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MATHEMATICAL MODELLING AND DESIGNING OF A UNIVERSAL CONICAL SPREADER FOR GRANULAR MATERIAL

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A universal conical spreader for uniform distribution of granular fertilizers and seeds of grain crops, grasses is proposed. The developed universal conical spreader is designed for subsurface application of above-mentioned granular materials using seed drills and can be used as a passive distributor in a wide variety of applications. The methods of theoretical mechanics and descriptive geometry, particularly the method of replacement of projection plane have been applied to arrive at the design of the cone – the shape of conical spreader. A parametric equation was derived for the truncated part of the cone, which is an ellipse. The unique design of the cone-shaped distributor has a truncating form in the direction transverse to the movement of the seeder. In order to determine the interval of variability of spreader parameters more precisely, an analysis was carried out using a Mathcad-15 software. The results of theoretical research were confirmed in the laboratory and field conditions. The width of seed distribution, uniformity, and stability of distribution were studied to arrive at the most effective cone distributor design. The smallest values of non-uniformity and instability of material distribution of experimental coulter are reached at the values of factors D = 117–119 mm, h = 17–18 mm, and H = 32–35 mm.

Keywords: coulter; distributor cone; fertilizer; seeder; sowing; subsoil application

The uniform distribution of solid and liquid materials with different physical and mechanical properties is necessary in agriculture and various industries (Liu et al., 2018; Nawi et al., 2020; Lin et al., 2022; Tanbayev et al., 2022). In agriculture, the uniform distribution of granular fertilizers and seeds of crops, grasses is important, and especially in subsoil application (Nukeshev et al., 2016; Alekseev et al., 2020). Studies have shown that the scattered subsoil method of sowing seeds creates the most favourable conditions for growth and development of cultivated crops (Machnev, 2001; Bulgakov et al., 2018; Mihretie et al., 2021). The best quality is provided by seeders equipped with swept coulters with distributors for subsurface sowing, which evenly distribute seeds throughout the field (Karayel and Özmerzi, 2007; Laryushin et al., 2012; Ignaciuk and Zarajczyk, 2020). Coulters with mechanical distributors have many advantages over pneumatic seeders, which are prone to clogging and bulky, which makes them unsuitable for small farms (Kozyukov and Struzhkin, 2011; Aduov et al., 2015; Bogus and Kuzmenko, 2019).

A mechanical seeder with a passive distributor using the force of gravity to scatter seed in the subsoil region can overcome these disadvantages (Nukeshev et al., 2021). However, these seeders suffer from the problem of uneven distribution of seeds and fertilizer granules over the working width.

The uniformity of seed distribution is higher in vibratory distributors; however, their design is complicated (Xu et al., 2017). Lopareva et al. (2021) have developed a grass seed spreader in the shape of a dihedral wedge, each face of which consist of two planes at different angles. A few researchers have studied the application of spreaders with conical form (Artamonov, 2007). The mechanical and technological basics of above-mentioned devices for materials with different physical and mechanical properties have not yet been developed (Sergeyev et al., 2012). We assume that a conical distributor should give a promising effect in uniform distribution of granular materials.

This study aimed to develop a universal conical spreader that can be used to achieve uniform distribution of metered granular solids, such as seeds and fertilizer granules, in the coulter of a broadcast seeder. The design of the conical spreader was derived theoretically and tested under laboratory and field conditions for desired characteristics.

Material and methods

The investigated grain and grass seeder was designed with conical spreader 1. It distributes both the seeds and fertilizer at different depths, over the full width of the working body of the coulter and, importantly, it allows work

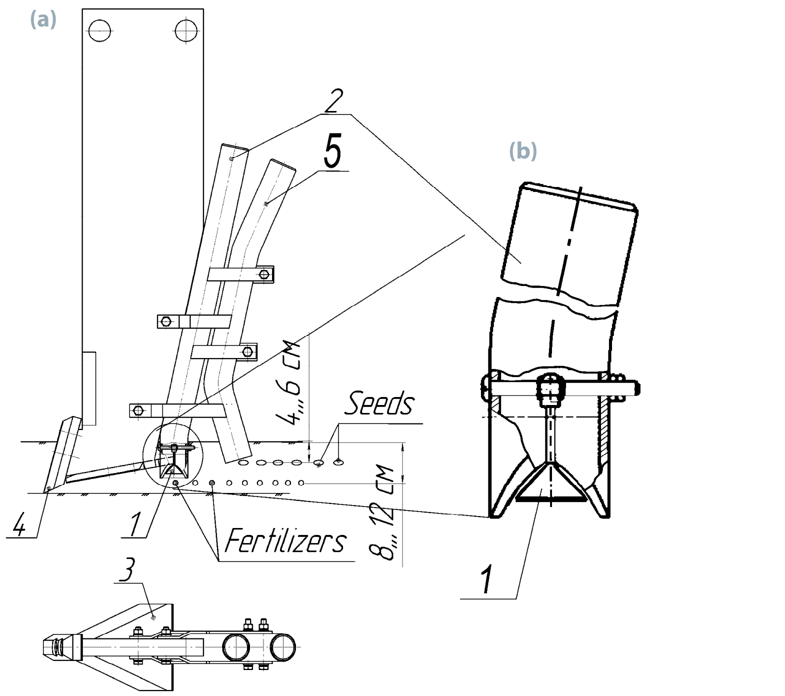

Fig. 1 Construction of seed drill coulters
(a) hoe opener; (b) conical spreader installation. 1 – conical spreader; 2 – fertilizers tube; 3 – knife; 4 – point; 5 – seeds tube

under no-till conditions. The proposed conical spreader 1 can be installed on both arrow-shaped coulters and hoe coulters.

A distinctive feature of the coulter design (Fig. 1a) is that point 4 cuts a vertical slit in the turf with a thickness of 20 mm, and knife 3 loosens the turf without turning the bed. Conical spreader 1 (Figure 1b) is hinged inside fertilizers tube 2 at the rear of knife 3. The mineral fertilizer from the hopper is fed by means of the sowing unit to the surfaces of conical spreader 1 and distributed along the trace of the working body. The conical spreader provides a fertilized strip along the trace of the working body covering the entire working width.

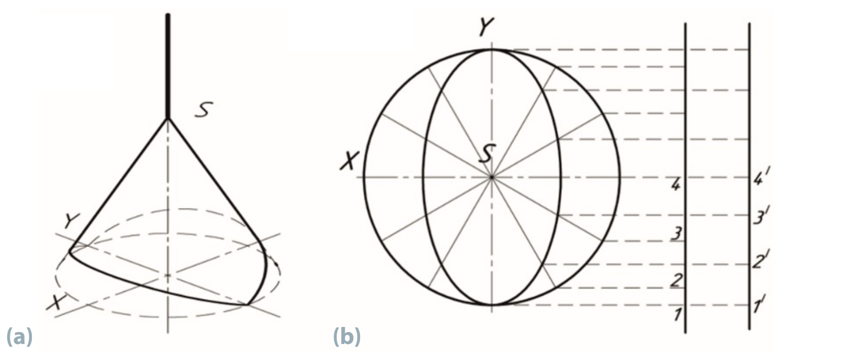

Fig. 2 Geometric consideration of the distributor surface (a) and its top view (b). The direction of movement of the coulter is towards *X*

To ensure the uniform distribution of bulk solids, it is proposed to truncate the cone in the transverse direction of movement, with the lower edge of the distributor in the form of a parabola, and in plan – an oval. It was hypothesized that with a properly chosen form of truncation of the cone, it is possible to obtain equally distributed traces of 1'-2', 2'-3', 3'-4' (Fig. 2).

In order to justify the parameters of the universal conical distributor, theoretical research based on the methods of descriptive geometry, higher mathematics, and theoretical mechanics has been carried out. When determining the natural form of desired distributor curve, projection transformation methods are used.

The quality of a cone spreader depends on its design and process parameters, which have been selected as the main controlling factors:

a) the diameter of the base of the conical spreader, *D* (mm);
b) the height of the conical spreader, *H* (mm);
c) the height of the cut part of the conical spreader, *h* (mm).

The parametric equation of the truncated part of the cone, which is an ellipse, is derived.

The results of theoretical research were confirmed by experimental studies conducted under laboratory and field conditions. Conical distributors with different parameters were made (Table 1), and the sowing process was studied using wheat seeds. The width of distribution, unevenness, and instability of material distribution over the width, which characterize the qualitative performance, were taken as optimization criteria. Further, the intervals of variability of spreader parameters were determined more precisely using Mathcad-15.

Particle velocity up to 3.5 $m \cdot s^{-1}$ was taken into account in calculations. According to Artamonov (2007), the particles in the closed space of the conical distributor have a fairly high

Table 1 Dimensions of the conical spreader based on the sub-sweep space parameters

Conical spreader variants (i)	1	2	3	4	5	6	7	8	9
***H* (mm)**	50	**40**	35	60	50	**35**	60	50	**33**
***D* (mm)**	140	**140**	105	120	120	**117**	100	100	**116**
***h* (mm)**	18	**15**	13	22	19	**13**	21	19	**13**

speed of 3–4.2 m·s^{-1} and, taking into account these speeds in the coulter space, the drag force of the medium acting on them was not taken into account. Only force of friction of particle against the metal surface was taken into account. The coefficient of friction of particle over steel surface of the cone spreader was in the range 0.35–0.55, as described by previous studies (Sergeyev, et al., 2012; Boac et al., 2010).

Results and discussion

Justification of conical spreader parameters

To justify the parameters of the conical spreader, we initially assume the following:

- particles descend on the conical spreader in a single layer;
- all particles have the same mass and dimensions;
- the initial velocities of all particles are the same.

A particle with velocity υ_s at point C descends in the gravitational field along the line CLL_π at a variable angle φ. The given geometrical parameters are cone height H, cone diameter D, and the height of the cut part h (Fig. 3). The distance of the base of the cone from the ground is Δ. The diameter AB is perpendicular to OM and, correspondingly, $AB \perp OL_1$. From the triangle ΔCL_1O, the relation of angle α (half of the solution of the cone) at the vertex C to the given parameters can be expressed as:

$$\cos\alpha = \frac{1}{\sqrt{1+\dfrac{D^2}{4H^2}}};\quad \sin\alpha = \frac{\dfrac{D}{2H}}{\sqrt{1+\dfrac{D^2}{4H^2}}};\qquad (1)$$

$$\tan\alpha = \frac{D}{2H};\quad 0<\alpha<\frac{\pi}{2}$$

Let us introduce the angles of the spherical coordinate system (the relationship between these angles is determined later):

$$<LOL_1 = \varphi;\ <LOL_\pi = \psi$$

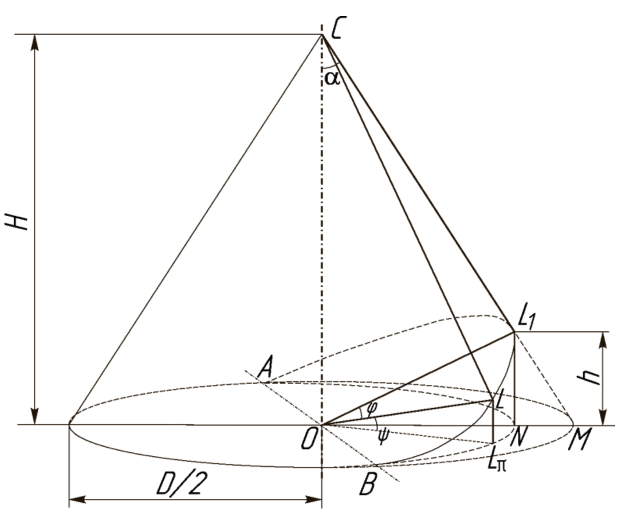

Fig. 3 Geometric characteristics of the truncated distributor cone

Consider the triangle ΔL_1ON. Obviously, the semi-major axis α_1 of the part of the ellipse AL_1B can be expressed as:

$$a_1 = OL_1 = \sqrt{h^2 + \frac{D^2}{4}\cdot\frac{(H-h)^2}{H^2}}$$

The semi-major axis of the ellipse is equal to the radius of cone's base: $b_1 = \dfrac{D}{2}$.

The radius of the ellipse is determined by the formula:

$$r = OL = \frac{a_1 b_1}{\sqrt{b_1^2\cos^2\varphi + a_1^2\sin^2\varphi}} = \frac{\sqrt{h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}}\cdot\dfrac{D}{2}}{\sqrt{\dfrac{D^2}{4}\cos^2\varphi + \left(h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}\right)\sin^2\varphi}}\qquad (2)$$

From the triangle ΔCOL, the following can be deduced from the sine theorem:

$$\cos(\alpha-\psi) = \frac{H}{r}\sin\alpha\qquad (3)$$

where: $0<\psi<\dfrac{\pi}{2}$

Taking into account Eq. (1, 2), the solution of trigonometric Eq. (3) is obtained as:

$$\psi = \arcsin\frac{\sqrt{\dfrac{D^2}{4}\cos^2\varphi+\left(h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}\right)\sin^2\varphi}}{\sqrt{h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}}\cdot\sqrt{1+\dfrac{D^2}{4H^2}}} - \arcsin\frac{1}{\sqrt{1+\dfrac{D^2}{4H^2}}}\qquad (4)$$

Thus, the initial variable parameter remains the angle φ. The particle goes down along the cone formation CL, the length of which is denoted by $CL = s$. From the triangle ΔCOL by the cosine theorem we find:

$$s = \sqrt{H^2 + \frac{\left(h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}\right)\cdot\dfrac{D^2}{4}}{\dfrac{D^2}{4}\cos^2\varphi+\left(h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}\right)\sin^2\varphi} - \frac{HD\sin\psi\sqrt{h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}}}{\sqrt{\dfrac{D^2}{4}\cos^2\varphi+\left(h^2+\dfrac{D^2}{4}\cdot\dfrac{(H-h)^2}{H^2}\right)\sin^2\varphi}}}\qquad (5)$$

In the particular case when the particle descends the line CL_1N:

$$s = (H-h)\sqrt{1+\frac{D^2}{4H^2}}$$

From the triangle ΔLOL_π it follows:

$$LL_\pi = r\sin\psi = \frac{\sqrt{h^2+\frac{D^2}{4}\cdot\frac{(H-h)^2}{H^2}}\cdot\frac{D}{2}\sin\psi}{\sqrt{\frac{D^2}{4}\cos^2\varphi+\left(h^2+\frac{D^2}{4}\cdot\frac{(H-h)^2}{H^2}\right)\sin^2\varphi}} \qquad (6)$$

The particle having initial velocity at point C equal to υ_s moves along a cone line CL with acceleration equal to the projection of free-fall acceleration in the direction of line CL, minus the deceleration of the particle under the action of the frictional force on the surface of the cone:

$$a = g(\cos\alpha - f\sin\alpha) \qquad (7)$$

At the section CL, the particle uniformly accelerates and, at the site LL_π the particle falls freely.

The time taken for particle's motion along the cone's formative and free fall to the ground surface:

$$t = \frac{\sqrt{v_s^2+2as}}{a} - \frac{v_s}{a} + \frac{\sqrt{v_B^2+2g(r\sin\psi+\Delta}}{g} - \frac{v_B}{g} \qquad (8)$$

where: V_B – the vertical component of velocity at the point L

Next, it is necessary to check at which values of the investigated parameters of the cone spreader H, D and h, the hypothesis of equality of the particle descent time along the CLL_π line, when varying the angle φ, is valid.

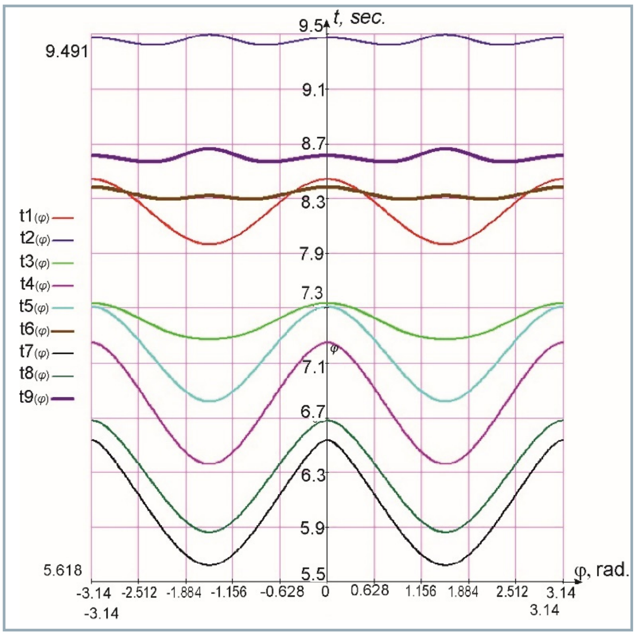

Fig. 4 Dependences of particle descent time t_i on angle φ
i – conical spreader variants from Table 1

The diameter and height of the cone is limited by the inner diameter of the coulter tube and the height of the wing lobe. Based on this, the height of the cone should be in the range H = 30–50 mm, cone diameter in the range D = 100–140 mm, and the height of the cut part h = 10–25 mm.

For more accurate determination of the intervals of variability of the initial parameters of cone, H, D and h, the plots of particle descent time according to Eq. (8) versus angle φ were created using Mathcad 15. The dimensions of the conical distributor in these intervals are taken on the basis of the sub-compartment parameters (see Table 1).

Figure 4 indicates that within the angles $0 < \psi < \frac{\pi}{2}$ and $-\frac{\pi}{2} < \varphi\frac{\pi}{2}$, descent time for all cone forming lines is the same for all spreaders with the parameters H = 40 mm, D = 140 mm, h = 15 mm, and H = 35 mm, D = 117 mm, h = 13 mm, and also for the parameters H = 33 mm, D = 116 mm, and h = 13 mm. These parameters are indicated in bold in Table 1.

The effect of varying of the cone base diameter on the total descent time is shown in Fig. 5. At values above 160 mm, there is a sharp increase in descent time along the formative lines. In addition, the values of diameter less than 100 mm are not recommended based on the size of the material conduit outlet. It can be seen from Fig. 5 that descent time is optimal when diameter varies from 110 to 140 mm.

The dependence plot of particle discharge time on the height of cone's cut part (Fig. 6) shows that the minimum time of particle descent is at the variation of height h = 6–14 mm. The dependence graph has a wavy nature, and there is obviously the second interval of height h = 40–50 mm, at which the minimum of descent time is observed. However, the value of height h has practical limitations related to the parameters of the under-chest space.

The performance of the proposed technical solution was verified by experimental research. As a result of mathematical processing of experimental data, the following regression equations in canonical form were obtained:

– for uneven width distribution:

$$Y_1 - 20.73 = 1.798\,x_1^2 + 0.921\,x_2^2 + 1.601\,x_3^2 \qquad (9)$$

– for unstable distribution:

$$Y_2 - 11.72 = 2.564\,x_1^2 + 1.278\,x_2^2 + 0.575\,x_3^2 \qquad (10)$$

The coordinates of the centre of the figure are:

$$x_{1S} = 0.0557;\ x_{2S} = -0.043;\ x_{3S} = 0.118$$

The natural values of coefficients: the diameter of spreader base, D = 117 mm; the height of spreader, H = 35 mm; and the height of cut-off part of spreader, h = 18 mm. In this case, the unevenness of seed distribution across the width of scattering is 11.78%.

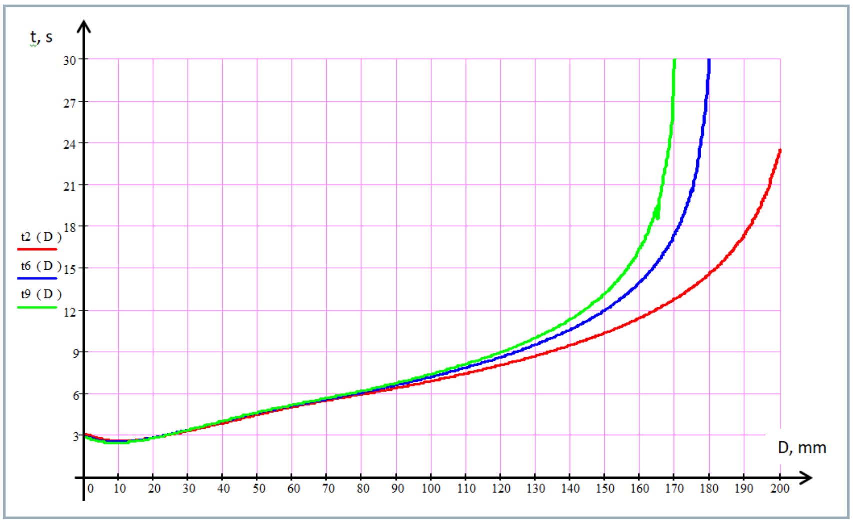

Fig. 5 Dependence of time t_i of particle outflow on base diameter (*D*)
Conical spreaders with number (*i*) of 2, 6 and 9

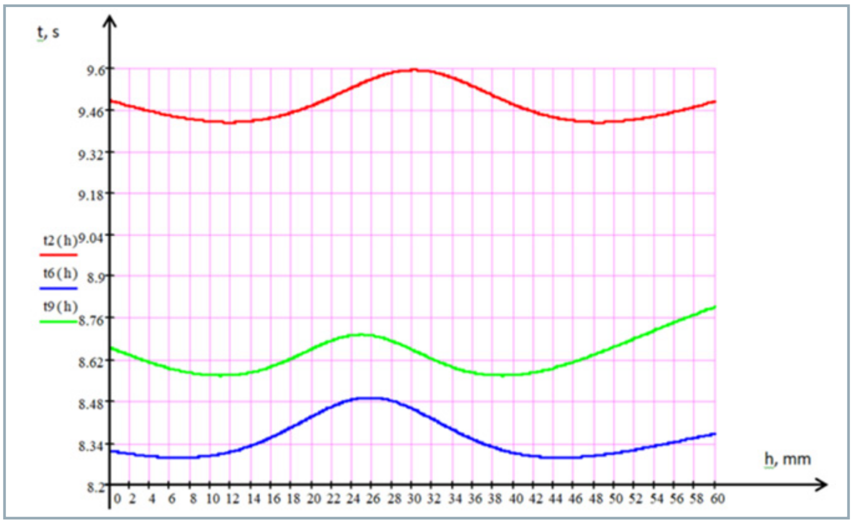

Fig. 6 Dependences of time ti of particle outflow on cut part height (*h*)
Conical spreaders with number (i) of 2, 6 and 9

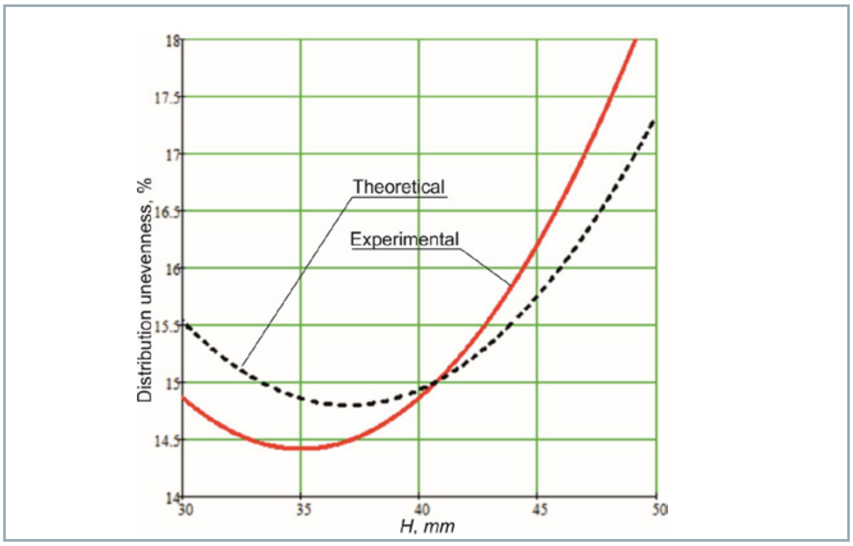

Fig. 7 Dependencies of unevenness on spreader height

In addition, having considered Eq. (5), the following natural values of factors in the centre of the distribution profile were obtained: D = 119 mm, H = 32 mm, and h = 17 mm. The unevenness of seed distribution at the centre is equal to 10.45%.

Experiments to determine the quality characteristics with optimum parameters were carried out using a laboratory bench on which a moving conveyor belt with adhesive tapes is mounted. Material distribution unevenness on spreader height is demonstrated in Fig. 7. The dependences of distribution unevenness on base diameter (*D*) and distributor height (*H*) showed that the deviation between theoretically and experimentally obtained indicators of material distribution unevenness is up to 10%.

As reported previously (Lopareva et al., 2021; Nukeshev et al., 2021), the efficiency of passive distributors depends on the proper choice of surface geometry. It is assumed that the correct shape of the distributor allows an orderly movement of the material (seeds or fertiliser granules) flowing to it chaotically.

The results of our theoretical studies have shown that the symmetrical truncation lines of the cone surface in a direction transverse to the motion of the coulter, which can help in achieving the uniform distribution of particles, is an ellipse.

The cutting plane must be directed perpendicular to translational velocity, crossing all the formations of the half-cone at an angle between it and its central axis other than $\pi/2$.

Assuming that the particle moves with a constant acceleration, the dependence of particle flow time on the height of the cut part of the cone *h*, diameter of the cone base *D*, and height of the cone *H* was determined, which is the novelty of the theoretical part of the work. The resulting formula makes it possible to find optimal parameters for any cone spreader.

Theoretical studies allowed us to find limiting values of parameters of the experimental coulter distributor, D = 100–140 mm, h = 10–26 mm, and H = 30–50 mm. For the convenience of analysis, the equations of regression (9) and (10) were reduced to a canonical form. Considering the equation of non-uniformity of material distribution by width in the canonical form, it can be noted that the response surface is an ellipsoid of rotation and has a minimum at the centre of the ellipsoid. The extremum lies in the studied region, which confirms the correctness of the choice of the limits of variation of variables.

The results indicate that the centres of unevenness of material distribution by width and instability of distribution practically coincide. The smallest values of unevenness and instability of material distribution of the experimental coulter are achieved with the values of the coefficients D = 117–119 mm, h = 17–18 mm, and H = 32–35 mm. Thus, the experimental results confirm the theoretical results.

The performance of the developed truncated conical spreader (seed dispenser) is similar to that of previously developed distributors of different shapes. Nukeshev et al. (2021) described the development and field testing of a hemispherical distributor that was pivotally hung in the under-sweep space and underwent oscillatory motion with the movement of the coulter. The unevenness of seed distribution was found to be 11%, which is comparable to the corresponding value of the developed distributor. Sergeyev et al. (2012) derived a formula for calculating the formative lines length of a seed spreader cone to justify the cone parameter depending on the required capacity.

A comprehensive substantiation of the parameters of the universal distributor of bulk and hard-to-bulk materials based on the results of this work requires further multifaceted experiments with different materials in the designs of various devices that require uniform and stable dosing of materials across the width. In this regard, we believe that this work can serve as a mechano-technological basis for future research in many scientific directions.

Conclusion

The parametric equations of the ellipse describing the truncated part of the conical spreader are established, and the geometric parameters that ensure uniform distribution of bulk materials in the soil are determined.

In order to obtain uniform distribution of granular materials, it is necessary to perform an elliptical truncation on the surface of the conical distributor, symmetrical and transverse to the direction of coulter movement. Accordingly, the secant plane must be directed perpendicular to the speed of movement, crossing all the formations of the half-cone at an angle between it and the central axis equal to or greater than the central angles $\pi/2$.

The formula for particle outflow time depending on the dimensions of the spreader as per the width of the coulter has been derived and optimal parameters of a cone distributor for a seed drill coulter are calculated based on the uniformity of flow of a particle along the cone formative lines. This formula can be used for scaling the spreader dimensions for use in other applications (industries) where the uniform distribution of materials is required.

The analysis of this formula made it possible to establish the optimum parameters of the cone distributor for the grain and grass seed drill coulter: the height of the cut part of the cone h = 17–18 mm, diameter of cone base D = 117–119 mm, and cone height H = 32–35 mm.

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