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Analysis of the relationship of forces acting on the material in the centrifugal air separator

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Abstract. The relevance of the study derives from the need to increase efficiency of dry beneficiation of minerals, in particular through improving methods of separation of finely dispersed materials. The research aimed to analyse the regularities of the relationship of forces acting on a material particle in the vortex airflow in the centrifugal separator. The paper uses the analytical research method and generalisation of existing studies dealing with determining the balance of forces acting on a material particle in a vortex airflow. The main results of the research consist in determining the dependencies between the most influential forces acting on a particle of a mineral with a relatively high density in a centrifugal air separator. The balance of the airflow resistance, gravity and centrifugal forces was established, which is a key aspect for improving designs and optimising operating modes of centrifugal separators. The dependencies determining positions of resultants of the main forces were established and allowed determining parameters of the rational operating mode of air separators and substantiating recommendations for improving efficiency of their operation. The obtained equations of the resultants are universal and do not depend on the specific design of the air separator, which allows them to be used to analyse and optimise operation of various models of centrifugal air separators as well as other classes of separators considering relevant adjustments. The practical value of the work consists in obtaining equations that determine positions of the resultants of the three main forces acting on a particle in the vortex airflow. This, in turn, enables determining parameters of the required mode of operation

Keywords: mineral beneficiation; centrifugal force; gravity force; airflow resistance force; balance of forces

Introduction

The problem of efficient sorting of fine-grade materials is becoming increasingly relevant in modern environment, when mineral beneficiation technologies require high process precision and optimality. Improvement of material separation methods is of crucial significance for increasing productivity and economic efficiency of mining and beneficiation enterprises. Employment of centrifugal air separators is of particular importance as they provide high efficiency of dry separation of finely dispersed materials, replacing inefficient screening.

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This equipment is becoming indispensable in conditions of increased application of dry mineral processing technologies instead of wet processing to reduce energy costs.

Sorting by centrifugal separators is an important operation, especially for materials with a high content of less than 0.1-0.5 mm fractions. However, efficiency of this equipment depends on understanding and considering the complex of forces acting on the material particles, in particular the centrifugal force, the airflow resistance force and weight. Improvement of these technologies requires detailed mathematical modelling to optimise separation processes. In current studies of centrifugal separators, much attention is paid to the analysis of forces that act on material particles. In particular, most researchers (Adamchuk *et al.*, 2021; Esmaeilpoura *et al.*, 2024) distinguish three main forces: particle weight, the airflow resistance force, and the centrifugal force. M. Madaliev (2020) presents differential equations that describe the motion of particles in vortex flows. The author notes that the centrifugal force and the airflow resistance force are the main forces that determine the trajectory of particles. S. Stepanenko (2019) provides formulas for determining these forces, but their application is complicated due to the need to determine additional coefficients. The above authors point out that mathematical modelling of such processes is critical for optimising operation of separators. S. Stepanenko & B. Kotov (2020) further highlight the lifting force generated by the Magnus-Zhukovsky effect, which acts in the direction opposite to the force of gravity. Thus, a comprehensive approach to modelling and consideration of all forces acting on particles is necessary to improve efficiency of the process.

The present work aimed to build mathematical models to determine prevailing forces influencing efficiency of material separation and to substantiate recommendations for improving process performance.

Materials and Methods

Specific features of the research object condition application of the analytical method when the research focuses not on a specific design, but only on the model of the separation process and its parameters. When considering movement of a single material particle in the vortex airflow, the following assumptions are made: the particle is a solid undeformed ball-shaped body, its density is $\rho_p = 3{,}500$ kg/m^3 (that corresponds to the density of iron-containing concentrates), the radius of the circle of the particle movement is accepted $r = 0.5$ m, the airflow has a uniform velocity field.

The following factors act on a single particle in the spiral flow vortex (Fig. 1):

- the particle weight (the vector is in the downward direction):

$$G = g \cdot m_p, \tag{1}$$

where m_p – the particle mass, kg; g – the free fall acceleration, m/s^2.

- the airflow resistance force, N (the vector is directed collinearly with the air velocity vector):

$$P_a = c_r \cdot k_s \cdot \rho_a \cdot \upsilon_\tau^2 \cdot \pi \cdot \frac{d_p^2}{8}, \tag{2}$$

where c_r – the coefficient of the airflow resistance of the particle; k_s – the coefficient that depends on the particle shape ($k_s = 1$ – for ball-shaped; $k_s = 1.1$ – for oval; $k_s = 1.5$ – for pyramidal; $k_s = 1.76$ – for longitudinal; $k_s = 3.8$ – for acicular ones); d_p – the equivalent diameter of the particle, m; ρ_a – air density, kg/m^3; υ_τ – the tangential air velocity component.

- the centrifugal force, N (the vector is in the radial direction from the centre):

$$P_c = \frac{\pi \cdot \rho_p \cdot \upsilon_\tau^2 \cdot d_p^3}{6 \cdot r}, \tag{3}$$

where ρ_p – the density of the particle material, kg/m^3; r – the radius of the particle location, m.

- the medium resistance force during the radial movement of the particle from the vortex centre, N:

$$P_r = \frac{C \cdot F_p \cdot \rho_p \cdot \upsilon_p^2}{2 \cdot g}, \tag{4}$$

where C – the factor depending on Reynolds number ($C = 0.48$ for $Re = 1000…200000$) of the airflow resistance of the particle; F_p – the particle cross-section area, m^2; υ_p – the speed of the particle's radial movement from the vortex centre.

υ_p is determined as:

$$\upsilon_p = \frac{d_p^2 \cdot \rho_p \cdot \upsilon_r^2}{18 \cdot \nu \cdot \rho_a \cdot r}, \tag{5}$$

where υ_r – the radial component of the air velocity, m/s; ν – the kinematic viscosity of air ($\nu = 1.5 \cdot 10 - 5$), m^2/s.

- the kinematic lifting force, N (the vector is in the opposite direction to gravity):

$$P_{kl} = \frac{m_p \cdot g \cdot \rho_a}{\rho_p}. \tag{6}$$

- the friction force of particles on the curvilinear surface of the separator housing, N (the vector is in the opposite direction to the airflow resistance force vector):

$$P_{fr} = k \cdot P_c, \tag{7}$$

where k – the coefficient of friction of the particle on the separator housing wall.

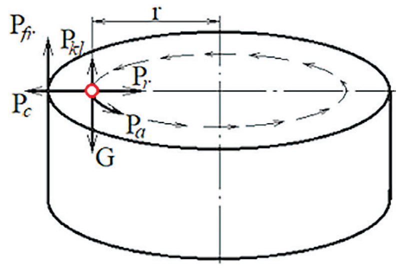

Figure 1. Forces acting on a material particle in the vortex airflow
Source: developed by the authors

Results and Discussion

The values of the forces acting on the particle under the same conditions are compared using the dependencies presented in the above methodology (Fig. 2).

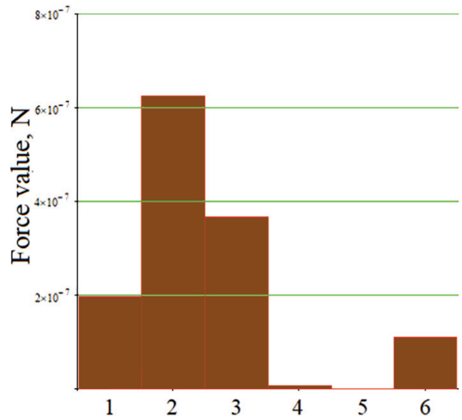

Figure 2. Comparison of the forces acting on the particle in the centrifugal separator under the same conditions
Notes: 1 – the particle weight G; 2 – the airflow resistance force P_a; 3 – the centrifugal force P_c; 4 – the medium resistance force during the radial movement of the particle from the vortex centre P_r; 5 – the hydrodynamic force P_{kl}; 6 – the friction force P_{fr}
Source: developed by the authors

Figure 2 demonstrates that the hydrodynamic force and the medium resistance force during the radial movement of the particle from the vortex centre are the smallest in comparison with the others. It should be noted that the relationship of the most influential forces of gravity, airflow resistance and the centrifugal force can vary significantly because they depend on the size and mass of the particles, the radius of their location inside the separator and the air velocity.

In the further force analysis, the hydrodynamic force and the medium resistance force during the radial movement of the particle from the vortex centre are not considered due to their relatively small values. In addition, the force of particle friction on the curvilinear surface of the separator housing is not considered either because the present work deals with movement of the particles in the airflow before their contact with the walls of the separator housing.

Analysing the three most influential forces acting on a particle in a centrifugal separator, it should be noted that their values depend on the size, weight (density) of the particle, the air velocity and the current radius of the particle's location inside the centrifugal separator. Therefore, this dependency cannot be plotted in its entirety because it is a hypersurface. The relationship of the three most influential forces acting on a particle is shown in Figure 3.

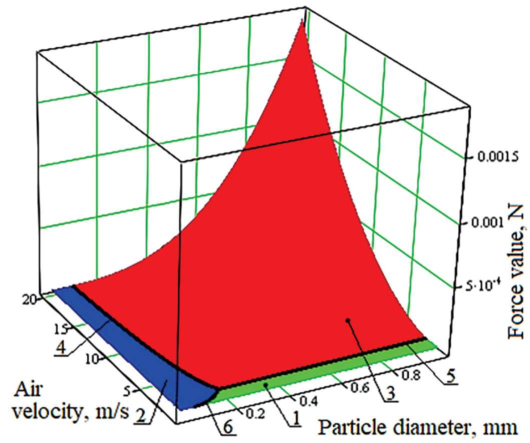

Figure 3. Relationship of the forces acting on a particle depending on its diameter and speed at the location radius of 0.5 m
Notes: 1 – the particle weight G; 2 – the airflow resistance force P_a; 3 – the centrifugal force P_c; 4 – the resultant of the airflow resistance P_a and centrifugal P_c forces; 5 – the resultant of the centrifugal force P_c and the particle weight G; 6 – the resultant of the airflow resistance force P_a and the particle weight G
Source: developed by the authors

Figure 3 shows that as the size and, accordingly, the weight of the particle and the air velocity increase, the centrifugal force becomes dominant. At low air velocities, the force of gravity is dominant. Finally, at small particle sizes and, accordingly, their weight, it is the airflow resistance force that dominates.

Special attention should be paid to the position of the resultants. The position of the resultant of the air resistance force and the centrifugal force determines the boundary of the material separation by size in centrifugal separators. Positions of the resultant of the airflow resistance force and the particle weight determine the boundary of the material separation by size in gravity separators. Based on (1) and (3), the equation of the projection of the resultant of the centrifugal force and the particle weight (Fig. 4) looks like:

$$\upsilon_{\tau}{}^{GPc}(d_p) = 3.13 \cdot \sqrt{r}. \quad (8)$$

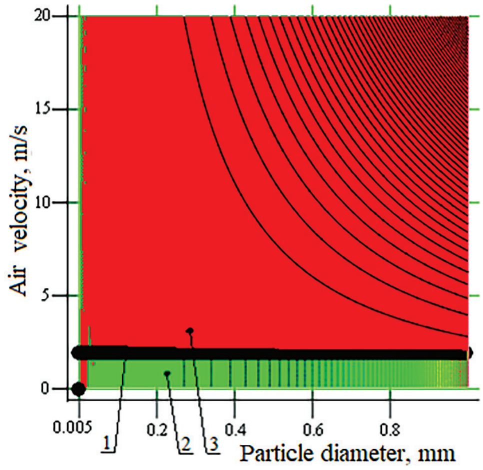

Figure 4. Projection of the resultant of the centrifugal force and the particle weight

Notes: 1 – the resultant; 2 – the particle weight *G*; 3 – the centrifugal force P_c

Source: developed by the authors

Then the condition of the centrifugal force exceeding the weight of the material particle looks like:

$$P_c > G, \text{ if } \upsilon_{\tau} > 3.13 \cdot \sqrt{r}. \quad (9)$$

It should be noted that the position of the resultant does not depend on the air velocity and is determined only by the radius of the particle location. Based on (1) and (2), the equation of the projection of the resultant of the airflow resistance force and the particle weight (Fig. 5) looks like:

$$\upsilon_{\tau}{}^{GPa}(d_p) = 1.003 \cdot d_p \cdot \sqrt[3]{\frac{\rho_p^2}{\nu \cdot k_s^2 \cdot \rho_a^2}}. \quad (10)$$

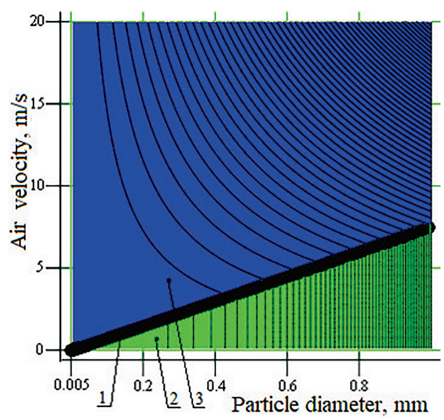

Figure 5. Projection of the resultant of the airflow resistance force and the particle weight

Notes: 1 – the resultant; 2 – the particle weight *G*; 3 – the airflow resistance force P_a

Source: developed by the authors

Then the condition of the airflow resistance force exceeding the material particle weight looks like:

$$P_a > G, \text{ if } \upsilon_{\tau} > 1.003 \cdot d_p \cdot \sqrt[3]{\frac{\rho_p^2}{\nu \cdot k_s^2 \cdot \rho_a^2}}. \quad (11)$$

The position of the resultant of the airflow resistance force and the particle weight is determined by the linear dependency and additionally depends on the density of material particles. Based on (2) and (3), the equation of the projection of the resultant of the airflow resistance force and the centrifugal force (Fig. 6) looks like:

$$\upsilon_{\tau}{}^{P_cP_a}(d_p) = \frac{95.0625 \cdot r^2 \cdot \nu \cdot k_s^2 \cdot \rho_a^2}{d_p^3 \cdot \rho_p^2}. \quad (12)$$

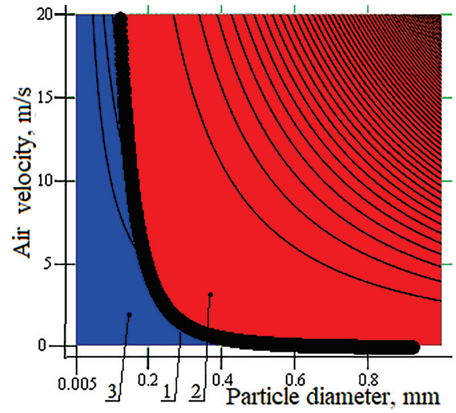

Figure 6. Projection of the resultant of the airflow resistance force and the centrifugal force

Notes: 1 – the resultant; 2 – the centrifugal force P_c; 3 – the airflow resistance P_a

Source: developed by the authors

Then the condition of the centrifugal force exceeding the airflow resistance force looks like:

$$P_c > P_a, \text{ if } \upsilon_{\tau} > \frac{95.0625 \cdot r^2 \cdot \nu \cdot k_s^2 \cdot \rho_a^2}{d_p^3 \cdot \rho_p^2}. \quad (13)$$

The performed analysis of the relationship of the acting forces confirms the conclusion made by K.W. Chu *et al.* (2011) that the centrifugal, gravity and airflow resistance forces are the predominant ones acting on a particle. The obtained conditions of positioning the resultant of the main forces acting on material particles in centrifugal separators enable quick determination of the required air velocity depending on the size of the separator and parameters of the processed material. The fact that the obtained equations do not depend on the specific design of the separator allows using them for analysing the entire class of centrifugal air separators, and, with some adjustments, other classes of air separators.

N.X. Ho *et al.* (2024) consider the influence of the additional medium resistance force which acts on the particle during its movement in the curvilinear flow.

This aspect differs from previous studies, in which this force was not taken into account. Interestingly, at low particle density and relatively large sizes, which are characteristic of agricultural but not mineral materials, the kinematic lifting force becomes more influential, as shown in the work by B. Kotov *et al*. (2019). Y. Zeng *et al*. (2020) and R. Shen *et al*. (2022) additionally mention the force of particle friction on the separator wall, which appears when the material comes into contact with the equipment housing. The work by N. Morkun *et al*. (2022), that dealt with the modelling and control of magnetic separator parameters, should also be considered in this connection.

Moreover, the airflow resistance force value depends more on the air velocity and particle size, and the centrifugal force value depends on the particle weight and location. Thus, closer to the axis of the separator, the centrifugal force prevails for heavy particles and pushes them outward to the housing wall; the airflow resistance force predominates for smaller particles with low mass and pick them up and carries them out for discharge. At that, as can be seen from the above graphs, to provide normal operation of centrifugal air separators with particles of large mass and size, the airflow velocity should be relatively high. This again confirms that centrifugal air separators operate more efficiently with small-sized particles of up to 0.1…0.5 mm.

Conclusions

The analysis performed has resulted in identifying regularities of the relationship of forces acting on particles of dense materials, such as mineral raw materials, and determining their trajectories and behaviour in the vortex airflow of the centrifugal separator. It has been established that the most influential forces are gravity, airflow resistance and centrifugal ones. The balance between them is determined by the particle size and mass (density), the air velocity and the current radius of the particle location in the separator. Thus, for heavy particles located closer to the separator axis, the centrifugal force prevails and pushes them outward to the housing wall; for smaller particles with low mass, the airflow resistance force predominates and picks them up and carries out for discharge. So, to provide normal operation of centrifugal air separators with particles of large mass and size, the airflow velocity should be relatively high.

The dependencies have been established that identify positions of the resultants of the main forces and allow determining parameters of the rational mode of operation of air separators and substantiating the recommendations for improving their efficiency. The obtained equations of the resultants are universal and do not depend on the specific design of the air separator, which allows them to be used to analyse and optimise operation of various models of centrifugal air separators, as well as other classes of separators considering relevant adjustment. Prospects for further research consist in determining designs of centrifugal air separators with the best balance of the three mentioned forces, which will contribute to increased efficiency of separation of finely dispersed mineral raw materials, as well as determination of possible ways to improve the separator design.

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None.

Conflict of Interest

None.

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Аналіз співвідношення сил, що діють на матеріал у повітряному відцентровому сепараторі

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Анотація. Актуальність дослідження зумовлена необхідністю підвищення ефективності процесів сухого збагачення корисних копалин, зокрема через вдосконалення методів поділу тонкодисперсних матеріалів. Метою дослідження був аналіз закономірностей співвідношення сил, що діють на частинку матеріалу у вихровому повітряному потоці у відцентровому сепараторі. У роботі використано аналітичний метод дослідження та узагальнення існуючих досліджень, орієнтованих на визначення балансу сил, що діють на частинку матеріалу в вихровому потоці повітря. Основні результати дослідження полягають у визначені залежностей між найвпливовішими силами, що діють на частинку мінеральної сировини, що відрізняється порівняно високою щільністю, у відцентровому повітряному сепараторі. Встановлений баланс між силою аеродинамічного опору, силою тяжіння і відцентровою силою, який є ключовим аспектом для вдосконалення конструкцій та оптимізації режимів роботи відцентрових сепараторів. Встановлено залежності, що визначають положення рівнодіючих між основними силами, та дозволяють визначати параметри раціонального режиму роботи повітряних сепараторів та обґрунтувати рекомендації щодо підвищення продуктивності процесу їх роботи. Отримані рівняння положення рівнодіючих є універсальними та не прив'язані до конкретної конструкції повітряного сепаратора, що дозволяє застосовувати їх для аналізу та оптимізації роботи різноманітних моделей відцентрових повітряних сепараторів, а також інших класів сепараторів з урахуванням відповідних уточнень. Практична цінність роботи полягає в отриманні рівняннь, які визначають положення рівнодіючих між трьома основними силами, що діють на частинку у вихровому повітряному потоці. Це, в свою чергу, дозволяє визначати параметри необхідного режиму роботи

Ключові слова: збагачення корисних копалин; відцентрова сила; сила тяжіння; сила аеродинамічного опору; баланс сил