За допомогою розробленої математичної моделі виконано аналіз процесу охолодження екструдованої полімерної плівки на барабані із внутрішнім охолодженням. Досліджено залежність середньої температури полімерної плівки за умови виходу барабана на стаціонарний (усталений) тепловий режим. Показано, що зі збільшенням товщини плівки та (або) зменшенням швидкості необхідно враховувати прогрів барабана під час його попередніх обертів до виходу на стаціонарний режим

Ключові слова: екструзія, плоска полімерна плівка, охолодний барабан, усталений тепловий режим, температурне поле

С помощью разработанной математической модели выполнен анализ процесса охлаждения экструдируемой полимерной плёнки на барабане с внутренним охлаждением. Исследована зависимость средней температуры полимерной плёнки при условии выхода барабана на стационарный (установившийся) тепловой режим. Показано, что с увеличением толщины плёнки и (или) уменьшением скорости необходимо учитывать прогрев барабана во время его предыдущих оборотов до выхода на стационарный режим

Ключевые слова: экструзия, плоская полимерная плёнка, охлаждаемый барабан, установившийся тепловой режим, температурное поле

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MODELING AND ANALYSIS OF THE PROCESS OF POLYMERIC FILM COOLING ON THE DRUM WITH A LIQUID COOLING AGENT

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1. Introduction

Thermoplastic polymers and plastic masses are mainly processed by extrusion into various products, many of which are flat and sleeve polymeric films for different purposes [1, 2].

In this case, one of the techniques of manufacturing flat polymeric films is the method of watering of polymer melt that is exiting form a plane-slot extrusion head on the cooled steel drum, partially immersed in a water bath [3–5]. The films, made in this way, are distinguished by the highest transparency and improved physical-mechanical properties, which is especially important for the packaging industry [6].

The main technological stages that affect the quality of the indicated polymeric films are [4, 5]:

– a process of preparation of polymer melt in the extruder;

– a process of orientation (pulling) of a semi-finished film along the section from the extrusion head to the cooling drum;

– a process of cooling a polymeric film on the drum.

However, while the processes of preparation of the melt and orientation of a semi-finished film have been sufficiently examined, research into cooling process of a polymeric film on the drum has not attracted enough attention. That is why a study of the process of processing a polymeric film on the drum taking into consideration its cooling system appears to be relevant.

2. Literature review and problem statement

An analysis of publications on the production of flat polymeric films [7–21] showed that majority of them are devoted to numerical and experimental modeling of separate stages of their production process. The focus on the process of preparation of polymer melt in the extruder [7–10], as well as the process of orientation of semi-finished film on the section from the extrusion head to the cooling drum [11– 16].

Thus, paper [7] explores mathematical modeling of three functional zones of the one-worm extruder: delivery, melting and homogenization. In this case, processing of polymer recycling in the indicated zones are considered separately from each other, which somewhat complicates analysis of the extrusion process as a whole. In article [8], an approach to integrated consideration of these zones, when each of them affects another zone and the extrusion process in general, is proposed, and in paper [9], the influence of a cooling agent in the cylinder of an extruder on a change in polymer parameters was studied. Research [10] considered various means of achieving high-quality polymer melt and products, derived from it, particularly plastic films.

In one of the earliest research [11], dedicated to analysis of orientation of a semi-finished film, the process is considered in isothermal approximation, which decreases accuracy of obtained results.

In [12, 13], the indicated process of orientation is explored in non-isothermal approximation, which greatly increases accuracy of calculations.

A similar approach is proposed in article [14], however the assumption was made that thermal-physical properties of the processed polymer do not depend on temperature, which causes a certain error in obtained results. A similar drawback is characteristic for work [15], in which thermo-physical properties of both processed polymer and ambient air are accepted as constant.

Paper [16], when studying the process of orientation of the melt, employs the Monte Carlo method, which allows prediction of obtaining of a polymeric polypropylene film of a certain structure, in particular development of crystalline areas in polymer.

Papers [17–21] address the process of a polymeric film cooling on the drum.

Thus, study [17] proposed the thermomechanical model of polymer melt orientation (semi-finished film) in the air between the extrusion head and the cooling drum as well as the process of film cooling on the drum. In this case, thermal conductivity of polymer is accepted as constant, and cooling process on the drum is calculated without taking into account the existence of a refrigerant in it.

Paper [18] contains results of research in cooling a film from polyamide 12 on the drum, in this case, temperature of the drum was accepted as constant, which is justified for a thin film with thickness of 80 μm, but is unacceptable for thick films.

In research [19], analysis of the effect of drum temperature on the structure of the resulting polymeric material was carried out, however, analysis of mutual influence of polymer and the drum on a change in their temperature was not considered.

Articles [20, 21] contain results of research in influence of temperature of the cooling drum on properties of a polypropylene film.

However, these papers do not consider the impact of refrigerant's parameters on achievement of a desired temperature on the working surface of the drum, which is of practical importance for obtaining high-quality polymeric films.

At the same time, in literature there are some papers, devoted to the problem of mathematical modeling of the process of cooling flat flexible materials on the cooling drum [4, 22, 23]. For this, two kinds of models of calculation of the specified process are used.

The first model implies provision of stable temperature on the surface of the drum. For this purpose, the following boundary conditions are assigned: on the outer surface of the drum – boundary conditions of the first kind, and on the free surface of a film – boundary conditions of the third kind [22]. The indicated model implies existence of a reliable system of thermal stabilization of the drum's working surface. This is possible only under conditions of cooling of thin films (usually up to 200 μm), as well as substantial consumption of cooling water in the drum, which is often economically impractical.

In accordance with the second model, one chooses the most effective heat carrier, moving in the drum, as well as its parameters that provide the required intensity of the cooling process [23]. To do this, it is necessary to solve the problem of film cooling with taking into account the parameters of the specified heat carrier. In this case, boundary conditions of the third kind are assigned on free outer surfaces of the drum's shell and polymeric film, and boundary condition of the fourth kind – in place of contact of the film with the drum.

In addition, it is assumed that in both cases the impact of a cooled film on the drum heating does not virtually exist. However, this approach to solution of the problem is acceptable only in the case of processing of thin films, moving at high velocity. On condition of cooling of thick films, as well as at low extrusion rate, when polymer gradually heats the drum and its temperature is stabilized only after several revolutions, these methods become virtually unacceptable.

3. The aim and objectives of the study

The aim of present research is to analyze the process in cooling of a flat polymeric film on the metal drum considering its heat exchange with both cooling fluid inside the drum and a specified polymeric film, cooled on its outer surface. This will make it possible to determine rational parameters of the cooling process (a type of cooling medium, its temperature and volumetric flow rate, as well as magnitude of cooling sections) for cooling a polymeric film to the desired temperature within certain time.

To accomplish the set goal, the following problems had to be solved:

– to develop a mathematical model of the process of cooling a flat polymeric film on the metal drum, considering its cooling system;

– to explore theoretically the process of cooling a flat polymeric film on the cooled metal drum, partially immersed in a water bath;

– to check experimentally the adequacy of the developed mathematical model;

– to formulate recommendations for rational implementation of the process of cooling a flat polymeric film on the metal drum.

4. Materials and methods of research into process of cooling a flat polymeric film on a drum

Polymer melt in the form of a film from the plane-slot extrusion head arrives at the receiving roller. From the roller, the film passes to the metal drum, the shell of which is cooled by water from the inner side. The drum is partially immersed in a bath with cooling water. After coming from the water bath, the film gets in contact with the ambient air, and at the location of the removable roller, it is removed from the drum (Fig. 1). Sometimes a take-up roller is replaced with an "air knife", that is, a narrow airflow pressing a film to the drum.

The film cooling zone on the drum can be divided into four sections. In each of these sections, heat exchange from the side of free surfaces of the film and the drum is carried out at boundary conditions of the third kind. In this case, heat exchange intensity depends on the type, temperature and motion mode of the cooling medium. Film cooling directly from the drum is carried out at boundary conditions of the fourth kind.

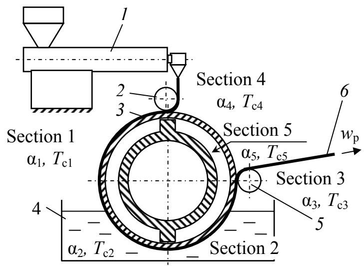

Fig. 1. Schematic of fabrication of a flat polymeric film with cooling on a metal drum that is partially immersed in a water bath: 1 — extruder; 2 — take-up roller; 3 — cooling drum; 4 — cooling bath; 5 — removing roller; 6 — polymeric film (α_i, T_{ci} are the heat transfer coefficient and temperature of cooling medium on the i-th section; w_p is the film velocity)

In the first section, film cooling from the free surface is carried out due to the contact with ambient air under conditions of free convection at temperature T_{c1} and heat transfer coefficient α_1. In the second section, the film interacts with the water in the cooling bath under conditions of convection at water temperature T_{c2} and heat transfer coefficient α_2. After exiting from water, the free surface of the film is cooled in the air at temperature T_{c3} and heat transfer coefficient α_3 under conditions of both free and forced (to remove water from the film surface) convection. At the beginning of the fourth section, the film is removed from the drum and the drum itself is, as a rule, blown over from the outer surface with hot air with temperature T_{c4} at heat transfer coefficient α_4 under conditions of forced convection (to remove residual water from the working surface of the drum).

We will also separate the fifth section, in which the inner surface of the drum' shell is cooled by water at temperature T_{c5} and at heat transfer coefficient α_5 under conditions of forced water motion inside the drum (usually in spiral channels).

In this case, temperature of the outer surface of the drum in the place of reception of a polymeric film usually gradually increases and is stabilized only after some time [4].

To calculate the process of film cooling, it is necessary to develop a mathematical model of the process taking into account heat transfer on each of these sections.

To do this, we will accept the following assumptions:

– there is no motion of film's layers relative to each other;

– dimensions of a film on the drum remain constant;

– there is no slip of a film on the surface of the drum;

– thermophysical properties of materials of a film and a drum, as well as of cooling agents (water and air) depend on temperature;

– there is no heat transfer along the axis of the drum (by width of a film).

It is expedient to consider the film cooling process on the drum in a cylindrical coordinate system. In this case, equation for non-stationary heat conductivity for a film and a drum's shell takes the form:

$$\rho_f(T)c_f(T)\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\lambda_f(T)\frac{\partial T}{\partial r}\right], \quad (1)$$

$$\rho_s(T)c_s(T)\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\lambda_s(T)\frac{\partial T}{\partial r}\right], \quad (2)$$

where ρ_f, c_f and λ_f are density (kg/m^3), mass isobaric thermal capacity (J/(kg·K)) and thermal conductivity (W/(m·K)) of material of a film (polymer) as function of temperature T, °C [24]; ρ_s, c_s and λ_s are density (kg/m^3), mass isobaric thermal capacity (J/(kg·K)) and thermal conductivity (W/(m·K)) of material of the drum's shell as function of temperature [25]; t is the time, s; r is the radius, m.

As the initial condition, we accept temperature distribution by thickness of the film and drum's shell at the beginning of the first section:

$$T_f\big|_{t=0}=T_{0f};\quad T_s\big|_{t=0}=T_{0s}. \quad (3)$$

Boundary conditions of the third kind:

– on 1–3 sections of film cooling:

$$\alpha_i(T)(T-T_{ci})+\lambda_f(T)\frac{\partial T}{\partial r}\bigg|_{r=(R_s+\delta)-0}=0, \quad (4)$$

where $i=\overline{1,4}$ is the numbers of sections of film cooling in accordance with Fig. 1; α_i is the heat transfer coefficient in the i-th section of film cooling, W/(m×K); R_r is the radius of the outer surface of the drum's shell, m; δ is the thickness of the film, m;

– in the fourth section

$$\alpha_4(T)(T-T_{c4})+\lambda_f(T)\frac{\partial T}{\partial r}\bigg|_{r=R_s-0}=0; \quad (5)$$

– in the fifth section

$$\alpha_5(T)(T-T_{c5})-\lambda_s(T)\frac{\partial T}{\partial r}\bigg|_{r=R+0}=0, \quad (6)$$

where R is the radius of the inner surface of the drum's shell, m.

Under conditions of industrial production, the cooling process is usually conducted on condition $T_{c1}=T_{c3}=T_{c4}$.

Boundary conditions of the fourth kind at the boundary of the contact of a film with the outer surface of the drum's surface:

$$T_s\big|_{r=R_s+0}=T_s\big|_{r=R_s-0};$$

$$\lambda_f(T)\frac{\partial T}{\partial r}\bigg|_{r=R_s+0}=\lambda_s(T)\frac{\partial T}{\partial r}\bigg|_{r=R_s-0}. \quad (7)$$

Heat transfer coefficient α_5 from the inner surface of the shell to the cooling fluid (water) inside the drum is calculated by criterial heat transfer equations at forced longitudinal fluid motion in the channels [26].

For a developed turbulent flow ($Re_5 \geq 10^4$), it is possible to use equation

$$Nu_5=0.021Re_5^{0.8}Pr_5^{0.43}\left(\frac{Pr_5}{Pr_w}\right)^{0.25}, \quad (8)$$

for laminar flow ($Re_5 \leq 2200$)

$$Nu_5=0.17Re_5^{0.33}Gr_5^{0.1}Pr_5^{0.43}\left(\frac{Pr_5}{Pr_w}\right)^{0.25}, \quad (9)$$

and for transient mode ($2200 < Re_5 < 10^4$)

$$\mathrm{Nu}_5 = B_0 \,\mathrm{Pr}_5^{0.43} \left(\frac{\mathrm{Pr}_5}{\mathrm{Pr}_w} \right)^{0.25}, \qquad (10)$$

where $B_0 = f(\mathrm{Re})$ (Table 1).

Table 1

Values of coefficient B_o depending on Re

Re×10^{-3}	2.2	2.3	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0
B_0	2.2	3.6	4.9	7.5	10.0	12.2	16.5	20.0	24.0	27.0	30.0	33.0

In equations (8)–(10), the following notations are accepted:

$$\mathrm{Re}_5 = \frac{w_{c5} d_5}{\nu_{c5}^2}$$

is the Reynolds criterion;

$$Gr_5 = \frac{g d_5^3}{\nu_{c5}^2} \beta_{c5} \left(T_w - T_{c5} \right)$$

is the Grashof's criterion;

Pr_5, Pr_w are the Prandtl criterion at average temperature of cooling fluid and temperature of the inner side of the drum's shell ($\mathrm{Pr}_5 = \frac{c_{pc5}\nu_{c5}\rho_{c5}}{\lambda_{c5}}$);

β_{c5} is the temperature coefficient of cooling fluid, 1/K;

ν_{c5} is the kinematic viscosity of cooling fluid, m^2/s;

c_{pc5} is the isobaric mass thermal capacity of cooling fluid, J/(kg·K);

ρ_{c5} is the density of cooling fluid, kg/m^3;

λ_{c5} is the thermal conductivity of cooling fluid, W/(m·K);

w_{c5} is the velocity of cooling fluid in the drum's channel, m/s;

T_w is the temperature of the wall of the channel, °C;

d_5 is the equivalent diameter of the drum's channel, m;

g is the free fall acceleration, m/s^2.

Heat transfer coefficient from drum's shell to cooling fluid is derived from expression for the Nusselt criterion:

$$\alpha_5 = \frac{Nu_5 \lambda_{c5}}{d_5}, \qquad (11)$$

where λ_{c5} is the thermal conductivity of cooling liquid, W/(m·K).

Thermophysical properties of cooling fluid in equations (8)–(11) are calculated at its average temperature.

To determine heat transfer coefficients α_1–α_4 from free surfaces of the film and the drum to air and water in the cooling bath, it is possible to use criterial equations of heat transfer from a rotating cylinder [27].

Each heat transfer coefficient α_1–α_4 (W/(m^2·K)) is determined as the sum of coefficients of heat transfer by radiation α_{rad} and convection α_{conv}

$$\alpha = \alpha_{rad} + \alpha_{conv}. \qquad (12)$$

Coefficient of heat transfer by radiation is calculated from formula

$$\alpha_{rad} = 5.67 \cdot 10^{-8} \varepsilon_{f(s)} \frac{T_{f(s)}^4 - T_{ci}^4}{T_{f(s)} - T_{ci}}, \qquad (13)$$

where $\varepsilon_{f(s)}$ is the blackness degree of a polymeric film and the drum's surface; $T_{f(s)}$ is the temperature of a polymeric film and outer surface of the drum, K.

Coefficient of heat transfer by convention α_{conv} is determined as follows.

If heat transfer takes place under conditions of free convection ($\mathrm{Re} \le \sqrt{\mathrm{Gr}\cdot\mathrm{Pr}}$), the value of the Nusselt criterion Nu in the appropriate section of cooling (sections 1–4) is calculated from critical equation

$$\mathrm{Nu} = 0.456 \left(\mathrm{Gr} \cdot \mathrm{Pr} \right)^{0.25}, \qquad (14)$$

where Gr and Pr are the Grashof's and the Prandtl criteria.

At values of $\mathrm{Re} \le 5 \cdot 10^4$, heat exchange takes place under conditions of joint influence of free and forced convection.

$$\mathrm{Nu} = 0.18 \left[\left(0.5\mathrm{Re}^2 + \mathrm{Gr} \right) \mathrm{Pr} \right]^{0.315}. \qquad (15)$$

At values of $\mathrm{Re} > 5 \cdot 10^5$, heat exchange takes place under conditions of forced convection.

$$\mathrm{Nu} = \frac{\mathrm{Re}\,\mathrm{Pr} \sqrt{0.5 f_D}}{5\mathrm{Pr} + 5\ln\left(3\mathrm{Pr} + 1\right) + \sqrt{0.5 f_D} - 12}, \qquad (16)$$

where f_D is the coefficient, the value of which is determined depending on magnitude $B = \mathrm{Re}\sqrt{f_D}$:

$$B = -1.828 + 1.77 \ln B \ \text{ at } \ B \ge 950;$$

$$\mathrm{Re}/B = -3.68 + 2.04 \ln B \ \text{ at } \ B < 950.$$

In dependences (16)–(18), the following notations are accepted:

$$\mathrm{Re} = \frac{4 R_r w_p}{\nu_{ci}}; \ Nu = \frac{2\alpha_i R_r}{\lambda_{ci}};$$

$$Gr = \frac{8 g R_r^3}{\nu_{ci}^2} \beta_{ci} \left(T_{r(p)} - T_{ci} \right); \ \ \mathrm{Pr} = \frac{c_{pci}\nu_{ci}\rho_{ci}}{\lambda_{ci}},$$

where β_{ci} is the temperature coefficient of medium, 1/K; ν_{ci} is the kinematic viscosity of medium, m^2/s; c_{pci} is the isobaric mass thermal capacity of medium, J/(kg·K); ρ_{ci} is the density of medium, kg/m^3; λ_{ci} is the thermal conductivity of medium, W/(m·K).

Thermophysical properties of media (air and water in water bath) are selected by average temperature

$$T = \left(T_{\mathrm{ci}} + T_{\mathrm{r(p)}} \right) / 2.$$

5. Results of numerical modeling of process of cooling of a flat polymeric film on the drum

Theoretical and experimental studies were conducted for the industrial production line, designed and manufactured by JSSPC "Bolshevik" (Kyiv, Ukraine). Parameters of cooling device of the line are given in Table 2.

Solution of equations of non-stationary heat conductivity for a film and a drum's shell (1) and (2) under selected initial conditions of form (3) and boundary conditions of form (4)–(9) was performed by the method of finite differences in the implicit scheme [4].

Table 2

Parameters of cooling of a polymeric film on the drum

Parameter	Value
Temperature of water in the drum, °C	10
Water velocity in the drum, m/s	0.5
Temperature of water in cooling bath, °C	15
Temperature of ambient air, °C	20
Temperature of air for blowing over the drum after a polymeric film's removal from it, °C	150
Velocity of air for blowing over the drum, m/s	0.5
Velocity of polymeric film, m/s	0.1; 0.2; 0.3
Thickness of polymeric film, mm	0.5; 1.0; 1.5
Original temperature of a polymeric film, °C	280
Outer radius of drum's shell, m	0.5
Inner radius of drum's shell (outer radius of drum's channel), m	0.485
Inner radius of drum's channel, m	0.475
Pitch of spiral drum's channel, m	0.048
Width of protrusion of drum's channel, m	0.004
Material of drum's shell	stainless steel
Angle of coverage of drum by a film from the place of its entrance to the drum to entrance to the water bath, ...°	120
Angle of coverage of drum by a film from the place of its entrance to the drum to exit from water bath, ...°	240
Angle of coverage of drum by a film from the place of its entering the drum to the place of removal from the drum, ...°	270

To determine the moment of the process settling in the stationary mode, temperature distribution was calculated by polymer and the drums' shell within its full revolution. After this, the calculated temperature distribution was compared with corresponding temperature distribution after the previous drum revolution. In this case, the process was considered steady if temperature difference at a certain point of the shell on the current and previous revolutions of the drum did not exceed 0.1 °C.

Fig. 2–4 show results of calculation of the average temperature of a flat polypropylene film of thickness of 1.5 mm depending on the angle of rotation of the cooling drum at different film velocities. Polypropylene was selected as material of the film, since most studies were conducted specifically for this polymer, the share of which in world consumption of polymers is about 25 % [28].

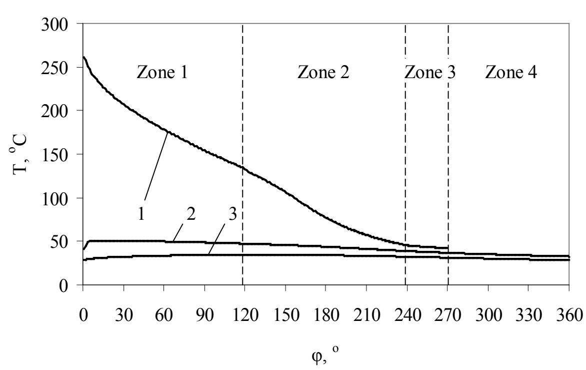

Fig. 2. Dependence of average temperature of polypropylene film of thickness of 1.5 mm (1), temperatures of surface of drum's shell (2) and average temperature of drum's shell (3) on angle of drum's turn φ at film velocity 0.1 m/s

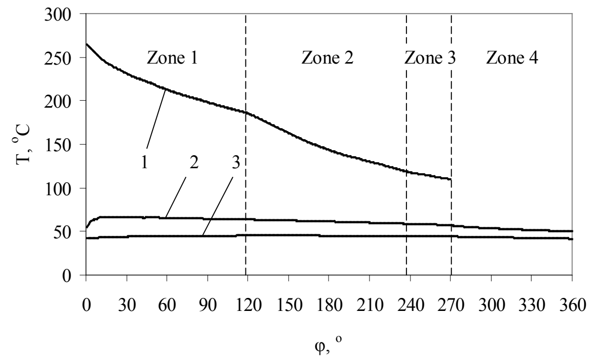

Fig. 3. Dependence of average temperature of polypropylene film of thickness of 1.5 mm (1), temperatures of surface of drum's shell (2) and average temperature of drum's shell (3) on the angle of drum's rotation φ at film velocity 0.2 m/s

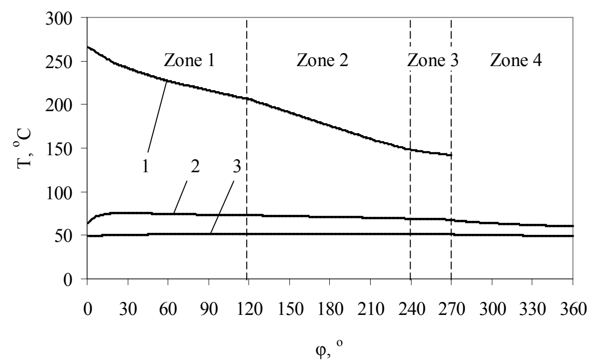

Fig. 4. Dependence of average temperature of polypropylene film of thickness of 1.5 mm (1), temperatures of surface of drum's shell (2) and average temperature of drum's shell (3) on the angle of drum's rotation φ at film velocity 0.3 m/s

In dependences of average film temperature on the arc of its contact with the drum's shell (Fig. 2–4) it is possible to separate three areas with various cooling intensity, corresponding to three sections of drum cooling (Fig. 1). Maximum intensity of film cooling is observed in zone 2, where the film from the outer surface side is cooled by water. Film cooling intensity in zone 3 is minimal, because the outer surface of the already sufficiently cooled surface interacts with the ambient air. In this case, cooling intensity is gradually aligned at an increase in film velocity throughout entire arc of its contact with the drum.

Fig. 5 shows dependence of average temperature of a film of thickness 1.5 mm on the arc of its contact with the drum on film velocity. The higher velocity, the higher average film temperature, in addition, film velocity (and performance of the technological line) is limited by condition of solidification of material of the film on the drum.

Fig. 6 shows dependence of average temperature of the film, moving at a constant velocity, on thickness of the film. In this case, the diagrams are similar to the diagrams, shown in Fig. 5. However, for relatively thin films, the main cooling section is zone 1, and with an increase in thickness of the film, the role of zone 2 increases. In this case, zone 3 plays the role of stabilization of average temperature of a film and alignment of temperature of the film by its thickness rather than the role of a cooling section. At cooling thin films in zone 3, their temperature can even slightly increase (on the one hand, due to contact with heated shell of the drum, on the other hand, due to decrease in cooling intensity in the air).

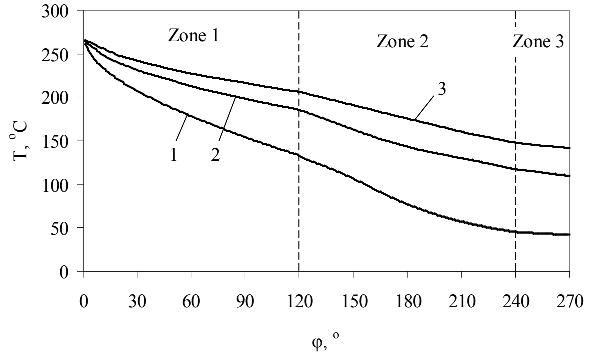

Fig. 5. Dependence of average temperature *T* of polypropylene film of thickness 1.5 mm on film velocity and the angle of drum's rotation φ: 1 – 0.1 m/s; 2 – 0.2 m/s; 3 – 0.3 m/s

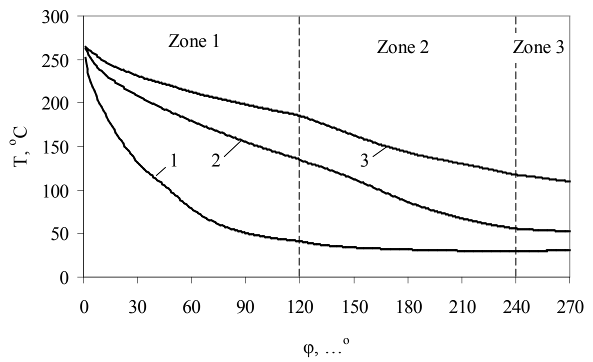

Fig. 6. Dependence of average temperature *T* of polypropylene film (film motion velocity 0.2 m/s) on film's thickness and the angle of drum's rotation φ: 1 – 0.5 mm; 2 – 1.0 mm; 3 – 1.5 mm

Fig. 7 shows temperature distribution *T* by thickness δ of drum's shell and a polymeric film in place of its removal from the drum at the fixed film's thickness and its various velocities, and Fig. 8 – at fixed film velocity and its various thickness.

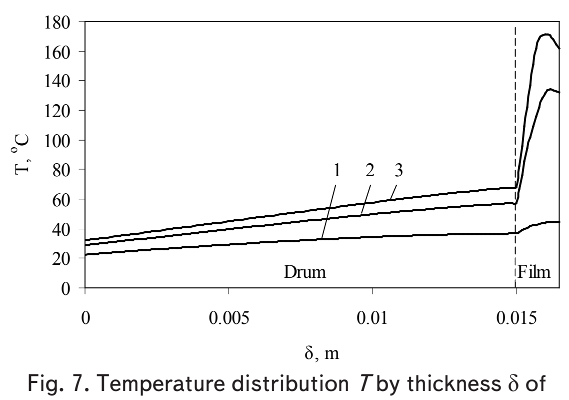

Fig. 7. Temperature distribution *T* by thickness δ of drum's shell and polymeric film of thickness of 1.5 mm in the place of its removal from the drum at film velocity: 1 – 0.1 m/s; 2 – 0.2 m/s; 3 – 0.3 m/s

It is seen from dependences that non-uniformity of temperature by thickness of the film increases with an increase in its velocity, and at constant film velocity – with an increase in its thickness.

The adequacy of the developed mathematical model was tested by comparing calculated and measured temperatures of the surface of the drum's shell in place of polymer melt's arrival on it (Fig. 9, 10). The specified temperature was measured using the pyrometer ThermoPoint TPT 62, manufactured by Agema Infrared Systems AB (Sweden).

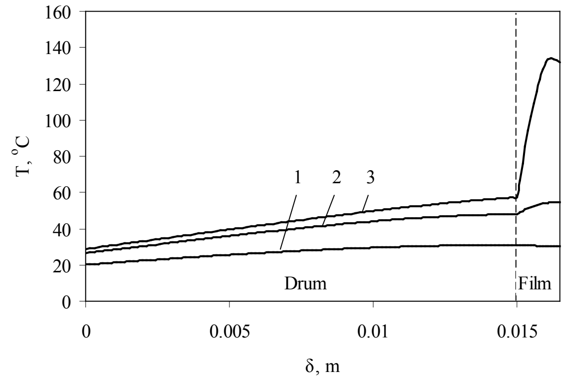

Fig. 8. Temperature distribution *T* by thickness δ of drum's shell and polymeric film in place of its removal from the drum at film velocity of 0.2 m/s and film thickness of: 1 – 0.5 mm; 2 – 1.0 mm; 3 – 1.5 mm

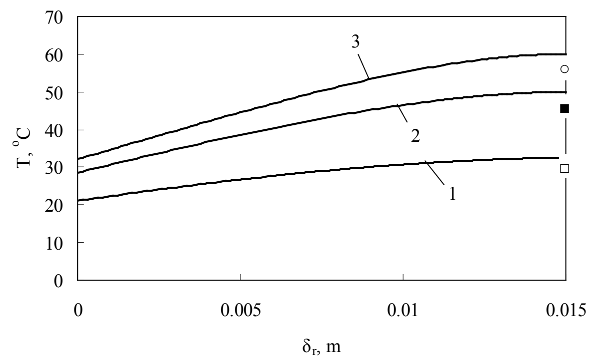

Fig. 9. Dependence of calculated initial temperature distribution *T* by thickness of drum's shell δ_r at steady mode of cooling of film, moving at different velocities (1 – 0.1 m/s; 2 – 0.2 m/s; 3 – 0.3 m/s; film thickness is 1.5 mm), as well as corresponding experimental values of the initial temperature of the surface of the drum's shell (1 – □; 2 – ■; 3 – ○)

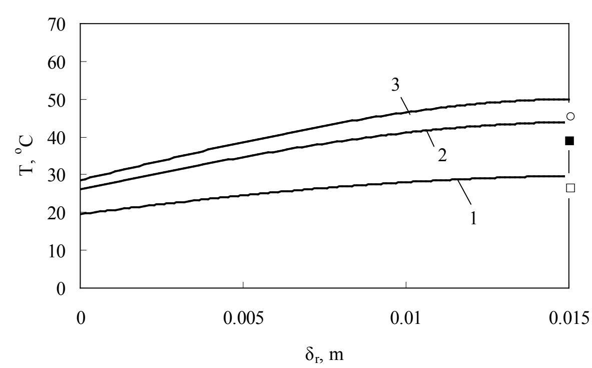

Fig. 10. Dependence of calculated initial temperature distribution *T* by thickness of drum's shell δ_r at steady mode of cooling a film of different thickness (1 – 0.5 mm; 2 – 1.0 mm; 3 – 1.5 mm; film motion velocity 0.2 m/s), as well as corresponding experimental values of initial temperature of surface of drum's shell (1 – □; 2 – ■; 3 – ○)

Divergence of calculated and measured values of the surface temperature of the drum's shell in the place of arrival of polymeric material on it in most cases was within 6–8 %. In this case, measured temperature values were slightly lower than calculated ones. This can probably be explained, above all, by additional cooling of the drum's shell from its sides.

6. Discussion of results of numerical modeling of the process of cooling of a flat polymeric film on the drum

A comparative analysis of the obtained results showed that results of numerical modeling are satisfactorily consistent with experimental data. The maximum difference of the calculated and measured values of temperature in the drum's shell in the place of entering of melt polymer on it amounted to 8.7 %, which is quite acceptable for performing engineering calculations.

As a result of research, it was found that the surface temperature of the drum's shell can significantly exceed the temperature of the refrigerant in it. Thus, the difference of temperature between the shell's surface and the refrigerant in the drum at cooling a film of thickness of 1.5 mm reaches 40–65 °C (Fig. 2–4). At an increase in thickness of the cooled polymeric material, the specified temperature difference will be even more. When using well-known calculation methods, temperature of the drum's shell is usually accepted as equal to the temperature of the refrigerant in it. However, this assumption can be used only at cooling thin films, moving at low velocities (Curve 1 in Fig. 8).

It is preferable to provide such cooling mode, in which difference of temperature by thickness of a film at its removal from the drum would not exceed the permissible value.

While manufacturing a film, it is desirable that at the point of separation from the drum, the polymer temperature should be below the temperature of its hardening, which for polypropylene is equal to 150...170 °C. Thus, the cooling mode, shown in Fig. 7, does not meet this condition and may not provide the required properties of the obtained film. At the same time, application of the known techniques in this case will prove the possibility of film cooling to the required temperature, which in practice will lead to output of defective products.

Thus, for analysis of high-speed technological lines for production of thick films and other roll polymeric materials (of thickness more than 500 μm), it is necessary to use boundary conditions of the third kind on the inner side of the shell of the cooling drum.

It is planned to perform subsequent research for analysis of systems of heating and thermal stabilization of polymeric films and other roll materials in drum-type devices as a part of technological lines both based on extruders and on calenders.

7. Conclusions

A mathematical model of the process of cooling an extruded flat polymeric film on the metal drum, partially immersed in a water bath, was developed. The model includes differential equations of non-stationary thermal conductivity for a film and the drum's shell, as well as correspondent initial and boundary conditions. Boundary conditions take into account the influence of the drum's cooling system, as well as of environment on temperature of the film and the drum. To determine the moment of the shell's settling under steady thermal mode, sequential refinement of the temperature field of the drum's shell in the place where a polymeric film enters it, was used.

The process of cooling a flat polymeric film on the cooled drum, immersed in the water bath, was investigated theoretically. Results of the study showed that the use of the developed model allows taking into account warm-up of the drum's shell and a temperature rise of its outer surface. It was shown that ignoring the fact of the drum's warm-up can cause insufficient cooling of a polymeric film and a possible decrease in its quality.

Experimental research in surface temperature of the drum's shell proved adequacy of the developed mathematical model.

The developed mathematical model can be used for analysis of the cooling process not only of a film, but also of the roll polymeric materials, obtained by both extrusive and rolling-calender method.

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