Determination of the Extent of Fraction in Air Separation of Grain Material

V V Piven
Tyumen Industrial University, 38, Volodarskogo St., Tyumen, 625000 Russia
E-mail: pivenvv@yandex.ru

Abstract. In the case of air separation of grain material, the trajectories of the components of the separated mixture depend on their aerodynamic properties, the parameters of the input of components into the air flow, and the velocity of entry. An exact mathematical description of the trajectories of motion makes it possible to determine the extent of the zone of reception of the material that has passed the separation. The obtained mathematical dependences allow to determine these parameters, and also can be used for optimization of the air separation process. The results of calculating the trajectories of motion can be used to determine the qualitative composition of the fractions obtained.

1. Introduction

Separation of grain materials by air flow is one of the main technological operations for post-harvest grain processing. Air separators can be used to extract impurities from the main grain stream, fractionate the original grain material [1], and remove impurities from the waste [2].

The efficiency of the operation of air separators and productivity is slightly dependent on moisture content and grain contamination in comparison with other working bodies. Therefore, the improvement of air separators [3], the search for new technological schemes for their use, the optimization of the parameters of air separators is an actual scientific task. The separation of multicomponent bulk mixtures by aerodynamic properties is widely used in various industries for the fractionation of powders, in the construction industry, in the mining industry, in the food industry.

The expediency of using air separators, their place in the technological scheme of grain cleaning should be evaluated in terms of energy costs for post-harvest grain processing [4].

Determination of the optimal parameters for the implementation of the air separation process is an urgent scientific task. The efficiency of the air separation process depends on the accuracy of determining the design dimensions of the separation chambers, the optimum values of the airflow velocity, the velocity and angle of the components entering the air flow, and the productivity [5, 6, 7, 8]. The quality criteria for the air separation process, when the source material is divided into two fractions is the completeness of the separation (percentage or fraction of light impurities from the main material to waste) and the loss of the main product into waste.

When the initial product is divided into three or more fractions (fractionation), the value of the redistribution of components between fractions is taken into account when assessing the quality of the separation process. Most often, the goal of fractionation is to obtain fractions with the maximum amount of a full-fledged product, fractions with a minimum amount of a high-grade product, and intermediate fractions containing the original components. For intermediate fractions, depending on their composition, it is then expedient to apply the separation technology to other separation features.

The expediency of using air separation technology is determined by the presence in the starting material of components that differ from the main product by aerodynamic properties. If there are no such differences, other methods of separation are used. If the physico-mechanical properties of the components of the initial mixture can be divided into several features, the technological line is arranged...
so that during the first stages of treatment it is possible to isolate the greatest amount of impurities and reduce the load on subsequent working organs. Up to 70% of the impurities in the original grain material, that comes to post-harvest processing are separated from the seeds of the main crop by aerodynamic characteristics. Given that the air separators have a fairly simple design, the efficiency of their operation is less dependent on the moisture content of the starting material compared to the screen separation; it is advisable to apply air separation in the first stage of treatment. The efficiency of the air separation process is enhanced by applying a high-velocity input of the raw material into the air flow. This effect is most palpable at a high (up to 15 - 20%) contamination of the initial material.

The location of the air separator in the production line is determined not only by the composition of the starting material, but also by the designation of the finished product.

For example, if the seed is processed, then at the last stage it is also advisable to conduct an air separation with a small concentration of components in the separation chamber.

The location of the air channel (horizontal, vertical, inclined), its cross-section and the direction of input of the initial material is determined by the purpose of the air separator and the composition of the initial material.

2. Materials and Method
To determine one of the main parameters of the separation chamber: -the length of the fraction receivers, we consider the force scheme acting on the particle of the material to be separated, which moves in the inclined air channel (Figure 1).

![Figure 1](attachment:figure1.png)

**Figure 1.** The force acting on a particle of the material to be separated in an inclined air channel.

The initial grain material with the initial velocity \( V_0 \) is introduced at an angle \( \alpha_0 \) to the direction of the air flow. The air flow has a velocity \( W \), and the angle of inclination of the air channel to the horizon is \( \gamma \). The current value of the velocity of the particle of the material to be separated is designated as \( V \). The velocity vector \( V \) forms an angle \( \alpha \) with the airflow velocity vector \( W \). The following system of forces acts on the particle of the material: gravity \( m \cdot g \) and the force of aerodynamic resistance \( R \). According to Newton's second law

\[
m \cdot \ddot{a} = \sum \vec{F}_k,
\]

where \( m \) – particle mass, kg; \( a \) – particle acceleration, m/s\(^2\); \( F_k \) – force acting on a particle, H.

\[
\sum \vec{F}_k = \vec{R} + m \cdot \vec{g}.
\]
It follows from equation (1) that, in the projection onto the coordinate axes \( X \) and \( Y \), the differential equations of particle motion, compiled for its arbitrary position, will have the following form:

\[
\begin{align*}
    m \frac{d^2x}{dt^2} & = R_x - m \cdot g \cdot \sin \gamma; \\
    m \frac{d^2y}{dt^2} & = m \cdot g \cdot \cos \gamma - R_y.
\end{align*}
\]  

(3)

The current value of the particle velocity vector \( \mathbf{V} \) is defined as the vector sum of the velocity of the air flow \( \mathbf{W} \) and the velocity of the particle relative to the air flow \( \mathbf{V}_R \). The force of aerodynamic resistance \( R \), acting on the particle from the side of the air flow, is directed opposite to the vector \( \mathbf{V}_R \), and its value is determined by the formula:

\[
R = 0.5 \cdot c_x \cdot \rho \cdot S_M \cdot V_R^2,
\]  

(4)

where \( c_x \) – dimensionless coefficient of drag of a particle; \( \rho \) – air density, kg/m\(^3\); \( S_M \) – the area of the median section (the area of the projection of the particle on the plane perpendicular to the relative velocity vector \( V_k \)), m\(^2\).

During the movement of the separated particles in the air stream, their position changes all the time. The particles have an irregular geometric shape. Therefore, during the motion of a particle in the air flow, its median cross section is not constant. Determination of the aerodynamic force according to formula (4) is difficult.

The aerodynamic properties of grain materials are most conveniently characterized by the velocity of flying. This is the rate of vertical air flow, at which the particle is in it in an equilibrium position. The force of the aerodynamic drag is balanced by the gravity of the particle. Thus, the speed of the winding takes into account the average position of the particle and all the features of the frictional forces arising on its surface, when flowing through the air stream. In this case, the averaged value of the aerodynamic properties of the particle is taken into account by the generalized coefficient of sail \( k_w \) [9, 10]. Then the force of the aerodynamic drag can be represented as

\[
R = k_w \cdot m \cdot V_t^2,
\]  

(5)

where \( k_w \) – coefficient of sail, m\(^{-1}\); \( m \) – mass of particle, kg; \( V_t \) – velocity of flying, m/s.

In a state of equilibrium when the particle is in the air stream in the suspended state then,

\[
k_w \cdot m \cdot V_t^2 = m \cdot g.
\]  

(6)

From the formula (6) a mathematical expression for determining the value of the coefficient of sail is obtained

\[
k_w = \frac{g}{V_t^2}.
\]  

(7)

The mathematical relationship between the coefficient of sail and the coefficient of drag can be established from the equality of the right-hand sides of formulas (4) and (5). Taking into account that in the suspended state the velocity of flying of the particle \( V_k \) is equal to the velocity of flying \( V_t \), we obtain

\[
k_w = c_x \cdot \rho \cdot S_M / (2 \cdot m).
\]  

(8)
The vector of the relative velocity of the particle \( V_R \) is the side of the parallelogram constructed on the vectors \( V_R \) and \( W \). The vector of the current value of the absolute velocity of particle \( V \) is the diagonal of this parallelogram. From the ratio of the sides of the triangle constructed on the vectors \( V, V_R \) and \( W \), it follows that

\[
V_R = \sqrt{W^2 + V^2 - 2 \cdot W \cdot V \cdot \cos \alpha}.
\]  

(9)

For transformations of the system of equations (3), we replace the projections of the velocity vector \( V \) on the \( X \) and \( Y \) coordinate axes as follows:

\[
\dot{x} = V \cdot \cos \alpha, \quad (10)
\]

\[
\dot{y} = V \cdot \sin \alpha. \quad (11)
\]

Similarly, a substitution for the projections of the accelerations on the coordinate axes is introduced:

\[
\ddot{x} = \frac{d^2x}{dt^2}, \quad (12)
\]

\[
\ddot{y} = \frac{d^2y}{dt^2}. \quad (13)
\]

The trigonometric functions of the angle \( \alpha \) are represented as

\[
\cos \alpha = \frac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2}}, \quad (14)
\]

\[
\sin \alpha = \frac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}}. \quad (15)
\]

By the sine theorem:

\[
\frac{V}{\sin \beta} = \frac{V_R}{\sin \alpha}. \quad (16)
\]

When the particle moves in the air stream, the aerodynamic force \( R \) depends on the relative velocity \( V_R \). Therefore, in determining \( R \) in expression (5), the parameter \( V_t \) must be replaced by \( V_R \). Taking into account the dependences (5) - (16), the differential equations of motion (3) take the following form:

\[
\ddot{x} = k_w (W - \dot{x}) \sqrt{(W - \dot{x})^2 + \dot{y}^2} - g \cdot \sin \gamma,
\]

\[
\ddot{y} = g \cdot \cos \gamma - k_w \cdot \dot{y} \sqrt{(W - \dot{x})^2 + \dot{y}^2}. \quad (17)
\]

The solution of the differential equations of motion of a material point in an air stream will be made by the method of expansion into power series in the form:

\[
x = x_0 + \dot{x}_0 \cdot t + \ddot{x}_0 \cdot t^2/(2!) + \cdots,
\]

\[
y = y_0 + \dot{y}_0 \cdot t + \ddot{y}_0 \cdot t^2/(2!) + \cdots, \quad (18)
\]

where the projection of the rate of particle input on the \( X \) axis is defined as
\[ \dot{x}_0 = V_0 \cdot \cos \alpha_0. \] (19)

Similarly, the remaining variables with the index "0" are defined in equations (18). This index means the initial conditions: the initial velocity of the particle, the angle of input (Fig. 1).

The calculations show that the fourth terms of equations (18) are an order of magnitude smaller than the previous ones and can be neglected in calculations.

To determine the separation time \( t_s \) (the time of finding a particle in an air channel of height \( H \)), the coordinate \( Y \) in the second equation of system (19) to the value of \( H \) are equated and the equation below is obtained

\[ t_s = \frac{(-V_0 \cdot \sin \alpha_0 + \sqrt{V_0^2 \cdot \sin^2 \alpha_0 + 2H \cdot \ddot{Y}_0})}{\ddot{Y}_0}. \] (20)

The formulas obtained make it possible to calculate the trajectory of the motion of a separated particle having certain aerodynamic properties.

3. Results and Discussion

The components of the initial grain mixture entering the air channel have a great variety in aerodynamic properties (Figure 2). The variational curves of the distribution of components in terms of the velocity of flying partially overlap and it is impossible to obtain the grain of the main culture or impurity in the pure separation. In its pure form, it is possible to obtain most of the impurities - zone A and part of the grain - zone C. In the B range, the variational curves intersect and in this range the velocity of flying an intermediate fraction consisting of the main crop grain and impurities is obtained.

![Figure 2](image_url)

Figure 2. An approximate plot of the distribution density \( p \) of the components of the main culture and impurities at the velocity of flying \( V_t \): 1 - for impurities; 2 - for the grain of the main crop; A - range of obtaining impurities in pure form; B is the range for obtaining the mixed fraction: the main crop grain and impurities; C - range of obtaining the main crop grain in its pure form.

The preparation of such an intermediate fraction is expedient, since a significant part of the components are isolated from the main stream in pure form. Further purification of the intermediate fraction should be carried out on other working organs, depending on the difference in the physico-mechanical properties of the components of this fraction. Separation of the intermediate fraction will be possible when it is divided by the width of the components, thickness or length.

The difference in the velocity of flying of the main culture components and impurities is used in separation in air channels of various shapes. At the first stage of grain cleaning from impurities, when high productivity is required, air channels horizontally or obliquely have an advantage.

In a vertical air channel, the particle is in the separation zone for a longer time. This allows for a higher quality of separation, but with lower performance. Therefore, vertical air channels in process lines are used most often at the last stages of grain cleaning.

Analysis of the equations obtained shows that the aerodynamic force acting on the components of the material to be separated, according to expression (5), depends on the velocity of the relative motion of the component.
\[ R = k_w \cdot m \cdot V_R^2. \]  

(21)

The value of \( V_R \) depends on the velocity of input of components \( V_0 \) and on the angle of input \( \alpha_0 \). Therefore, in order to increase the aerodynamic force acting on the components of the separable material and to improve the separation quality, it is necessary to increase the rate of entry of the starting material into the air flow.

Calculations of the trajectories of the components of the grain material were carried out with the following parameters: the velocity of input of the components into the air flow \( V_0 = 5 \text{ m/s} \), the angle of entry \( \alpha_0 = 60^\circ \), the air velocity \( W = 8 \text{ m/s} \), the height of the air channel \( H = 0.3 \text{ m} \). As a result, calculation of the trajectories of motion with the help of equations (18) it is established that for wheat grain with a range of the velocity of flying of 8.9 ... 11.5 m/s, the value \( X_D = 0.265 \text{ m} \) (Figure 3). This coordinate corresponds to the beginning of precipitation of the heaviest grains. The data were obtained with the height of the air channel \( H = 0.3 \text{ m} \). The length of the reception zone for a full grain \((D_1 + D_2)\) is 0.059 m.

The beginning of the impurity precipitation zone \((X_D + D_1)\), having the velocity of flying of 0...9.5 m/s, is 0.294 m. Light impurities are carried out by the air flow and do not precipitate. In zone \(D_2\), both full grain and impurities precipitate.

![Figure 3. Trajectories of the movement of the main culture components and impurities during air separation in the inclined air channel: \( X_D \) - the abscissa of the beginning of the zone of precipitation of the full grain; \( D_1 \) - length of the zone of reception of pure grain; \( D_2 \) - length of the zone of reception of pure grain and impurities; \( D_3 \) - the length of the zone of reception of impurities.](image)

With the help of the mathematical dependences obtained in this paper, it is also possible to determine the maximum value of the particle velocity that is carried out by the air flow through the channel and will not precipitate in the receiver of the fractions. For the above example, this value of the velocity of flying is 0.56 m/s. Considering that a significant part of light impurities will settle downstream after zone \( D_3 \), when designing air channels, it is necessary to provide for collection and removal of this part of impurities.

4. Conclusion
The obtained equations of motion of the components of the separated material in the air flow make it possible to determine the trajectories of the particles to be dispersed depending on their aerodynamic
properties, the velocity and angle of the input of the components of the air flow, the air flow and the angle of inclination of the air channel, and the channel height.

The construction of the trajectories of the motion of the components makes it possible to obtain the coordinates and the extent of the reception zone of components having different aerodynamic properties. Optimization of the air separation process should be carried out by establishing optimum values for the input parameters of the separated mixture and the air flow rate.

During operation, the aerodynamic properties of the components and the initial weed of the material may vary. Therefore, in the zone for receiving fractions, it is necessary to provide adjusting devices (rotary flaps, movement of the fraction receivers along the X axis), correcting the location of the receiving zones of the finished product, depending on the state of the initial mixture.

In the case of overlapping of the distribution curves of the distribution of the components of the material to be separated in terms of the velocity of flying in the receiving zone of the finished product, several fractions can be obtained: pure grain, impurities, intermediate fractions containing grain and impurities.

Separation of homogeneous fractions from the total flow of processed material allows to unload the main equipment for grain cleaning, to reduce grain damage, to reduce the energy costs for post-harvest processing.

The construction of the technology for further purification of the obtained fractions must be carried out taking into account the purpose of the material being processed, its initial state, and the qualitative parameters of the operation of the air separator.

References
[1] Piven V 2017 The theoretical justification for the fractionation of bulk materials during separation MATEC Web of Conferences 106, 03005 doi: 10.1051/matecconf/201710603005
[2] Saitov V E, Kurbanov R F and Suvorov A N 2016 Assessing the adequacy of mathematical models of light impurity fractionation in sedimentary chambers of grain cleaning machines Procedia Engineering 2 series "2nd International Conference on Industrial Engineering, ICIE 2016" pp 107–110
[3] Avdeev N E, Chernuhin Y V and Stranadko O G 2012 The search for new principles of separation Proceedings of the Voronezh State University of Engineering Technologies 3 pp 24–26
[4] Ivanov N M and Chepurin G E 2017 Power Consumption at After-Harvesting Grain Processing Achievements of Science and Technology of AICis 31 no 4 pp 87–90
[5] Semenov E V, Slavyanskii A A and Antipov S T 2015 Calculation of efficiency of process of fractionation of loose mix in the working volume of a pneumatic separator Proceedings of the Voronezh State University of Engineering Technologies 3(65) pp 43–49
[6] Burkov A I, Glushkov A L and Lazykin V A 2015 Research of vertical pneumatic separating channel with supporting mesh An Agrarian Science of Euro-North-East 1(44) pp 73–79
[7] Burkov A I, Glushkov A L and Lazykin V A 2014 Research of the dividing chamber of the fractional pneumoseparator at clearing of seeds of fodder grasses An Agrarian Science of Euro-North-East 5(42) pp 69–74
[8] Shukhanov S N 2015 Planning and methods of carrying out experimental studies of the drum-type grain thrower Izvestia Orenburg State Agrarian University 5(55) pp 71–73
[9] Glushkov A L 2016 Analysis of moving process of grain material components in suction chamber of grain-cleaning machine An Agrarian Science of Euro-North-East 4 pp 69–75
[10] Shukhanov S N 2015 Interaction elements of particles of grain lots with air during the work of the tape thrower Agrarian Scientific Journal 12 pp 58–59