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Theoretical Justification of Optimal Design and Process Parameters of Pneumomagnetic Separation

V.G. Kozlov
Voronezh State Agricultural University named after Emperor Peter the Great
1, Michurina ave., Voronezh, 394087, Russia
E-mail: vya-kozlov@yandex.ru

E.A. Izvekov
Voronezh State Agricultural University named after Emperor Peter the Great
1, Michurina ave., Voronezh, 394087, Russia

***Abstract*—The preparation of high-quality seed grains at seed-testing stations requires their magnetic cleaning. In case of pneumomagnetic separation, the seed mixture particle is affected by various forces, which intensity and direction change depending on design requirements of the inductor and the particle position in its magnetic field. The analysis of a particle motion in a working channel, as well as the mathematical model itself may take into account certain conditions. The solution of the differential equation system at various combination of speed and direction of particle input into a channel, as well as different correlation of horizontal and vertical components of a magnetic force allowed defining the main pattern of pneumomagnetic separation and provided for the theoretical study of the influence of design and process parameters of the pneumomagnetic separator working body on separation. The analysis of seed motion paths related to a dodder and a clover made it possible to build the particle motion curves taking into account various magnetic force in a working channel, as well as to present a diagram illustrating the possibility to implement pneumomagnetic separation depending on the correlation of the air speed and the magnetic force impacting a particle.**

Keywords—component; formatting; style; styling; insert

I. Introduction

The preparation of high-quality seed grains to grow valuable forage and industrial crops, such as lucerne, clover, melilot, sainfoin, vetch, flax and others requires magnetic cleaning. The use of other methods to clean small-seeded crops from quarantine weeds is not efficient. This is caused by the fact that the seeds of crop plants and the seeds of quarantine weeds are similar in size and aerodynamic properties.

Cleaning of grass seeds via the pneumomagnetic method is based on the ability of seeds to demonstrate their resistance to air environment in case of their relative motion and the ability of weed seeds, having rough surface and covered with magnetic powder, to interact with a magnetic field of the separator's inductor thus triggering the magnetic force, which intensity and direction is defined by the nature of the inductor magnetic field.

II. Materials and methods

The following affect all seed mixture particles during pneumomagnetic separation: the descending gravity force, the resistance force of air environment directed sidewards opposite the particle relative velocity vector in the airflow. Besides, the weed seeds are influenced by the magnetic force, which intensity and direction change depending on design requirements of the inductor and the particle position in its magnetic field.

The separation is affected by a variety of factors, which are quite difficult to consider and sometimes are even not possible. The separated mixture gets into a working channel from a feed unit as a multilayered jet with some variable initial velocity v0, but not as single isolated seeds. Since the airflow is uneven along the channel section, then when moved inside the seeds, interacting with each other, collide, rotate, pass from one layer to another. The magnetic powder is unevenly distributed along the surface of weed seeds, and certain seeds have different mass of magnetic powder on the surface. Depending on the position of weed seeds in relation to the inductor, the acting magnetic force continuously changes. Under the influence of the above factors, the particles move through complex routes [1, 3, 6, 9].

It is possible to analyze the particle motion in a working channel of a pneumomagnetic separator if certain conditions are considered, namely let us assume that:

- a particle is a single mass point;
- particles do not interact with each other;
- the airflow is uniform throughout the entire channel section;
- all seeds are evenly covered with magnetic powder.

With this in mind it is possible to build a mathematical model of particle motion regarding a separated seed mixture, to determine velocity, acceleration and motion path. Such values will provide for better understanding of separation of a loose seed mixture and the influence of various factors on its efficiency.

It should be noted that the below equations describe only the motion of weed seeds, which surface is covered with magnetic powder. Since the seeds of crop plants are not covered with magnetic powder, they are not influenced by the magnetic field, and their motion path is described by well-known equations of the air cleaning theory [2, 5].

The particle motion in the air channel may be considered based on its translational motion together with the airflow and the particle motion in relation to the airflow. Then the vector of absolute velocity $\overline{v}$ of a particle will equal [4]

$$\overline{v} = \overline{V} + \overline{u}, \tag{1}$$

where $\overline{V}$ – vector of airflow velocity, m/s;

$\overline{u}$ – vector of particle relative velocity, m/s.

Given the rectangular fixed coordinate system X, Y and taken the particle entry point into the working channel for the origin of coordinates (Figure 1), it is possible to write the differential equation of a particle motion in the accepted system of coordinates.

$$m\frac{d\overline{v}}{dt} = \overline{G} + \overline{F_R} + \overline{F}, \tag{2}$$

V – airflow velocity; v – particle velocity; v0 – initial velocity of a particle; α_0 – angle of particle input into the channel; G – gravity; F – magnetic force; Fx – projection of magnetic force F on the plane normal to the airflow velocity vector; Fy – projection of magnetic force F on axis parallel to the airflow velocity vector; FR – aerodynamic force.

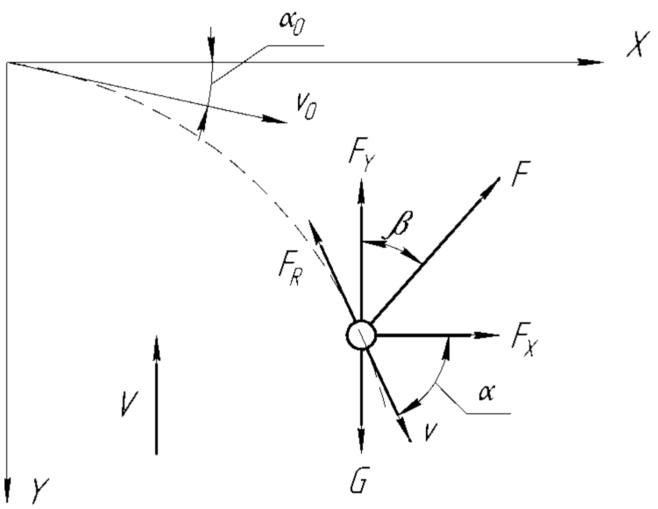


Fig. 1. Scheme of forces acting on a particle in a working channel

Let us project the absolute velocity vector on axis X and Y:

$$\overline{v} = (v_x, v_y). \tag{3}$$

$$v_X = v\cos\alpha,\ v_Y = v\sin\alpha. \tag{4}$$

$$v = |\overline{v}| = \sqrt{v_X^2 + v_Y^2}, \tag{5}$$

Projections of vector equation (2) on axes X and Y will equal:

$$\begin{cases} m\dfrac{dv_X}{dt} = -F_R \cdot \cos\alpha + F_x \\ m\dfrac{dv_Y}{dt} = mg - F_R \cdot \sin\alpha - F_y \end{cases} \tag{6}$$

It is known that the highest efficiency of separation is ensured through the turbulent motion of the airflow. In this mode, the resistance force of a body in the airflow more depends on the dynamic force of the airflow. To determine the resistance force let us use the Newton's formula [7].

$$F_R = mk_П u^2. \tag{7}$$

where $k_п$ – particle wind resistance depending on aerodynamic properties of a particle.

By inserting the expression (7) into equations (6), we get:

$$\begin{cases} m\dfrac{dv_X}{dt} = -m \cdot k_П \cdot u^2 \cdot \cos\alpha + F_x \\ m\dfrac{dv_Y}{dt} = m \cdot g - m \cdot k_П \cdot u^2 \cdot \sin\alpha - F_y \end{cases} \tag{8}$$

By dividing both members of equation (3) into m and considering that:

$$u_x = u \cdot \cos\alpha, \quad u_y = u \cdot \sin\alpha, \tag{9}$$

$$u = |\overline{u}| = \sqrt{u_x^2 + u_y^2}, \tag{10}$$

we get:

$$\begin{cases} \dfrac{dv_X}{dt} = -k_П \cdot u_x\sqrt{u_x^2 + u_y^2} + \dfrac{F_x}{m} \\ \dfrac{dv_Y}{dt} = g - k_П \cdot u_y\sqrt{u_x^2 + u_y^2} - \dfrac{F_y}{m} \end{cases} \tag{11}$$

Since according to the accepted assumption, the airflow velocity is invariable regarding direction and size, then the expression (1) can be presented as follows:

$$u_X = v_X, \qquad u_Y = V - v_Y \tag{12}$$

Considering the expression (12) the system of equations (11) may be rewritten as the system of four differential equations describing particle motion in a working channel:

$$\begin{cases} \frac{dv_X}{dt} = -k_{\Pi} \cdot v_x \sqrt{v_x^2 + (V - v_Y)^2} + \frac{F_x}{m} \\ \frac{dv_Y}{dt} = g - k_{\Pi} \cdot (V - v_Y)\sqrt{v_x^2 + (V - v_Y)^2} - \frac{F_y}{m} \\ \frac{dx}{dt} = v_X \\ \frac{dy}{dt} = v_Y \end{cases} \qquad (13)$$

Since according to process conditions the separated seed grains get into the working channel with certain initial velocity, then according to the existence theorem the system of differential equations (13) has the only solution, i.e. a particle of the separated seed mixture will have only one possible motion path, which may be designed by solving the system of equations (13).

The obtained quasilinear system of differential equations was solved by the Runge-Kutta numerical method [8, 10] within MathCad package.

The solution of the system of differential equations at various combinations of velocity and direction of a particle input into the channel, as well as different correlation of horizontal and vertical components of a magnetic force allowed defining the main patterns of pneumomagnetic separation and provided for the theoretical study of the influence of design and process parameters of the pneumomagnetic separator working body on separation.

It is found that the correlation of horizontal and vertical components of a magnetic force exerts a considerable impact on a particle motion path.

$$\frac{F_x}{F_Y} = tg\beta \qquad (15)$$

The particle motion paths at various tgβ values are shown in Figure 2.

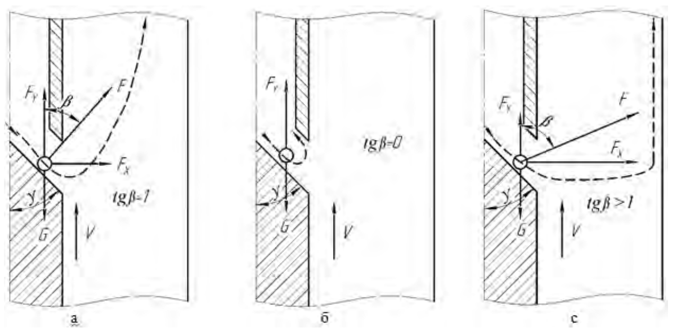


Fig. 2. Particle motion paths in a working channel

The horizontal component of magnetic force F_x exerts significant positive effect on particle input into a working channel. The higher the tgβ, the quicker a particle will leave a material layer. The most optimal option shall be the option when the magnetic force directed perpendicular to the moving flow influences the particle, i.e. when β = γ. In this case, F_x provides for preliminary delamination of material prior to its entrance into the channel thus moving weeds to the top layers of a flow even before entering the airflow. Figure 2 shows the disposition of forces at β = γ =450.

In the absence of F_x component, i.e. at tgβ = 0, the magnetic force will act against the flow and will push particles back into the feeder thus leading to complexities with material supply to the working channel (Fig. 2, b). Since magnetic particles before entering the separation zone will move in the opposite direction from the main flow, the feeding channel will be plugged.

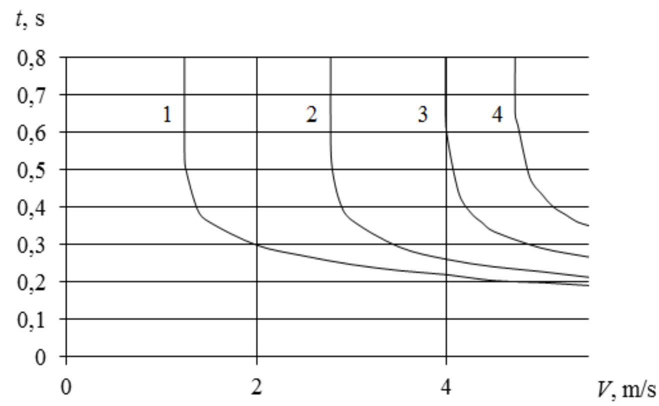
After a particle enters the working channel, the F_x will adversely affect the separation, since it will attract particles to walls of the working channel thus disturbing the uniform distributions of particles over a cross section. At a wide F_x margin the particle cross the channel in transverse direction rather quickly, which may lead to their sticking on the channel walls and disturb the separation (Fig. 2, c).

Thus, it was found that the tgβ increase has a positive impact on the process when entering the channel and negatively influences with further motion. The analysis showed that the optimal tgβ value to ensure the separation process makes from 0.07 to 0.28.

When a particle is lifted, i.e. approaches the inductor edge, the tgβ increases, and exceeds 1 in rim zones, i.e. F_x component is higher F_y and the particle velocity drops to zero. To remove it from the channel it is necessary to increase the airflow velocity to the velocity higher the seed hovering velocity, for example due to the reduction of the channel cross section in a convergent tube located in the rim zone of the inductor.

Though F_x exerts a considerable impact on the process at the time of particle input and removal from the working channel, the F_y component necessary to lift particles up the channel has a determining impact on the separation.

The analysis of seed motion paths of a dodder and a clover resulted in curves shown in Figure 3. The curves are built at various values of magnetic force F_y and reflect the time dependence of a particle lifted to the top point of the working channel on airflow velocity.



1 – F=7.3·10^{-6}H; 2 – F=6.1·10^{-6}H; 3 – F=4.5·10^{-6}H; 4 – F=3·10^{-6}H.

Fig. 3. Time dependence of a particle (t) lifted to the top point of the working channel on airflow velocity (V) at various magnetic forces (Fy)

The diagram shows that the separation of dodder and clover seeds is possible within a certain range of the airflow velocity, which lower limit significantly changes depending on the value of the magnetic force acting on a particle. The separation of seeds is impossible if the airflow velocity is less than the lower range limit. In this case, the sum of the air resistance force and the magnetic force will be less than the value of gravity, and a particle will fall down. The upper range limit is defined by the hovering velocity of the main crop seeds (for a clover the hovering velocity is accepted as 5.2 m/s). It is impossible to increase the airflow velocity above this value due to process conditions, since the seeds of the main crop will be removed from the working channel by the airflow, which is not acceptable.

Figure 4 shows the diagram built following the solution of the system of differential equations (13) illustrating the possibility of implementing the pneumomagnetic separation depending on the correlation of the airflow velocity and the magnetic force acting on a particle.

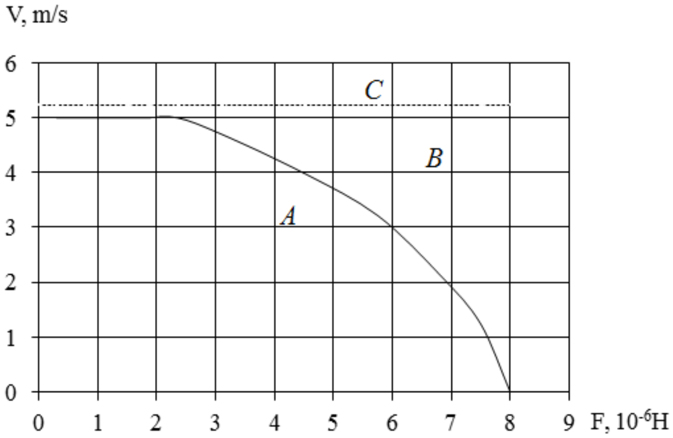


Fig. 4. Influence of the correlation of the airflow velocity V and the magnetic force Fy on separation

The diagram, illustrating the joint effect of the magnetic force F_y and the airflow velocity V on the nature of separation of clover and dodder seeds, shows that the separation is only possible when the considered parameters have the intersection point in area B, i.e. above the limit relation line of these parameters. The efficiency of separation will be improved with the increase of the airflow velocity and with the increase in the magnetic force. If the intersection point of V and F parameters lies within area A, i.e. below the limit relation line of these parameters, then the sum of the particle resistance force to the airflow and the magnetic force will be less than the gravity of a particle, and the separation will be impossible.

In area C, lying above the dashed line, the high-quality separation is impossible since the airflow velocity will be higher than the hovering velocity of the main crop seeds accepted in calculations as equal to 5.2 m/s, which corresponds to the hovering velocity of clover seeds. In case the airflow is more than 5.2 m/s, the clover seeds will be removed from the working channel together with weed seeds, which is not acceptable by process specifications.

Besides, the diagram shows that the separation of seeds in the working channel can also be carried out without the airflow. It is possible if the magnetic force created by the inductor is higher $8 \cdot 10^{-6}$H. However, it is impossible to ensure this process without the airflow, since the removal of seeds from the rim zones of the inductor is impossible through magnetic forces only as the weed seeds will be stuck in the rim zones of the inductor. The airflow is required to remove the weed seeds from the magnetic field coverage and shall be at least 3.5 m/s.

III. Conclusions

The obtained characteristic curve illustrating the influence of such design and process parameters of the working body being part of pneumomagnetic separator as airflow velocity and magnetic force allows determining the possibility of separation and the nature of pneumomagnetic separation as such.

It is found that pneumomagnetic cleaning of clover seeds from a dodder can be carried out at the airflow velocity of 3.5÷5.2 m/s and the magnetic force of 3.4·10-6÷$8 \cdot 10^{-6}$H. For the magnetic force to have this value in the working channel there is a need to ensure the induction of the magnetic field equal to 0.115÷0.177 T.

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