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PROCESSES AND DEVICES OF CHEMICAL MANUFACTURES

Simulation of Liquid Cooling of an Extruded Sleeve Plastic Film

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Abstract—A mathematical model of a liquid cooling was considered for a tubular plastic film produced by extrusion down. The developed model allows for a preset film speed (extruder) and film parameters to determine a length of a cooling zone or for a preset length of the cooling zone calculation of maximum speed of the film with the preset parameters.

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Tubular plastic films are among the most common polymer products [1]. The essence of the method of their production is to form in an extrusion die a tubular polymer billet which swells up to a sleeve of the required diameter and wall thickness by the air supplied inside the sleeve through the holes of the extrusion die. After cooling, the molded sleeve is placed by guide plates, pulled by pulling rollers, and spooled into a roll. Modern extrusion equipment allows obtaining a film with a considerable speed, but the cooling system can not always provide timely reduction in a sleeve temperature. As a rule, cooling of a sleeve is carried out by air blowing, however, in some cases it is advisable to use a more efficient liquid cooling, especially in manufacture of thick films (typically 100 μm). If in the case of air cooling a sleeve is formed by a "drawing up", in the liquid cooling is usually used the scheme of "drawing down." In this scheme, the sleeve is cooled by a water film flowing down on an outer surface of the sleeve. After contact of the water with sleeve further swelling stops because on the sleeve surface the polymer solidifies almost instantaneously [2].

The cooling system efficiency (the intensity and uniformity of cooling) determines essentially the production line productivity and quality of the film. Thus, simulation of this process that allows substantiation of the effective mode of the cooling is of great importance.

In most papers devoted to mathematical modeling of the cooling of the sleeve plastic film, a possibility of determining the average temperature across the film thickness is examined [2, 3]. Such an approach is acceptable only for an analysis of the cooling process of thin films.

The film flowing of liquid under the force of gravity is characterized by a presence of a section with a laminar character of the fluid flow and within which the cooling of the sleeve is finished. In this regard, it is possible to describe the process by the convective heat transfer equations for laminar fluid flow.

To develop a mathematical model we choose a fixed coordinate system with an origin in a cross section of the water contact with the sleeve surface (Fig. 1). Since the thickness of the sleeve wall (the film thickness) is much smaller than its diameter, then the process will be considered in a rectangular coordinate system.

The equation of motion for the film of fluid flow under gravity has the form

$$\rho_{\text{в}} w_x \frac{\partial w_x}{\partial x} = \rho_{\text{в}} g + \mu_{\text{в}} \frac{\partial^2 w_x}{\partial y^2}, \quad (1)$$

where ρ_w is a water density, kg m^{-3}; μ, water viscosity, Pa s; g, acceleration of free fall, m s^{-2}.

The continuity equation for determining the average liquid film thickness can be written in integral form

$$\int_{\delta_p}^{\delta_p+\delta_w} w_x dy = \Gamma_V,$$

where Γ_V is a bulk sprinkling density (volumetric fluid flow per unit of a wetted perimeter), m^2 s^{-1}.

Let us set the boundary conditions for a solution of Eq. (1).

Due to the small slit widths b of a sprinkler of the cooling water, we assume that the water flow in the slit is laminar with a parabolic velocity profile, and therefore the boundary condition at the inlet to the cooling region is given by

$$w_{x|x=0} = \frac{6\Gamma_V}{b^3}\left(yb - y^2\right).$$

After coming out of water from the sprinkler the boundary conditions relative to velocity have the following form:

$$w_{x|y=\delta_p} = w_p, \quad (2)$$

$$\frac{\partial w_x}{\partial y}\bigg|_{y=\delta_p+\delta_w} = 0. \quad (3)$$

Condition (2) is a condition of sticking (in this case the velocity of the sleeve movement w_f is determined from an equation of mass flow of the polymer), and condition (3) means that on the free surface of the water film shear stresses are absent.

The energy conservation equation for the polymer film has the form [4, 5]

$$\rho_p c_p w_p \frac{\partial T}{\partial x} = \frac{\partial}{\partial y}\left(\lambda_p \frac{\partial T}{\partial y}\right),$$

where ρ_p, c_p, and λ_p are density, kg m^3; mass heat capacity, J kg^{-1} K^{-1}, and thermal conductivity of the polymer, W m^{-1} K^{-1}, that is a function of temperature, respectively.

Then for the water film we can write

$$\rho_w c_w w_x \frac{\partial T}{\partial x} = \frac{\partial}{\partial y}\left(\lambda_w \frac{\partial T}{\partial y}\right),$$

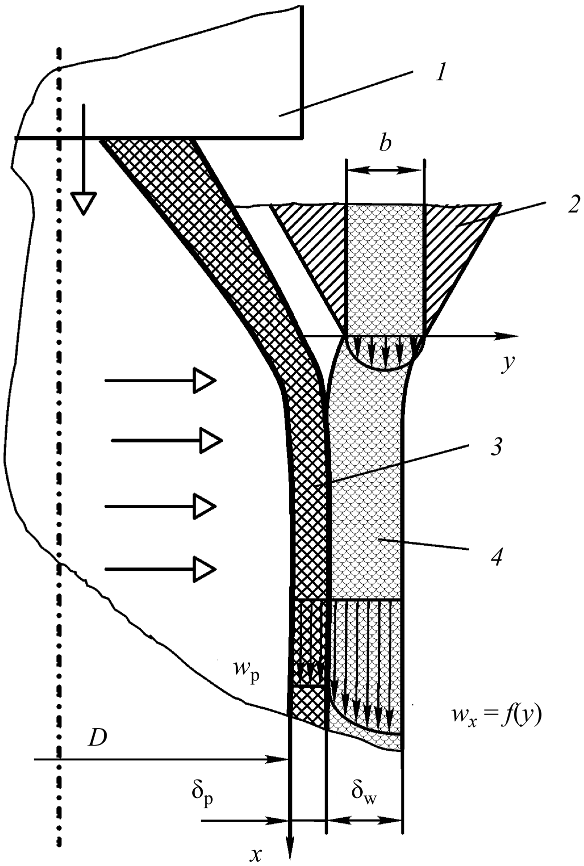

Fig. 1. Scheme of the cooling of the sleeve plastics film: (*1*) extrusion die, (*2*) circular sprinkler of water, (*3*) plastic film, (*4*) cooling water film; (*D*) diameter of sleeve, m, δ_p thickness of sleeve plastic film, m; (δ_w) thickness of water film, m; (*b*) width of the sprinkler slip, m, (*x* and *y* coordinates directed along the film and across the film thickness, m; (w_p) velocity of the plastic film, m s^{-1}; (w_x) velocity of cooling water along the coordinate *x*, m s^{-1}.

where λ_w is thermal conductivity of water, W m^{-1} K^{-1}.

Since the cooling of the sleeve in its movement from the extrusion die to the contact area with water is small, then the temperature of the polymer at the entrance to the cooling zone can be taken as the temperature of the polymer at the end of the die T_0. Accordingly, we assume that the fluid temperature at the entrance is constant and equal to T_w. Then the boundary temperature conditions for the x axis are as follows:

$$T\Big|_{\substack{x=0 \\ 0\le y\le\delta_p}} = T_0,$$

$$T\Big|_{\substack{x=0 \\ \delta_p\le y\le\delta_w}} = T_w.$$

The heat transfer inside the sleeve (between the inner surface of the sleeve and the air that it blows up) can be neglected, and on the contact surface "polymer–water" we assume that the temperature of the polymer and water is the same, and the heat flow from the polymer to the water is constant. Then the boundary temperature conditions for coordinate y can be written:

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = 0,$$

$$T\big|_{y=\delta_p - 0} = T\big|_{y=\delta_p + 0};$$

$$\lambda_p \left.\frac{\partial T}{\partial y}\right|_{y=\delta_p - 0} = \lambda_w \left.\frac{\partial T}{\partial y}\right|_{y=\delta_p + 0},$$

$$\left.\frac{\partial T}{\partial y}\right|_{y=\delta_p + \delta_w} = 0. \qquad (4)$$

From condition (4) follows that heat transfer between the water film and air outside the sleeve is absent.

The developed mathematical model is solved numerically and allows determination of the velocity and temperature fields, as well as the length of the cooling zone of the sleeve to the preset temperature of the polymer at various modes of cooling. That is necessary for the design of the operation device.

First we consider the results of numerical simulation of the film flow of the cooling water. In the annular sprinkler of water with the slit width of 0.4…0.6 mm the flow is laminar with the parabolic velocity profile. Once the water comes out of the sprinkler, one of the bounding surfaces disappears and a free surface of the film is formed which contacts with the air whose resistance can be neglected. The parabolic velocity profile is converted to semiparabolic. Since the volumetric flow rate is constant then the water film thickness is gradually reduced due to acceleration of the flow. Nature of the change in the velocity field of water on section of its acceleration is shown on Fig. 2, which shows how is gradually formed the semiparabolic velocity profile, an acceleration of the water flow occurs, and the film thickness reduces.

Variation of the thickness of the liquid film along x cooling zone for different values of Reynolds number Re is shown on Fig. 3. As can be seen the section of the film acceleration for the given Re numbers is less than 0.02 m and its length slightly rises with the Re number increase. Further, the film thickness remains almost constant that corresponds to the condition of stable flow when gravity is balanced by the viscosity, and inertia forces are virtually absent. The velocity profile remains unchanged.

In the motion of the polymer film the film thickness of the cooling water is reduced: it seems that a polymer film "stretches" the water film. In practice, this can cause a discontinuity (gap) of the water film and, respectively, the cooling process failure.

Now we consider the cooling of the sleeve. The temperature profiles in the polymer and liquid films as a function of dimensionless coordinate (y/δ_p or y/δ_w) at the sprinkling density Γ_V = 0.0001 m² s⁻¹ for different values of the length of the cooling zone are shown in Fig. 4. The water temperature at the inlet of the cooling zone is taken to be 20°C. It is seen from Fig. 4 the temperature of the polymer and liquid films are gradually equalized. With a decrease in the sprinkling density the liquid film can be quickly heated whereupon the cooling

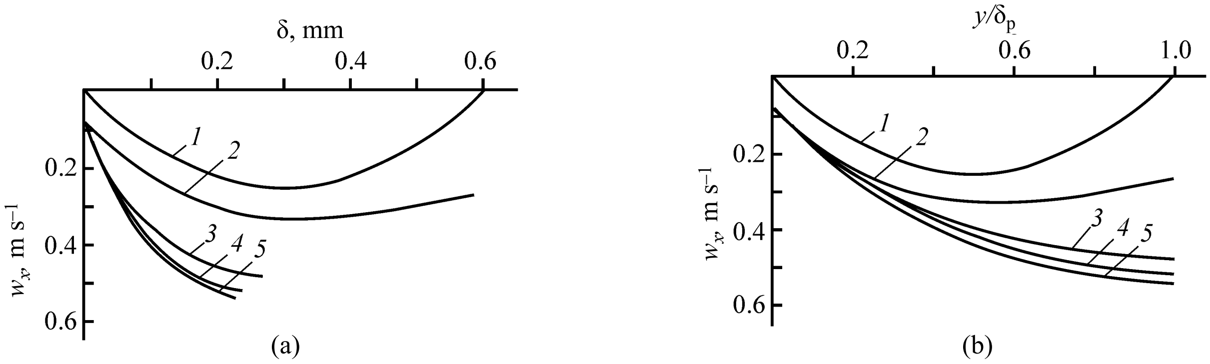

Fig. 2. Variation of the velocity w_x along (a) the water film thickness and (b) the dimensionless coordinate depending on coordinates x, m: (*1*) 0, (*2*) 0.005, (*3*) 0.03, (*4*) 0.045, (*5*) 0.06.

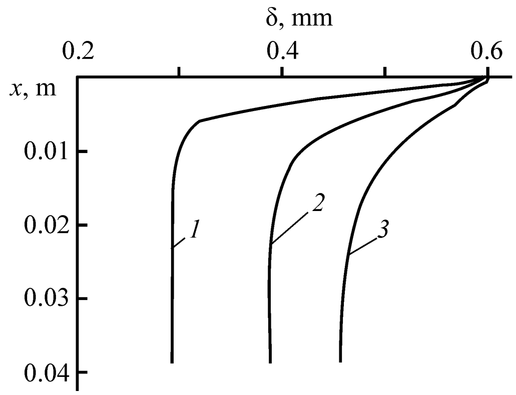

Fig. 3. Variation of the water film thickness along the length of the cooling zone depending on Re number : (*1*) 500, (*2*) 1000, (*3*) 1500.

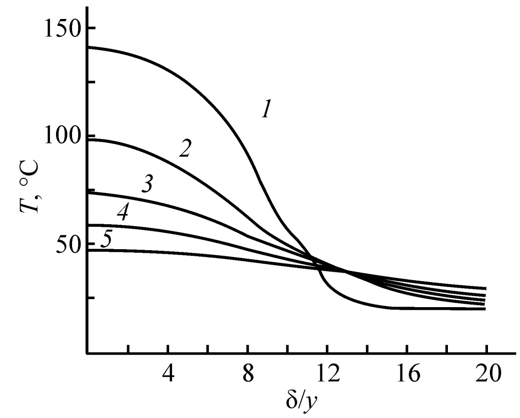

Fig. 4. Temperature distribution over the thickness of the polymer and fluid films depending on the coordinate *x*, m: (*1*) 0.015, (*2*) 0.025, (*3*) 0.035, (*4*) 0.045, (*5*) 0.06.

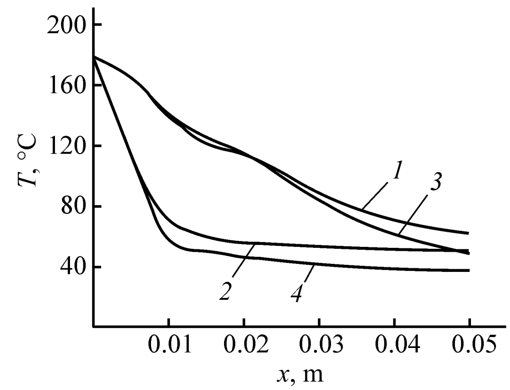

Fig. 5. Dependence of temperature of (*1, 3*) inner and (*2, 4*) outer surfaces of the polymer films along the cooling length *x*, m: (*1, 2*) Re = 120, (*3, 4*) Re = 1500.

of the polymer film almost stops, since the water film, which has a large mass heat capacity, begins to act as a heat insulation layer. It should be noted that under real conditions, the sprinkling density should not be less than some minimum value, after which continuity of the liquid film is disrupted. The value of the minimum sprinkling density depends on the design of the annular sprinkler of fluid, which should ensure even distribution of water on the sleeve surface.

The curves of cooling the inner and outer surfaces of the polymer film at various Reynolds numbers are shown in Fig. 5, which shows that the cooling rate is significant and an increase in the sprinkling density affects slightly the length of the cooling zone, which is 40...60 mm. On the curve of a temperature change of the inside surface there exists a characteristic “shelf” in a region of the solidification temperature of the polymer due to a significant increase in the mass heat capacity in this temperature range.

The results of numerical simulations were tested in producing polyolefin blown films in an extrusion laboratory setup of the Department of machines and equipment of chemical and oil refineries manufactures of Ukrainian Technical University. The laboratory setup was designed to study the processes of production of plastic pipes and sleeve plastic films of small diameter and was constructed based on an industrial lines LT201/10 equipped with a worm press CHP20×25.

Since an experimental researches of the heat transfer in the course of the water cooling of the sleeve plastic film are fairly complex they was conducted only qualitatively. During the experiment we fixed coordinate of the section on which the polymer film loses its opacity (cloudy) that was a result of the polymer hardening, which occurred at a specific temperature. Comparison of experimental and theoretically calculated preset coordinates showed a sufficient adequacy of the model to the real process of cooling.

Examination of the liquid cooling of the sleeve plastic film confirms its high efficiency and application feasibility for cooling of thick sleeve films. The cooling of these films is limited not by the external but internal problem, i.e., by thermophysical properties of the polymer. Cooling mode within certain limits can be controlled by selection of the initial temperature of the cooling water, as well as by use of a zone by zone cooling.

DESIGNATIONS

c is mass heat capacity, J kg^{-1} K^{-1}; *D,* diameter of a plastic sleeve, m; *g,* acceleration of free fall, m s^{-2}; *b,* slit width of the fluid sprinkler, m; *T,* temperature, °C; *w,* linear velocity, m s^{-1}; *x* and *y,* coordinates directed along the film and across the film thickness, m; Γ_V bulk sprinkling density (volumetric fluid flow per unit of wetted perimeter), m^2 s^{-1}; δ, film thickness, m; μ, viscosity, Pa s; ρ, density, kg m^{-3}.

Main indices: 0 is for starting values; *V* is for volume; *x,y* are for corresponding coordinate; w denotes cooling water; p denotes polymer.

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