Досліджено взаємозв'язок кута початку руху матеріалу та критичної частоти обертання шнеку, а також їх вплив на рівняння поверхні майданчика додаткової лопаті шнекового конвеєру. Встановлено графічну залежність піднімально-рушійної сили від кута нахилу шнека класичної та модернізованої конструкцій. Визначено рівняння поверхні додаткової лопаті, гвинтової поверхні спіралі шнеку та лінії їх взаємного перетину

Ключові слова: додаткова лопать, шнековий конвеєр, рівняння гвинтової поверхні, піднімально-рушійна сила, стружка

Исследована взаимосвязь угла начала движения материала и критической частоты вращения шнека, а также их влияние на уравнение поверхности площадки дополнительной лопасти шнекового конвейера. Установлена графическая зависимость подъемно-движущей силы от угла наклона шнека классической и модернизированной конструкций. Определены уравнения поверхности дополнительной лопасти, винтовой поверхности спирали шнека и линии их взаимного пересечения

Ключевые слова: дополнительная лопасть, шнековый конвейер, уравнение винтовой поверхности, подъемно-движущая сила, стружка

UDC 621.867.427
DOI: 10.15587/1729-4061.2016.80606

DETERMINING THE EQUATION OF SURFACE OF ADDITIONAL BLADE OF A SCREW CONVEYOR

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1. Introduction

At present stage of development of machine-building, an important factor is the use of metal working waste because of the high cost of raw materials (alloyed steel, non-ferrous metals, etc.), which belongs to the non-renewable natural resources. The annual amount of metal chips formed on the territory of machine-building enterprises of Ukraine is growing rapidly and has already reached about 3000 t/year. This amount is the determining factor for the introduction of environmental and energy-saving technologies to machine-building enterprises. The amount of chips and sludge in this country enables us to stress the appropriateness and global importance of the issue. Along with economic expediency of the issue of transporting the waste of machine tools to the processing facilities, an environmental aspect of the issue remains open. Owing to the presence of elements of organic origin on the transported chips that are included in the composition of coolant, the storage of waste leads to bactericidal formations.

According to the concept of Ukraine's transition to sustainable development, one of the strategic measures in the industrial sector is improving productivity of manufacturing with simultaneous introduction of waste-free or low-waste technologies. Therefore, the reduction of energy consumption by screw conveyors for transportation of metal chips is a relevant scientific-practical task. Determining geometric parameters and mathematical models of structural elements of the transporting bodies allows developing the most efficient technological designs of screw conveyors. With regard to the fact that a screw conveyor is the most effective for the transportation of chips from the machine to the common shop line and that the main disadvantages of augers are a relatively low performance efficiency and high energy intensity of the process of transportation, we have all prerequisites to address these deficiencies through structural upgrades and improvements. The introduction of new energy-saving techniques and technologies should not be reflected by the decrease in the performance of the upgraded units and machines. The increased productivity under conditions of declining or stable energy intensity is possible through technological upgrades of nodes and mechanisms. Therefore, modernization of transport for the transportation of waste from machine-building enterprises is an important energy and environmental issue and is the priority task for the industry of Ukraine. To design the modified elements of conveyors, it is necessary to know the principles and laws of moving the transported material along the auger's surface and by its blades. Without the knowledge of the laws and equations of motion of elements along the surface of the blades, we cannot calculate the forces of friction that will arise between the elements of auger's design and the transported materials. This in turn limits the possibilities of calculating lifting and driving force, which is caused by partial removal by additional blades of layer of chips from the general stream in the gutter of a screw conveyor. So obtaining the equation of surface of additional moving element of a conveyor is the main prerequisite for further development of energy efficient technologies in the transportation by screw transport and in machine-building in general. The impact of additional blade depends on the laws of motion of materials along its surface and ascent to the body of auger's spiral. Thus, once we have the equation of surface of additional blade and the line of intersection with the auger's spiral, we will be able to design screw conveyors with increased efficiency without additional energy costs.

2. Literature review and problem statement

Transport at machine-building enterprises is a significant indicator of the pace of development of the industry. For the transportation of industrial wastes for short distances, the most appropriate are the screw conveyors. There is a considerable variety of designs of screw conveyors and devices, which are protected by copyright certificates in Ukraine and foreign countries, aimed at modernization and correction of the prototypes. The main modernizations are as follows:

– change in the geometry of loading and unloading openings; combined use of additional hydraulic and pneumatic transport;

– change in the diameter of the screw (stepless);

– the use of additional chambers (aeration);

– change in dimensions of a conveyer by connecting the augers via intermediate bearing supports;

– the use of parallelly arranged screws; change in the winding step and diameter of the screw;

– connecting loading and unloading pipelines;

– combined change in the step and diameter of the screw; the use of elastic spiral of the combined profile;

– the use of cascade system of mutually perpendicular and revolving nozzles;

– the use of additional winding on the gutter case;

– the use of rodless spiral screw;

– locating the driving elements outside the case.

All of the above mentioned directions of modernization of designs of screw conveyors and devices (dispensers and mixers) are meant to improve the performance by simplifying the design, changes in manufacturing technology, introduction of ancillary elements and mechanisms, change in kinematics and geometry, etc.

The studies are quite often conducted on transporting, and stirring, the material by the conveyor with a spiraled screw. The following main parameters are determined in experiments on a laboratory setup: coefficient of friction by the screw spiral and coefficient of filling the gutter [1]. They also use the technique of selecting rational parameters of the screw – diameter, spiral step, thickness of the main shaft, etc. [2]. The most common are the studies on determining rational angle of inclination of the screw's spiral [3]. There are also achievements in the increased productivity due to the change in design of the gutter [4] and the form of the screw's spiral itself [5]. There are also papers dedicated to changing the angle of inclination of blades along with regard to the angle of inclination of the screw itself [6], as well as the use of changes in design parameters – step growth of diameter of the screw, uneven spiral step [7]. There are combined technological solutions on the change of step and thickness of the screw's spiral with simultaneous application of conical driving shaft [8].

However, not a single design either considers or touches upon the issue of improving performance by installing and fixing blades on the body of the lane of the screw.

The papers devoted to examination of the influence of the angle of the screw itself consider concentration of the chips on one side of the stream relative to the vertical axis of the screw from the circulation state («current» of chips) to collapse (Fig. 1).

Considerable attention is paid to the described process, given the essential relevance of application of screw conveyors, since their design is significantly simpler in comparison with scraper conveyors, which hold significant position in the process of transporting the chips.

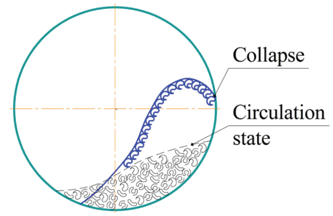

Fig. 1. Distribution of material in the gutter of screw conveyor

In most cases, the problem of improving the performance of the conveyor is solved through the movement of material inside the gutter of conveyor, which is considered as the motion of a material point along the axis of the conveyor on the screw surface of the auger's spiral. However, the mentioned theories do not describe the complex motion of a material point on the screw surface in the direction of motion at the screw rotation.

Considerable attention in the issue of increasing productivity of the screw conveyor is given to:

– determining the optimal inclination angle of the screw's spiral;

– research into mechanism of interaction between the transported material and the screw's spiral;

– establishment of the optimal values of angle of the spiral climb;

– examination of the influence of inclination angle of the spiral, regarding the screw core, on its transportation quality;

– substantiation of rational range of inclination angle of the screw's spiral;

– establishment of ribs on the inside surface of the gutter;

– examination of the mechanism of interaction between transported material and the rib case;

– influence of angle of installation of the case ribs on the transportation quality of screw conveyor;

– substantiation of the optimum value of inclination angle of ribs and theoretical dependency for determining this angle;

– variation of critical rotation frequency of the screw;

– change and characteristics of kinematics of motion in the rotating and stationary cases.

It was found by the conducted analysis of literature sources that a variety of designs of screw transporting mechanisms, as well as their basic geometric and structural parameters [9], are predetermined by the physical and mechanical properties of materials [10] that are transported and can be described by different mathematical dependencies. The impact of the speed of screw rotation [11] and lasting nofailure operation of the conveyor [12] are taken into account. However, there are practically no publications on studying impact of design of the screw with mounted and fixed blades on the screw lane body of horizontal screw conveyor on the process of transportation of materials. The main disadvantage of screw conveyors is a relatively low productivity.

There are not many authors on the territory of Ukraine whose works are devoted to examining the screw surfaces [13], to the problem of optimization of parameters of the drive [14] or to an increase in productivity under conditions of declining or stable energy consumption of screw conveyors [15]. However, the above mentioned papers are aimed at upgrading the drive, rather than structural changes in the geometry of transporting elements and the auxiliary parameters of transportation: the number and forms of additional blades, filling of the gutter, and the material of structural elements.

According to the conducted analysis of the literature sources about existing methods and technologies of improving performance of the workshop conveyor transport, it was found that:

– the issue of improving performance of screw conveyors is described quite extensively, however, no method of improving the performance contains the specifics regarding the influence of filling the gutter;

– the vast majority of the means of performance improvement are based on the method of variation of the drive capacity rather than on structural improvements and upgrading of the main elements of conveyor;

– the existing procedures of designing and calculation of the inclined conveyors are meant to change the step and inclination angle of the screw rather than to introduce auxiliary elements of design.

In most cases, the problem of improving performance of the conveyor is considered through mathematical model of the stressed-strained state of elastic screw with regard to the uneven distribution of loads along its length [16] or solved through the movement of material inside the gutter of conveyor, which is considered as the motion of a material point along the conveyor axis on the spiral surface of the screw [17]. Despite the existing ways of upgrading the conveyor transport, there are actually no articles devoted to the description and calculation of the complex motion of a material point on the surface of additional blade taking into account the passage to the surface of the spiral and the line of their intersection, which will allow designing screw conveyors with regard to the properties of trajectory of motion of the material, which affect the performance.

3. The aim and the tasks of the study

The aim of the work is to obtain equation of the intersection line of the screw surface and the surface of the area of additional blades of screw conveyors, which have significant energy efficiency and increased productivity for transporting metal chips.

To achieve the aim, the following tasks should be solved:

– analysis of conditions of applying screw conveyors in the mechanical shops at industrial enterprises, the study of their structures and requirements for screw conveyors;

– the study of mechanism of interaction between metal chips and additional blades on the screw's spiral.

4. The method of research into determining the equation of the surface of additional blade of a screw conveyor

The study was carried out on a specially constructed stand, which is actually the screw with additional blades fixed on the surface of the screw's spiral (Fig. 2). Additional blades are mounted so that it may be possible to change the angle of attack.

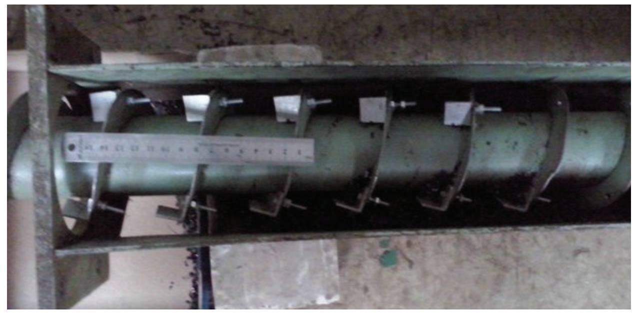

Fig. 2. Experimental screw

Screw conveyor works in the following way (Fig. 3). With the help of electric motor 1, the torque is transmitted to the worm regulator 2, which triggers the screw 3. Chips, loaded in the gutter 4, are transported in the direction of the unloading opening with the help of the screw 3. Using the ribs 5, installed on the spiral working surface of the screw 3, chips are discharged in the transportation direction and thrown to the other side of the screw axis which allows emptying the useful volume of the gutter.

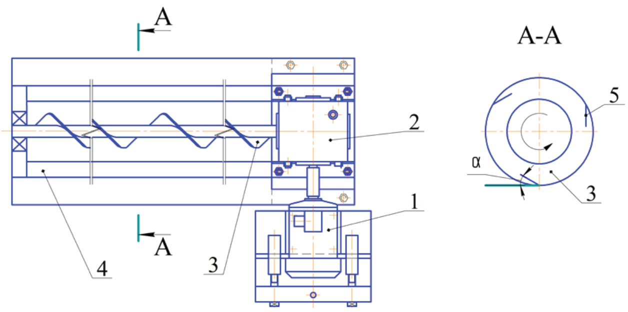

Fig. 3. Design of experimental stand of screw conveyor

Additional blade is an area, which has its own axes of coordinates that depend on inclination angle of the screw's spiral and on the position of the screw in space at a specific point in time with regard to rotation frequency. A particle of chips begins its motion at the moment, predetermined by the dependency of angle of attack of additional blades on the inclination of the screw's spiral they are attached to. The angle, which is formed at the moment the chips begin to move on the blade surface, is accepted as the angle of start of the motion of material. A particle of chips is to move simultaneously on the surface of the blade in two planes. The curved line of movement of the particle describes equation of the surface of additional blade, along which it is moving. During the movement of the particle, the photo fixation takes place, which allows describing the blade surface in its own coordinate system. Graphic transfer of the particle's movement gives the equation of the blade surface and the line of intersection with the spiral at a certain point of time.

5. Results of determining equation of the surface of additional blade of screw conveyor

The numerical value of angle of attack of additional blade – α [18], at which the particle of metal chips begins to move, depends on its position on the surface of additional blade, that is, on the magnitude of angle of beginning of movement of material – β. It was experimentally established that the screw with additional blades requires significantly less magnitude of lifting and driving force to move the cargo in comparison with a classic screw (Fig. 4).

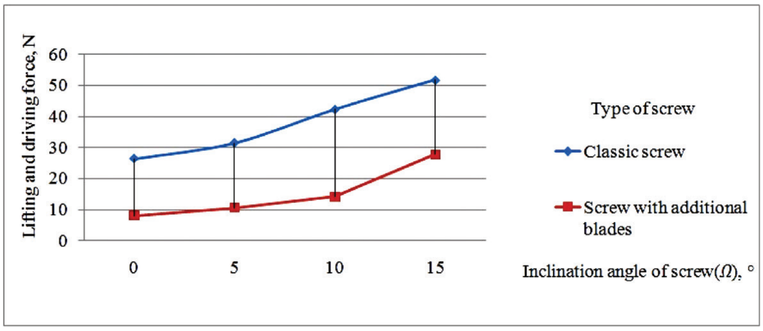

Fig. 4. Dependency of lifting and driving force on inclination angle of screw

Conducted experimental research on a specially constructed stand gave us the opportunity to graphically demonstrate dependencies of angle of beginning of movement of material on the angle of attack of tadditional blade (Fig. 5).

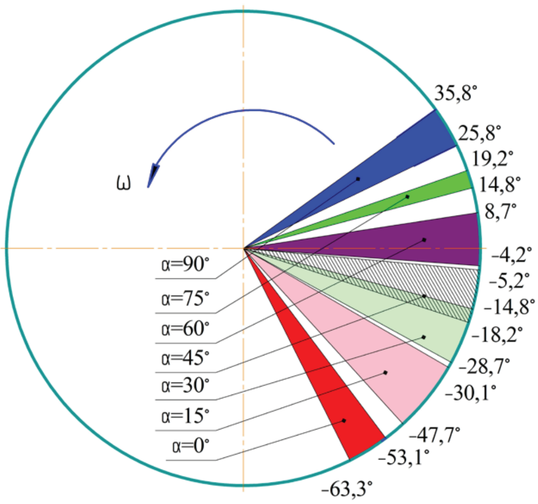

Fig. 5. Variations of dependency of location of angle β on the angle of attack α

From Fig. 5 we have the following dependencies of angle of beginning of movement of material on the angle of attack of additional blades:

– at the value of angle of attack of additional blade α=0°, the angle of beginning of movement of material varies from –63,3° to –53,1°;

– at the value of angle of attack of additional blade α=15°, the angle of beginning of movement of material varies from –47,7° to –30,1°;

– at the value of angle of attack of additional blade α=30°, the angle of beginning of movement of material varies from –28,7° to –14,8°;

– at the value of angle of attack of additional blade α=45°, the angle of beginning of movement of material varies from –18,2° to –5,2°;

– at the value of angle of attack of additional blade α=60°, the angle of beginning of movement of material varies from –4,2° to 8,7°;

– at the value of angle of attack of additional blade α=75°, the angle of beginning of movement of material varies from 14,8° to 19,2°;

– at the value of angle of attack of additional blade α=90°, the angle of beginning of movement of material varies from 25,8° to 35,8°.

Based on the conditions of accepted geometric parameters of a blade as a rectangular plane in space, we can write down equation of the surface of the area of additional blade in a general form:

$$\cos\alpha_x(x-x_0)+\cos\alpha_y(y-y_0)+\cos\alpha_z(z-z_0)=0, \quad (1)$$

where α_x, α_y, α_z are the angles between the normal and correspondent axes; x_0, y_0, z_0, x, y, and z are the coordinates of a point in the moment of time.

If one knows the point with the coordinates (x_0, y_0, z_0) through which the surface passes, the equation will take the form:

$$x\cos\alpha_x+y\cos\alpha_y+z\cos\alpha_z-l=0, \quad (2)$$

where l is the distance to the surface, α_x, α_y, α_z are the angles between the normal and the corresponding axes, x, y, and z are the coordinates of a point in the moment of motion. According to Fig. 6, (o_b, y_b, x_b are additional coordinate system of the blade) for the initial position of the point on the blade of equation takes the form:

$$(x-R)\cos\alpha+y\sin\alpha=0, \quad (3)$$

then for the normal loop we obtain equation:

$$x\cos\alpha+y\sin\alpha-R\cos\alpha=0, \quad (4)$$

where $R\cos\alpha=l$.

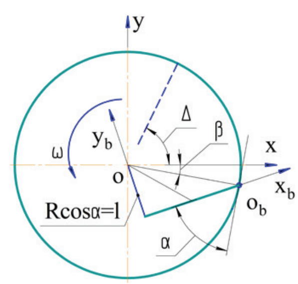

Fig. 6. Cross-section of screw in the frontal plane, taking into account additional blade (where o, x, y are the coordinate system of screw; x_b, y_b, o_b are the coordinate system of additional blade; l is the distance to surface of additional blades to the axis of screw; α is the angle of attack of additional blades; R is the radius of screw; w is the angular speed of screw; β is the angle of beginning of movement of material along additional blade; Δ is the angular parameter of derivative of blade of placement of additional blade in a moment of time (fluid angle), which is measured from the Ox axis of stationary coordinate system)

Then the equation of plane of the area of additional blade, taking into account the angle of beginning of movement of material, is expressed:

$$x\cos(\alpha+\beta)+y\sin(\alpha+\beta)-R\cos\alpha=0. \quad (5)$$

However, angle β is the angle of beginning of movement of material along the additional blade, and, at the same time, the inclination angle of the blade to the plane of the screw's spiral. During the spatial displacement, it describes the equilibrium of forces along the axis, which coincides with the projection of the area of additional blade.

We will set up equation of forces on the axis, which is perpendicular to the plane:

$$N-G\sin(\alpha+\beta)+F_u\sin(90-\alpha)=0, \quad (6)$$

where N is the force of reaction of support; G is the force of weight of the particle, $G=m\cdot g$, m is the mass of the particle of chips, g is the acceleration of free fall; α is the angle of attack of additional blade; β is the angle of beginning of movement of material; F_u is the centrifugal force, $F_u=mw^2R$, w is the angular speed of the screw, R is the radius of the screw.

Here we obtain equation of critical frequency:

$$w_{kp}^2R(\sin\alpha+f_{mp}\cos\alpha)=g[\cos(\alpha+\beta)+f_{mp}\sin(\alpha+\beta)], \quad (7)$$

$$w_{kp}=(g/r\cdot\cos(\alpha+\beta)+f_{mp}\sin(\alpha+\beta)/\sin\alpha+f_{mp}\cos\alpha)^{1/2}=$$
$$=(g/r\cdot\cos(\alpha+\beta-\varphi)/\sin(\alpha+\varphi))^{1/2}, \quad (8)$$

where $\varphi=\mathrm{arctg}f_{mp}$ is the angle of friction, w_{kp} is the angular speed of the screw (critical), f_{mp} is the coefficient of friction to the additional blade.

To specify the angle of beginning of movement, we can use equation:

$$(w_{kp}^2R/g)\sin(\alpha+\varphi)=\cos(\alpha+\beta-\varphi). \quad (9)$$

From here we obtain improved angle of beginning of movement of material along the surface of additional blade:

$$\beta=\mathrm{arcos}[(w_{kp}^2R)/g)\cdot\sin(\alpha+\varphi). \quad (10)$$

Then

$$x\cos\alpha`+y\cos\alpha-r_0=0, \quad (11)$$

where $\alpha`=90-\Delta$; $r_0=R\sin\Delta$, Δ is the angular parameter of derivative of the blade of position of the additional blade in the moment of time (fluid angle), which is measured from the Ox axis of the fixed coordinate system.

Therefore,

$$x\sin\alpha`+y\cos\alpha`-R\sin\Delta=0,$$
$$x\cos\Delta+y\sin\Delta-R\cos\alpha`=0 \quad (12)$$

Let us proceed to the polar coordinate system:

$$\varphi_0=-(90-\alpha`)=\alpha`-90, \quad (13)$$

provided φ_0: $p=p_0=R\sin\alpha`$.

With moving Δ:

$$p=(r_0/\sin(90-\alpha`+\Delta))=$$
$$=(R\sin\alpha`/\cos(\alpha`-\Delta))=r_0/\sin(\alpha+\Delta)). \quad (14)$$

Thus, in the polar coordinate system, equation of the blade surface will be described by dependency:

$$p=(R\cos\alpha/\sin(\alpha+\Delta));$$
$$p=(R\sin\alpha`/\cos(\alpha-\Delta)),$$
$$p=(R\cos\alpha/\cos(90-\alpha-\Delta))=(R\cos\alpha/\sin(\alpha+\Delta)). \quad (15)$$

Screw surface of the auger's spiral, as it is known, in parametric form will be described by dependencies:

$$x=p\cos\Delta;\ y=p\sin\Delta;\ z=T/2\pi\cdot\Delta, \quad (16)$$

where T is the step of the screw, p is the radial parameter in the polar coordinate system.

Accordingly, after substitution of parameter Δ we obtain equation of the line of intersection of the screw surface and the area surface:

$$x=(R\sin\alpha`\cos\Delta/\cos(\alpha`-\Delta));$$
$$y=(R\sin\alpha`\sin\Delta/\cos(\alpha`-\Delta));$$
$$z=\Delta T/2. \quad (17)$$

6. Discussion of results of research into the surface of additional blade

For conducting experimental research into equation of the surface of additional blade, we designed, manufactured and tested under laboratory and industrial conditions the sample of screw conveyor, which can be used in the process of designing similar conveyors for specific workshop conditions. By the results of research, the original design of the screw conveyor with additional blades was developed (Fig. 7), besides, the results of experimental and theoretical research gave us the opportunity to continue scientific practical and theoretical research into the processes of transportation with the help of screw conveyors with additional blades

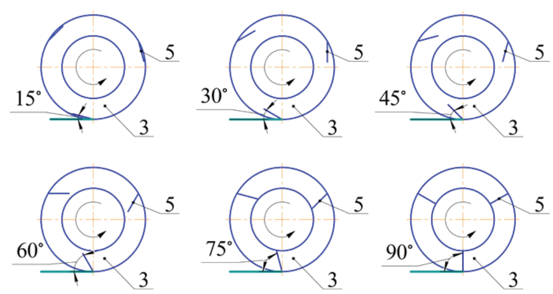

Fig. 7. Variations of screw conveyor with additional blades at different angles of attack (where pos. 3 is screw's spiral; pos. 5 is additional blade; 15°, 30°, 45°, 60°, 75° and 90° are angles of attack of additional blades)

The main achievements of this work, to our understanding, are obtaining the formula of determining improved angle of beginning of movement of material on the surface of additional blade; describing the dependency of equation of the blade surface in the polar coordinate system, and developing the equation of the line of intersection of the screw surface and the surface of the area in the parametric form. These achievements gave us the opportunity to theoretically prove positive impact of additional blades of screw conveyor on decreasing the lifting and driving force for moving metal chips due to the reduction of forces of internal friction of transported metal chips, which is achieved by partial removal by additional blades of the layer of chips from the general stream in the gutter of a screw conveyor. The obtained equations of the line of intersection of screw surface and the surface of blade area make it possible to describe the motion of a material point along these surfaces, and thus to predict the direction of motion of material transported by the conveyor. Mathematical dependency for determining the effective angle of beginning of the metal chips motion on the additional blade of the screw's spiral was received, and the law of its movement along the blade was established. Practical outcomes include the development, production and testing under laboratory and industrial conditions of research sample of the screw conveyor, which can be used in the process of designing similar conveyors for specific workshop conditions. The existing disadvantages include the fact that the impact of the type of transported material and its geometry are not considered in the calculation models, nor is the possibility of using these calculations in vertical conveyors. These unrevealed factors of influence are planned to be examined. In addition, the obtained equations of the blade surface should be included in the mathematical models of determining the productivity and energy consumption of screw conveyors with additional blades. This work continues the scientific technique meant to increase the performance of screw conveyors under conditions of stable or not rising energy costs. Subsequent work in this direction may be aimed at upgrading structural parameters of conveyors, determining the influence of the type of material and, most importantly, applying the methods of increasing the performance efficiency of screw conveyors to the majority of existing types of transport and auxiliary machine building processes.

7. Conclusions

1. The main requirement for the screw conveyors in mechanical shops of industrial enterprises is to ensure the transportation of a certain amount of material within a set distance in a set period of time when it is impossible to use other kinds of conveyor transport. The main requirements for the screw design are proportional ratio of a driving shaft's dimensions to the screw's spiral, which provides for sustainable but rather low performance efficiency at the required durability and non-restarting of work. Increased performance is achieved through the use of more powerful drives and, accordingly, the increased energy costs.

2. In the course of studying the mechanism of interaction between metal chips and additional blades on the screw's spiral, we revealed and reasonably substantiated positive impact of additional blades of the screw conveyor on the decrease in lifting and driving force for moving metal chips. This occurs as a result of reduction of forces of internal friction of transported metal chips, which is achieved by partial removal by additional blades of the layer of chips from the general stream in the gutter of a screw conveyor. Mathematical dependency for determining the effective angle of beginning of metal chips motion along additional blade of the screw's spiral was obtained, and the law of its movement along the blade was established.

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