Analytical study of separation efficiency of grain in vertical pneumatic separating channel

Taking into account the insufficient amount of theoretical research of the influence of the conditions of grain feeding into the pneumatic separating channel (PSC) on the efficiency of the process of separating grain mixture into fractions there arises a scientific task to define regularities of the interaction of the grain material with the air flow while feeding it into the vertical PSC. The movement of grain particles in a vertical PSC under one-layer feeding was considered in the article. The theoretical dependences which allow optimizing basic parameters of the PSC and defining the time of the grain in the air flow were acquired.

separation of grain mixture, separation, air flow, grain material, pneumatic separating channel (PSC), conditions of grain feeding, movement of grain particles

Problem statement. Ukraine holds one of the leading places in the world in the production of crops. The quality (the class) of grain depends on the effectiveness of the post-harvest processing. The harvested grain after direct combining have a great amount of foreign grains of various quantitative and qualitative compositions. These grains are poly-fractional by their size, moisture and biological composition mixture. Therefore, the task of effective separation of foreign, damaged and defective grains is the essence of the problem of increasing technical and technological efficiency of grain cleaning machines.

Air separation (pneumatic separation) is one of the widely used ways of grain cleaning and pneumatic separators are less expensive, simple and reliable in operation than pneumatic-sieve machine. Modern pneumatic systems of cleaning machines can separate light and small impurities as well as partially decrease moisture of the cleaned grains due to the air flow. Therefore, further development of the design of this class of machines and the improvement of the separation technology with the help of air flow are the actual and up-to-date technological tasks.
Analysis of recent research and publications. The problem of regularities of grain behaviour in the air flow has been not studied completely as this process has a stochastic character and depends on many factors.

Theoretical research of the pneumatic separation was done by many scholars [2-5] but they did not pay enough attention to the conditions of the process of filling the pneumatic separating channel (PSC) with grain. As research shows [6], a considerable part of the surface of the cross-section of the PSC operates ineffectively because of the non-uniform distribution of grains and as a result the separation efficiency decreases by 20% and productivity by 25%.

One of the effective ways to solve this problem is to apply a multi-stream feeding of grains. The author [7] grounds the efficiency of the creation of grain streams which form grain micro-channels while filling the angle channel. That enables to decrease the air-dynamic resistance of the mixture and levels the speed of the air flow. But in the case of considerable increase of the specific performance, the thickness of grain streams increases which negatively influences the quality indicators of the separation process.

The author [8] studies the issue of the rational feeding of grain mixture into the air flow. The conditions which provide minimal necessary distribution of grain mixture on the surface of the cross-section of the PSC were defined. But there is no analysis of the grain movement under the above-mentioned conditions and this fact does not allow assessing analytically and apply it for further research.

According to the theoretical analysis of work [9] it may be concluded that the rational density of the grains in the process of moving them into the PSC it was possible to get the conditions which provide maximum possible introduction without reducing the efficiency of the process in accordance with the indicators of the movement into the air flow.

The authors of work [10-11] prove the necessity of exfoliation of grain material in the process of feeding in order to increase the surface of their contact with air flow, especially during the increase of the unit load on the PSC.

In spite of a considerable number of scientific works devoted to the provision of the ideal conditions of grain separation into fractions, the possibilities of further improvement of pneumatic-separating systems of grain cleaning machines have not been studied fully. That is why theoretical investigation which is directed to the increase of the efficiency of operation of pneumatic-separating machines is of great importance.

Objective of research. Taking into account the insufficient volume of theoretical research of the influence of conditions of the feeding into PSC on the efficiency of the process of separation of grain mixture into fractions there arises a scientific task to highlight the regularities of the interaction of the air-flow with grains while moving into the vertical PSC.

Main material. Let us consider a monolayer movement of grains in the PSC.

In order to analyse the object of research we have to make the following assumptions:
– the layers of grain mixture are not mixed in the PSC;
– grain and admixture are in the form of a bullet inside and they are similar in size;
– the mass of an average grain is much bigger than the mass of an average admixture;
– the grain material and admixtures are uniformly located in the flow of every layer.

Let us introduce the rectangular Cartesian coordinate system \( OXY \) (Fig. 1) in which the axis \( OY \) is directed to the side of the movement of the air-flow and the axis \( OX \) is directed in such a way that the system \( OXY \) is situated on the right.

The speed of the air flow \( V_{\Pi} \) is chosen in such a way that while going through the PSC (Fig. 1, a):
– the grains will follow their trajectory which takes place if there is no air flow. In other words the speed of the air flow \( V_{\Pi} \) is lower than the speed of grains’ flow \( V_{\Pi,3} \);
– the admixtures do not follow the trajectory which takes place if there is no air flow. In other words the speed of the air flow is higher than the speed of the admixtures’ flow \( V_{\Pi,4} \).
In this case the speed of the air flow meets the condition:

$$V_{B.D.} < V_{II} < V_{B.3}.$$  \hspace{1cm} (1)

Under the accepted assumptions there is a clear separation of the grain flow. Grains and admixtures move in the opposite directions and do not interact. When the grain is fed into the PSC it follows the trajectory and the admixtures go upward.

Let us describe the grain and admixtures movement in case they are separated in the PSC with one-layer feeding of the grain material.

When a particle appears in the air flow it is influenced by: gravity $P = m_3 g$ (where $m_3$ is the mass of an average particle, $g$ is acceleration of the Earth’s attraction), inertia force $m_3 a$ ($a$ is acceleration of an average particle) and air resistance force $F_{III.3}$:

$$m_3 a + P + F_{III.3} = 0. \hspace{1cm} (2)$$

The speed of the air flow $V_{II}$ is quite high ($V_{II} = 8 < 2 m/s$), that is why the air resistance force $F_{III.3}$ is proportional to the square of relative speed of the particle [3] and is directed oppositely to its speed movement

$$F_{III.3} = -|\vec{V}| \vec{V} m_3 k_3, \hspace{1cm} (3)$$

where $\vec{V} = (\dot{x}, \dot{y} - V_{II})$ is a speed vector of particle movement relatively to the air flow; $k_3$ is a coefficient of the particle’s windage.

In the projections on the axis of the system $OXY$ the equation (3) has the following solution

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The scheme of grain and admixtures movement}
\end{figure}
The horizontal and vertical components of the particle’ speed are changed in the limits of 0.5…0.7 m/s and -0.1…0.1 m/s. They are considerably lower than the speed of the air flow \( V_{\text{II}} = 8 \text{ m/s} \), that is why

\[
|V| = \sqrt{\dot{x}^2 + (\dot{y} - V_{\text{II}})^2} \approx |V_{\text{II}} - \dot{y}| \approx V_{\text{II}}
\]

and the equation (4) has the following solution:

\[
\begin{aligned}
\dot{x} &= -V_{\text{II}} \dot{x}_3 \\
\dot{y} &= \dot{x}_3 (V_{\text{II}}^2 - V_{\text{III}}^2)
\end{aligned}
\]  

(6)

where \( V_{\text{III}} = \sqrt{\frac{g}{k_3}} \) is the speed of the particles’ flow.

The equation of the system (6) is independent. Let us decrease the order of the equations by changing \((\dot{x} = u, \dot{y} = v)\):

\[
\begin{aligned}
\dot{u} &= -V_{\text{II}} u \dot{x}_3 \\
\dot{v} &= \dot{x}_3 (V_{\text{II}}^2 - V_{\text{III}}^2)
\end{aligned}
\]

Divide the variables

\[
\begin{aligned}
\frac{d\dot{u}}{u} &= -V_{\text{II}} k_3 dt \\
\frac{d\dot{v}}{v} &= k_3 (V_{\text{II}}^2 - V_{\text{III}}^2) dt
\end{aligned}
\]

and integrate

\[
\begin{aligned}
\ln |u| &= -V_{\text{II}} k_3 t + \ln C_1 \\
v &= k_3 (V_{\text{II}}^2 - V_{\text{III}}^2) t + C_2
\end{aligned}
\]

where \( C_1, C_2 \) are integration constants. Do inverse substitutions \((u = \dot{x}, v = \dot{y})\)

\[
\begin{aligned}
\dot{x} &= C_1 e^{-V_{\text{II}} k_3 t} \\
\dot{y} &= k_3 (V_{\text{II}}^2 - V_{\text{III}}^2) t + C_2
\end{aligned}
\]

(7)

After integrating system (7), we have the following
where \( C_3, C_4 \) are integration constants.

Integration constants \( C_1, C_2, C_3, C_4 \) are found from the boundary conditions

\[
x(0) = 0, \dot{x}(0) = \dot{x}_0, y(0) = 0, \dot{y}(0) = \dot{y}_0.
\]

From (7) – (9) we get:

\[
C_1 = \dot{x}_0, C_2 = \dot{y}_0, C_3 = \frac{\dot{x}_0}{V_\Pi k_3}, C_4 = 0.
\]

Substituting (10) by (8), we get:

\[
\begin{align*}
x &= \frac{\dot{x}_0}{V_\Pi k_3} \left( 1 - e^{-V_\Pi k_3 t} \right) \\
y &= k_3 \left( V_\Pi^2 - V_{B,3}^2 \right) \frac{t}{2} + \frac{\dot{y}_0 t}{2}
\end{align*}
\]

The first equation allows defining the time \( t \), which is necessary for the particle to move from the front side of the PSC to the back side. That is the time when the particle is present in the channel. And if the depth of the channel equals \( L \), then the time \( t \) is the solution of the equation

\[
L = \frac{\dot{x}_0}{V_\Pi k_3} \left( 1 - e^{-V_\Pi k_3 t} \right).
\]

Substituting the equation (12) we get:

\[
t = -\frac{1}{V_\Pi k_3} \ln \left( 1 - \frac{L V_\Pi k_3}{\dot{x}_0} \right).
\]

Graphic interpretation (Fig. 2) of the acquired dependences (11) – (13) allows defining the possibility and conditions of separating grain mixture into fractions.

The analysis of graphic dependences (Fig. 2) allows making the following conclusion.

There is a possibility to separate grain mixture into fractions by setting up necessary parameters and operation modes of the PSC including feeding conditions. It is possible for the grain mixture which is characterised by the following values \( k_3 = 0.075...0.12 \) for the standard grain, \( k_3 = 0.11...0.14 \) for non-standard grain and \( k_3 = 0.125...0.55 \) for admixtures.

In case of feeding with the angle of 40° in the direction of the activity of the air flow speed vector (Fig. 2, a) and in the depth of the channel \( L = 4 \) cm we can observe full separation into the fractions of light admixtures and standard grain. By adjusting the air flow speed in the PSC \( V_\Pi = 7.5 \) m/s, at the depth of \( L = 10 \) cm there is a possibility to separate up to 98% of light admixtures into the sediment box. In return we shall have losses of standard grain into the waste.
a) is the angle of feeding to PSC 40° in the direction of the activity of the speed vector of the air flow; b) is the angle of feeding to PSC 40° in the opposite direction of the activity of the speed vector of the air flow; c) is the angle of feeding to PSC 0° in the direction of the activity of the speed vector of the air flow

Figure 2 – The trajectories of flying and separating of grain mixture into fractions in the following conditions: initial speed of feeding into PSC $\chi_0 = 0.5 \text{ m/s}$, the air flow speed $V_{II} = 7.5 \text{ m/s}$

In case of feeding with the angle of 40° in the opposite direction of the activity of the air flow speed vector or horizontally (Fig. 2, b, c) there is no losses of standard grain (for $V_{II} = 7.5\text{ m/s}$), but the quantity of separated admixtures is not higher than 30% – 60%. The improvement of the quality of separation demands more energy consumption to create air flow in the PSC dimensions at the expense of the channel depth.

**Conclusion.** In order to improve the efficiency of pneumatic separating channels of grain cleaning machines we made theoretical analysis of the interaction of grain mixture with the air flow of one-layer distribution of the grain in the PSC. According to the results of the research we can state that the process of movement of particles in the air flow is under the influence of the conditions of feeding into the PSC.

Thus, by selecting rational parameters of feeding grain into the PSC and adjusting corresponding air dynamic parameters and operating modes it is possible to separate up to 98% of light admixtures out of the grain mixture. In this case the losses of standard grain are minimal.

The objective of further research is to study the interaction of grain mixture with air flow of multi-layer distribution of the grain in the PSC.

**References**

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Аналітичне дослідження ефективності розділення зернового матеріалу у вертикальному пневмосепаруючому каналі

Повітряна сепарація є одним із найпоширеніших способів очищення зернових сумішей різних культур, а пневмосепаратори набагато дешевші, простіші і надійніші в експлуатації ніж пневморешітні машини. Тому подальший розвиток конструкцій цього класу машин і вдосконалення технології сепарації повітряним потоком є актуальною і своєчасною науково-технічною проблемою.

Враховуючи недостатню кількість теоретичних досліджень впливу умов введення в пневмосепаруючий канал (ПСК) на ефективність процесу розділення зернової суміші на фракції, постало наукове завдання по встановленню закономірностей взаємодії зернового матеріалу з повітряним потоком при подачі до вертикального ПСК. В статті розглянуто рух зернових часток в вертикальному ПСК при їх однорівневому однощаровому введенні.

Отримані теоретичні залежності, які дозволяють оптимізувати основні параметри ПСК та визначити час перебування зернової частки в повітряному потоці. Для зернової маси, що характеризується значеннями \( k_0=0.075...0.12 \) – для повноцінного, \( k_0=0.11...0.14 \) – для некондиційного зерна та \( k_0=0.125...0.55 \) – для смішаних домішок, спостерігається можливість чітко розділити зернову суміш на фракції, встановивши відповідні параметри і режими роботи ПСК, а також умови введення. За рахунок підбору раціональних параметрів введення матеріалу в ПСК та встановлення відповідних аеродинамічних параметрів і режимів можливо виділити з зернової суміші до 98% легких домішок, забезпечивши при цьому мінімальні втрати повноцінного зерна у відходи.

Метою подальших досліджень є побудова встановлення взаємодії зернової суміші з повітряним потоком при багатошаровому розміщенні матеріалу в ПСК.

Розділення зернової суміші, сепарація, повітряний потік, зерновий матеріал, пневмосепаруючий канал (ПСК), умови введення зерна, рух зернових часток

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