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POLYMERIC TECHNOLOGIES

Heat Exchange in Granulating Thermoplastics

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Abstract—Cooling of polymer granules and strands in air and water was examined. The greatest effect of a turbulence of air flow on the cooling rate of granules was revealed in the starting period. An analysis of the cooling of granules in water demonstrated that the rate of heat transfer from a volume of thermoplastic material to its surface was a rate-limiting step and, thus, an effect of turbulization of a water flow on the cooling was negligible. We showed that it would be appropriate to install partitions destroying a heated boundary layer of water for intensifying process in a cooling bath since an actual cooling of the strands in the water bath longer corresponds to the case when water moves together with strand.

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A permanent growth in a polymer application, the world manufacturing of which in 2008 achieved 245 million tons necessitates disposal of the waste [1]. One of the most appropriate ways is regranulation of the thermoplastic polymers and using the produced granules in manufacturing of various products [1–4].

Hot and cold granulations are the main methods of the thermoplastics granulation. In the first case the strands being formed by an extrusion head are cut into granules directly close to the head and then they being hot are entrained by air or water flow in which are simultaneously cooled. In cold granulation the formed strands at first are cooled in a water bath and pass through a pulling device and only then they are cut into granules.

In the case of incomplete cooling granules can stick together during packing forming agglomerates unsuitable to further use in polymer treating equipment, e.g., in extrusion apparatuses. This effect occurs due to temperature equalization along a radius of a granule (as a result of cooling the inner and heating the outer layers of the granules) under conditions when heat exchange of the granules with surrounding air is poor due to mutual contact of a large amount of granules of thermoplastics with low thermal conductivity.

Thus, a relative low temperature of a surface of the strands in the course of their granulation is necessary but insufficient condition to yield the high-quality granular product.

In addition in treatment of crystal polymer the material structure in obtained granules is formed upon cooling strands of granules and depends on a cooling mode. The structure of granules defines also a structure of products from them and therefore an examination of cooling is of great importance in designing technological and auxiliary equipment [2–5].

The cooling processes of granules or strands are simulated by the equation of unsteady heat conduction. For its solution commonly used boundary conditions of the first [6] or the third kind [7]; i.e., it is assumed that is is known either the surface temperature of granule or strand taken as the temperature of the cooling medium or heat transfer coefficient to the cooling medium. However in the first case since there is the boundary layer of the cooling medium near the polymer surface, it is almost impossible to ensure a constancy of its temperature (in this case it should be ensure large cooling water flow [6]), therewith in the second case determination of the heat transfer coefficient is quiet difficult in respect to experimental studies. In addition, known theoretical solutions of equation of heat conduction does not account for a dependence of thermophysical properties on temperature that leads to great errors because a thermoplastic material is cooled from a viscous fluid to solid state and its properties essentially change.

The goal of the investigations is to simulate cooling of granules and strands without use of the heat transfer coefficients and accounting for the dependence of the thermophysical properties on temperature.

SIMULATION OF COOLING OF GRANULES

Let us consider at first cooling of spherical granules in a cooling flow of air or water (Fig. 1).

Based on analysis of the process we assumed that after forming the granules were hardly deformed, and there were no dissipative sources of energy in the volume of granules. Accounting this cooling process can be considered symmetrical relative to the center of granules, and therefore the heat equation in spherical coordinates takes the following form

$$\rho_t c_t \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\lambda_t r^2 \frac{\partial T}{\partial r}\right), \quad (1)$$

where ρ_t, c_t, and λ_t are density, kg m^{-3}, mass heat capacity, J кг$^{-1}$ K^{-1}, and heat conductivity, W m^{-1} K^{-1}, of thermoplast material as function of temperature; *t,* time, s.

Since the granules are entrained by air or water flow we can suggested that a relative motion of granules and cooling medium are negligible. Then accounting for the assumptions the temperature field of cooling medium is symmetrical relative to the center of granule and therefore equation of energy conservation for the cooling medium (air or water) surrounding granule is similar to Eq. (1):

$$\rho_{cm} c_{cm} \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\lambda_{cm} r^2 \frac{\partial T}{\partial r}\right), \quad (2)$$

where ρ_{cm}, c_{cm} and λ_{cm} are density, kg m^{-3}, mass heat capacity, J кг$^{-1}$ K^{-1}, and heat conductivity, W m^{-1} K^{-1}, of the cooling medium as function of temperature.

Initial conditions for solutions of Eqs. (1) and (2) have form:

$$T\Big|_{\substack{t=0 \\ 0 \le r \le R}} = T_0; \quad (3)$$

$$T\Big|_{\substack{t=0 \\ R < r \le \infty}} = T_{cm}. \quad (4)$$

Since the cooling process is symmetrical then in the center of a granule a condition of symmetry is a boundary condition

$$\frac{\partial T}{\partial r}\Big|_{r=0} = 0. \quad (5)$$

We assumed that on contact surface of a granule with the cooling medium the temperature of the thermoplastic material and cooling medium was equal and, moreover, the constancy of the heat flow being removed from a granule by the cooling medium remained.

$$T\Big|_{r=R-0} = T\Big|_{r=R+0} \quad \lambda \frac{\partial T}{\partial r}\Big|_{r=R-0} = \lambda_{jc} \frac{\partial T}{\partial r}\Big|_{r=R+0}. \quad (6)$$

At a sufficient distance from the contact surface ($r/R \to \infty$) temperature of the cooling medium becomes equal to T_{cm}. In numerical computations this distance can be a distance where temperature T is different from T_{cm} by a preset value, e.g., by 1…2 °C. The solution of presented models by numerical techniques allows determination of a cooling time of a granule and

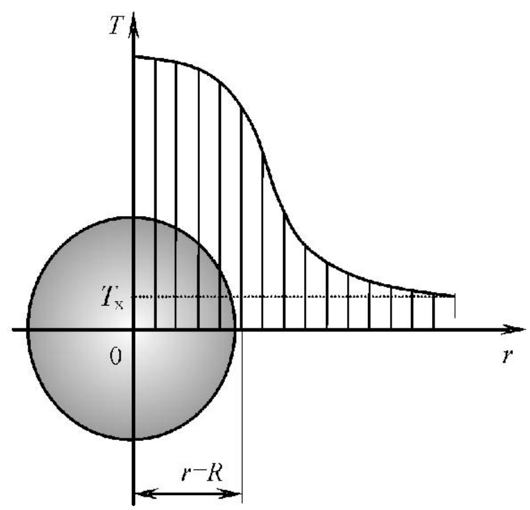

Fig. 1. Calculation scheme pf the cooling of a spherical graniles: (r) coordinate directed along the granule radius, m; (R) granule radius, m; (T, T_{cm}) current temperature and temperature of cooling medium, °C.

evaluation of a temperature variation of the medium surrounding the granule. Entering in this model instead of the heat conductivity of the cooling medium an equivalent heat conductivity enables evaluating an effect of environmental factors on the cooling time and determining advisability of accounting for these factors in the technique of engineering computation.

SIMULATION OF COOLING OF STRANDS

The cooling of strands in the cold granulation is considered in cylindrical coordinates. In view of evident simplifications the equation of unsteady heat conduction takes the following form:

$$\rho_t c_t \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_t r \frac{\partial T}{\partial r}\right). \quad (7)$$

Strands move through the cooling bath at constant velocity V_z that can be calculated from equation of mass flow of thermoplastics G_t (Fig. 2)

$$V_z = \frac{4G_t}{\pi d^2 n \rho_t},$$

where n is a number of strands; d, a diameter of strand, m.

Let us denote a length of path of strand in the bath as z then time t is associated with this length by dependence $t = z/V_z$. Accounting for this dependence Eq. (7) takes the following form

$$\rho_t c_t V_z \frac{\partial T}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_t r \frac{\partial T}{\partial r}\right). \quad (8)$$

Let us consider now heat exchange in the cooling bath.

Moving with constant speed V_z strand entrains a certain layer of liquid, whose velocity varies from V_z on the contact surface to zero at some distance (boundary layer). On should be notes that a heat exchange problem in liquid is not similar to heat exchange in the case of fluid motion over solid surface: a strand is fixed, fluid moves, because heat exchange along z depends on the cooling conditions in subsequent layers along the coordinate z. Nevertheless, the assessment can be done if we consider two extreme cases: the fluid is stationary and the fluid moves together with a strand with a linear velocity V_z (Fig. 2).

The equation of energy conservation for the second case has the form (in this case the cooling medium is water)

$$\rho_{cm} c_{cm} V_z \frac{\partial T}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_{cm} r \frac{\partial T}{\partial r}\right). \quad (9)$$

In the first of the cases velocity $V_z = 0$.

Initial conditions for solution of Eqs. (8) and (9) are described by dependences (3) and (4), the boundary conditions in the center of a strand is determined by Eq. (5), and other boundary conditions are similar to those for cooling of spherical granules and described by dependences (6).

Solution of presented models of cooling of spherical granules and strands enables computation of the cooling time and at a preset temperature of an extruder dimensions of cooling devices. The numerical simulation enables assessing an effect of environmental factors in cooling and determining advisability of accounting for these factors in the technique of engineering computation.

EXPERIMENTAL

Results of the numerical simulation of the cooling were tested in granulation of waste of manufacture of low density polyethylene (LDPE) of grade 10803-020, State Standard 16337–77, on an extrusion laboratory setup (Department of Machines and Devices of Chemical and Petroleum Manufactures of Ukrainian Technical University "Kyiv Polytechnical Institute") (Fig. 3).

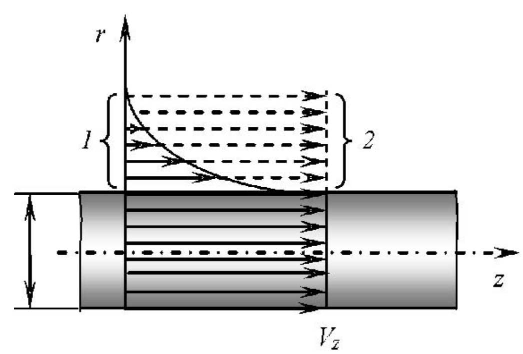

Fig. 2. Velocity fields of strand and cooling medium: (r, z) coordinates directed along the strand radius and axis, m.

Because an examination of the cooling of granules associated with some difficulties (mainly due to difficulty of determination of average granule temperature) relevant researches were conducted only for strands. Adequacy of the developed model was evaluated with the aid of the average temperature of strand at the cold outlet of the setup (in an area of a receiver) because simultaneous determination of strand temperature over the time (along a length of a cooling section) due to small diameter of strand is also complicated.

Calculation of the average temperature of strand was carried out according to the following order.

– The dependence of the temperature distribution along the radius of a strand at an inlet to the receiving device was calculated by the above methods depending on the initial temperature of strand (it was assumed that it was equal to an average temperature of the melt at the outlet of the strand heads);

– the temperature of water in the cooling bath and a length of a water cooling section;

– ambient air temperature and a length of an air cooling section;

– velocity and diameter of strands.

Distribution of temperature of a strand along its cross section was determined for m points ($i = \overline{1,m}$), the first of which corresponded to the center of strand, and the last, to its surface. Because the specific volume of the material (a fraction of an area of the cross section) corresponding to a calculated temperature on a certain radius increased from the strand center to its periphery the average theoretical temperature of a strand in a certain cross section was computed by the following way.

(1) An area of central circular section of the cross section of a strand corresponding to maximum temperature (average between T_1 and T_2) was

$$F_1 = \frac{\pi}{4}(2dr)^2,$$

where dr is a step of calculation over strand radius ($dr = d/[2(m-1)]$).

(2) An area of the first (from strand center) ring section of the cross section of strand

$$F_2 = \frac{\pi}{4}\left[(4dr)^2 - (2dr)^2\right].$$

(3) An area of the each subsequent ring section of the strand cross section

$$F_i = \frac{\pi}{4}\left[(2i\,dr)^2 - \left(2(i-1)\,dr\right)^2\right]$$

or

$$F_i = \pi dr^2(2i-1). \quad (10)$$

Equation (10) is valid for any value of i.

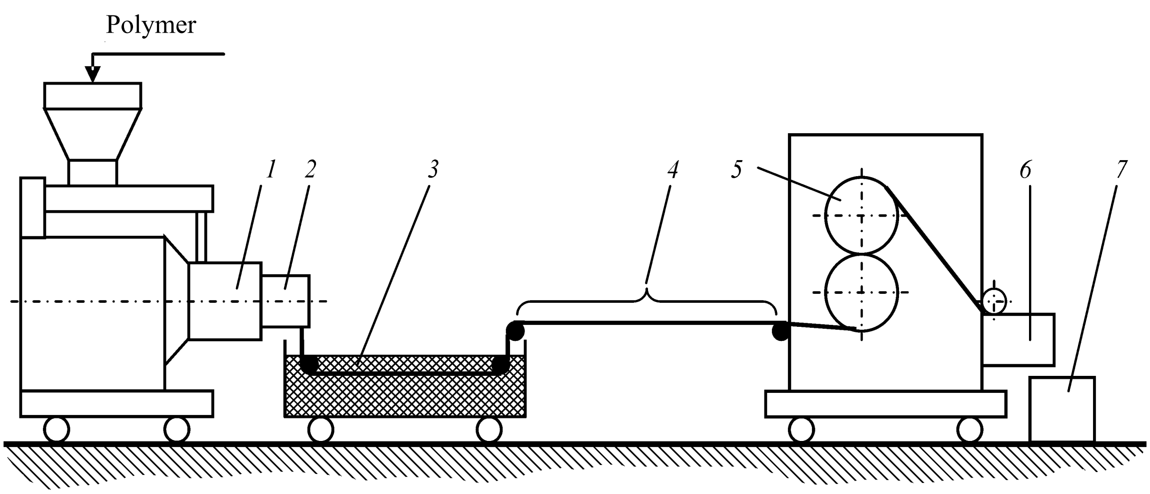

Fig. 3. Extrusion laboratory setup for granulation of polymers: (*1*) on-disk-worm extruder; (*2*) extrusion strand head; (*3*) cooling bath; (*4*) section of air cooling; (*5–7*) traction, granulating and receiving devices.

(4) Accounting for that area of the strand cross section is equal to $F = \pi[(m–1)\ dr]^2$, a value of the average theoretical temperature of strand in the certain cross section is

$$T_t = \frac{1}{2(m-1)^2}\sum_{i=1}^{m-1}(T_i + T_{i+1})(2i-1). \qquad (11)$$

An experimental value of the average temperature of a strand we determined by the follwing way:

The receiver of the extrusion laboratory setup to carry out experiments was designed in a form of an insulated tank that was filled out by a certain amount of water.

(1) The heat accumulated by water contained in the receiver is computed as follows:

$$Q_в = M_w c_w T_w, \qquad (12)$$

where M_w is water weight in the receiver (this weight was measured on a balance VNTs-2M, a measuring range from 0 to 2000 g, a limit of permissible error 1 g in a measurement range from 10 to 1000 g); c_w, mass heat capacity of water at temperature T_w [this temperature was recorded by a thermoelectric converter TKhK-259 (HCX L, a measuring range 0...400 °C), equipped with an automatic potentiometer of an A-565-001-01 type with an accuracy 0.15/0.05, a measuring range from –50 to 800°C and a degree of sampling digital frame 0.1°C

(2) The heat accumulated by polymeric granules trapped by the receiver is computed as follows:

$$Q_t = M_t c_t T_t, \qquad (13)$$

where $M_т$ is weight of the granules in the receiver (this weight was measured on a balance VNTs-2M after retrieving these granules from the receiver and drying on the research setup); c_t, mass heat capacity of the granule material at temperature T_t.

(3) The heat accumulated by a water–granules system in the receiver is computed as follows:

$$Q_{w-t} = Q_w + Q_t. \qquad (14)$$

(4) Weight of the water–granules system was

$$M_{w-t} = M_w + M_t. \qquad (15)$$

(5) Mass heat capacity of the water–granules system c_{w-t} was calculated according to the following dependence

$$c_{w-t} = \bar{x}_w c_w + \bar{x}_t c_t, \qquad (16)$$

where $\bar{x}_w$ and $\bar{x}_t$ are weight fraction of the cooling water and thermoplastics of the water–granules system.

(6) The average temperature of the water–granules system was

$$T_{w-t} = \frac{Q_{w-t}}{M_{w-t} c_{w-t}}.$$

According to the reported technique an experimental value of the average temperature of strands was conducted in the following order:

(1) By experimental determination of T_{w-t}, M_w, M_t, computation of M_{w-t} by Eq. (15), and also of c_{w-t} value at temperature T_{w-t} by Eq. (16) temperature of the water–granules system can be found;

(2) Then by Eq. (12) is computed the heat accumulated by water, and by Eq. (14), the heat accumulated by polymeric granules.

(3) The average temperature of strands T_t is calculated by Eq. (13) (when necessary it is specified the value of c_t, depending on the calculated temperature and computed the final value of temperature T_t by the method of successive approximations).

The determined by this way experimental value of the average temperature of strands was compared with calculated by Eq. (11).

An example of a comparison of theoretical and experimental results of the studies of the average temperature of strand at the cold outlet of the setup was presented below.

The cooling process of 4 mm diameter strand of secondary LDPE of grade 15803-020 State Standard 16337–77 was analyzed. A starting temperature of strand at the outlet of the extrusion strand head was 170°C (Fig. 3). The water weight on the receiver was 1.5 kg, its temperature, 20.8°C; the weight of the polymeric granules in the receiver, 0.53 kg; temperature of the water–granules system, 24.1°C.

As a results of calculation according suggested technique in the end of the cooling section for 11 points over the radius of strand (a calculation step over the radius dr = 0.2 mm) we obtained the following a temperature distribution, °C: 59; 58.5; 57; 55; 52; 48; 44; 39; 34; 29; 23. The average temperature of strand calculated by Eq. (11) was 39.6°C.

After that we defined an experimental value of the average temperature of strands. Weight of the water–granules system was $M_{w-t} = M_w + M_t = 1.5 + 0.53 = 2.03$ kg.

Mass heat capacity of the granule material at the water–granules system temperature was equal to 2268 J kg^{-1} K^{-1} [8, 9], then heat capacity of the water–granules system calculated by the following equation:

$$c_{w-t} = c_w \frac{M_w}{M_{w-t}} - c_t \frac{M_t}{M_{w-t}}$$

$$= 4190 \frac{1.5}{2.03} + 2268 \frac{0.53}{2.03} = 3688 \text{ J kg}^{-1} \text{ K}^{-1},$$

the heat accumulated by this system $Q_{w-t} = M_{w-t} \times c_{w-t} T_{w-t} = 2.03 \times 3688 \times 24.1 = 180428$ J, the heat accumulated by water $Q_w = M_w c_w T_w = 1.5 \times 4190 \times 20.8 = 130728$ J, the heat accumulated by the polymeric granules

$$Q_t = Q_{w-t} - Q_w = 180428 - 130728 = 49700 \text{ J}.$$

Therefore, the experimental value of the average temperature of strand in the first approximation , °C was:

$$T_t = \frac{Q_t}{M_t c_t} = \frac{49700}{(0.53 \times 2268)} = 41.3.$$

After clarification of a value of mass heat capacity of the strand material depending on the calculated temperature we finally determined an experimental value of the average temperature of strands that was 36.5°C, that differed from the theoretical value (39.6 °C) by 7.8%.

Comparison of experimental and calculated data showed their satisfactory agreement (the discrepancy did not exceed 15%).

The numerical simulation has enabled rationale of implementing the air section at the outlet from the cooling bath and also of the parameters both of the water and air cooling.

RESULTS AND DISCUSSIONS

Initial data for calculation of the granule cooling are: diameter of a granule d; initial temperature of gtanule T_0; temperature of a cooling medium T_{cm}; a final temperature to which the granule center is cooled T_f; functions which describe dependency of thermophysical properties of a polymer and cooling medium on temperature.

The cooling was studied for LDPE of grade 15803-020 State Standard 6337-77, the thermophysical properties of which for ease of use were processed by the method of least squares.

An advantage of the developed mathematical model of cooling consists in a solution of the model based on the assumption that heat transfer from the granule surface to liquid occurs only due to heat conduction. The air and water flows, in which granule moves, in fact, are turbulent. An effect of a turbulent transfer can be evaluated using the coefficient of equivalent heat conductivity that takes into account the turbulent transfer. The equivalent heat conductivity can be determined by dependence $\lambda_{equiv} = \eta\lambda$, where $\eta \geq 1$ is a coefficient that accounts for the turbulent transfer. It should be noted that value η_w in the flow is not constant because near the interface in the cooling medium occurs formation of the boundary layer where energy transfer performs mainly by heat conductivity. In this layer the value of η is close to unity near the granule surface and rises to maximum in the flow core.

To analyze the cooling process we carried out calculation of temperature fields in a volume of granule of 3 mm diameter and in a cooling medium. On Figs. 4, 5 we pictured temperature variation along the radius for various values of the cooling time and coefficient η. A change of value η over the radius was not taken into account: when calculating it was taken constant. Figures 4 and 5 show that the rate of temperature variation in the granule volume rises with an increase in η.

An effect of the flow turbulence on the cooling is demonstrated by Fig. 6, that shows the temperature variation in the granule center over time at $\eta = 1$ and $\eta = 5$. First a rapid drop in the temperature occurs and upon an increase in the cooling time an intensity of decreasing temperature reduces. In the region of the melting point of the polymer cooling curves of the granule center are almost horizontal due to a significant increase in mass heat capacity in this region. The rate of the temperature variation with the increase in the cooling time of the granule center is negligible and for a small decrease in the temperature is required a sufficiently long period of time. It is evidence, that the required cooling time and length of the cooling section should be chose after construction of the cooling curve. From Fig. 6 follows that the turbulence of the flow in a region of temperature to which the granule center should be cooled exerts small influence on the cooling time.

Similar calculations were performed for the case of cooling a spherical granule of 4 mm diameter in the water flow.

Figure 7 shows that in the case of the water cooling water temperature near the granule surface reduces almost to temperature T_{cm} at the distance less than 1 mm, i.e., within the slow-moving boundary layer around the granules. The cooling curves of the granule center and surface for η = 1 and η = 5 are pictured on Fig. 8 that shows that the flow turbulence exerts small influence on the cooling rate of a granule in water.

It can be explained by a high value of mass heat capacity and density of the cooling water. The flow turbulence exerts much greater influence on the cooling granule in air than in water. In the latter case, the cooling to a greater extent is limited by the internal problem, i.e., by the rate of heat transfer from a granule volume to its

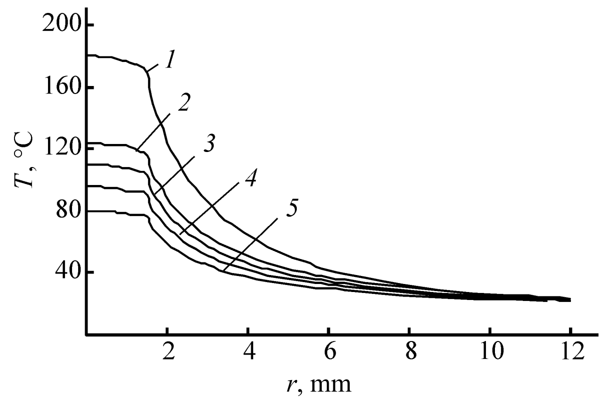

Fig. 4. Variation of temperature *t*, s, over the radius of granule cooled by air (η = 1): (*1*) 1; (*2*) 20; (*3*) 40; (*4*) 60; (*5*) 78.

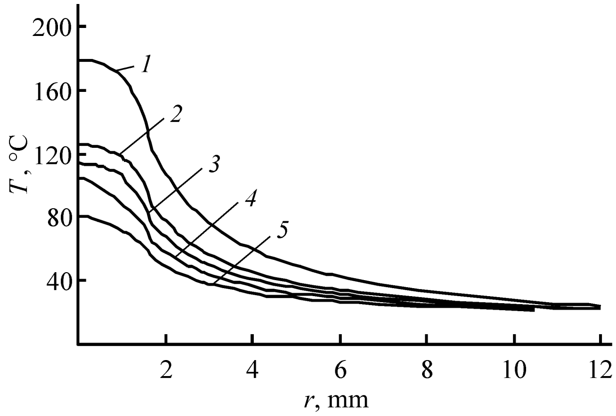

Fig. 5. Variation of temperature *t*, s, over the radius of granule cooled by air (η = 5): (*1*) 1; (*2*) 6; (*3*) 11; (*4*) 14; (*5*) 21.

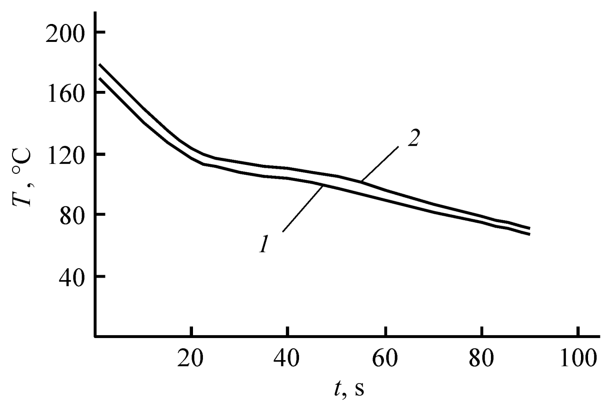

Fig. 6. Temperature of granule center as function of air cooling time when (*1*) η = 1 and (*2*) η = 5.

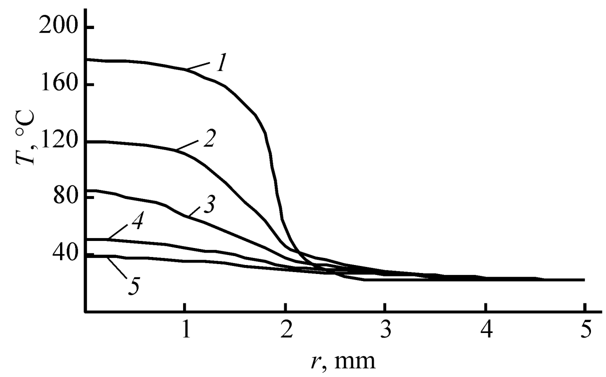

Fig. 7. Variation of temperature *t*, s, over the radius of granule in the course of its water cooling: (*1*) 1; (*2*) 7; (*3*) 14; (*4*) 21; (*5*) 27.

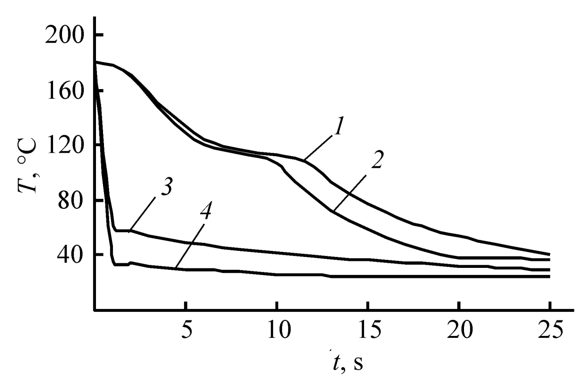

Fig. 8. (*1, 2*) Temperature of granule center and (*3, 4*) of its surface as function of water cooling time when (*1, 3*) η = 1 and (*2, 4*) η = 5.

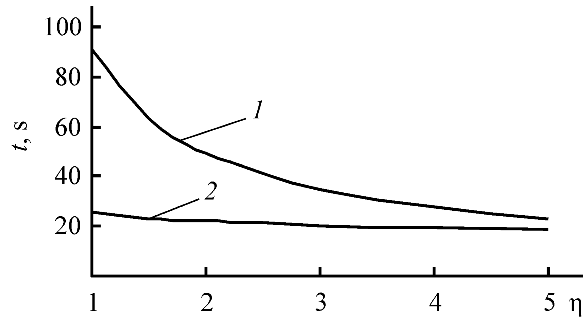

Fig. 9. Dependence of cooling time t of granule center on η: (*1*) air cooling; (*2*) water cooling.

surface (Fig. 9). However, it should be noted that in the numerical simulation the value of η was assumed the same for all flow and its variation over a thickness of the boundary layer was ignored.

For engineering calculations it is expedient to construct the cooling curve and choosing the cooling time in view of the reduction in the cooling rate over time, and for the guaranteed cooling in the case of selection of cooling devices the calculations can be done for values of η close to unity.

The numerical calculation of the cooling of strands of 4 mm diameter was performed also for LDPE of grade 15803-020 State Standard 16337-77. Initial data for calculation of the cooling the strands are: diameter of a strand d; mass output G_t, the amount of strands that come out of the head, n; initial temperature of strands T_0; temperature of cooling water T_{cm}; a final temperature of the strand center T_f; functions which describe dependency of thermophysical properties of a thermoplastics and water on temperature.

Figure 10 and 11 show curves of temperature variation over the strand radius for cases when water in the bath is stationary (i.e., the maximum possible relative velocity of the strand and water in the bath) and moves together with the strand (thus the relative velocity of strand and water in the bath is absent). Therefore, in the case of stationary water the thickness of the formed heat boundary layer is lesser and then an intensity of heat exchange increases. As it was noted these cases are the boundary, and the actual process of cooling corresponds to the conditions inside these boundaries

For comparison on Fig. 12 we presented the curves of temperature variation of the strand surface and center along the length of the cooling zone for these boundary cases. It is seen that significant deviations of the calculation results begin when the strand temperature reaches

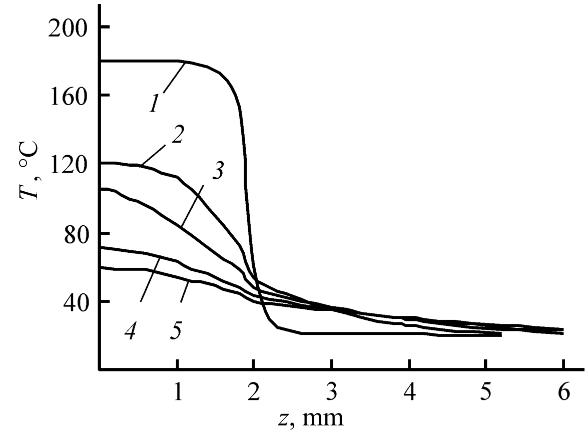

Fig. 10. Variation of temperature over the radius of strand in the case of unmovable water relative to cooling bath: (*1*) z = 0.05 m; (*2*) z = 2 m; (*3*) z = 4 m 14; (*4*) z = 6 m; (*5*) z = 7.15 m.

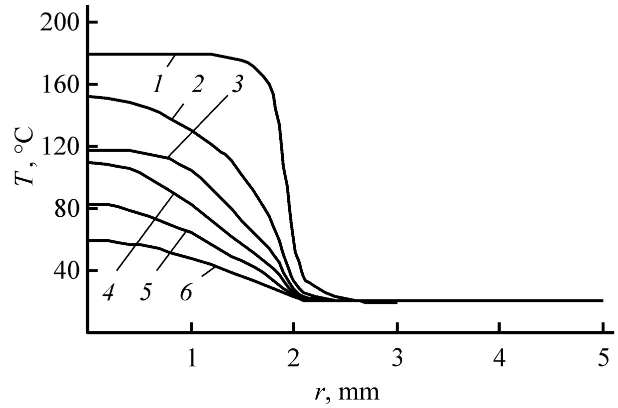

Fig. 11. Variation of temperature over the radius of strand in the case of movable water relative to cooling bath: (*1*) z = 0.05 m; (*2*) z = 1 m; (*3*) z = 2 m 14; (*4*) z = 4 m; (*5*) z = 5.1 m.

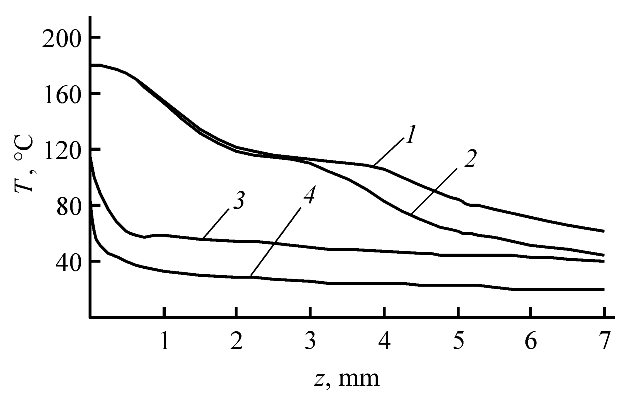

Fig. 12. Dependence of temperature of (*1, 2*) strand center and (*3, 4*) its surface on cooling time in the cases of (*1, 3*) unmovable water and (*2, 4*) movable water relative to cooling bath.

the melting temperature of the polymer, and then both curves are almost equidistant. The temperature of the strand surface in the case of the stationary water is close to water temperature. As in the case of the granule cooling the value of η in the calculations was taken constant though in fact these values change from unity on the strand surface to maximum in the flow core.

In the real cooling water in the cooling bath is inactive and the flow turbulence is practically unavailable. At high velocities the turbulence of the boundary layer is possible, but achieving such velocities in the granulation process is unlikely.

CONCLUSIONS

In cooling of granules in air the turbulence enhances the process only in its starting stage after which the intensity of the cooling reduces. In the cooling of granules in water the internal problem arises, thus the turbulence of water flow affects the process slightly.

Analysis of the results of the numerical simulation of the cooling of strands in the water bath shows that the real process of cooling is closer to the case where the water moves together with the strand, therefore, for engineering calculations it is expedient to use the algorithm for calculating the cooling of strands in the water flow which is motionless with respect to strands.

For enhancing the cooling in the cooling bath it is appropriate to install partitions (e.g., elastic to prevent damages of strands) with holes for strands disrupting the heated boundary water layer [10].

NOTATIONS

c mass heat capacity, J kg^{-1} K^{-1}; d strand diameter, m; F area, m^2; G mass flow, kg s^{-1}; i serial nimber; m number of points over strand cross-section; M weight, kg; Q heat flow, W; n number of strands; r coordinate directed along the granule or strand radius, m; R radius of granule, m; t time, s; T temperature, °C; V linear velocity, m s^{-1}; $\bar{x}$ mass fraction of component system; z coordinate directed along axis of strand, m; α heat transfer coefficient, W m^{-2} K^{-1}; η coefficient accounting for flow turbulence; λ heat conductivity, W m^{-1} K^{-1}; ρ density, kg m^{-3}.

INDEXES

0 denotes initial values; z, coordinate directed along axis of strand; w, cooling water; f final value; cm, cooling medium; t, thermoplastics; equiv, equivalent value.

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