MATERIAL MOVEMENT WITHIN A SINGLE-SCREW EXTRUDER
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ДВИЖЕНИЕ МАТЕРИАЛА В ОДНОШНЕКОВОМ ЭКСТРУДЕРЕ

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ABSTRACT
In present-day economic conditions, extrusion is one of the advanced feedstuffs and food production processes involving intensive manifold heat and force action. During extrusion, the main function is performed by a compression mechanism which includes a forcing screw unit built into the cylinder (cowling). The forcing mechanism performs the task of transferring material while concurrently compressing it up to a required pressure and increasing the material's temperature due to compression and friction against the cowling's sides. The temperature affects the quality of the resulting product. Thus, the research aims at obtaining a heat balance equation to optimize the extrusion process and the operating parameters of the extruder itself.

РЕЗЮМЕ
В современных экономических условиях одним из прогрессивных технологических процессов в производстве кормов и продуктов питания является экструдирование, при котором материал подвергается мощному комплексному тепловому и силовому воздействию. Главную функцию при экструдировании выполняет прессовочный механизм, который включает в себя нагнетающий шнековый блок, вмонтированный в цилиндр (кожух). Задача прессовочного механизма, перемещать, одновременно сжимая материал до необходимого давления, повышая температуру от сжатия и трения о стенки кожуха. Температура влияет на качество получаемой продукции. Таким образом исследования направлены на получение уравнения теплового баланса с целью оптимизации процесса экструзии и рабочих параметров самого экструдера.

INTRODUCTION
In present-day economic conditions, extrusion is one of the advanced feedstuffs and food production processes involving intensive manifold heat and force action. During extrusion, the main function is performed by a compression mechanism which includes a forcing screw unit built into the cylinder (cowling). The forcing mechanism performs the task of transferring material while concurrently compressing it up to a required pressure and increasing the material's temperature due to compression and friction against the cowling's sides.

When analyzing material movement within the screw, the authors use the scientific abstraction approach, i.e., instead of using an actual material body they use its simplified model. This approach uses two main techniques. In the first case, the actual arrangement is replaced by movement of the material within "a channel with a floating lid", or between parallel planes with one of the planes moving *(Sagirov. S.N., 2011).*

After that, the Navier-Stokes equation is resolved for the case of movement of a Newtonian liquid, together with the continuity equation under various assumptions and with various representations of the obtained solution *(Barsukov V.G., Grakholskaya E.V., Volk O.S., et al., 2009; Mikulionok I., Gavva O., Kryvoplias-Volodina L., et al., 2018).* Further development of this technique lies in the analysis of the extruded material which has properties different from Newtonian liquid, and the problem is viewed as a one-dimensional, two-dimensional, and even three-dimensional problem *(Didyk T.A., 2005; Kryuchkova L.G., Dotsenko S.M., Burmaga A.V., Cheredov A.V., et al., 2014).*

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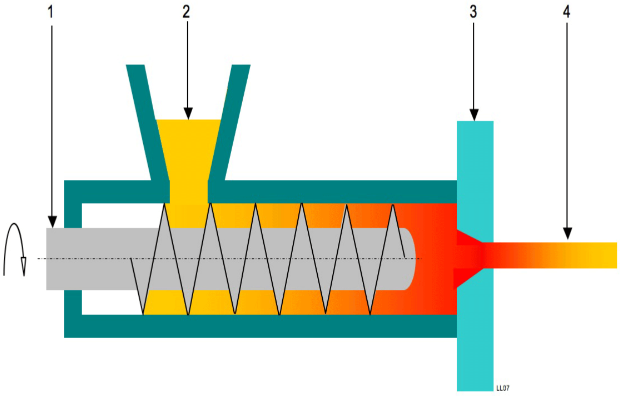

Fig. 1 – Extruder operation process flow diagram
1 – effector (screw); 2 – loaded raw material; 3 – forming die; 4 – finished product

MATERIALS AND METHODS

The second technique views the compressed material as a flowing medium (either continuous or granular) throughout the screw's length *(Adigamov K.A., Chernenko A.V., 2010; Zubkova T.M., Kolobov A.N., 2015).* An extension of this technique is an approach which attributes both flowing and pseudoplastic body properties to the material *(Ostrikov A.N., Ospanov A.A., Vasilenko V.N., et al., 2019).* In this case, the use of the continuous model of a flowing medium is more advisable since the differential body equilibrium equations are similar to the equation of the theory of elasticity and plasticity. This approach, when used in analyzing stress condition of the compressed mass, allows to substitute all the actual forces acting on specific particles at points of contact with other particles with assumptive forces distributed uniformly along an arbitrary section of the material *(Wu M., Sun C.H., Bi F. et al., 2019).* Therefore, this makes it possible to make a transition from a material particle to a system of particles that collectively make up the flowing medium.

In our view, the first technique is appropriate when a material which is moving within the compression area is in viscous-flow state. The second technique is optimal for theoretical description of areas of loading, transportation, and compression (melting) where the working pressure is maintained.

In his research, *Grigoryev A.M.* developed a system of motion equations of a material particle resting on the surface of an inclined screw and pressed against its wall (Fig. 2) *(Evstratova N.N., Apachanov A.S., Grigoryev V.I., 2009)*:

$$\begin{cases} N_1\cos\alpha - f_1 N_1 \sin\alpha - ma\left(\frac{d^2\varphi}{dt^2}\right) - G\cos\gamma - f_2 N_2 \sin\beta = 0 \\ G\cos\gamma\sin\varepsilon + f_2 N_2\cos\beta - f_1 N_1\cos\alpha - N_1\sin\alpha - mr\left(\frac{d^2\varphi}{dt^2}\right) = 0 \\ G\sin\gamma\cos\varepsilon + mr\omega_0^2 + mr\left(\frac{d\varphi}{dt}\right)^2 - N_2 - 2mr\omega_0\left(\frac{d\varphi}{dt}\right) = 0 \end{cases} \quad (1)$$

where:

N_1 is the normal response of the inclined plane, [N];
f_1 - the coefficient of friction of the material against the screw blade;
m - the weight of the material element [kg];
α - the elevation angle of the screw section of the screw [rad];
ω_0 - the angular rate of rotation of the screw [s^{-1}];
G - the weight of the material element [N];
γ - the angle of inclination of the screw shaft axis to the vertical axis [rad];
N_2 - the normal response of the cowling [N];
f_2 - the coefficient of friction of the material against the cowling wall;
φ - the angle of deflection of a particle when rotating at a constant rate of angular rotation ω_0;
$\frac{d\varphi}{dt}$ - the rate of angular rotation of relative movement of a material point, [s^{-1}];
ε - the angle which determines the position of the point against the vertical plane; $\varepsilon = \omega_0 t + (-\varphi)$;
r - the outer radius [m];
$mr\left(\frac{d^2\varphi}{dt^2}\right)$ - the tangential inertia force [N];
$mr\omega_0^2$ - the centrifugal inertia force of the translation motion [N];

$mr\left(\frac{\mathrm{d}\varphi}{\mathrm{dt}}\right)^2$ - the centrifugal inertia force of the relative movement [N];
$2mr\omega_0\left(\frac{\mathrm{d}\varphi}{\mathrm{dt}}\right)$ - the Coriolis force [N];
$ma\left(\frac{\mathrm{d}^2\varphi}{\mathrm{dt}^2}\right)$ - the axial inertia force [N].

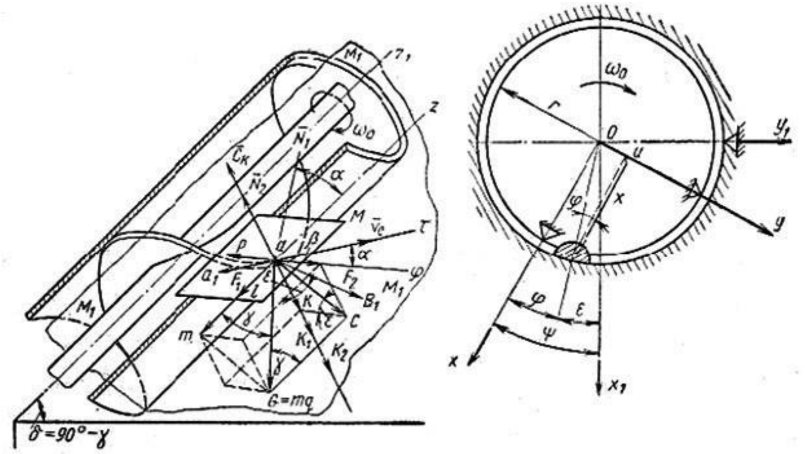

Fig. 2 – The diagram of forces applied to a material point which moves along the screw, as well as of the locations of the moving and fixed reference systems

The author notes that during the screw operation, the period of non-steady movement is minute, lasting several fractions of a second to several seconds, after which the movement steadies (this is characterized by stable values of average axial velocity and absolute angular rate of rotation ω.

Thus, during the steady mode of operation of the screw with $\frac{\mathrm{d}\varphi}{\mathrm{dt}} = \mathrm{const}$ and $\frac{\mathrm{d}^2\varphi}{\mathrm{dt}^2} = 0$, when the rotation axis of the screw is horizontal (i.e., γ = 90°), the equation system (1) could be written as follows:

$$\begin{cases} N_1\cos\alpha - f_1N_1\sin\alpha - f_2N_2\sin\beta = 0 \\ f_2N_2\cos\beta - f_1N_1\cos\alpha - N_1\sin\alpha = 0 \\ G\cos\varepsilon + mr\omega_0^2 - N_2 - 2mr\omega_0\left(\frac{\mathrm{d}\varphi}{\mathrm{d}t}\right) = 0 \end{cases} \tag{2}$$

After the reduction and translation, this gives us the following:

$$N_2 = m\left(g\cos\varepsilon + r\omega_0^2 - 2r\omega_0^2\frac{\operatorname{ctg}\alpha - f_1}{\operatorname{ctg}\alpha + \operatorname{tg}\alpha}\right) \tag{3}$$

$$N_1 = m\left(g\cos\varepsilon + r\omega_0^2 - 2r\omega_0^2\frac{\operatorname{ctg}\alpha - f_1}{\operatorname{ctg}\alpha + \operatorname{tg}\alpha}\right)\frac{f_2\cos\beta}{f_1\cos\alpha + \sin\alpha} \tag{4}$$

Based on the expressions (3) and (4), forces of friction of the material against the screw and cowling surfaces, respectively, may be determined as follows:

$$F_1 = m\left(g\cos\varepsilon + r\omega_0^2 - 2r\omega_0^2\frac{\operatorname{ctg}\alpha - f_1}{\operatorname{ctg}\alpha + \operatorname{tg}\alpha}\right)\frac{f_2\cos\beta}{\cos\alpha + \sin\alpha} \tag{5}$$

$$F_2 = m\left(g\cos\varepsilon + r\omega_0^2 - 2r\omega_0^2\frac{\operatorname{ctg}\alpha - f_1}{\operatorname{ctg}\alpha + \operatorname{tg}\alpha}\right)f_2 \tag{6}$$

Movement of the compressed material along the screw chamber of the screw, its compression and liberation of moisture occurs due to the difference of the positive force of friction F_2 and negative force of friction F_1 *(Bostandzhiyan S.A., Stolin A. M., 1965; Roland W., Marschik C., Krieger M. et al., 2019).*

In accordance with the expressions (5) and (6), the difference of the effective and the negative force of friction could be written as follows:

$$\Delta F = F_2 - F_1 = mf_2\left(g\cos\varepsilon + r\omega_0^2 - 2r\omega_0^2\frac{\operatorname{ctg}\alpha - f_1}{\operatorname{ctg}\alpha + \operatorname{tg}\alpha}\right)\left(1 - \frac{\cos\beta}{\cos\alpha + \sin\alpha}\right) \tag{7}$$

An analysis of the resulting expression makes is possible to conclude that the friction force difference affecting the material particle depends on the weight of the compressed material m, travel time parameters of the screw operation (the angular rate of rotation ω_0 and the angle β), geometric parameters of the screw (the diameter of the screw, the elevation angle of the screw section α). The difference in friction forces is also affected by the physical and mechanical properties of the transported material, the extrusion machine's screw and ring (the coefficients of friction f_1 and f_2). It should be noted that the dependency on the angular rate of rotation has an exponential form *(Wu M., Sun C.H., Bi F. et al., 2018).*

Let us consider the dependency of the friction force difference ΔF on the travel time property of the screw operation ω_0. In order to exclude the effect of particle weight on the final value, let us analyze the specific difference of friction forces $\Delta F / m$.

Let us determine the critical value of angle β using the following formula *(Kryuchkova L.G., Dotsenko S.M., Burmaga A.V., et al., 2014):*

$$\beta = 90° - (\alpha + \varphi_1) \tag{8}$$

where:

φ_1 is the angle of friction of the transported material against the screw metal [degrees].

Based on the results of analysis of the resulting graph (Fig. 3) is could be seen that at the considered interval of angular rate of rotation ω_0 = 1…10 s^{-1} (the value of the screw rotation rate interval n = 9.6…95.5 min^{-1}), with the increase of ω_0 the effective difference of friction forces F_1 and F_2 decreases, while at the angular rate of rotation of $\omega_0 \approx 9.3$ s^{-1} (n = 88.8 min^{-1}) their values become the same. During the following increase ω_0, the difference between friction forces increases, on the contrary, towards F_1. Thus, the increase of the screw rate of rotation impairs the effectiveness of the processes of compression of the transferred material and squeezing of the liquid fraction. This may result in a situation where the movement of the material relative to the screw stops and instead the material rotates together with the screw.

The optimal difference of the specific friction forces ΔF is comparatively small. This difference may be improved by making the interior surface of the screw cowl ribbed *(Ostrikov A.N., Platov K.V., Sokolov I.Y., 2004).*

This would result in a different friction factor f_2. As can be seen from the diagram, changes of the friction factor within the range of f_2 = 0.4 to f_2 = 0.5 result in the increase of specific friction force difference by 25%, while changing it from f_2 = 0.5 to f_2 = 0.6 results in a 20% increase, with the screw angular rate of rotation of ω_0 = 1 s^{-1}. With the increase of the angular rate of rotation, the effectiveness achieved by increased friction factor f_2 reduces, and at ω_0 = 9.3 s^{-1} levels out completely. Thus, it is advisable to make the interior surface of the screw cowling ribbed if the extruder's screw operates at low rotation rates.

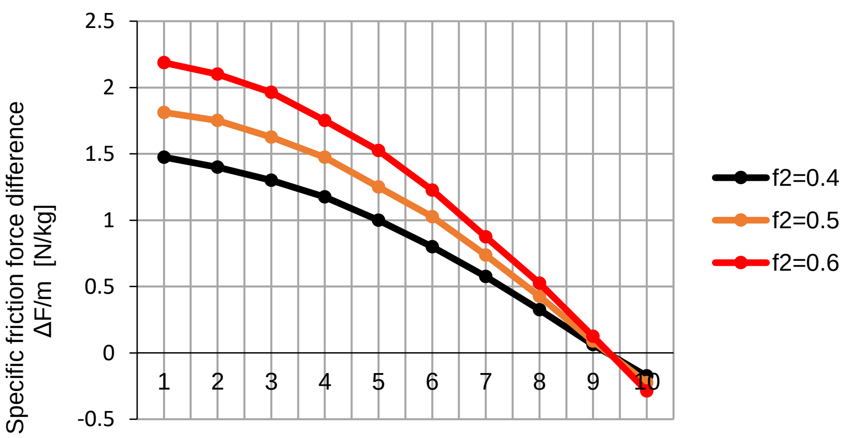

Fig. 3 – The diagram of dependency of friction forces of transported material at the cowling and screw surfaces on the angular rate of rotation of the screw at different friction coefficient f_2 values

Apart from affecting the advance of the material inside the extruder, the friction forces also affect the rate of heat generation within the extruded material *(Rauvendaal K., 2008*) as follows:

$$\dot{Q} = F_{\text{tr}} \cdot \Delta\upsilon \tag{9}$$

where:

$\dot{Q}$ is the rate of heat generation [W/s];
F_{tr} - the force of friction [N];
$\Delta\upsilon$ - the relative velocity of the transported material against the cylinder [m/s].

$$\Delta\upsilon = \upsilon_c \frac{\sin\alpha}{\sin(\theta+\alpha)} \tag{10}$$

where:

υ_c is the annular velocity of the extruder's screw [m/s];
α - the elevation level of the screw section of the screw [rad];
θ - the solid material feed angle (the angle between the velocity vectors $\Delta\overline{\upsilon}$ and $\overline{\upsilon}_c$).
The annular velocity of the cylinder is

$$\upsilon_c = \omega_0 \frac{D_c}{2} \tag{11}$$

where:

ω_0 is the angular rate of the screw rotation [s^{-1}];
D_c is the screw cylinder diameter [m].
The solid material feed angle may be determined using the following formula:

$$\theta = \arcsin\left[\frac{\left(1+f_1^2-x^2\right)^{0,5}-f_1 x}{1+f_1^2}\right] - \alpha \tag{12}$$

where:

$$x = \frac{H}{f_2\, z}\ln\frac{P}{P_0} + \frac{f_1}{f_2}\left(1+\frac{2H}{W}\right) \tag{13}$$

where:

H is the blade height [m];
z - the screw channel length [m];
P - the pressure at the considered point [Pa];
P_0 - the initial pressure at z = 0 [Pa];
W - the screw channel width [m].

All the heat generated under the action of friction forces within the solid material is transferred due to thermal conductivity and is distributed between the material itself, the cylinder walls and the screw *(Subbotin E.V., Trufanova N.M., Scherbinin A.G., 2012).*

The rate of thermal conduction within the material is described by the Fourier's law as follows:

$$\dot{Q}_z = -k_z A_z \frac{\partial T}{\partial z} \tag{14}$$

where:

$\dot{Q}_z$ is the thermal flux (the rate of thermal conduction) [W/s];
k_z - the thermal conduction coefficient [W/m·C];
A_z - the area perpendicular to the flux [m^2]; A_z = W·H; $\frac{\partial T}{\partial z}$ is the temperature gradient.

By equating the expressions (9) and (14) and after the reduction and translation this gives us the following:

$$\frac{\partial T}{\partial z} = -\frac{F_{tr}\omega_0 D_c \sin\alpha}{2k_z W H \sin(\theta+\alpha)} \tag{15}$$

The resulting expression makes it possible to estimate the variation of the temperature against the screw channel length.

Based on the equations (5) and (6) developed previously, we obtain the distribution of temperature within the area of contact of the material with the screw.

$$\frac{\partial T_a}{\partial z} = -\frac{m\omega_0 D_c \sin\alpha}{2k_z WH\sin(\theta+\alpha)}\left(g\cos\varepsilon + r\omega_0^2 - 2r\omega_0^2\frac{\operatorname{ctg}\alpha - f_1}{\operatorname{ctg}\alpha + \operatorname{tg}\alpha}\right)\frac{f_2\cos\beta}{\cos\alpha + \sin\alpha} \tag{16}$$

as well as within the area of contact of the material with the cowling wall.

$$\frac{\partial T_c}{\partial z} = -\frac{m\omega_0 D_c \sin\alpha\, f_2}{2k_z WH\sin(\theta+\alpha)}\left(g\cos\varepsilon + r\omega_0^2 - 2r\omega_0^2\frac{\operatorname{ctg}\alpha - f_1}{\operatorname{ctg}\alpha + \operatorname{tg}\alpha}\right) \tag{17}$$

RESULTS AND DISCUSSION

The heat generation resulting from friction forces acting upon the material depends mainly on the weight of the compressed material m, traveltime parameters of the screw operation, geometrical parameters of the screw, the friction factors f_1 and f_2, as well as the material's thermal conduction coefficient k_z.

Let us make a graphical representation of the dependencies (16) and (17) (Fig. 4). The diagrams make it possible to conclude that the major part of temperature is generated due to the action of friction forces when the screw rate of rotation is ω_0 = 5 s^{-1}. Further increase of angular rate of rotation of the screw causes the temperature gradient to decrease since the amount of friction forces decreases.

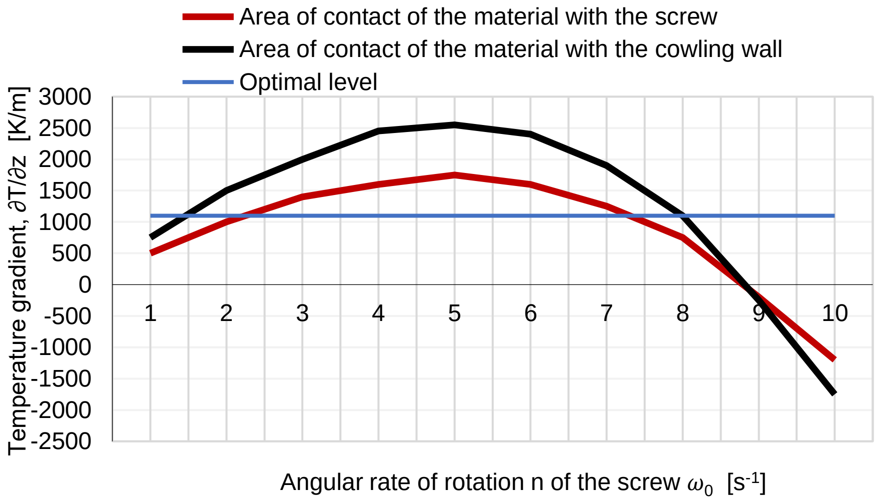

Fig. 4 – Diagram of temperature gradient change depending on the angular rate of rotation of the screw

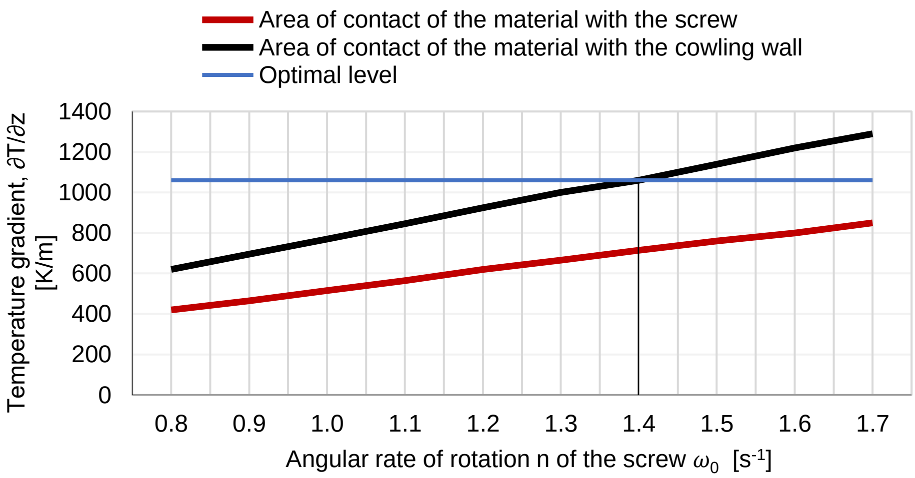

Fig. 5 – Diagram of temperature gradient change depending on the angular rate of rotation of the screw

Experimentally it was determined that when extruding lentils, the optimal temperature within the pre-die area was 105ºC to 115°C. This conforms to the data of other experiments *(Jiang, Q.H., Wu K., Sun Y., 2019; Orisaleye, J.I., Ojolo S.J., 2019).* If the initial raw material temperature is assumed to be 20 °C, and the total length of the loading, transportation and compression (melting) areas is assumed to be 0.7*L*, where *L* is the length of the screw channel, then the optimal level of the temperature gradient is approximately 1080K/m.

At lower values of the gradient, the melting temperature within the pre-die area decreases, at higher values it increases resulting in product overheating. In both cases, maintenance of the optimal temperature regime requires additional heat supply or extraction, which is not effective.

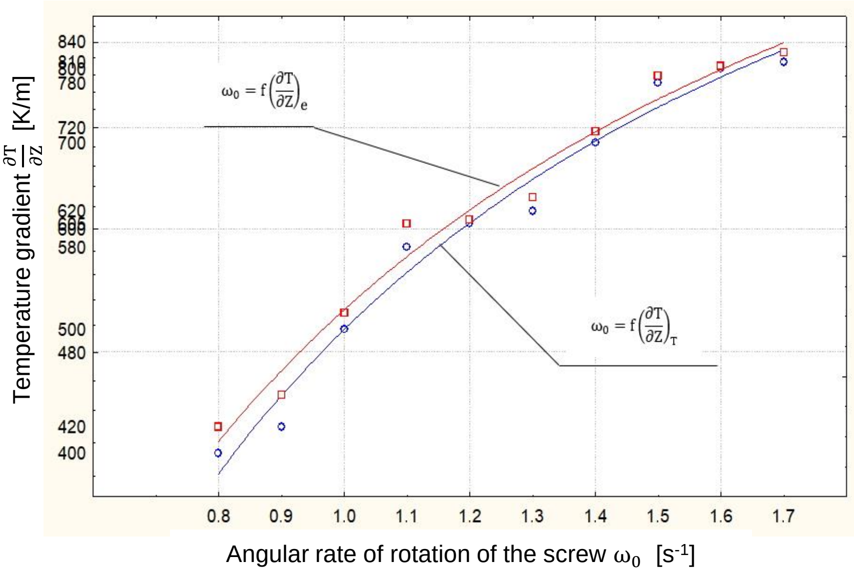

Fig. 6 – The diagram of dependency of the theoretical $\left[\left(\frac{\partial T}{\partial z}\right)_T\right]$ and experimental $\left[\left(\frac{\partial T}{\partial z}\right)_e\right]$ temperature gradients within the area of contact of the material with the screw with the angular rate of rotation of the screw

If we consider the resulting dependencies in more detail (Fig. 5), we will see that the optimal angular rate of rotation of the screw is approximately $\omega_0 \approx 1.4$ s^{-1}. This conforms to the data obtained experimentally and the results of experiments conducted earlier.

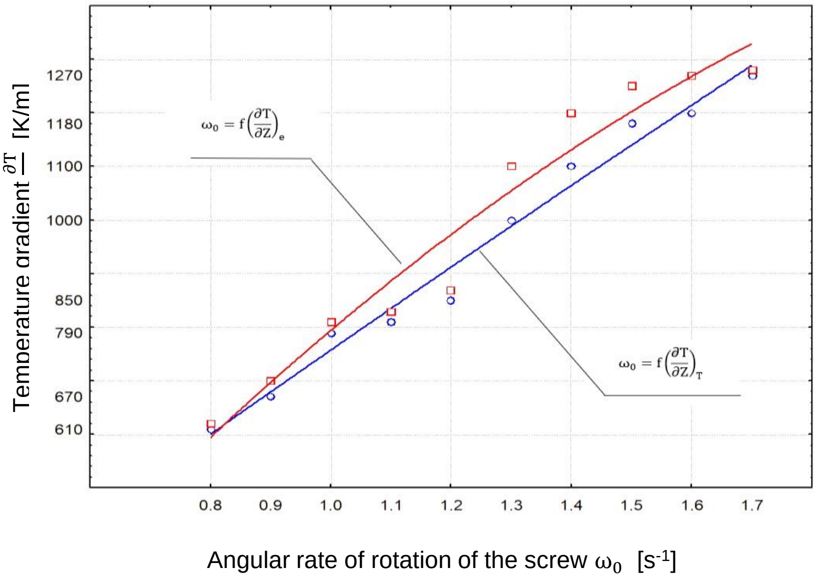

Fig. 7 – The diagram of dependency of the theoretical $\left[\left(\frac{\partial T}{\partial z}\right)_T\right]$ and experimental $\left[\left(\frac{\partial T}{\partial z}\right)_e\right]$ temperature gradients within the area of contact of the material with the cowling wall on the angular rate of rotation of the screw

CONCLUSIONS

To sum the above information up, optimal level of the temperature gradient is approximately 1080 K/m. At lower values of the gradient, the melting temperature within the pre-die area decreases, at higher values it increases resulting in product overheating. The optimal angular rate of rotation of the screw is approximately $\omega_0 \approx 1.4$ s^{-1}. This is corroborated by the diagram shown in Figure 4 and Figure 5.

Conducted experiments showed good repeatability of theoretical and experimental data (the deviation amounted to no more than 3%). This is corroborated by the diagram shown in Figure 6 and Figure 7.

Also, as a result of the conducted studies, expressions were obtained that allow us to estimate the temperature distribution inside the screw channel with the specified basic parameters.

ACKNOWLEDGEMENTS

Consequently, the results of the study can be used when composing the heat balance equation in order to optimize the extrusion process and the operating parameters of the extruder itself.

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