Air magnetic separator for the preparation of forestry seed material and its theoretical justification

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Abstract. The preparation of high quality seed material requires cleaning on special seed graders. Seeds of different cultures have particular surface and shape. Taking into account these differences, various plants have been developed and are widely used. The need for magnetic cleaning is caused by the impossibility of high-quality separation of seeds of different forestry crops. The analysis of modern technical means for the preparation of seed material showed that the idea of combining air and magnetic cleaning deserves special attention. In air magnetic separation, various forces influence a seed particle, the magnitudes and direction of which vary depending on the design parameters of the inductor and the position of a particle in the magnetic field of an inductor. It is possible to investigate the movement of a particle in the working channel, as well as to create a mathematical model by accepting some assumptions, the result of which will determine the main regularities of the air magnetic separation process and theoretically study the influence of the structural and technological parameters of the air separator on separation process. The particle motion curves were constructed for various values of magnetic force in the working channel according to the results of the analysis of seed motion trajectories. During the course of the research the graph illustrating the possibility of performing the process of air magnetic separation depending on the ratio of the air flow rate and magnetic force influencing a particle is presented.

1. Introduction
The need for high-quality forestry seed material is steadily increasing every year. The main tasks facing forestry are presented by integrated and inexhaustible forest management, the development of forest seed production as a base for reforestation, as well as increasing forest productivity. The successful solution of the above mentioned tasks will contribute to the consolidation of the role of increasing the productivity and sustainability of forests through the genetic and selected base. The use of improved seed material in the reproduction of forests will ensure in the future the increase in the productivity of timber stand, which will result in additional production from 15 to 30 m³ of wood depending on tree species [1].

The process of seed preparation is based on the use of the basic properties and characteristics of seed mixture: aerodynamic properties, size, specific gravity, surface condition, differences in the shape of seed. Taking into account these differences, various plants have been developed and are widely used for
the preparation of seed material, but the preparation of seed material imposes strict requirements on the quality of material, which cannot be satisfied with existing methods of cleaning.

The need for magnetic cleaning is caused by the impossibility of high-quality separation of seeds of different crops.

The analysis of modern technical means for the preparation of seed showed that the idea of combining air and magnetic cleaning [2, 3] deserves special attention. The result of the combination of two types of cleaning will allow creating an air magnetic separator, which will increase the productivity of the preparation of seed material due to air force and provide magnetic cleaning of high quality.

2. Materials and methods

The physical process of the work of air separator is as follows: seed material having a different surface (smooth, rough, porous, bumpy, film-coated, villous) mixes with magnetic powder and is fed into the vertical aspiration leg, in which air flow is generated with a rate of slower rate of seed flooding of the main crop, where simultaneously an inductor magnetic field is superimposed on the field of aerodynamic forces (the last one may have different design solutions).

Aerodynamic and magnetic forces are given the same direction, as a result of which seeds covered with magnetic powder are carried out in the direction of air flow, and smooth seeds (not covered with magnetic powder) fall down under the action of gravity.

In air magnetic separation, all particles of seed are influenced by: downward force of gravity, resistance of air medium, directed opposite to the vector of relative velocity of particle in air flow, however, magnetic force also affects weed seeds depending on the design parameters of an inductor and the position of a particle in the magnetic field of an inductor.

It is quite difficult to take into account the influence on the separation process of all factors, and sometimes it is not possible, therefore it is necessary to introduce a number of assumptions, namely let us suppose that:
- Particle is material point;
- Particles do not interact with each other;
- Air flow is steady throughout the cross section of the leg (laminar air flow);
- All the seeds of weeds are uniformly covered with magnetic powder;
- The separated mixture enters the working channel from the feeding device by a multilayer stream with some variable initial velocity $v_0$, rather than with single seeds, isolated from one another.

By adopting these assumptions, it is possible to build a mathematical model of the movement of a particle of a separated seed mixture, to determine the velocity, acceleration and trajectory of a particle. These values will provide an idea of the process of separation of loose seed mixture and the degree of influence of various factors on its effectiveness.

It is necessary to note that the above mentioned equations describe the movement only of seeds whose surface is covered with magnetic powder. Seeds without magnetic powder cover will not be affected by the magnetic field, and their trajectory will be described by the well-known equations of the air treatment theory [2, 5].

The movement of a particle in the air leg can be considered as composed one of its portable movement along with the air flow and the movement of a particle relative to the air flow.

Then the vector of the absolute velocity of a particle will be equal to $\vec{v}$ [4]

$$\vec{v}=\vec{V}+\vec{u},$$

where $\vec{V}$ - air velocity vector, m/s; $\vec{u}$ - the vector of relative velocity of a particle, m/s.

Having a fixed rectangular coordinate system $X$, $Y$ and taking the point of entry of a particle into the working channel as the origin of coordinates (Figure 1), we can write the differential equation of particle motion in the adopted coordinate system.

$$m\frac{d\vec{v}}{dt}=\vec{G}+\vec{F}_v+\vec{F},$$

Let us project the vector of absolute velocity on the axis $X$ and $Y$: 
The projections of the vector equation (2) on the X and Y axes will be equal to:

\[
\begin{aligned}
m \frac{dv_x}{dt} &= -F_R \cdot \cos \alpha + F_s \\
m \frac{dv_y}{dt} &= mg - F_R \cdot \sin \alpha - F_y
\end{aligned}
\]  

(6)

It is known that the separation process is most effective when the air flow is turbulent. In this mode, the resistance force of a body in the air flow is more dependent on the dynamic impact of the flow on a body. In order to determine the resistance force, we use the Newton formula [7].

\[F_R = m k \cdot u^2,\]  

(7)

where \(k\) – the coefficient of wind resistance of a particle depending on the aerodynamic properties of a particle.

Plugging expression (7) into equations (6), we obtain:

\[
\begin{aligned}
m \frac{dv_x}{dt} &= -m \cdot k \cdot u^2 \cdot \cos \alpha + F_s \\
m \frac{dv_y}{dt} &= m \cdot g - m \cdot k \cdot u^2 \cdot \sin \alpha - F_y
\end{aligned}
\]  

(8)

Dividing both sides of equation (3) by \(m\) and considering that:

\[u_x = u \cdot \cos \alpha, \quad u_y = u \cdot \sin \alpha,\]  

(9)

\[u = |u| = \sqrt{u_x^2 + u_y^2},\]  

(10)

We obtain:

\[
\begin{aligned}
\frac{dv_x}{dt} &= -k \cdot u_x \sqrt{u_x^2 + u_y^2} + F_s/m \\
\frac{dv_y}{dt} &= g - k \cdot u_y \sqrt{u_x^2 + u_y^2} - F_y/m
\end{aligned}
\]  

(11)

Since, according to the accepted assumption, the air flow rate is constant in direction and magnitude, then the expression (1) can be represented as follows:

\[v = (v_x, v_y),\]  

\[v_x = v \cdot \cos \alpha, \quad v_y = v \cdot \sin \alpha,\]  

\[v = |v| = \sqrt{v_x^2 + v_y^2},\]  

(3)

(4)

(5)

**Figure 1.** Diagram of forces influencing a particle in the working channel: \(V\) – the rate of air flow; \(v\) – the rate of a particle; \(v_0\) – initial rate of a particle; \(\alpha_0\) – the angle of the entry of particles into the leg; \(G\) – gravity force; \(F\) – magnetic force; \(F_x\) – the projection of magnetic force \(F\) on the surface normal to the air velocity vector; \(F_y\) – the projection of magnetic force \(F\) on the axis parallel to the air velocity vector; \(F_R\) – aerodynamic force.
Taking into account the expression (12), the system of equations (11) can be rewritten as a system of four differential equations describing the process of particle motion in the working channel:

\[
\begin{align*}
\frac{dv_x}{dt} &= -k_{\mu} \cdot v_x \sqrt{v_x^2 + (V - v_y)^2} + \frac{F_x}{m}, \\
\frac{dv_y}{dt} &= g - k_{\mu} \cdot (V - v_y) \sqrt{v_x^2 + (V - v_y)^2} - \frac{F_y}{m}, \\
\frac{dx}{dt} &= v_x, \\
\frac{dy}{dt} &= v_y.
\end{align*}
\]

(13)

Since, according to the conditions of technological process, the seed material being separated enters the working channel with a certain initial velocity, and with regard to the existence theorem, the system of differential equations (13) has one single solution, that is, the particle of separated seed mixture will have only one possible trajectory of motion that can be determined by solving the system of equations (13).

3. Result and discussion.

The obtained quasilinear system of differential equations was solved by the Runge–Kutta numerical method [8, 10] in the suite of mathematical programs MathCad.

The solution of a system of differential equations with different combinations of velocity and direction of particle entry into the channel, as well as different ratios of the horizontal and vertical components of the magnetic force allowed determining the main regularities of the air magnetic separation process and theoretical studying of the influence of structural and technological parameters of air separator on the process of separation.

It is revealed that the ratio of horizontal and vertical components of the magnetic force has a significant effect on the trajectory of a particle.

\[
\frac{F_x}{F_y} = \tan \beta
\]

(14)

The trajectories of a particle at different values of \(\tan \beta\) are presented in Figure 2.

\[\text{Figure 2. The trajectories of a particle in the working channel.}\]

The horizontal component of the magnetic force \(F_x\) has a significant positive effect on the process of introducing particles into the working channel. The more \(\tan \beta\), the faster the particle will leave the layer of material. The most optimal variant is one in which the magnetic force influencing a particle is directed perpendicular to the moving stream, that is, when \(\beta = \gamma\). In this case, the force \(F_x\) allows creating a
preliminary separation of the material before it enters the channel, moving weeds to the upper layers of the stream, even before entering the air stream. Figure 2a shows the distribution of forces at $\beta = \gamma = 45^\circ$.

In the absence of the $F_x$ component, that is, at $\text{tg}\beta = 0$, the magnetic force will act against the flow and push particles back into the feeder, which will lead to difficulties in feeding the material into the working channel (Figure 2b). Since the magnetic particles, even before entering the separation zone, will rush in the direction opposite to the main flow, the feed channel will be clogged.

After the particle leaves the working channel, $F_x$ begins to negatively affect the separation process. It can be explained by the fact that it will attract particles to the walls of the working channel, disrupting the uniform distribution of particles over the cross section. With a significant value of $F_x$, particles quite quickly cross the channel in the transverse direction, which can lead to sticking on the channel walls and disrupting the separation process (Figure 2c).

Thus, it was revealed that an increase in $\text{tg}\beta$ has a positive effect on the process when entering the channel and negative effect on subsequent movement. The analysis showed that the optimal value of $\text{tg}\beta$, performing the separation should be from 0.07 to 0.28.

When the particle rises, approaching the inductor edge, $\text{tg}\beta$ increases, and directly in the edge zones it becomes greater than 1, that is, the $F_x$ component becomes larger than $F_y$ and the particle velocity decreases to zero. In order to remove of the channel, it is necessary to increase the rate of the air flow to a rate greater than the rate of the levitation of seeds, for example, by reducing the cross section of the channel in the confuser located in the edge zone of an inductor.

Although $F_x$ has a significant impact on the process at the moment of entry and at the moment of removal of a particle from the working channel, however, the component $F_y$ is of decisive importance for lifting the particle up the channel.

Figure 3 presents a graph based on the results of processing the solutions of the system of differential equations (13), illustrating the possibility of air magnetic separation process depending on the ratio of the air flow rate and the magnetic force which influences a particle.

![Graph](image)

**Figure 3.** The influence on the separation process of the ratio of the air flow $V$ rate and the magnetic force $F_y$.

From the graph illustrating the joint effect on the course of the seed separation process, the magnetic force $F_y$ and the air flow rate $V$, it can be seen that the separation process is possible only when the values of the considered parameters have an intersection point in zone $B$, i.e. above the limit ratio of these parameters.

The efficiency of separation will improve with both the increase in the air flow rate and the increase in the magnitude of magnetic force. If the intersection point of the parameters $V$ and $F$ lies in the zone $A$, that is, below the line of the limiting ratio of the values of these parameters, then the sum of resistance force of a particle to the air flow and the magnetic force will be less than the force of gravity of a particle, and the separation process will be impossible.

In zone $C$, which lies on the graph above the dotted line, a qualitative separation process is impossible, since the air flow rate will be greater than the rate of levitation of the qualitative seeds of
main crop. When increasing the rate of the air flow above the limiting value of vitality of main crop, the seeds will be removed from the working channel along with the seeds of weeds, which is unacceptable under the conditions of technological process.

4. Conclusion.
Thus, the resulting graphical dependence, showing the influence of such structural and technological parameters of air separator as the air flow rate and the magnitude of magnetic force, makes it possible to identify the possibility of the separation process and the nature of air magnetic separation process.

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