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EXPERIMENTAL STUDY OF THE SNOW REMOVAL PROCESS BY HELICAL BLADE OF THE MILLING FEEDER

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The article presents the process effectiveness evaluation of the throwing snow mass from the face into the operating area of the snowplow rotor-thrower by a milling feeder, when using a paddle type intensifier. During the operation of the milling-rotor snowplow, an operational problem sometimes arises, arising from an incorrectly set slope (angle of elevation) of the helical line of the milling feeder, due to which snow is thrown forward by it along the snowplow, forming an additional amount of snow for processing, which increases the overall energy costs for the development of snow and the movement of the machine in the snow massif and at the same time reduces the performance of the snowplow [1, 2]. The area of rational values of the design and operating parameters of the milling feeder and the bladed intensifier of the snowplow has been calculated. The process of efficiency increase of the milling-rotary snowplow (MRS) and its performance by adjusting the helix angle α and installing a bladed intensifier reducing the power of the working process will make it possible to perform work on clearing snow and ice formations using reduced number of machines, moreover in much less time. A more massive supply of snow mass to the blades of the rotor-thrower due to the use of an intensifier will lead to a decrease in the total energy costs for the snowplow working process. Therefore, by increase the working equipment efficiency of a MRS with the energy intensity decrease of snow development by selecting rational parameters for its design and workflow is the simplest and most effective way to rationally organize the workflow and improve machines of this type of snowplow.

Keywords: snow, milling-rotary snowplow, drag prism, screw feeder, snow throw distance

1 INTRODUCTION

Transportation is carried out all year round, in summer and winter, and ensuring its stability in winter. When the regularity of transportation can be hindered by weather conditions (heavy snowfalls, blocking roads and airfields), road maintenance services become the main task. The efficiency of road maintenance services has increased requirements in the winter period. The performance indicators of the relevant services include the ability to high-speed cleaning of significant volumes of snow masses, the power consumption of snow-removing equipment for emergency work at a high rate.

As with any emergency operation, snowplow operations have their own challenges that will help ensure the most efficient and stable transport operations.

The main challenge will be to provide the most productive snow blowers with the least energy expended. It makes no sense to equip all municipal organizations with heavy, powerful snow blowers, since they can be out of work for years, and the throughput of snow blowers is sometimes insufficient to process a significant amount of abnormally fallen snow. When the screw feeder of the rotary snowplow interacts with the developed snow face, part of the snow is thrown forward by the feeder, forming a drag prism, which increases the energy consumption for the development of snow and for the movement of the machine in the snow mass and at the same time reduces the performance of the snowplow.

To improve the performance of the most common milling-rotor snowplows, this article proposes to equip them with paddle intensifiers, which, while maintaining all the main parameters of the snowplow, allow both to increase the speed and volume of the removed snow mass, and to reduce the energy and time costs of high-performance snow removal.

The theoretical and experimental material of this constructive improvement of snow blowers is offered in this article for discussion.

The article is the third in a series of articles devoted to the problem under consideration, therefore, in the course of the article there will be some references to the materials of previous studies [1-3].

Analysis of the MRS working process.

It is necessary to consider a new design of a milling-rotary working body of a snowplow, in which, unlike the known ones, a bladed intensifier of the working process is added, which processes the snow mass at an accelerated pace, including a drag prism, and its area of action corresponds to the highest saturation (up to 70%) of the discarded snow mass accumulated in the form of a prism in the center in front of the snowplow.

Increasing the efficiency of the screw feeder due to rational operating modes and the use of a paddle intensifier (which prevents losses due to the movement of the snow dragging prism) will increase the speed of snow passage precisely in places where it is excessively accumulated, where the bulk of the snow comes from the feeder to the operating area of the rotor-thrower. This will reduce the overall energy costs, since it will not be necessary to transport the dragging prism from the snow in front of it, which the feeder did not have time to process before and rested against it.

The main hypothesis in this case is that the paddle intensifier, installed in the middle of the working body and rotating at a speed greater than the speed of screw feeder rotation, will allow the snow mass to be fed to the rotor-thrower in an accelerated mode, usually accumulating in the form of a drag prism in front of the working body. This will completely eliminate the formation and accumulation of a snow prism, as well as reduce energy costs for clearing snow and for moving a car in a snowy corridor. These energy inputs were previously spent on the forced transportation of a snow drag prism, and at the same time increase the operating speed and performance of the snowplow.

1.1 Calculation of the snow dragging prism in well-known studies

When calculating the distance of throwing snow mass by a bladed intensifier-thrower, as well as when calculating the productivity of a helical line of a milling feeder, 2 main schemes for loading MRS can be considered: 1) when the height of the processed snow mass is higher than the middle of the screw feeder, i.e. more feeder radius; 2) when the height of the snow mass is below the radius of the feeder [1, 2]. Both of these schemes, their geometry and the forces on the milling feeder are fully described. To compile a mathematical model of the working process of a milling-rotor snowplow with a paddle intensifier, the first design case has been taken into account, It will be more energy-intensive, besides, according to this scheme, it is possible to immediately check the effectiveness of using the MRS with a bladed intensifier in the development of anomalous snow masses, as well as check the most rational layout of the MRS working equipment [3-6].

It is necessary to consider the MRS screw feeder scheme (Figure 1), in the middle of which, between the left semi-mill (1) and right semi-cutter (2), a bladed intensifier (3) is installed, in the form of a throwing drum with blades, which has an autonomous drive and rotation independent of the feeder.

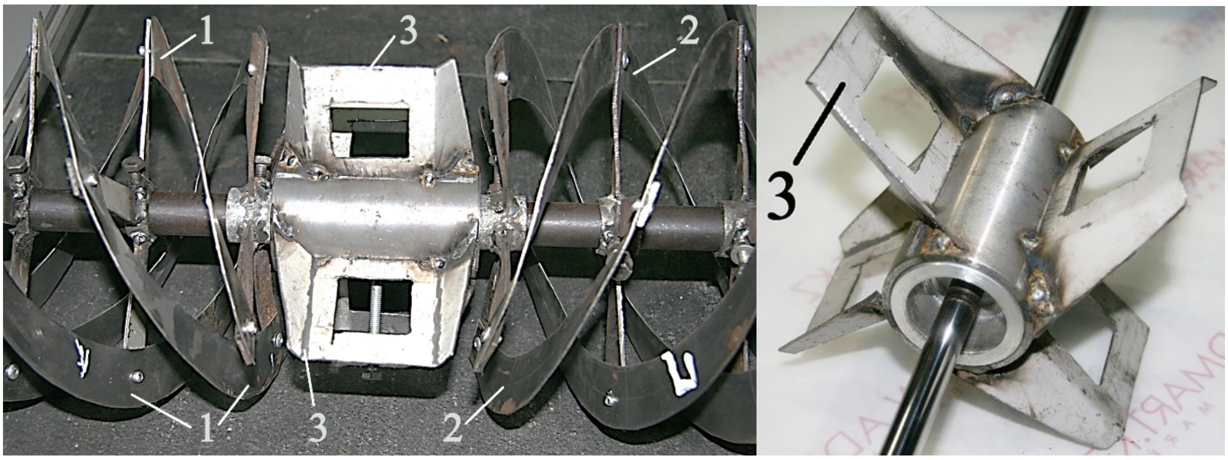

Fig.1. Scheme of the FRS screw feeder: 1 - left semi-mill; 2 - right semi-cut; 3 - bladed intensifier

It is accepted that the mass of snow processed by the MRS feeder, passing through the through window of the body into the thrower (thrower), consists of the mass discarded by the screw feeder and the mass accumulated on the intensifier blades. The direction of rotation of the drum with blades must coincide with the direction of rotation of the milling feeder. Otherwise, the snow mass captured by the intensifier blades will not be thrown into the thrower, but mainly forward to the face, which will cause a sharp decrease in productivity with a significant increase in energy consumption for the MRS workflow [7].

The elementary volume of snow formed on one radial blade of the intensifier in the zone of interaction with the snow mass (Figure 2)

$$dq = \int_{x_1}^{x_2} b_l \cdot h_l \cdot R_i d\varphi \quad (1)$$

where b_l – intensifier blade width; h_l – blade height; R_i – radius of the intensifier rotation; $d\varphi$ – elementary rotation angle of the blade in the face; x_1 and x_2 – limits of integration, x_1=0; x_2=φ_p. φ_p – snow cutting angle.

Then

$$q = b_l \cdot h_l \cdot R_i \cdot \varphi p \quad (2)$$

The snow mass on the blades of the intensifier located in the interaction zone with the snow face:

$$m_2 = q \cdot \gamma \cdot z' = q \cdot \gamma \cdot \frac{\varphi_p}{2\pi} \cdot Z_i \quad (3)$$

where z' - the number of blades simultaneously located in the bottom;

Z_i –number of blades in the intensifier;

γ - snow density.

The total value of the horizontal and vertical forces and the moment of resistance to rotation on the milling working body with a blade-type intensifier are presented as an algebraic sum of forces on the feeder and on the intensifier in previously published articles [1, 2, 8].

A fragment of snow, located on the blades of the intensifier, is affected in the radial direction by the force of inertia and the component of gravity, causing the occurrence of a friction force of the specified fragment against the bottom.

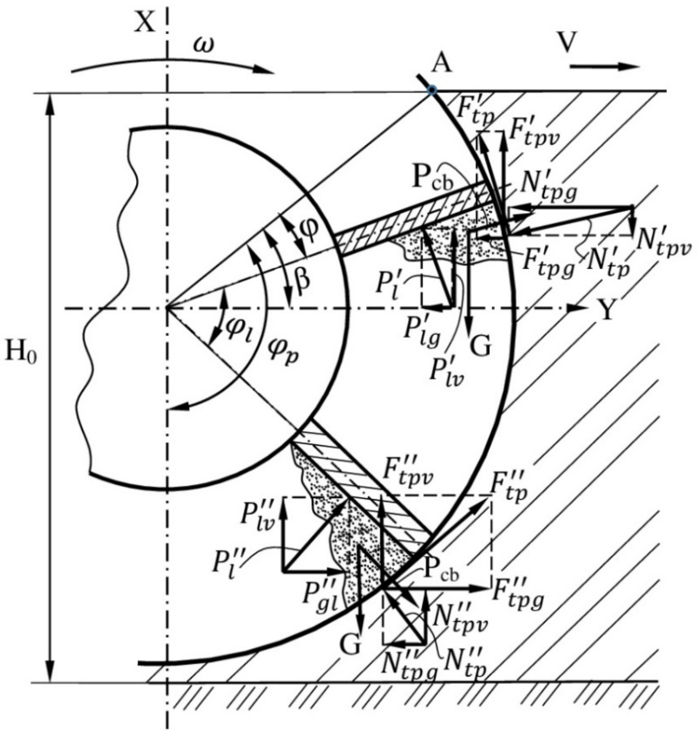

Figure 2 - Forces applied to the intensifier blades

After some mathematical transformations:

$$F_{tr} = \frac{F_l \cdot R_i \cdot \gamma \cdot q \cdot f_2 \cdot z}{2\pi} \cdot \left[\frac{R_i \cdot \omega_i^2}{q} \cdot \varphi_p + sin\left(\varphi_p - \beta\right) + sin\beta\right] \qquad (4)$$

where β - a specific angle of rotation of the screw feeder from the horizontal axis Y to point A of the outer surface of the developed snow (Figure 2);

φ_p - angle of the screw feeder rotation from the vertical axis X to point A.

Considering the friction force of the particles moved by the screw snow feeder at the place of its development, the moment of resistance will be equal to:

$$M_{tr} = F_{tr} \cdot R_i \qquad (5)$$

The components of the friction forces of snow in the horizontal plane, generated by the friction of the snow mass particles located on the intensifier blade against the developed volume of snow, in the rotation range of the angle φ from the value of β to the value of φ_p and from the value of *0* to the value of β, have different directions [1, 9-11], therefore taking into account their values, the horizontal force P_{gtr} will have the form:

$$P_{gtr} = \frac{F_l R_i \gamma \frac{z}{2\pi}}{2\pi}\left\{\beta\left[R_i \omega_i^2 f_2\left(cos\beta - \frac{sin\beta}{f_2} - 1\right) + q f_2\left(\frac{sin^2\beta}{2f_2} + \frac{\beta}{2} - \frac{sin2\beta}{4}\right)\right] - \right.$$

$$\left. -\left(\varphi_p - \beta\right)\left[R_i \omega_i^2 (sin\theta + f_2(cos\theta - f_2) + q\frac{sin^2\theta}{2} + f_2\frac{\theta}{2} - f_2\frac{sin2\theta}{4}\right]\right\} \qquad (6)$$

where $\theta = \left(\varphi_p - \beta\right)$.

The vertical component of the friction forces of the snow located on the intensifier blades against the face, after transformations, takes the form:

$$P_{vtr}=\frac{F_l R_i \gamma \frac{z}{2\pi}}{2\pi}\{R_i\omega_i^2[f_2(sin\theta-sin\beta)-cos\theta+cos\beta]+$$
$$+q\left[f_2\left(\frac{sin^2\theta}{2}-\frac{sin^2\beta}{2}\right)+\frac{\theta}{2}-\frac{\beta}{2}-\frac{sin^2\theta}{4}-\frac{sin2\beta}{4}\right]\} \quad (7)$$

To maintain the optimal rate of snow removal from the intensifier blade, it is necessary to know the extreme critical angular velocities of the intensifier ω_{kr}. During the unloading time t_p, the blades must be completely free of snow accumulated on them. At a certain value of the angular velocity of the intensifier, the snow prism may not have time to leave the blades in the process of the latter passing by the intake pipe, which will lead to the transfer of snow through the screw feeder. The condition for unloading the blades from the snow mass, expressed through the geometric and kinematic parameters of the intensifier, is determined by the inequality:

$$\frac{h_l}{V_p}=\frac{\varphi_p}{\omega_{kr}}. \quad (8)$$

Substituting the previously obtained dependencies, after the transformations it is obtained:

$$\omega_{kr}=\frac{\varphi_p\left[2ae^{k_1t}cf_1^2\left(1+\frac{c}{2f_1}\right)+2f_1^2be^{k_1t}c\right]}{(1+f_1^2)^2(2f_1+e^{k_1t}c)[\varphi_p 2h_l e^{k_1t}cf_1(2f_1+c)-h_l(2f_1+e^{k_1t}c)]} \quad (9)$$

where $a=2gsin\varphi_0 f_1-gcos\varphi_0(1-f_1^2)$; $b=2gcos\varphi_0 f_1+gsin\varphi_0(1-f_1^2)$; $c=-f_1+\sqrt{f_1^2+1}$.

The condition for unloading a bladed intensifier can be represented as follows: $\omega_{kr}>\omega_i>\omega_0$.

Under the condition $\omega_i<\omega_0$, there is no process of unloading the intensifier from snow, i.e. the accumulated snow prism does not have time to leave the blade at the moment the latter passes by the through window in the casing, which leads to the transfer of snow forward and the formation of a drag prism in front of the snowplow working body, thereby causing an increase in traction resistance to the movement of the machine and, as a result, a decrease in operating speed and snow blower performance. Under the condition $\omega_{kr}<\omega_i$, the intensifier blades are unloaded in the upper square of the through window in the casing, i.e. against the movement of the rotor-thrower, and contributes to the accumulation of the dragged volume of snow in front of the snowplow screw feeder. In addition, when $\omega_{kr}<\omega_i$, the snow mass is intensively thrown by the blades of the intensifier through the feeder, causing prism formation of dragged snow in front of the screw feeder.

2 EXPERIMENTAL STUDIES

Laboratory experimental studies of the milling-rotary snowplow (MRS) model working with natural snow turned out to be not reproducible with the same initial parameters, due to the constant change in the properties of snow that got into a warm room. The snow melted, changed its structure, looseness, stickiness, etc. It was decided to replace natural snow with a material that most closely imitates snow and has a reproducible constancy of properties, especially since recommendations were found according to which the starting materials were selected, namely sawdust, sand and paraffin, a mixture of which in a certain percentage proportion was imitating snow material [4, 6, 7, 12]. The same materials were used in previous experiments, so the physical and mechanical properties of the material simulating snow did not differ from those known [1, 2, 13].

With the help of special measuring equipment from the company GCTS RDS 200 [5], the physical and mechanical parameters of the material simulating snow were determined.

2.1 Experimental EQUIPMENT

When conducting experimental studies under the contract, a test laboratory bench of a milling and rotary snowplow of the Moscow Automobile and Road Institute was used, the physical model of the screw feeder of which included: 1 - model of the left half-cutter of the screw feeder, 2 - model of the right half-cutter of the screw feeder, 3 - bladed intensifier, 4 - hollow shaft of rotation of the left half-cutter, 5 - hollow shaft of rotation right half-cutter, 6 - outlet window of the snow plow housing, 7 - material being developed.

The initial material came from a hopper (not shown) and was evenly fed by a conveyor belt directly into a screw feeder equipped with a tensometric suspension, from the sensors of which the necessary indicators were taken. Each of the feeder half-mills and the paddle intensifier had its own independent electric drive, controlled from the control panel.

Since the external conditions during the experiment can lead to systematic errors in the response function, the experiments were carried out in random order, but over the entire planning matrix.

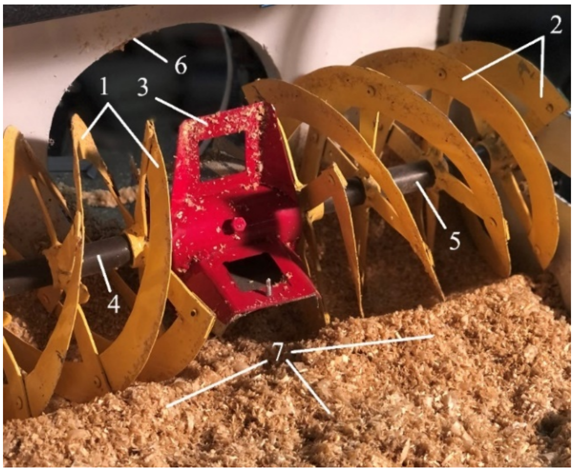

Fig. 3. Physical model of the MRS with a paddle intensifier, mounted on an experimental stand to study the working processes of snowplows

Based on known methods [4-7, 14], a multivariate experiment was performed, in which, with a significance level of α=0.05, the adequacy of the models was determined during the processing of experimental indicators, and the numerical values of the regression coefficients and their significance were found.

Of particular scientific interest is the general functional model obtained in the form of a regression equation for variables in natural form for the distance of throwing the developed snow:

$$L_{otbr} = -8{,}097 + 0{,}0404n - 0{,}0399V + 0{,}038\alpha + 5{,}3h - 0{,}025nh - 0{,}00005n^2 + 0{,}0014V^2 - 0{,}0006\alpha^2 + 32{,}5h^2, \text{ m.} \quad (10)$$

Based on the obtained regression equation [1, 2], which takes into account the distance of throwing L_{otbr} the snow mass as a function of the design and operating modes of the feeder, graphical dependences of L_{otbr} as a function of α, n and V_{per} are plotted (Figures 4 and 5). This parameter for a milling screw feeder can be used to evaluate the efficiency of the process of throwing snow mass onto the blades of the thrower rotor.

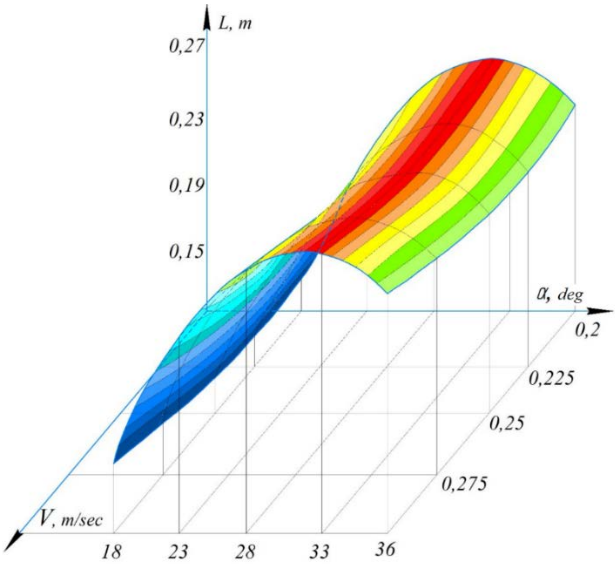

Fig. 4. Helix angle rise α and operating speed V (at n=400 min^{-1}; h=0.1m) affecting the snow mass throwing distance

As the angle of helix elevation α changes from 18^0 to 28^0…30^0, the ejection range increases, with a further increase in the value of α, the value of L_{otbr} begins to decrease, since due to the flattening of the helical cavities of the feeder, the ejection angle β of the mass transported by the cutter increases.

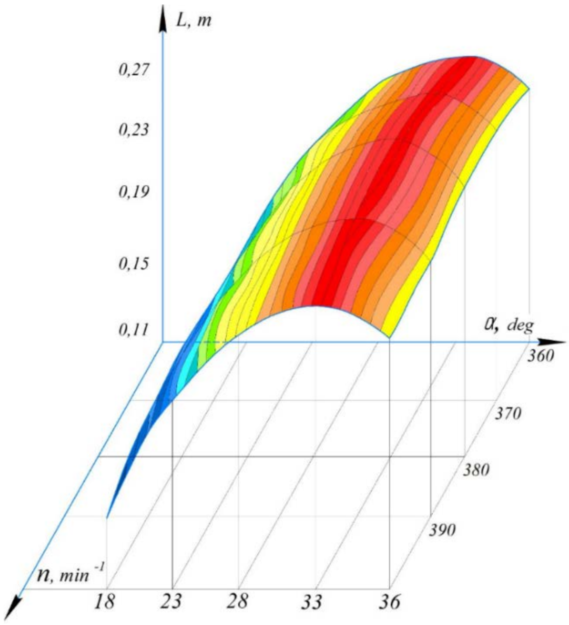

Fig. 5. Helix angle elevation α and screw feeder speed n (at V_{per}=0.3s^{-1}; h=0.1m) affecting the snow mass throwing distance

As shown by the changes in the photograms of the process of ejection of material from the inlet of the feeder casing (Figure 6), the average values of this angle β are within the following limits:

$\alpha = 18^0$ $\beta = 15^0 \ldots 20^0$

$\alpha = 28^0$ $\beta = 21^0 \ldots 27^0$

$\alpha = 30^0$ $\beta = 30^0 \ldots 35^0$

Fig. 6. Photograph of the material ejection process by a milling feeder into the conditional area of operation of the rotor-thrower with the angle of helix elevation: 1) $\alpha=38^0$; 2) $\alpha=28^0$; 3) $\alpha=18^0$

It should be noted that the smaller value of the angle β corresponds to the values V_{per} = 0.28…0.3 m/s and h = 0.09…0.1 m for the snowplow model, which is caused by the increased load of the screw feeder during operation. Determination of L_{otr} allows estimating the energy of ejection of material by the milling feeder into the area of operation of the rotor-thrower.

When the blade of the rotor-thrower meets the mass of snow thrown by the screw feeder, the kinetic energy of the rotor is lost, which can be determined as follows [7]

$$T = \frac{m_p - m_c}{m_p + m_c} \cdot \frac{V_p^2}{2} \quad (11)$$

where m_p – rotor mass; m_c – snow mass; V_p – circumferential speed of the rotor.

To rationally match the operation of the rotor-thrower and the screw feeder by throwing the developed snow mass into the operating area of the rotor-thrower, we will reduce the associated energy losses that occur during the acceleration of the snow mass by reducing the work of the rotor-thrower to transport the snow mass to match the level of the ejection pipe [4, 6].

In addition, it was found [5] that the rotor-thrower uses the maximum power is expended to accelerate snow particles to give them the necessary speed by the time they are thrown. Therefore, in order to reduce the energy consumption of the rotor, it is necessary to simultaneously throw the mass of snow that has descended from the blades of the screw feeder onto the rotor blades.

An essential parameter is the so-called acceleration path L_{razg}, i.e. the length of the section for transporting snow by the rotor blades along the inner surface of the guide pipe, covering the thrower. The more L_{razg}, the higher the energy expended by the rotor for transporting snow.

Thus, for the rational organization of the work of the feeder and the thrower, it is important to direct the snow based on the constructive relative position of both, at an angle β of no more than 18^0 ... 20^0. This value is achieved when using a cutter as a feeder, as shown by experimental studies, with a helix angle of α ~ 18^0, which confirms the rationality of using a cutter of this design.

When studying the model of a milling screw feeder, all arising forces were strain-metered and at the same time its constructive efficiency was evaluated by varying the angles of helix elevation and the associated losses that occurred during the operation of the MRS feeder were determined.

$$K_{eff} = \frac{G_{opyt} - G_{otbr}}{G_{opyt}} \quad (12)$$

where G_{opyt}- the total weight of the material simulating snow used in the experiments;

G_{otbr} – the weight of the snow mass dragging prism formed in front of the MRS, taking into account the already developed snow thrown forward by the feeder.

A photogram of the process of throwing forward a mass of material simulating snow through itself by a milling screw feeder with a different angle of inclination of the helix is shown in Figure 7.

The influence of the helix angle α and the height of the developed snow h on the efficiency coefficient K_{eff} is graphically shown in Figures 8 and 9.

The volume of snow thrown over itself during the operation of the screw feeder increases with an increase in the angle of elevation of its helix *α*, while the efficiency coefficient of the feeder K_{eff} decreases.

Fig. 7. Photogram of the process of throwing forward a mass of material simulating snow by a milling feeder:

1) α=38^0; 2) α=28^0; 3) α=18^0; 4) α=18^0 + paddle type intensifier

In the process of developing an array with a height equal to the diameter of the feeder, the value of $K_{eff} \rightarrow 1$, due to the overlap of the free space for transferring the mass of snow through the feeder, and the feeder turns out to be, as it were, completely closed, one half of the casing of the working body, and the other half of the developed array.

Summarizing the results of experimental tests of the physical model of the screw feeder of the milling snowplow with different helix angles, it is possible to establish the range of rational values of the design and set parameters of the snowplow screw feeder: the angle of helix elevation of the milling feeder is 18^0 ... 20^0, the cutter rotation speed (at any operating speed) is 12, 56 s^{-1}...13.0 s^{-1}.

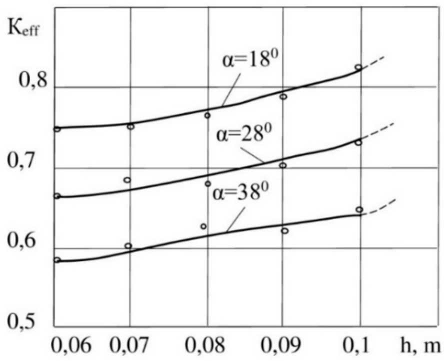

Fig. 8. Influence of the helix angle *α* and the height of the developed snow *h* on the efficiency coefficient K_{eff}

In addition, the analysis of the working process of feeders with different helix angles α allows concluding that the rational design of the feeder in terms of minimum energy consumption is:

- according to the cutting and transporting (lossless) ability of the feeder with α=180...200;
- according to the discarding (unloading) capacity of the feeder with α=180.

Dependence of the working process efficiency of the milling snowplow on the speed of paddle intensifier rotation

The speed of the blade intensifier rotation of the screw feeder is an adjustable parameter that depends on the size of the snow accumulation prism in front of the working body of the milling-rotor snowplow and affects both the resistance forces for snow removal, and its productivity and energy consumption.

When constructing a theoretical model, a hypothesis was adopted about the need for equality between the performance of a screw feeder and the performance of a paddle intensifier. In case of insufficient performance of the intensifier, it is impossible to ensure complete removal of the snow mass accumulated in the central part of the screw feeder. This leads to an increase in the components of the snow development effort and an increase in power costs for the work process.

The rotation ω speed increasing of the intensifier leads to productivity increase, but upon reaching a certain value, the process of throwing snow over itself by the blades of the intensifier is observed due to the inequality of the circumferential speed of the intensifier and the radial speed of the snow mass coming off the blades, i.e. the blades do not have time to completely unload in the process of passing by the intake pipe, as a result of which there is an intensive accumulation of snow in front of the working body in the form of a drag prism, which significantly increases the energy consumption for the working process and reduces the performance of the snowplow. In addition, with an increase in the speed of rotation of the intensifier, the power consumption for the drive of the screw feeder with the intensifier increases. Therefore, a hypothesis was put forward about the need for equal productivity of the screw feeder and the bladed intensifier.

Experimental dependences are graphically combined in the Figure 9.

Dependencies change in the cost of total power and effort in the function ω_{int} show that within the speed of rotation of the intensifier 57.1 s^{-1}...62.2 s^{-1}, the smallest values of these parameters are observed. When compared with the angular speed of the milling feeder, we establish that the range of variation in the speed of the intensifier should be within (1.4 ... 1.5) ω of the milling feeder.

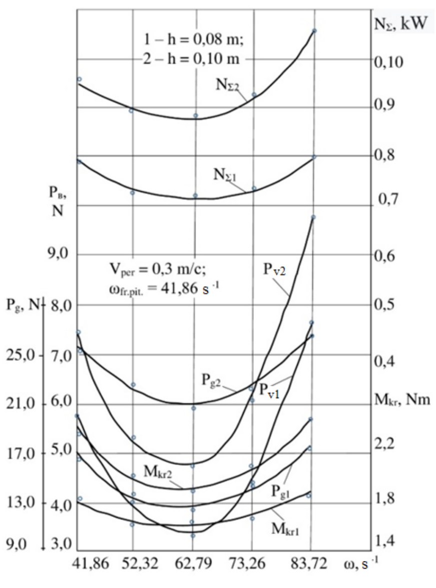

Fig. 9. Influence of the rotation speed of the bladed intensifier *ω* on the torque M_{kr}, total power N_{Σ}, vertical P_v and horizontal P_g forces: 1) h = 0.08 m; 2) h = 0.10 m

3 CONCLUSION

1. When installing an intensifier on a milling feeder with α=180, the horizontal and vertical forces are reduced by 35…40%, when using a paddle intensifier, the moment of resistance on the screw feeder is reduced by 38 ... 40%.
2. The main parameters of the paddle intensifier, which have a dominant effect on the characteristics of the snow development process, on the total power costs for the snow removal process by a milling feeder with an intensifier, are the diameter and rotation speed.
3. The area of optimal from the point of view of the minimum total power consumption, rotation speeds of the bladed intensifier is in the range ω_{int}= (1.4-1.5) ω_{fr}.pit.
4. The use of the intensifier of the proposed design makes it possible to increase the efficiency of the feeder by 20-25%, which is characterized by an increase in the mass of snow entering the thrower rotor with a decrease in the mass transferred through the feeder.
5. An analysis of the efficiency of the milling-rotary snowplow with a feeder intensifier shows that when using a bladed intensifier, the energy intensity of the snow throwing process decreases by 22–26% with a slight (by 1.5–2%) increase in metal consumption.

4 ACKNOWLEDGMENT

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