http://www.moderntechno.de/index.php/meit/article/view/meit25-01-040
DOI: 10.30890/2567-5273.2023-25-01-040

UDC 621.77.043

DIFFICULTIES IN MODELING PROCESSES IN THE ZONES BEFORE ENTERING THE EXTRUDER MATRIX AND IN THE EXTRUDER MATRIX AND THEIR SOLUTION BY CREATING A UNIVERSAL MATHEMATICAL MODEL

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Abstract. *The article analyzes the existing mathematical models and methods for calculating the process of extrusion processing of plant materials. Based on the analysis, their main advantages and disadvantages are determined. It has been established that most models consider the process in loading and compression zones where raw materials are only crushed and mixed. At the same time, very few mathematical models describe the zones where the raw material passes into the viscoplastic state, in particular, the zones before entering the matrix and in the matrix. However, it is in these zones that the most complex hydrodynamic, heat exchange, biochemical and structural transformations occur. Because of such difficulties, a number of simplifications are adopted in existing models that do not allow determining the real parameters of the process and making such models unsuitable for designing extruders.*

The mathematical model developed by the authors takes into account the main determining factors that allow applying the model and calculation program for different types of extruders and for different types of raw materials. The developed program allows you to calculate the dynamics of thermal and hydrodynamic processes along the entire channel and at local points. At the same time, it is possible to assess the contribution of each of the dissipative factors responsible for the heating of raw materials and calculate the loss of heat to the environment.

Key words: *extruder, matrix, plant raw materials, heat transfer.*

Introduction. Research and analysis of scientific works in the field of development of modern extrusion equipment for the food industry showed that most experimental studies are devoted to the study of quality indicators finished products. At the same time, the heat exchange and hydrodynamic processes in the extruder channel remain poorly studied. The mechanism of their influence on the depth of structural and physics-chemical transformations in raw materials also remains poorly understood. Although it is these factors that determine the effectiveness of the method and are responsible for the quality of the product. The lack of data in the literature is associated with the complex specifics of the process, in particular, its short duration and the inability of measuring equipment to access the extruder channel for experimental study of the process.

Having investigated the state of the problem and taking into account the previous experience of scientific works, the authors formulated the following tasks:

- development of a mathematical model that will allow you to calculate the real parameters of the process at any point in the channel in the most complex zones before entering the matrix and in the matrix. simultaneously take into account the shortcomings and simplifications of mathematical models known in the literature;
- develop a universal calculation algorithm for different types of extruders and various types of raw materials.

Main text.

Mathematical models known in the literature, considering the extrusion process in the processing of plant materials, divide it into several functional zones. Each of them is described by the corresponding equations. Most models known in the literature calculate the feeding zones (dosage), grinding (compression) and homogenization, since they are the simplest when modeling. In these zones, there are no phase transitions of raw materials, but only grinding and mixing. The number of models that consider the zone before entering the matrix and in the matrix itself is limited due to the complexity of the calculation. This is caused by the fact that in these zones there is a transition of mass from dispersed bulk to viscous and plastic. This condition is accompanied by a decrease in viscosity due to compression, grinding, additional fat release and melting carbohydrates. In addition, the calculation is complicated by the absence in the literature of thermophysical and rheological properties of raw materials.

When modeling zones before entering the matrix and in the matrix, most authors consider separately the zone in front of the matrix, assigning it to the homogenization zone and the matrix zone, which does not allow obtain the dynamics of changes in temperatures, pressures and velocities. Very often, mathematical models are based on the assumption of the isothermal nature of the process, based on the fact that the extruder body is made with thermal insulation or is heated. This does not take into account an important extrusion mechanism – heating the melt due to viscous dissipation. However, this factor is the main in the cone part of the channel [1,2].

In the overwhelming majority of works, the simulation does not take into account the rotation of the screw and, accordingly, does not take into account the influence of centrifugal forces on the melt and the effect of shear stresses of the tangential velocity. Moreover, the component of viscous dissipation due to the rotation of the cone and the heating of the liquid associated with this is not taken into account. Very often in models, the melt in front of the matrix is assumed by a Newtonian liquid that moves at a constant temperature and, accordingly, the viscosity coefficient in this zone is unchanged, and non-Newtonian properties appear only in the matrix channel. This assumption simplifies the model, but does not allow obtain real results of the process [2, 3]. The vast majority of works, citing a mathematical model, do not give the results of calculations at all, and therefore such models cannot be used in practice. Most models are designed to calculate only one type of raw material and when processed in an extruder of only one type [3, 4].

In this paper, in the process of modeling, the authors took into account the shortcomings of existing models. In particular, the raw material in the zone in front of the matrix and in the matrix is considered as a homogeneous non-Newtonian viscoplastic liquid. An orthogonal conical coordinate system is also used, which makes it possible to take into account the rotation of the screw in the zone in front of the matrix. For the matrix channel, a cylindrical coordinate system is used, which is associated with a conical coordinate system by simple geometric ratios.

The initial data for the developed calculation algorithm are the geometric dimensions of the channel, the speed of rotation of the screw, pressure, temperature and moisture content at the entrance to the corresponding zones, thermophysical and rheological properties of raw materials, as well as temperature, pressure and thermophysical properties of the environment – air.

The basic equations of the developed model and algorithm are the classical equation of motion, the continuity equation, the energy conservation equation and the empirical equation for determining viscosity, in which the dissipative function is the quadratic tensor of the deformation velocities. The solution of the system of the first three equations according to the standard scheme makes it possible to calculate the speed of flow, pressure and temperature of the liquid along the channel before entering the matrix and in the matrix, taking into account the rheological properties of the liquid.

The solution of the equation of motion allows us to evaluate both the total change in pressure in the channel and the contribution of each component separately. In particular, a reversible pressure drop associated with a decrease in the cross-sectional area of the annular channel, an irreversible pressure drop caused by the action of normal stresses during channel narrowing, an irreversible loss of pressure under the action of shear stresses in the radial direction caused by friction of the axial flow with the wall, a change in pressure due to centrifugal forces caused by the rotation of the screw. The equation does not take into account the component of mass gravitational forces, since this value does not significantly affect the change in pressure in the channel.

Evaluation of pressure losses caused by shear stresses due to friction of the flow with the channel wall was carried out under boundary conditions: $v_z(R_1)=0$ and $v_z(R_2)=0$. Determination of the change in pressure associated with the rotation of the screw in the area in front of the matrix is carried out under boundary conditions: $v_\theta=\omega_0 Rx_1$ at $u=Rx_1$ and $v_\theta=0$ at $u=Rx_2$. The solution of each component of the equation of motion for the zone before the matrix is carried out in a conical coordinate system.

The change in pressure in the matrix channel is caused only by friction of the flow with the channel wall. Therefore, the equation of motion is calculated in cylindrical coordinate systems with boundary conditions: $v_x = 0$ at $u = R_f$ and $dv_x / du\, 0$ =0 at u =0.

The basic equations of motion and the continuity equation include local viscosity, which depends on the flow temperature and on the local values of the shear velocities. During the calculation, averaging of local values is performed in each section of the channel, which is later used in the equations as the value of the effective viscosity.

The temperature change in the channel is associated with the viscous dissipation of mechanical energy under the cumulative action of shear stresses, which are considered as internal volumetric heat sources, as well as due to heat transfer to the environment.

The continuity equation allows you to evaluate the contribution of each of the components separately. In particular, the conductive transfer of heat through the wall in the radial direction due to the temperature difference between the liquid and the channel wall, the conductive transfer of heat in the liquid along the channel. At $\mathrm{Re} > 1$ this component can be neglected and therefore it is not taken into account in the calculation algorithm. Viscous dissipation of mechanical energy, which includes the following dissipative components: the first is the action of normal stresses on the segment dz in the direction of the axis z; the second is viscous dissipation due to friction between the flow and the wall; the third is viscous dissipation associated with the rotation of the conical wall of the channel in the zone in front of the matrix. Due to the dissipation of mechanical energy, the flow is heated intensively, and the temperature of the raw material along the channels in front of the matrix and in the matrix is continuously increasing.

The change in the average temperature of the liquid along the channel is calculated by averaging along the cross section and takes into account the heat loss due to the heat transfer of the liquid with the environment. It is considered as three components. The first is the transfer of heat by convection due to the temperature difference between the liquid and the channel wall at a given coefficient of heat return. The second is the conductive transfer of heat through the housing of the extruder in the radial direction due to the difference of temperatures between the outer and inner walls of the housing at a given coefficient of thermal conductivity. The third is heat transfer from the surface of the hull to the surrounding air due to radiation and free convection with a known effective total heat transfer coefficient. All coefficients are calculated by standard heat exchange equation. The value of the heat flux, both for the zone before the matrix and for the matrix, is determined by the overall temperature potential and the sum of three resistances. The calculation of the value of the heat flux allows you to determine the temperature potential for each of the three thermal resistances and, thus, estimate the temperature of the walls.

Based on the developed model, a computer program has been created that can be used in calculating the zone before entering the matrix and in the matrix zone. A computer program is universal for different types of extruders and different types of raw materials.

Summary and conclusions.

Calculations were carried out using numerical methods, in the program Turbo Pascal. The main results of the calculations are shown in Figure 1. In the process of passing the zone in front of the matrix and matrix, the temperature of the raw material is constantly growing. Calculated dependences of temperature changes showed that along these two zones there is an increase in temperature. The change in temperature in the channel is associated with the action of a number of dissipative factors.

Figure 1 in relative units shows the change in the components of the temperature gradient caused by the action of each of these factors: 1) shear stress due to screw rotation (component $(dT_z/dz)_w$); 2) shear stress due to friction of the axial flow with the channel wall (component $(dT_z/dz)_{rz}$); 3) by the action of normal stresses (component $(dT_z/dz)_{zz}$). In addition, a change in temperature gradient is shown $(dT_z/dz)_q$, associated with the loss of heat in the surrounding air.

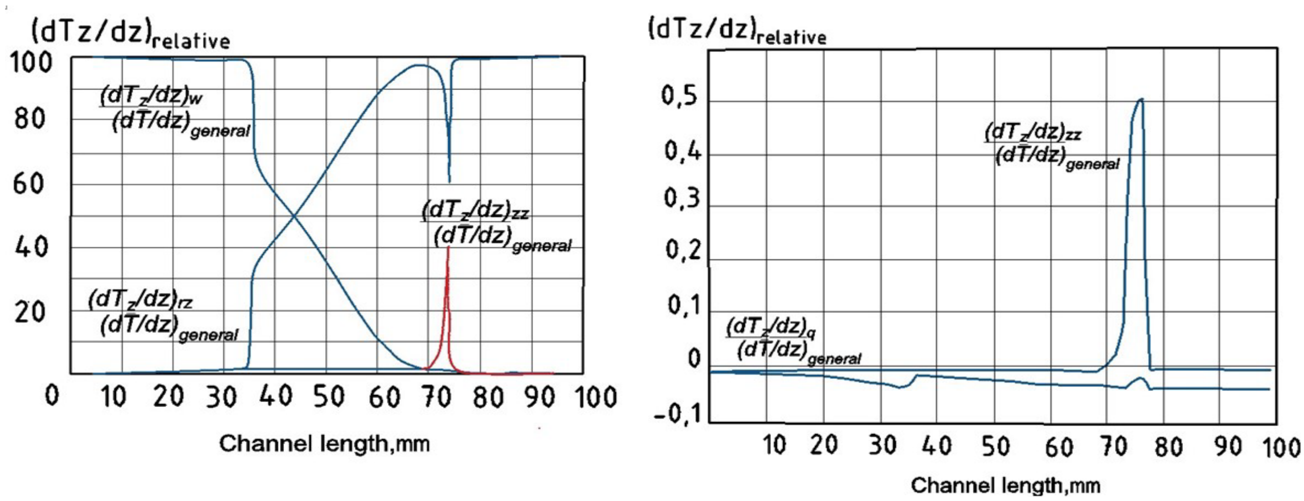

Figure 1 - Change in the relative values of the components of the temperature gradient along the two zones before entering the matrix and in the matrix

The contribution of each of these factors is different as well as their area of action. The increase in temperature in the area in front of the matrix is due to the gradient $(dT_z/dz)_w$ and caused by the action of tangential stress due to the rotation of the screw. Further, the influence of this component gradually decreases to zero, but the role of the component increases $(dT_z/dz)_{rz}$, which is explained by the narrowing of the channel and the increase in flow rate. The influence of the component $(dT_z/dz)_{zz}$ is insignificant and manifests itself only during the transition from zone to zone. It was found that the loss of heat to the environment $(dT_z/dz)_q$ is insignificant compared to dissipative heating.

The model proposed by the authors allows you to calculate the change in speed, temperature, pressure and viscosity along the entire channel and at local points. At the same time allows you to estimate the loss of heat in the environment. Also determine the degree of heating of raw materials due to the viscous dissipation of mechanical energy caused by active factors and assess the influence of dissipative factors on pressure losses along the channel. In addition, it allows you to analyze the change in the nature of the flow, the degree of heating and structural changes that are associated with the peculiarity of the channel geometry or the speed of rotation of the screw. The model is as close as possible to the real condition of the processing process. All this in the end makes it convenient for practical use. In addition, it is universal and can be used for different types of extruders and different types of raw materials, as well as in the design of the geometry of the channel of two zones before entering the matrix and matrix.

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***Анотація**. В статті проаналізовано існуючі математичні моделі і методи розрахунку процесу екструзійної обробки рослинної сировини. На основі аналізу визначено їх основні переваги та недоліки. Встановлено, що більшість моделей розглядають процес в зонах завантаження та стискання, де сировина лише подрібнюється та перемішується. У той же час дуже мало математичних моделей, які описують зони, де сировина переходить у в'язкопластичний стан, зокрема, зони перед входом в матрицю і в матриці. Однак, саме в цих зонах відбуваються найбільш складні гідродинамічні, теплообмінні, біохімічні та структурні перетворення. Через такі складнощі в існуючих моделях приймається ряд спрощень, які не дозволяють визначати реальні параметри процесу і роблять їх непридатними при проектуванні екструдерів.*

В розробленій авторами математичній моделі враховано основні визначальні фактори, які дозволяють застосовувати модель та програму розрахунку для різних типів екструдерів та для різного виду сировини. Розроблена програма дозволяє чисельно розрахувати динаміку термічних та гідродинамічних процесів вздовж всього каналу та в локальних точках. Одночасно оцінити вклад кожного з дисипативних факторів, відповідальних за нагрів сировини та обчислити втрати теплоти в оточуюче середовище.

***Ключові слова:** екструдер, матриця, рослинна сировина, теплообмін*

Article sent: 17.02.2023