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METHODS OF MIXING QUALITY CONTROL DURING POLYMER PROCESSING ON A DISK EXTRUDER

Today, the market dictates the need for extrusion systems capable of processing a wide range of different polymers with maximum efficiency. One of the options for such installations is a resource- and energy-saving cascade disk-gear extruder consisting of a metered-discharge disk extruder and a gear pump. The disk extruder is characterized by high mixing capacity and has proven itself as a melt-homogenizer. However, at present there is no unified methodology for selecting the technological parameters of the disk extrusion process depending on the quality of mixing of the material at the outlet, which greatly complicates the introduction of this equipment into the technological schemes of modern production facilities. Based on the analysis of recent scientific publications, a system of equations has been created that describes the movement of material in the disk gap and allows determining the residence time of the material and the length of the trajectory of material movement in the disk gap. Graphs of the dependence of the trajectory length and the duration of the material's stay in the disk gap on the distance to the moving disk are presented. Taking into account the previously obtained empirical data and using the correlation between the criterion of mixing quality and the value of the accumulated strain, a computer program was developed that is capable of selecting the technological parameters of disk extrusion depending on the required mixing quality. Based on the developed system of equations, graphs showing the dependence of the accumulated strain on the size of the disk gap and the rotation frequency of the working body were constructed. Depending on the required mixing quality and extruder performance, the program provides the values of the optimal size of the disk gap and the rotation speed of the working body, which greatly simplifies the process of setting up equipment for specific production conditions and types of materials.

KEYWORDS: *disk extruder, mixing quality control, accumulated shear strain*.

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Statement of the problem

Plastics are characterized by high efficiency in terms of technology, consumer and economic performance. Often, a polymer-based material is able to combine strength at the level of metals, low density, resistance to aggressive environments, low thermal conductivity and other important technological characteristics. As a result, plastics are effectively used in almost all industries, which is reflected in their widespread use and steady growth in production and processing volumes. [1 - 6].

Plastics, in addition to the polymer itself, also consist of fillers, dyes, stabilizers, and other special additives, the purpose of which is to ensure that the product obtains the required properties.

To expand the range of technological and operational properties, composite materials are becoming increasingly common. Their use makes it possible to produce polymeric materials with increased wear resistance, resistance to shock loads, etc. However, changes in the composition of the material being processed can have a strong impact on the technological properties, which in turn either makes it impossible to process the required composition on an existing single- or twin-screw extruder or worsens the quality of the finished product. This disadvantage is avoided by cascade extrusion units, in which each operation is performed by a separate working body.[7] Among the developed schemes, a cascade extrusion unit, consisting of a metered-discharge disk extruder that serves as a melt-homogenizer and a gear pump used for dosing and pressure creation, stands out for its efficiency [8-13]. Despite the promise of this scheme, it is currently used to a limited extent due to the insufficient theoretical basis for its description.

As of today, no comprehensive methodology has been developed that would make it possible to select the technological parameters of the disk extrusion process depending on the quality of material mixing, which is a critical factor for the distribution and use of this device, since it serves not only as a melter but also as a mixer.

Analysis of recent studies and publications

The scientific principles of designing and calculating disk extruders were discussed in detail in [14]. The authors developed an algorithm for finding the geometry of the disk and its rotation frequency, which together provide a given final melt temperature at the outlet of the extruder. However, these algorithms do not take into account the required mixing quality of the resulting melt, which is definitely a disadvantage.

Existing methods for quantifying the mixing process are based on statistical analysis. The application of statistical criteria requires the study of real material samples, which is accompanied by their physical destruction, and does not allow predicting the result of mixing directly in the process of their manufacture. Therefore, the use of criteria that are non-statistical in nature, based on the determination of the strain accumulated by the melt, the temperature inhomogeneity of the melt, etc. is of particular importance. For example, the authors of [15] conducted a study to assess the mixing efficiency depending on the intensity of the supplied energy using statistical analysis methods and by scanning the melt temperature field across the channel with a multi-point mesh thermocouple installed at the outlet of the extruder. The results showed that the discrepancy in the assessment of mixing efficiency does not exceed 8%. However, the state of the material inside the extruder remains unknown.

The study of particle trajectories in the disk gap was described in [16 - 19]. The authors created programs capable of constructing material flow trajectories in a plane-plane and cone-cone gap, on the basis of which the effect of the size of the disk gap on the structure and properties of the extruded material was considered.

Statement of the task

The aim of this work is to develop equipment and an algorithm for its calculation that will allow to accurately and conveniently select the technological parameters of the disk extrusion process based on the correlation between the mixing quality criterion and the value of the accumulated strain. In order to achieve this goal, it is necessary to analyze the velocity fields and shear stresses that arise when the melt moves in the working gap of a disk extruder.

Presentation of the main study

The disk extruder works as follows. The polymer is dosed into the inlet 1 and transported by a multi-pass screw thread made on the side surface of the rotating disk 2 into the working gap 3 formed by the body and disk. Melting of the polymer and homogenization of the melt is carried out in the channels of the screw thread and in the gap, and the resulting melt exits through the hole 4. The main disadvantage of disk extruders is the low pressure at the outlet of the device (up to 1 MPa), so this type of device is effectively used with gear pumps as a dosing device [10 - 13]. Disk extruders are characterized by high efficiency in terms of both capital and operating costs, as well as a wide range of processed materials.

In cascade extrusion schemes, a disk extruder acts as a melter-homogenizer. The screw-cutting zone is responsible for melting 50-60% of the material, and the disk gap completes the transition of the material to a viscous-fluid state and homogenizes the resulting melt [14].

Existing methods for quantitatively describing the mixing process are based on statistical analysis based on comparing the total dispersion with the actual value of the standard deviation of the concentration of the dispersed substance [7].

Currently developed methods for describing the mixing effect make it possible to estimate the average value of the shear strain per unit volume of the mixed material. Comparison of the calculated values of the shear strain with the experimentally determined statistical criteria of mixing quality indicates the existence of a correlation between them. The mixing quality criteria initially depend significantly on the shear strain, but then a kind of saturation occurs. Once this optimum value of shear strain is reached, further increases in shear strain do not affect the criteria. Thus, there is a certain optimal mixing duration. Obviously, if the system manages to realize the average shear strain, then the maximum possible homogeneity of the mixture is achieved for this apparatus and further increasing the duration of mixing to increase the homogeneity of the mixture is irrational. [7]. It is important to remember that with this method of estimating the shear strain, its optimal value will characterize only the mixing system for which the correlation was determined.

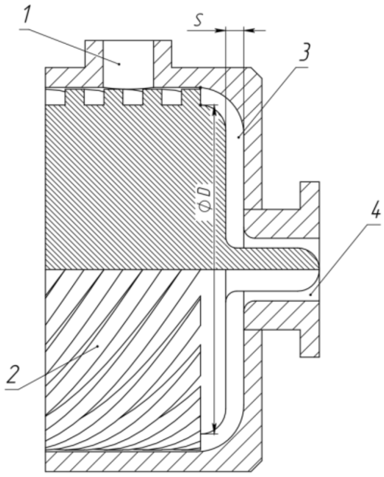


Fig. 1 - Schematic diagram of a disk extruder: 1 - inlet, 2 - screw thread, 3 - disk gap, 4 - outlet.

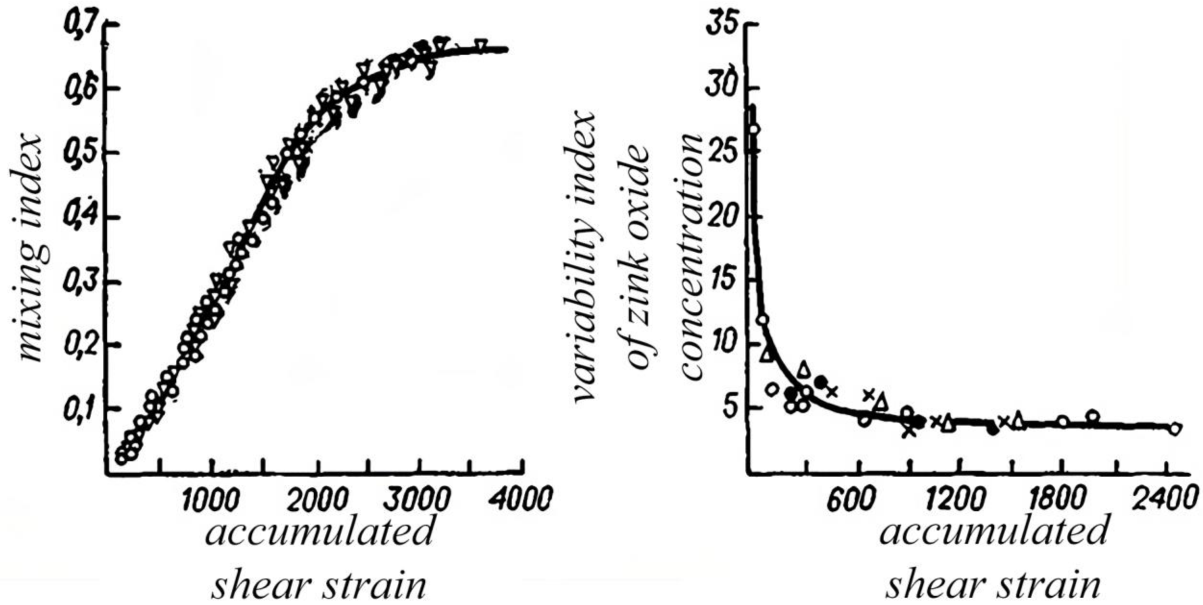


Fig. 2 - The effect of shear strain on the mixing index of polymer mixtures obtained using roller machines (1) and rotary mixers (2)

The total (accumulated by the mixture during the mixing process) shear strain $\dot{\gamma}_{summ}$ can be defined as the product of the average shear rate and the duration of mixing (shear duration) [7].

$$\gamma_{summ} = \bar{\dot{\gamma}} \cdot t \qquad (1)$$

where $\bar{\dot{\gamma}}$ is the average shear rate, s^{-1}; t is the mixing duration, s.

Metered-discharge disk extruders have the ability to adjust such parameters as the size of the disk gap and the rotational speed of the working body, which provides ample opportunities to control the mixing effect by changing both the value of the shear rate and its duration.

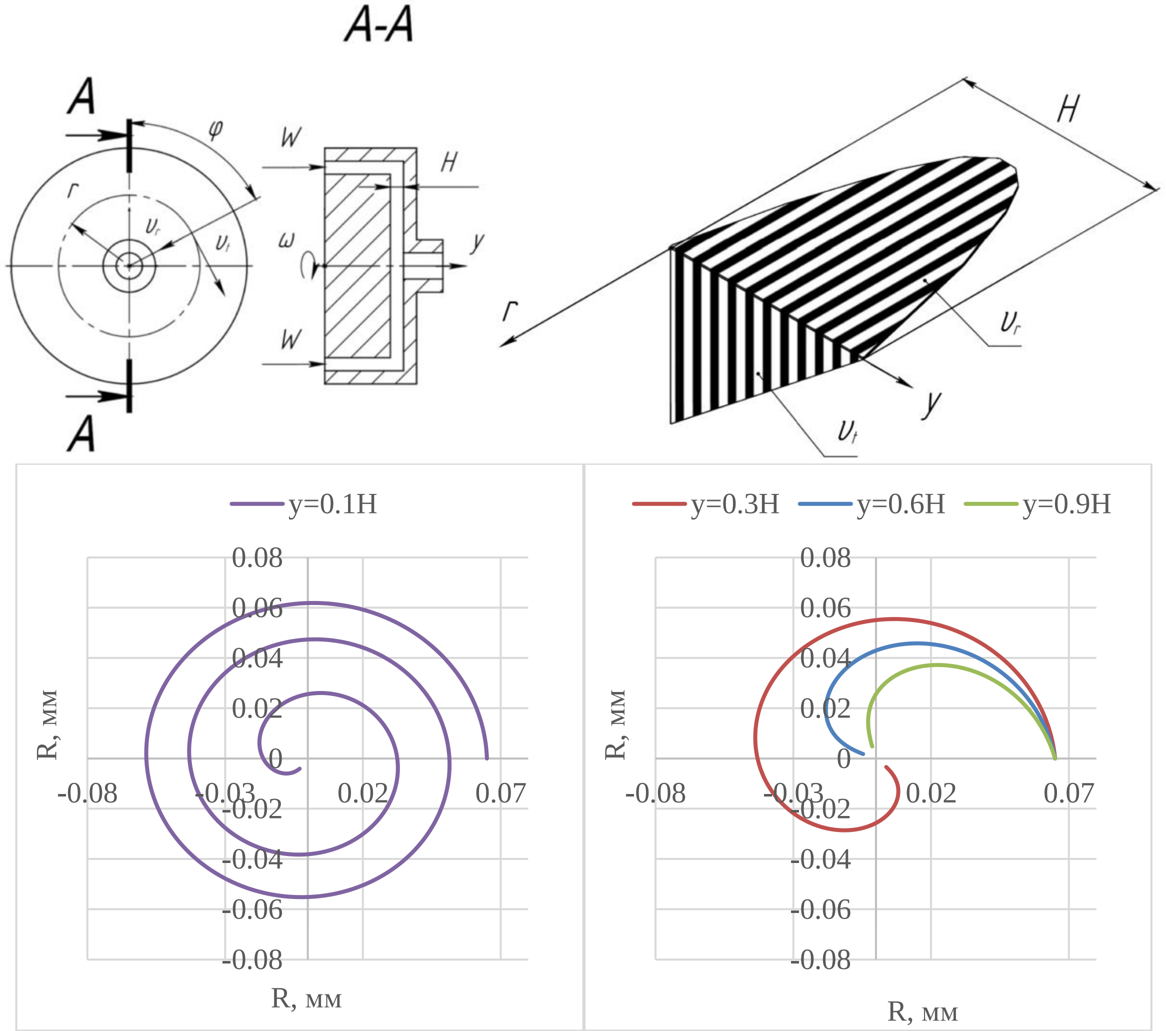
A prerequisite for determining the mixing effect of a disk extruder is the availability of information on the velocity distribution in the material flow.

The nature of the polymer movement in the disk gap is determined by the result of the interaction of two mutually perpendicular velocities: radial and tangential. The profile of the radial velocity component has a linear profile, and the profile of the tangential component is parabolic.

$$\upsilon_t = V_t \frac{y}{H} = 2 \cdot \pi \cdot r \cdot n \cdot \frac{y}{H} \qquad (2)$$

$$\upsilon_r = \frac{3 \cdot Q}{\pi \cdot H^3 \cdot r} \cdot y \cdot \left(H - y\right) \qquad (3)$$

As a result, the trajectories of the material in the disk gap take on a shape similar to Archimedes' spirals [16]-[19]. The trajectory depends on the volume capacity of the extruder, the distance of the cross-section from the moving disk, the disk rotation speed, and the size of the disk gap.



$R = 0{,}065м$, $r = 0{,}005м$, $W = 7{,}928 \cdot 10^{-6}\, м^3/с$, $H = 3 \cdot 10^{-3} м$, $n = 0{,}318$ с$^{-1}$.

Fig. 3 - Trajectories of particles in the slit gap of a worm-disk extruder: 1 – at $y = 0.1H$; 2 - at $y = 0.3H$ $y = 0.6H$ and $y = 0.9H$

Integrating the equations in the range from 0 to / and from R to r, we obtain:

$$r=\sqrt{R^2-\frac{6\cdot W\cdot y\cdot(H-y)}{\pi\cdot H^3}\cdot\Delta t} \qquad (4)$$

The time spent by the element in the zone bounded by the radiuses R and r is equal to

$$\Delta t=\frac{\left(R^2-r^2\right)\cdot\pi\cdot H^3}{6\cdot W\cdot y\cdot(H-y)} \qquad (5)$$

To determine the components of the shear rate, we differentiate the velocity equation along y:

$$\gamma_t=\frac{d\upsilon_t}{dy}=\left(V_t\frac{y}{H}\right)\frac{d}{dy}=\frac{2\cdot\pi\cdot r\cdot n}{H} \qquad (6)$$

$$\gamma_r=\frac{d\upsilon_r}{dy}=\left(\frac{3\cdot Q}{\pi\cdot H^3\cdot r}\cdot y\cdot(H-y)\right)\frac{d}{dy}=\frac{3\cdot Q}{\pi\cdot H^3\cdot r}\cdot(H-2\cdot y) \qquad (7)$$

Using the obtained equations to find the values of the components of the strain rate and the duration of their action, it is possible to determine the value of the total accumulated strain.

The total shear strain in the system can be found using the equation:

$$\gamma_{summ}=\gamma_x+\gamma_z=\sum_i\left|\dot{\gamma}_{xi}\right|\cdot\Delta t_i+\sum_i\left|\dot{\gamma}_{zi}\right|\cdot\Delta t_i \qquad (8)$$

Based on the equations described above, a program was created that is capable of constructing material movement trajectories, calculating the length of this trajectory, determining the time the material stays in the disk zone, and calculating the shear strain γ_x, γ_z, and $\gamma_{сум}$ accumulated by the material not only in one section but in the entire disk gap. As a result, the following graphs of the distribution of the above characteristics over the width of the disk gap were obtained.

A nomogram was used as empirical data to determine the optimal operating parameters of a disk extruder. [20]

Table 1 shows the data obtained by substituting the experimentally determined parameters of the disk extruder into the system of equations described above.

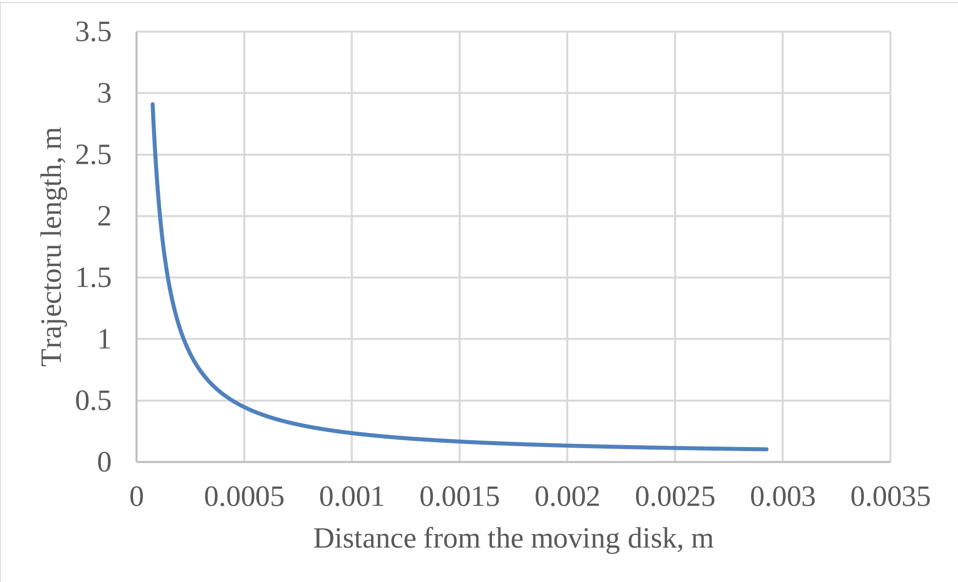


Fig. 4 - Graph of the dependence of the length of the particle trajectory on the distance from the moving disk when moving in the disk gap of a worm-disk extruder at $R=0,065m$, $r=0,005m$, $W=7,928\cdot10^{-6}\ m^3/s$, $H=3\cdot10^{-3}m$, $n=0,318$ s^{-1}.

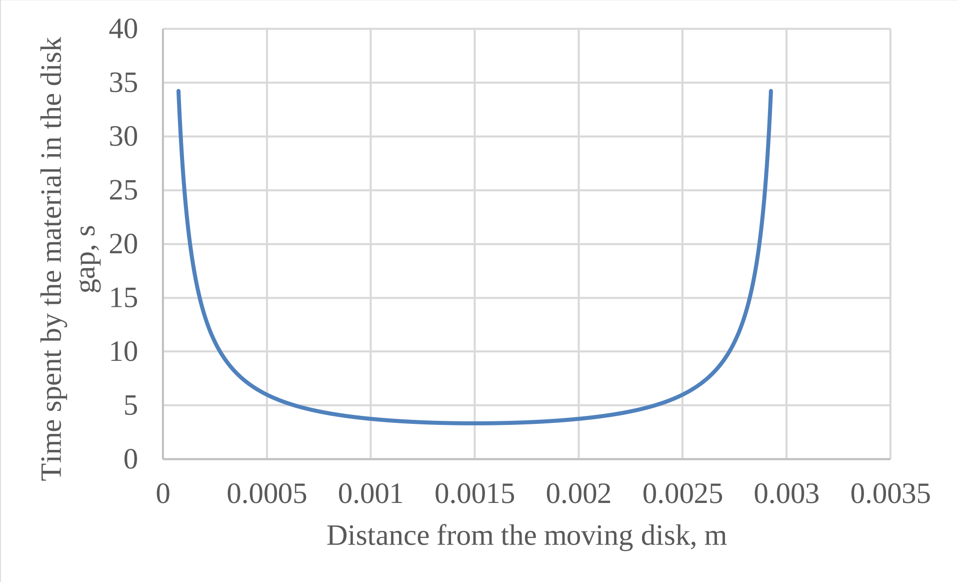


Fig. 5 - Graph of the dependence of the time spent by the material in the disk gap on the distance from the moving disk when moving in the disk gap of a worm-disk extruder at $R = 0,065m$, $r = 0,005m$, $W = 7,928 \cdot 10^{-6}\, m^3/s$, $H = 3 \cdot 10^{-3} m$, $n = 0,318$ s^{-1}.

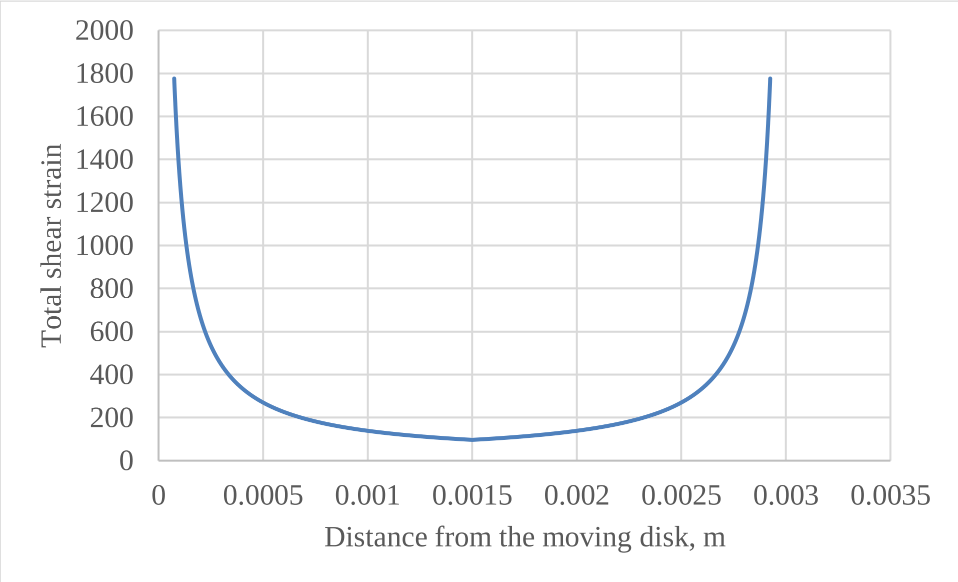


Fig. 6 - Graph of the dependence of the total shear strain on the distance from the moving disk at $R = 0,065m$, $r = 0,005m$, $W = 7,928 \cdot 10^{-6}\, m^3/s$, $H = 3 \cdot 10^{-3} m$, $n = 0,318$ s^{-1}.

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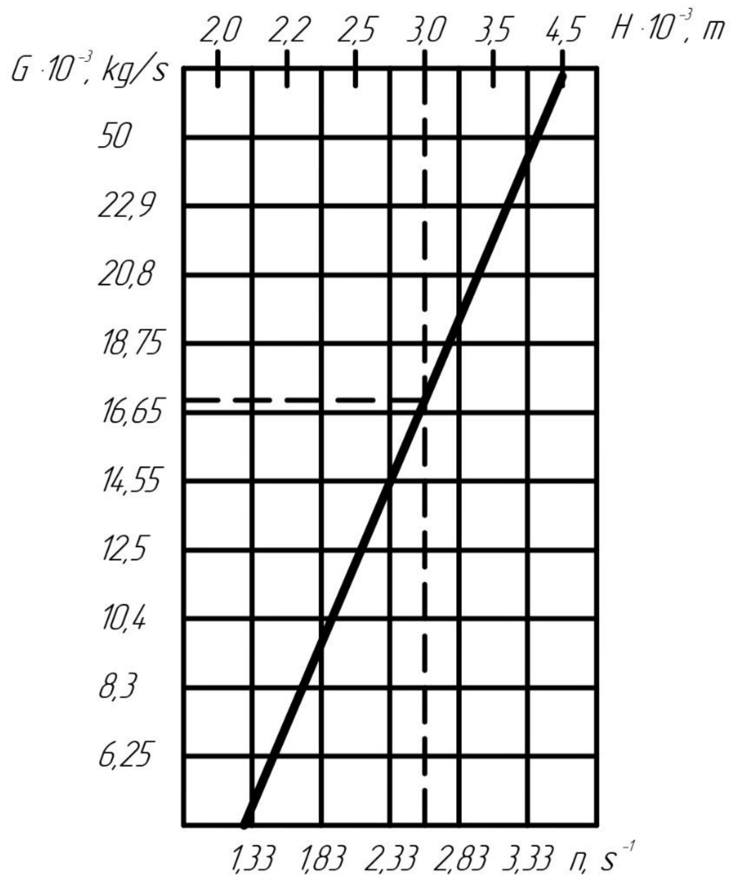

Fig. 7 - Nomogram for determining the optimal technological parameters of a two-gap disk extruder for processing LDPE of the 15802-020 brand.

Table 1

Values of accumulated shear strain at parameters determined by the nomogram

Таблиця 1

Значення накопиченої деформації зсуву при параметрах, визначених номограмою

Rotation frequency n, s^{-1}	Mass productivity G - 10^{-3}, kg/s	Gap between disks, $H\cdot10^{-3}$, m	Accumulated shear strain γ_{summ}
2,33	14,55	2,80	1497
2,57	17,00	3,00	1429
2,80	18,75	3,19	1418
3,03	20,8	3,41	1392

At optimal technological parameters of the process, the calculated value of the accumulated strain is 1400-1500, so it is impractical to develop an accumulated shear strain in a disk extruder that does not belong to this range. Using the developed model for the parameters $R = 0,087m$, $r = 0,018m$, $W = 2,91\cdot10^{-5}\, m^3/s$, $n = 2,33$ s^{-1}, the values of the accumulated shear strain were calculated depending on the size of the disk gap and the rotation frequency. The graphs show that the rotation frequency of the working body has a greater influence on the value of the accumulated shear strain than the value of the disk gap.

Table 2

Dependence of the accumulated shear strain on the size of the gap between the disks.

Таблиця 2

Залежність накопиченої деформації зсуву від величини зазору між дисками.

Gap between disks, H, m	Accumulated shear strain γ_{summ}
0,002	1483
0,00225	1486
0,0025	1490
0,00275	1496
0,003	1502
0,00325	1508
0,0035	1514
0,00375	1521
0,004	1528
0,00425	1534

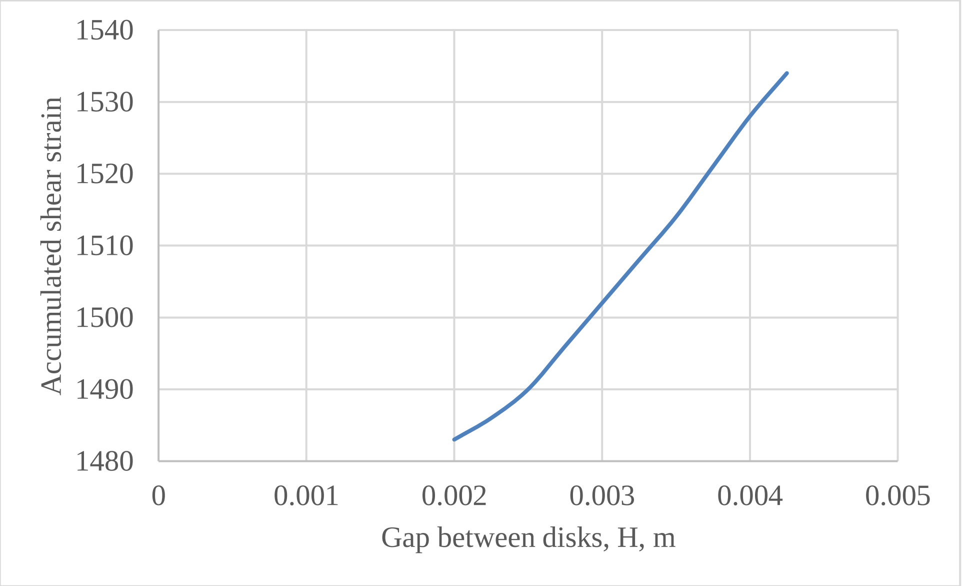

Fig. 8 - Graph of the accumulated shear strain versus the gap between the disks.

Table 3

Dependence of the accumulated shear strain on the rotational speed of the working body.

Таблиця 3

Залежність накопиченої деформації зсуву від швидкості обертання робочого органу.

Rotation frequency n, s^{-1}	Accumulated shear strain γ_{summ}
2	1315
2,25	1453
2,5	1591
2,75	1729
3	1867
3,25	2004

Rotation frequency n, s^{-1}	Accumulated shear strain γ_{summ}
3,5	2142
3,75	2280
4	2418

Conclusions

The movement of particles in the gap of a disk extruder is the result of two mutually perpendicular velocities. The flow from the outer diameter of the disk to the outlet is caused by the pressure created by the screw thread and has a parabolic profile. The flow tangent to the radius is caused by the rotation of the moving disk and has a linear profile. As a result, the flow trajectory has a complex shape similar to the Archimedes spiral and depends on the disk rotation speed, extruder performance, disk gap size, and the distance of the flow from the moving disk.

The effect of the distance from the moving disk on the trajectory length, the time spent by the material in the disk gap, and the amount of strain accumulated by the material is analyzed. Using the described model, the effective amount of accumulated shear strain is 1400-1500. It is determined that the disk rotation frequency has a greater influence on the amount of accumulated strain than the size of the disk gap.

The obtained mathematical model and system of equations makes it possible to accurately and in a more convenient form to select the technological parameters of the process based on the correlation between the criterion of mixing quality and the value of the accumulated strain.

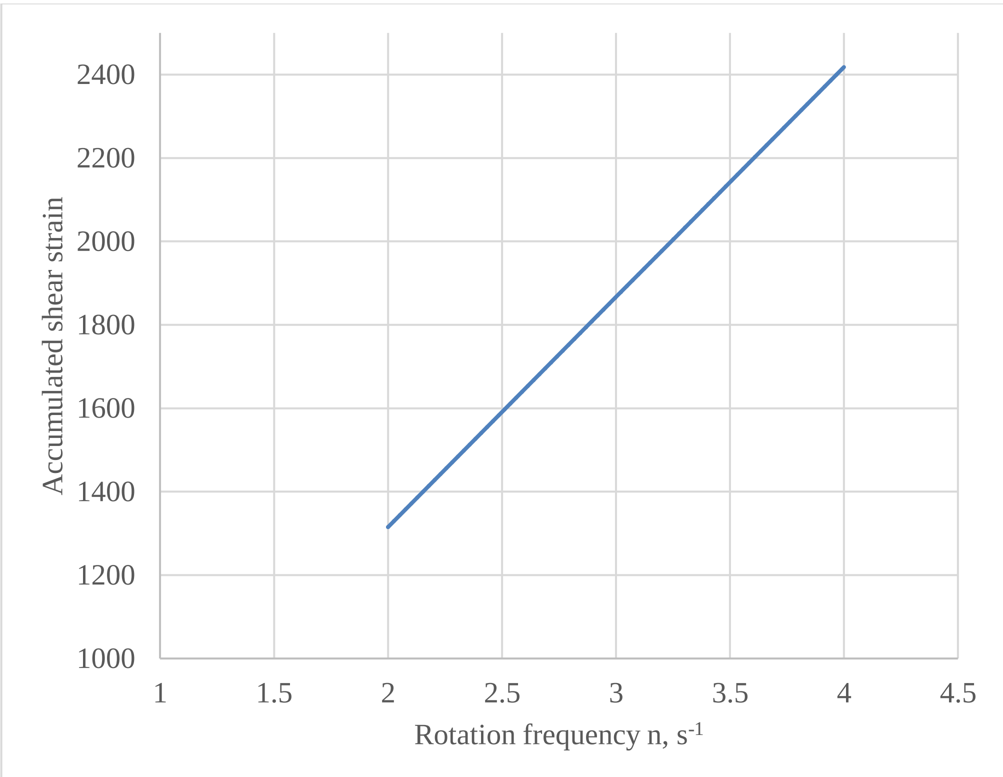

Fig. 9 - Graph of the dependence of the accumulated shear strain on the working body rotation frequency.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of the manuscript. In addition, the authors fully complied with ethical standards, including plagiarism, data falsification, and double publication.

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МЕТОДИ РЕГУЛЮВАННЯ ЯКОСТІ ЗМІШУВАННЯ ПРИ ПЕРЕРОБЦІ ПОЛІМЕРІВ НА ДИСКОВОМУ ЕКСТРУДЕРІ

Станом на сьогодні ринок диктує потребу в екструзійних установках, здатних переробляти широкий спектр різноманітних полімерів з максимальною ефективністю. Одним з варіантів таких установок є ресурсо-енергоощадний каскадний дисково-шестеренний екструдер, що складається з дискового екструдера з дозованим живленням та шестеренного насоса. Дисковий екструдер відзначається високою змішувальною здатністю і добре зарекомендував себе як розплавлювач-гомогенізатор. Однак, на цей час не існує уніфікованої методики підбору технологічних параметрів процесу дискової екструзії залежно від якості змішування матеріалу на виході, що значно ускладнює впровадження даного обладнання в технологічні схеми сучасних виробництв. На основі аналізу останніх наукових публікацій створено систему рівнянь, яка описує рух матеріалу у дисковому зазорі і дозволяє визначити час перебування матеріалу, а також довжину траєкторії руху матеріалу у дисковому зазорі. Наведено графіки залежності довжини траєкторії та тривалості перебування матеріалу у дисковому зазорі від відстані до рухомого диска. З урахуванням раніше отриманих емпіричних даних та використовуючи кореляцію між критерієм якості змішування та величиною накопиченої деформації, було розроблено комп'ютерну програму здатну підібрати технологічні параметри дискової екструзії залежно від необхідної якості змішування. На основі розробленої системи рівнянь були побудовані графіки, що показують залежність величини накопиченої деформації від розміру дискового зазору та частоти обертання робочого органа. Залежно від необхідної якості змішування та продуктивності екструдера, програма надає значення оптимального розміру дискового зазору та частоти обертання робочого органа, що значно спрощує процес налаштування обладнання для конкретних виробничих умов та типів матеріалів.

КЛЮЧОВІ СЛОВА: *дисковий екструдер, контроль якості змішування, величина накопиченої деформації зсуву.*

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