COMPUTER INVESTIGATION OF MINERAL FERTILISER PARTICLE MOVEMENT ALONG CENTRIFUGAL SPREADER DISC INCLINED UNDER ANGLE TO HORIZONTAL PLANE

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Abstract. Spreading of mineral fertilisers on the surface of the soil is the most widely used and effective way to increase the harvest of agricultural crops. The new construction of a centrifugal fertilizer spreading apparatus with the spreading disc the axis of which is inclined to the horizontal plane, developed by the authors, allows for essential increase of the distance of mineral fertiliser particles from leaving the blades of the disc. Nevertheless, the constructive peculiarities of the inclined spreading disc require comprehensive substantiation of the parameters of the disc and feeding mineral fertilisers from the feeder and the tank. The aim of the research is substantiation of the working width of the machine for mineral fertiliser spreading and productivity depending on the constructive and kinematic parameters, as well as the place where the mineral particles will be deposited on the surface of the spreading disc that is inclined at the angle to the horizon based on the performed computer analysis of movement of particles along the surface of the disc of the centrifugal spreader. The present research has been performed using the methods of modeling, theoretical mechanics and higher mathematics, as well as the methods of calculation, using graphs and computer modeling. Based on the mathematical model, previously developed by the authors, for spreading mineral fertiliser particles and the obtained differential equations of the movement of mineral fertiliser particles along the disc of the inclined under an angle to the horizontal plane working body and equations of the absolute movement of the particle leaving the disc of the working body, computer calculations are performed. The graphs of dependence of the absolute speed of mineral fertiliser particles leaving the disc of the working body on the time and the above mentioned parameters have been obtained, on which the distance of the mineral fertiliser particle after leaving the disc blade of the working organ is dependent. The angle speed of the disc and radius of feeding have higher influence on the relative speed of the particle leaving the blade. Rational values of the radius of the fertilizer supply do not exceed 0.5 of the radius of the disk of the fertilizer spreading working body. Changing the angle of the disc within 0º…40º does not influence the dispersion time of the particles and the values of the relative and absolute speed of particles leaving the blade. Rational disc inclination values to the horizontal plane are within 20º … 30º.

Keywords: fertilisers, spreading, particle, absolute movement trajectory, computer analysis.

Introduction

In the leading countries of the world machines equipped with centrifugal working organs are dominating (more than 90%). Developers of new machines try to ensure increasing of the productivity of the machines in the operation of spreading mineral fertilisers by constructing appropriate working bodies.

Productivity of machines for spreading mineral fertilisers depends on their working width, speed of the aggregate and the coefficient of the exchangeable time. Potential reserves for increasing the mentioned productivity by increasing the working speed of the aggregate and the coefficient of the exchangeable time have already been used. Increasing of the productivity of the machines is possible only by increasing the working width, but it is also limited by increasing the rotation frequency of the working bodies and the height they are above the surface of the soil. Due to this, improvement of productivity of the machines for spreading mineral fertilisers by inreasing the working width is a topical problem that needs to be solved by the necessary constructive solutions and scientific research.

Many local and foreign scientists have investigated theoretically and experimentally the working bodies of centrifugal disc fertilizer spreading machines. They have studied the influence of constructive shapes of discs, blades and other elements of working bodies, parameters and regimes of their work, physical-mechanical properties of mineral fertilisers, working conditions and the working width of machines, distance, regularity of spreading fertilisers etc. [1-15].

Considering the possibility of crashing the granules of mineral fertilisers, it was stated that the linear speed of the blades in the zone of feeding fertilisers to the fertilizer spreading working body should not exceed 10 $m \cdot s^{-1}$ for spreading of nitrogen fertilisers and 25 $m \cdot s^{-1}$ – for phosphorous and potassium fertilisers. [16]. Based on this, it is not difficult to conclude that there are limits for kinematic regimes of the work of the fertilizer spreaders. Besides, it was also stated that the maximal angle between the vector of the absolute speed of fertilisers from the fertilizer spreading working body vertical axis of rotation and the horizontal plane, depending on the kind of fertilisers, is within 11.9…15.7º and it is achieved by placing the blades at the angle to the horizontal disc within 35…40º [17]. So, increasing of the working width of the machine by means of increasing the angle between the blade and the horizontal plane will not give the desired result.

The results of investigations on determination the speed of fertilisers leaving the disc of the fertilizer spreading working body on which the distance of spreading mineral fertilisers is dependent are more important. For instance, in the articles [18; 19] the movement of the fertiliser particle along the blade connected to the surface of the disc of the working body is investigated. The article [18] discusses the radial version of the blade and the variant with incline to the radius of the disc in the direction to its rotation along the vertical axle. These investigations are described more widely in [19] discussing the versions where the blades are mounted with inclination to the radius of the fertilizer spreading working body in the direction of its rotation as well as against it. In the result of analysing the mentioned investigations, equations were obtained for determining the relative speed of fertiliser movement along the blade of the working body at any moment of time.

The investigations described in [18; 19] were further developed in [17], where a system of equations for determination of the time of fertiliser particle movement along the blade and the relative speed of leaving the disc with the blade at the angle to the horizontal plane of the disc as well as to its radius was constructed. After the analysis it can be concluded that: at present there are theoretical investigations in the result of which equations are obtained for determination of the time of fertilizer particle movement along the blade and its relative speed leaving the fertilizer spreader working organ for a common case of construction of the working body with a vertical axis of rotation where the blades are placed at the angle to the horizontal plane as well as to its radius in both directions.

The results on determination of the absolute speed of the fertiliser particle leaving the disc of the fertilizer spreader working body for separate and common versions are described in [20-22]. In the article [22] it is proved that the distance of fertiliser particles as well as the working width of the machine for spreading minefral fertilisers depend on the angle between the vector of absolute speed and the horizontal plane. In the known centrifugal fertilizer spreading working bodies with a vertical axis of rotation increasing of the angle to the horizon is formed only due to increasing the relative speed, i.e the speed the fertiliser moves along the blades. At the same time the fertilizer spreading working speed considerably influences the absolute speed of fertiliser leaving the disc of the fertilizer spreading working body [26-28]. Due to this, we have developed a new construction of the fertilizer spreading working apparatus with a distribution disk the axis of which is inclined at an angle to the horizontal plane what ensures considerable increase of the distance of fertiliser spreading and also increase of the working width and productivity of the machine. The aim of the present work is to describe computer modeling to prove the given statement.

The aim of the research is to substantiate the working width of the machine for spreading mineral fertilisers and its productivity depending on the constructive and kinematic parameters as well as the placement of mineral fertiliser particles on the surface of the spreading disc inclined at the angle to the horizon based on the performed numerical analysis of particle movement along the surface of the spreading disc.

Materials and methods

The equations of mineral fertiliser particle movement along the disc of the fertilizer spreading working body and leaving the disc obtained by differential equations of the particle movement are the mathematical basis for the developed computer model [22]. Creating the mathematical model, well-known theoretical studies on mechanics, kinematics and energy [29-32] were used.

Using this model, complex calculation experiments on computer are performed with the aim to research in the following kinematic characteristic peculiarities of fertiliser particle movement along the blade of the working body [22]:

- $L(t)$– distance until the particle leaves the disc of the fertilizer spreader working body;
- ωt – angle of the disc turning until the moment the particle leaves the blade;
- V_{BC} – relative speed of the particle movement along the blade;
- V_{GO} – absolute speed of the fertiliser particle leaving the disc.

The following constructive–kinematic parameters of the working body are cosidered as initial conditions:

- α – angle of the disc to the horizontal plane (α = 10º, 20º, 30º, 40º);
- ω – angle speed of the disc ω = 30, 60, 90, 120 s^{-1};
- r_o – distance from the place of feeding the fertiliser particle to the axis of rotation of the working body (radius of feeding fertilises) r_o = 0.1, 0.2, 0.3, 0.4 m;
- R – radius of the disc of the working body (R = 0.2, 0.3, 0.4, 0.5 m);
- f_f – coefficient of friction of the fertiliser particle along the blade and the disc (f_f = 0.1, 0.3, 0.5, 0.7);
- k – number of the sector of feeding the particle (k = 1, 2, 3, 4).

Results and discussion

At the beginning we performed computer analysis of the relative movement of the fertiliser particle along the disc and blade of the inclined fertilizer spreading working body.

Using the obtained mathematical models, we have developed a computer programme by means of which based on the computer calculations graphical dependences were obtained describing the influence of the parameters and working regimes of the inclined working body and physical – mechanical properties of the fertiliser particle on its dispersion.

At first, the movement of the fertiliser particle on the blade of the working body in the second sector (k = 2) at the angle of the blade turning γ_0 = 15º was analysed. It was stated that the distance 0.3 m (Fig. 1) along the blade of the working body changing the angle speed within 30…120 s^{-1} is covered by the fertiliser particle at different times. That is, the angle speed considerably influences the acceleration time of the mineral fertiliser particle. Besides, the given time decreases with increasing the angle speed of the disc.

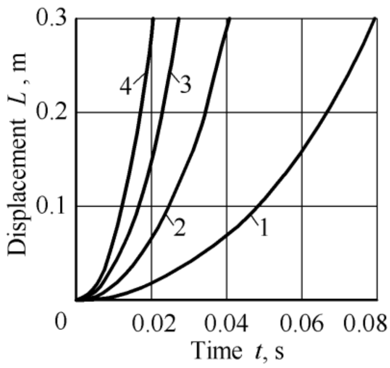

Fig. 1. **Dependence of movement *L* of mineral fertiliser particles along the blade of the fertilizer spreading working body on the time *t* and the angle speed ω of its disc at f_f = 0.3, α = 30º, r_o = 0.1 m:** 1, 2, 3, 4 – angle speed ω equals 30, 60, 90, 120 s^{-1}

Analysing the graphs in Fig. 2, we can conclude that the dispersion time of the mineral fertiliser particle changes depending on the coefficient of friction. It means that different kinds of mineral fertilisers will have different dispersion time depending on their coefficient of friction, i.e. increase of the given coefficient will result in increase of the dispersion time of the fertilisers.

It was also stated that increasing the radius of feeding fertilisers to the blades of the fertilizer spreading working body, i.e. at the feeding zone closer to the blades, results in decrease of the fertiliser particle exchangeable time, but changing the disc inclination angle α to the horizontal plane does not influence the time *t* of the particle movement till it leaves the blade.

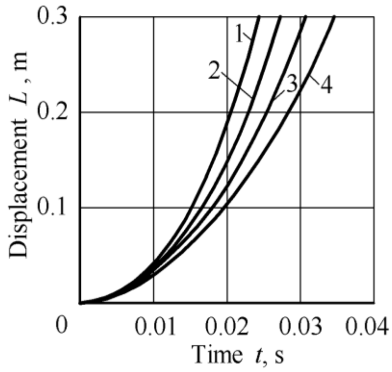

Fig. 2. **Dependence of movement *L* of mineral fertiliser particles along the blade of the working body on the time *t* and the coefficient f_f of friction at ω = 90 s^{-1}, α = 30º, r_o = 0.1 m:** 1, 2, 3, 4 – coefficient f_f of friction of mineral fertiliser particle equals to 0.1; 0.3; 0.5; 0.7

It can be explained by the fact that centrifugal force of inertia dominantly influences the movement of the particle in comparison to the weight force of the fertiliser particle.

Further we will investigate the relative speed V_{BC} which is an important kinematic parameter of fertiliser particle movement along the blade influencing the absolute speed of the particle at the moment it leaves the blade.

The graphs in Fig. 3 prove that increase of the angle speed of the disc rotation results in increase of the relative speed of the particle leaving the fertilizer spreading working body.

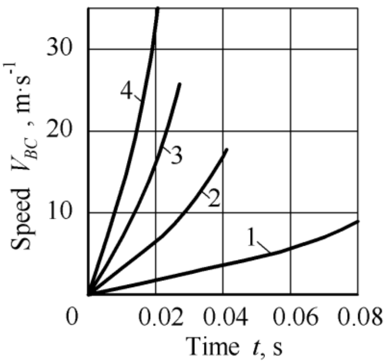

Fig. 3. **Dependence of the relative speed V_{BC} of fertiliser particles on the time t and the angle speed ω of the working body disc at f_f = 0.3, α = 30º, r_o = 0.1 m:** 1, 2, 3, 4 – angle speed ω of the disc equals 30, 60, 90, 120 s^{-1}

At a higher disc angle speed ω = 120 s^{-1} the relative speed V_{BC} = 35 m·s^{-1} of the particle leaving the disc will be higher within the time $t \approx 0.02$ s.

Increasing the coefficient of fertiliser particle friction results in increasing of the time of dispersion along the blade of the working body and decreasing of the relative speed of the particle leaving the blade (Fig. 4). For instance, increasing the friction coefficient of the mineral fertiliser particle from f = 0.1 to f = 0.7, the relative speed will decrease from 32 to 18 m·s^{-1}, but the time the particle gets on the blade will increase $t \approx 0.023$ s to $t \approx 0.034$ s.

The radius r_o of feeding the particle essentially influences the time of the particle leaving the blade of the fertilizer spreading working body. The calculations were performed at r_o = 0.1, 0.2, 0.3, 0.4 m. In the result, it was stated that the closer the feeding zone of the working body to the centre of the disc, the higher the relative speed of the fertiliser particle leaving the disc. And vice versa, the further the zone of feeding from the centre of the disc, the lower the relative speed of leaving the blade.

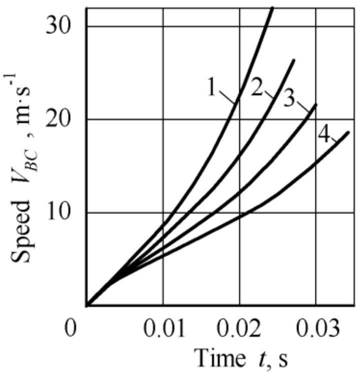

Fig. 4. **Dependence of the relative speed V_{BC} of fertiliser particles on the time t and the coefficient f_f of friction at ω = 90 s^{-1}, α = 30º, r_o = 0.1 m:** 1, 2, 3, 4 – coefficient of friction f_f of mineral fertiliser particles equals 0.1, 0.3, 0.5, 0.7

On the contrary, the angle of the disc inclination that was 10º, 20º, 30º and 40º during the research process did not influence the dispersion time of the fertiliser particle, it also did not influence the value of the relative speed of the particle leaving the blade of the working body.

The graphs of the relative speed of the particle at the moment it leaves the blade can be constructed not only depending on the time *t*, but also on the constructive parameters and working regimes, as well as physical-mechanical properties of the mineral fertilisers. It allows for more precise evaluation of their influence.

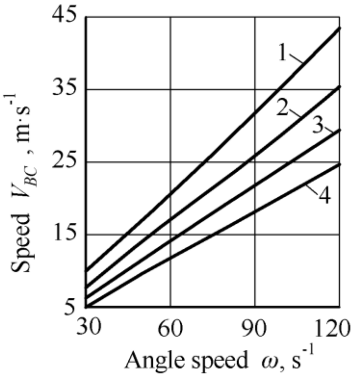

Fig. 5. **Dependence of the relative speed V_{BC} of particles at the moment leaving the blade of the working organ disc at the angle speed ω of the disc and the friction coefficient f_f at α = 30º and r_o = 0.1 m:** 1, 2, 3, 4 – friction coefficient f_f equals 0.1, 0.3, 0.5, 0.7

According to the data in Fig. 5, it can be concluded that the relative speed of the fertiliser particle movement along the blade increases with the increase of the angle speed of the disc and decreases at the increase of the coefficient of friction of the fertiliser particle. So, these regularities are characteristic also for the relative speed of the particle leaving the disc of the working body. With this, at the least coefficient of friction f_f = 0.1 and highest angle speed ω = 120 s^{-1} there is the highest relative speed of the particle leaving the disc, the value of which is V_{BC} = 42 m·s^{-1}. Increasing of the angle speed within 30…120 s^{-1} ensures higher increase of the relative speed of the particle leaving the disc than changing the coefficient of friction within 0.1…0.7.

Increasing the radius of fertiliser particle feeding (Fig. 6) results in considerable decreasing of the relative speed of the particle leaving the blade. Besides, this regularity is characteristic for all researched values of the friction coefficient of fertilisers. The relative speed decreases most intensively at the values of the particle radius more than 0.5R.

It follows that the construction of the fertilizer spreading working body should exclude feeding of fertilisers to the blades at the radius of feeding higher than 0.5R.

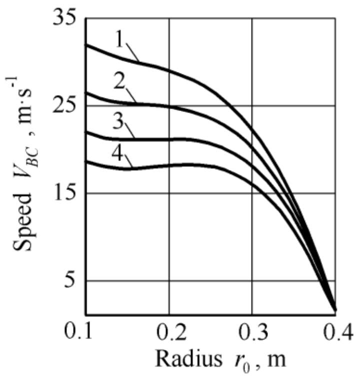

Fig. 6. **Dependence of the relative speed V_{BC} of particles at the moment leaving the blade on the radius r_o and the friction coefficient f_f at ω = 90 s^{-1} and α = 30º:** 1, 2, 3, 4 – coefficient of friction of mineral fertiliser particle equals 0.1, 0.3, 0.5, 0.7

Computer calculations also showed that increasing of the angle speed ω of the disc within 30…120 s^{-1} at all researced values of the radius of feeding mineral fertiliser particles causes increasing of the relative speed of fertilisers leaving the blade (Fig. 7).

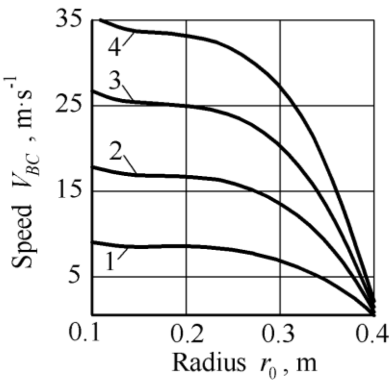

Fig. 7. **Dependence of the relative speed V_{BC} of particles at the moment leaving the blade on the radius r_o and the angle speed ω of the working organ disc at f_f = 0.3 and α = 30º:** 1, 2, 3, 4 – angle speed ω of the disc of the working body equals 30, 60, 90, 120 s^{-1}

Increasing the inclination angle of the disc to the horizontal plane does not cause changes of the absolute speed of the particle leaving the blade at all researched radius values.

In the result of calculations, it was also stated that for all kinds of mineral fertilisers (f_f = 0.1…0.7) increasing the radius of the disc increases the absolute speed of the particle leaving the blade. Still, increasing the working organ radius has constructive limitations. If the radius is considerably increased, it is necessary to equip the machines with two additional horizontal conveyers for placing the working bodies.

Further computer analysis of the absolute speed of the fertiliser particle movement along the inclined working body was performed.

The value of the absolute speed of the fertiliser particle leaving the blade depends not only on its absolute speed of movement along the blade but also on the fertilizer spreader working speed. In anloguous way as the graphical dependences of the relative speed V_{BC} were constructed (Fig. 5, 7), the graphs for the absolute speed V_{GO} for the particle leaving the blade in dependence of the parameters of the working body were constructed (Fig. 8, 9).

Increasing the absolute speed ω of the disc (Fig. 8), causes increasing of the absolute speed V_{GO} of the particle at the moment it leaves the blade for all kinds of mineral fertilisers (f_f = 0.1…0.7). It can be accertained that the changes of the relative speed V_{BC} (Fig. 5) and the absolute speed V_{GO} (Fig. 8) have equal character depending on the angle speed of ω of the disc.

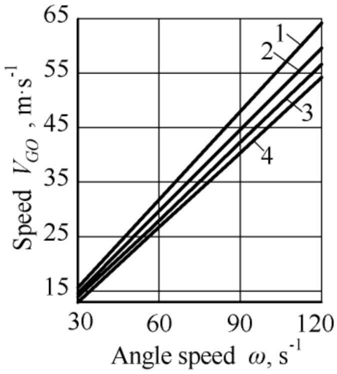

Fig. 8. **Dependence of the relative speed V_{BC} of particles at the moment leaving the blade on the angle speed of the disc ω and the coefficient of friction f_f of the fertiliser particle at α= 30º and r_o = 0.1 m:** 1, 2, 3, 4 – coefficient of friction equals f_f 0.1, 0.3, 0.5, 0.7

The influence of the mineral fertilizer particle friction coefficient f_f and the radius r_o on the absolute speed V_{GO} is similar to analoguous influence on the relative speed V_{BC}. The absolute speed of the particle leaving the blade is more intensively decreased at the values of the feeding radius bigger than 0.5*R*. So, the construction of the working body must exclude the radius of feeding fertilisers bigger than 0.5*R*.

Dependencies of the absolute speed V_{GO} of the fertiliser particle at the moment of leaving the blade on the radius r_o of feeding the particle and the angle speed ω of the disc are shown in Fig. 9.

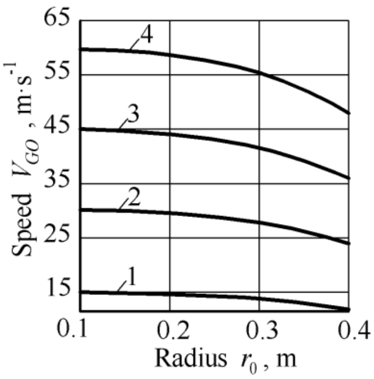

Fig. 9. **Dependencies of the absolute speed V_{GO} of fertiliser particles at the moment leaving the blade on the radius r_o of feeding and the angle speed ω of the disc at f_f = 0.3 and α = 30º:** 1, 2, 3, 4 – angle speed of the disc of the working body is equal 30, 60, 90, 120 s^{-1}

A greater value of the angular velocity ω corresponds to a greater value of the absolute velocity V_{GO} of a fertilizer particle at the moment of its departure from the blade of the inclined fertilizer-dispersing working body for all studied values of the fertilizer particle feeding radius.

Based on computer calculations it is proved that changing the inclination angle α of the disc to the horizontal plane from 0º to 40º practically does not influence the value of the absolute speed V_{GO} of the fertiliser particle at the moment of leaving the blade at all researched values of the radius r_o of feeding the fertiliser particles, but the angle between the vector of the absolute speed V_{GO} and the horizontal plane decreases.

It was also stated that the absolute speed V_{GO} of the fertiliser particle at the moment of leaving the blade directly proportionally depends on the radius R at all researched values of the friction coefficient of the particle of mineral fertilisers.

Still, the maximal diameter of the fertilizer spreading working body has constructive limits that should be considered developing new machines for spreading mineral fertilisers.

The absolute trajectories of the fertiliser particle movement along the blade constructed by means of computer analysis allow for more precise determination of the influence on the constructive parameters and working regimes of the working organ. Fig. 10 shows the constructed absolute trajectories of the fertiliser particle moving along the blade of the working body at α = 30º, r_o = 0.1 m, ω = 90 s^{-1} and γ_0 = 15º.

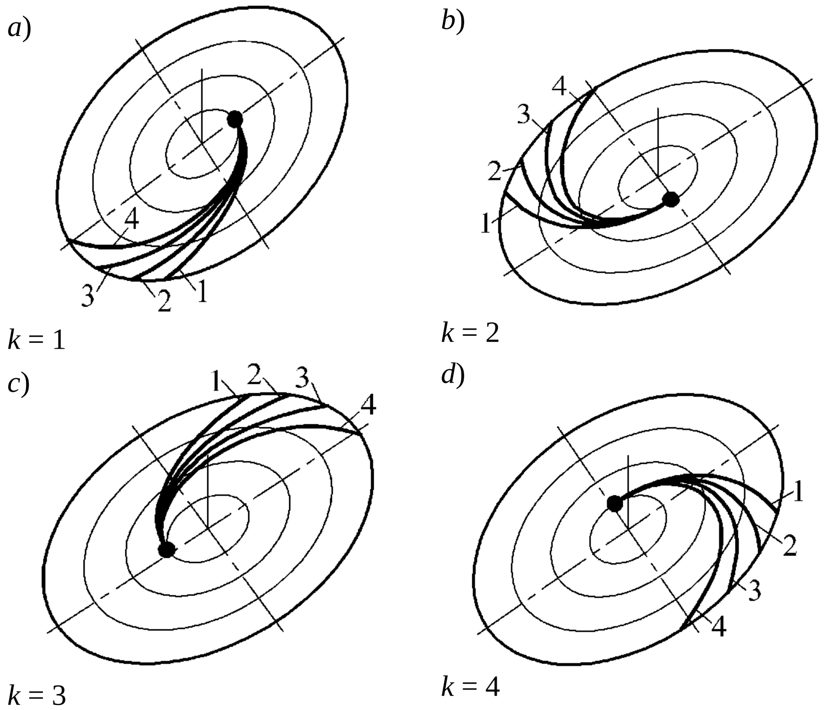

Fig. 10. **Absolute trajectories of the fertiliser particle movement along the blade of the inclined working body till it leaves the blade depending on the number *k* of the sector of feeding and the fertiliser particle friction coefficient f_f :** *a*, *b*, *c*, *d* – sector *k* is 1, 2, 3, 4; 1, 2, 3, 4 – friction coefficient of the fertiliser particle equals 0.1, 0.3, 0, 0.7

The scheme in Fig. 10 shows that the bigger the friction coefficient f_f, the higher the dispersion time from the blade at rotation of the disc at the angle close to 180º. It means that at these initial conditions the variant of feeding particles at the first sector should be excluded as they will be directed downwards. The necessary direction for distribution is ensured by feeding the fertilisers at the second sector of the disc as then the particles will be directed upwards.

The direction of the particle from the blade of the working body essentially depends also on the radius of its feeding. Therefore, we have obtained also thetrajectories of the particle movement fed to the blade at the beginning of the second sector at a different radius r_o. In the result it was obtained that the particle fed to the disc with the radius r_o = 0.2…0.4 m from the rotation axis of the disc is also directed downwards at the moment of it leaving the blade what is not acceptable, and only at the radius r_o = 0.1 m it is directed upwards.

One of the ways for uniform spreading of fertiliser particles along the disc is by forced vibrations [23]. An analysis of the qualitative indicators of the technological process, depending on the fluctuations of the working body, was carried out in [24; 25].

It was also stated that the absolute trajectory of the particle movement from the working body practicaly does not depend on the angle speed ω, i.e. the angle of dispersion is equal.

It was proved that the values of the angle of dispersion of mineral fertilisers practically does not depend on the number of the disc sector of the working body from which the fertilisers are fed at the change of the disc angle speed from 30 to 120 s^{-1}, the coefficient of friction from 0.1 to 0.7 and the radius of fertiliser feeding to the disc from 0.1 to 0.4 m. It means that the machines equipped with inclined fertilizer spreading working bodies at regulation of the disc rotation frequency do not need correction of the zones of feeding, but at feeding fertilisers with another coefficient of friction it is necessary to make corrections of the feeding zone.

Conclusions

1. The relative speed of the mineral fertiliser particle leaving the blade of the inclined fertilizer spreading working body does not depend on the number of the feeding sector, but it increases at increasing the angle speed of the disc and decreasing the radius of feeding as well as the friction coefficient of the fertilisers.
2. The angle speed of the disc and the radius of feeding have higher influence on the relative speed of the particle leaving the blade. At the friction coefficient of the fertilisers 0.3, the radius of feeding 0.1 m, inclination angle to the hoprizontal plane 30º and the angle speed of the disc 30, 60, 90 and 120 s^{-1}, the relative speed of the particle leaving the blade of the working organ equals to 9.0, 17.5, 26.5 and 35.0 $m \cdot s^{-1}$. At the same time, at the angle speed of the disc 90 s^{-1} and the given parameters of the working body and the feeding radius 0.1, 0.2 and 0.3 m, the relative speed equals to 26.5, 25.0 and 20.0 $m \cdot s^{-1}$. Rational values of the radius of the fertilizer supply do not exceed 0.5 of the radius of the disk of the fertilizer spreading working body.
3. Changing of the angle of the disc within 0º… 40º does not influence the dispersion time of the particles and the values of the relative and absolute speed of particles leaving the blade, it only changes the angle between the vector of absolute speed of particles leaving the working body and horizontal plane.
4. It is advised to feed the fertilisers to the inclined fertilizer spreading working body in the second sector of the disc.
5. Rational disc inclination values of the working body to the horizontal plane are within 20º… 30º.

Author contributions

All authors have contributed equally to creation of this article. All authors have read and agreed to the published version of the manuscript.

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