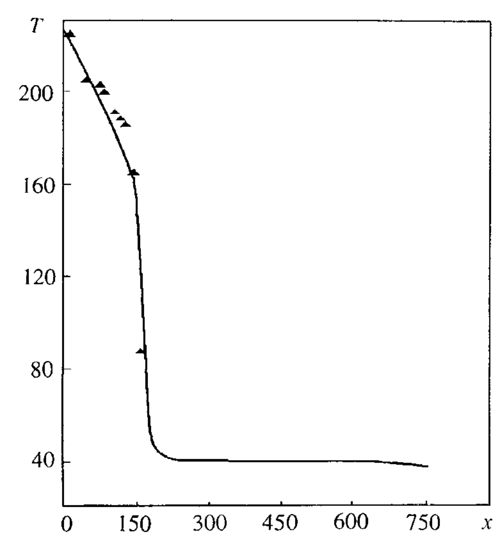




Fig. 10. Temperature characteristics of the polymer film in the presence of an air (1) and glycerin (2) space between the contacting surfaces.

Fig. 11. Comparison of the calculated (curve) and experimental (triangles) temperatures of the polymer film $T$ ($^o$C) over its length $x$ (mm) for the values of the parameters $T_d = 40^o$C, $\delta_c = 200$ μm, $T_0 = 225^o$C, $U_{s.c} = 0.0483$ m/sec, and $x_1 = 150$ mm.

velocity of flow of the jet out of the slot hole $U_j$. As we see, jet cooling plays a determining role on the portion from the spinneret to the line of contact of the film and the drum. The influence of the parameter $h/l$ on cooling conditions is small (see Fig. 7), and it is selected within $h/l = 6$–10.

Another parameter that can affect cooling conditions is the distance from the spinneret to the line of contact of the film with the drum $x_1$. As follows from Fig. 8, the intensity of cooling of the film increases with increase in this distance; however its variation does not substantially affect the process of cooling for low velocities of motion of the film but becomes noticeable for high values of $U_{s.c}$.

The most important factors determining the capacity of a cooling device are the temperature of the drum surface and the degree of roughness of the drum surface. Figure 9 shows the change in the temperature distributions over the film length as a function of the temperature of the drum surface $T_d$. As we see, the temperature of the cooled film approaches the temperature of the drum; therefore, $T_d$ is of importance in designing heat-exchange equipment. To evaluate the influence of the degree of roughness and the thickness of the air space between the film and the drum, Fig. 10 shows the change in the film temperature in the case of filling of the cavities between the film and the roughness tips with air and glycerin. The analysis of the curves obtained demonstrates a significant influence of this factor on cooling conditions.

Figure 11 compares the results obtained using the computational model and the experimental data obtained at the UKrNIIplastmash of the Ministry of Chemical Engineering Industry. The maximum computational error is no higher than 12%.

From the numerical investigations we can draw the following conclusions:

1. The developed mathematical model of the processes of transfer makes it possible to determine the local thermal characteristics of polymer films in the case of their cooling on a drum and to study the mechanisms of heat exchange on the film surface in greater detail.

2. The influence of the main factors on cooling conditions has been investigated and means of improving the capacity of cooling devices have been determined.

3. It has been shown that the determining factor is heat exchange between the film and the drum, and the conditions of its intensification have been studied.

4. The calculated and experimental data have been compared and their good agreement has been found.

## NOTATION

$x$ and $y$, longitudinal and transverse coordinates; $x_f$, coordinate of the beginning of formation of the boundary layer; $T$, temperature of the polymer film; $T_\infty$, temperature of the incoming flow or of the external heat-transfer agent; $q$, density of the removed heat flux; $\alpha(x)$, local coefficient of heat transfer; $\lambda$, thermal conductivity of the polymer; $c_p$, specific heat of the polymer; $\rho$, its density; $\delta$, film thickness; $U_j$, velocity of the jet flow; $U_s$, velocity of motion of the film in a given cross section; $q_{1r}$ and $q_{2r}$, densities of the heat fluxes removed from the film surfaces; $x_1$, coordinate of flowing of the jet; $x_2$, coordinate corresponding to the point of separation of the film from the drum; $T_0$, film temperature at the exit from the spinneret; $T_d$, temperature of the drum surface; $h$, distance from the slot to the film surface; $l$, slot width; $L$, total length of the film; $X = x/L$, dimensionless coordinate; $\theta = (T - T_\infty)/(T_0 - T_\infty)$, dimensionless temperature. Subscripts and superscripts: *, isothermal surface; f, beginning of formation of the boundary layer; c, crystallization region; 1 and 2, exterior and interior surfaces of the film; r, region of the surface differing in heat-exchange conditions ($r = 1, 2, 3$, for the interior surface, $r = 1, 2$, for the exterior surface); s, surface; t, total; con, thermal conductivity of the heat-transfer agent; mat, contacting material; d, drum; j, jet; $'$, running value of the variable in the integral; s.c, velocity of motion of the film surface in crystallization.

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