Розроблено математичну модель процесу сепарування гетерогенних полідисперсних сумішей у запропонованих енергозберігаючих вихрових сепараторах, яка представлена системою диференціальних рівнянь, що зв'язує параметри регулювання процесом із геометричними розмірами апарату. Показано можливість розв'язання математичної моделі на основі методу сіток для визначення вихідних параметрів і параметрів управління процесом сепарування, а також для визначення координат компонент з різними формами, щільностями, аеродинамічними та газодинамічними властивостями. Це зменшить час на розрахунки газодинамічних вихрових сепараторів будь-яких сумішей. Доведено достовірність розрахунку на основі методу сіток за допомогою зіставлення його з результатами експерименту. Це дозволяє розраховувати і проектувати вихрові сепаратори без дорогих калібрувальних сит і енергоємного вібраційного обладнання. Встановлено область зміни загальноприйнятих у зерноперероблювальній промисловості коефіцієнтів ефективності і чіткості сепарування суміші борошна, які вказують на наявність невідсепарованих шкідливих компонент у вихідному продукту та вміст якісних компонент у відходах, що не повинні перевищувати 2 %. Визначено граничні значення коефіцієнтів ефективності $\eta_е$=88 % і чіткості $\eta_ч$ =0,9 суміші борошна вищого, першого і другого сортів, які можуть прийматися вихідними при проектуванні вихрових сепараторів. Доведено можливість управління процесом сепарування внаслідок зміни газодинамічних параметрів гетерогенної суміші на вході у сепаратор. Це дозволить змінювати швидкості перерозподілу компонент суміші і отримати необхідні показники по вихідному продукту з наперед заданим ступенем чистоти. Результати досліджень доводять можливість втілення вихрових сепараторів у промислове виробництво, що значно зменшить затрати на підготовку сировини у зернопереробнювальній, вугільній та ін. галузях, а також при виробництві доломіту, будівельних матеріалів, тощо. Застосування вихрових газодинамічних сепараторів у технологічних процесах дозволить покращити екологію виробництва і знизити експлуатаційні витрати на обслуговування і ремонт, тому що працюють за замкнутім циклом і не мають багатокоштовних калібрувальних сит і електроприводів.

Ключові слова: вихровий сепаратор, гетерогенна суміш, газодинамічні параметри, коефіцієнт ефективності, коефіцієнт чіткості, продуктивність

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CONSTRUCTING A MATHEMATICAL MODEL OF THE GAS-DYNAMIC SEPARATION FOR DESIGNING ENERGY-SAVING VORTEX SEPARATORS

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1. Introduction

Modern technological processes of separation and mixing of heterogeneous polydisperse media have high energy and economic costs. Main disadvantages of such processes are the design complexity, a large number of moving mechanisms, nodes, parts, separating sieves, etc., unsatisfactory environmental performance. In this regard, it is a relevant task to develop devices, which would make it possible to remove moving elements and separating sieves from technological processes, where main energy costs per unit of finished products are the prevailing value in relation to the cost of equipment and costs for preparation of raw materials.

Gas-dynamic processes, which occur in vortex devices, irrespective of shapes and parameters of discrete particles of heterogeneous streams, because of interaction with incident fluxes, enable the control over a mass exchange between lines of streams and the concentration of individual components in coordinates. This makes it possible to apply gas-dynamic vorticial devices in various technological processes of mixing or separation of components and to reduce overall dimensions, metal capacity, energy intensity and their cost, compared to existing machines.

It is possible to resolve the problem of elimination of separation of heterogeneous mixtures of moving sieves, elements and nodes that determine the level of energy consumption in modern separators by the introduction of developed vortex gas-dynamic separators to technological processes [1, 2]. Comprehensive studies of separation of heterogeneous mixtures show that the main characteristics of vortex separators, such as efficiency and precision, do not always meet the requirements of technological processes. This is explained, first of all, by the fact that the segregated mixtures consist of components that vary widely in granulometric composition, density, aerodynamic parameters, critical velocities, concentration, and others. According to our classification, such heterogeneous mixtures include:

– coal grinding, which consists of coal, rock, soil, sulfur mixtures, pure sulfur, etc.;

– abrasive materials, electric-rundum mixtures, etc.;

– sand mixtures, which consist of quartzites and dolomites;

– grain mixture with hardly separable admixtures;

– flour and cereal grains and the like.

Increasing the efficiency of any construction of separators does not reach the most advantageous values yet, as well as precision of separation, that is, the presence of useful components in separation waste. As well as reducing the amount of harmful admixtures in flows, that must meet the requirements for a resulting mixture.

The task statement requires a multilevel analysis of the vortex thermodynamic process. The exact description of it has often unsubstantiated assumptions.

2. Literature review and problem statement

A number of design engineering bureaus, research institutes and enterprises have worked on the problem of separation of individual fractions of heterogeneous mixtures with necessary parameters for hundreds of years. However, until now, it is not possible to eliminate moving elements, sieves, electric drive units, etc. [3].

The analysis of known and accessible information on modern technological processes, grain-processing machines and other products, as well as principles used for purification or distribution (separation) of mixtures, gives the right to conclude that today this is not a limiting condition. It is necessary to improve the separation technology both in design, and in operational parameters, both in reliability and in energy consumption per unit of processed output product [4]. The current level of mathematical modeling solves the theory and calculation for processes of mixing, evaporation and combustion of carbohydrate fuels and changes in thermal-physical and gas-dynamic parameters completely. However, known theories do not yet provide satisfactory results for calculation and design of necessary separators for distribution (separation) of heterogeneous mixtures [5].

This is explained, first of all, by the fact that, it is not possible to determine initial information that should be given to devices with sufficient accuracy although bases of mathematical analysis of modeling processes are ahead of a physical presentation of them [6]. And this should be the basis for initial (output) data, and boundary conditions (coordinates and a degree of purity) of components of a heterogeneous flow that passed temporary, thermal-physical and gas-dynamic boundaries, are most often accepted not satisfying by the change from the output parameters to the final ones [7]. This led to so much variety of designs of separators and their parts, in which main energy costs belong to vibration equipment [8].

The tasks related to the mentioned problem and the problem of removal of expensive gauging sieves have remained unresolved [9].

There is a well-known and widely used theory of the vortex effect by Rank and its complete description in mathematical representation of gas-dynamic functions gives principle approaches to physics of vortex flows and to relative flows of heterogeneous components, which constitute a source product [10]. The analysis of basic points of distribution of air to cold and hot streams established that parameters determine the mass-energy exchange [11]. It is possible to determine parameters of a homogeneous medium only with a help of the theory of gas-dynamic distribution [12]. The influence of geometry of an entrance channel of a vortex device is known for parameters of an airflow of energy separators only [13]. It provided the basis for possible creation of devices with a physically similar process of distribution of heterogeneous vortical streams into components of individual fractions.

Proceeding from the analogy one can formulate problems of distribution of heterogeneous flow of a wide fractional composition into components, which have strictly limited ranges of changes in thermal-physical parameters, as well as changes in gas-dynamic functions of parameters of vortex flows of components as non-stationary components in a constant vortical motion of an according fraction [14].

Based on the accepted analogy there were laboratory and semi-industrial vortex gas-dynamic grain separators for purification from heavy admixtures (darnel, ergot, tatar buckwheat, etc.) designed and calculated [15]. In the proposed separators, researchers took into account the main advantages (mentioned above) for any process of distribution with a use of a mathematical device to describe the mentioned above vortex process of grain separation.

Thus, we should base creation of vortex gas-dynamic separators on solution of problems with the following initial assumptions:

– a base of a device is vortex flows [16];

– thermal-physical and gas-dynamic parameters of components change in time of a flow in vortex flows only [17];

– a degree of purity of the desired fraction must meet final requirements of a technological process (of a customer);

– stability of control of differential bonds within limits of parameters of an output heterogeneous flow must be adaptive to internal variables regardless of a level of excitations in vortex flows [18];

– we consider vortex flow of an initial heterogeneous mixture from the beginning of free vortices to potential as adiabatic flow, as well as internal disturbances without expenses for work of changing of the direction of free vortices and controlling of parameters of a change of forced vortices (due to the absence of mobile friction pairs);

– we ignore loss or restoration of energy in adjacent flows, as well as energy of collision of components or energy consumption to change the position of components along the main axis, due to smallness of a change in relation to energy of aerodynamic resistance on an average medullar intersection of components;

– we take into account external perturbations for amplitude-frequency characteristics in vortex flow zones (of free, forced, and potential vortices) only by changes in parameters of the micro volume state, its impulse and energy as parameters that determine changes in forces and trajectories of individual components;

– geometric dimensions of a vortex separator should depend on productivity and relative concentration in an output flow of released harmful admixtures taking into account initial parameters of a carrier phase.

3. The aim and objectives of the study

The objective of the study is to develop a mathematical model of the separation process of polydisperse heterogeneous mixtures in vortex separators and to compare it with experimental data. This will make it possible to develop and design new separators for any heterogeneous mixtures.

It was necessary to solve the following tasks to achieve the objective:

– establishment of a relationship between regulated parameters at the inlet to a separator and geometrical parameters that determine the structure of a device;

– proposition of a method for solution of a system of differential equations, which describe processes in vortex separators;

– determination of limits of a change of output parameters that affect efficiency and accuracy of separation for a particular mixture.

4. Vortex separator for separating the heterogeneous mixtures

We will solve the problem of determination of interconnections between regulated parameters at the inlet to a separator and geometric dimensions, which are a base for evaluation of gas-dynamic parameters of interacting heterogeneous stream, by the theory of vortex flows created by the tangential nozzle in a vortex separator (Fig. 1). The most important feature in the proposed gas-dynamic separator is loading device 1, which consists of Laval nozzle 14 with an inlet opening equal to a tangential section and control reactor 2. The air intake goes along the axis of nozzle 12, and an intake of heterogeneous mixtures 13 goes through a loading-regulated device in a region of the critical section of the Laval nozzle. There is an external perturbation regulator 10 installed at the beginning of a zone of free vortices I. The regulator, together with the tangential input, creates a rotary-translational motion of a flow in a zone of forced vortices II.Thus, a heterogeneous mixture, together with the air, is in propellant movement from the input device to the exit from reactor 15.

We use basic thermal-gas-dynamic equations derived in papers [1, 2] to determine velocities of flows and pressure on a section of a vortex device, but we take into account viscosity of a flow.

The description of a mathematical model of separation refers to a heterogeneous mixture which consists of several components with forms and densities close to each other, but which differ in concentration significantly. Such a mixture gives possibility to formulate basic assumptions that simplify a mathematical apparatus. In addition, we can neglect a change in temperature of components, heat exchange with other parameters in vortex gas-dynamic flows:

– we consider a vortex flow with external excitement as adiabatic one;

– we do not take into account an influence of flows going the same way and forwarding flows;

– we do not take into account a collision of heterogeneous streams, which distorts a trajectory (only for the mixture given in this study);

– aerodynamic parameters of heterogeneous components remain constant, independent on the orientation of symmetry axes of heterogeneous components to a line of a flow of a carrier phase of vortex (spiral) trajectories for variable coordinates;

– a heterogeneous carried phase is evenly distributed over a section, and components are the same in a shape at the inlet to a vortex separator;

– we exclude friction, adjacent layers of heterogeneous components and velocity circulation from the description (the static lift and the earth's gravity are almost equal).

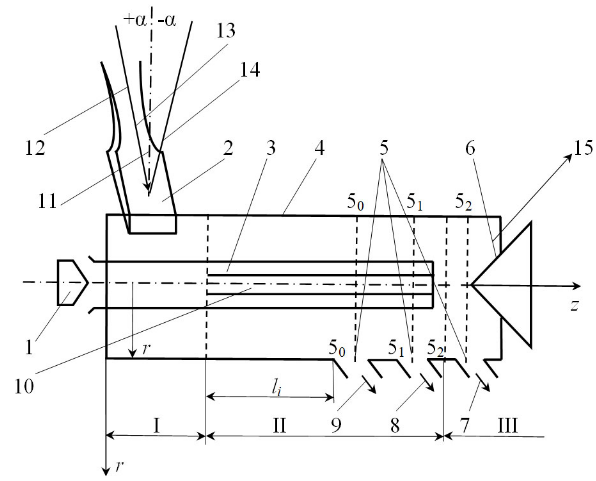

Fig. 1. Schematic of vortex separator: I — zone of free vortices; II — zone of forced vortices; III — zone of potential vortices; 1 — loading device; 2 — control reactor; 3 — pulsator (external perturbation); 4 — cylindrical part of a vortex separator; 5 — collectors of selected factions; 6 — vortex frequency regulator; 7, 8, 9 — flows of individual components with a carrier phase; 10 — regulator of external perturbation; 11 — heterogeneous flow; 12 — carried fraction (air); 13 — carried fraction; 14 — Laval nozzle; 15 — output of the carried fraction

The heterogeneous phase, flour (wheat) of the first grade, fully corresponds to the assumption. In 1 kg of such a mixture, the mass fraction of the highest-grade flour makes up M_0=0.155 kg, of density r_0=596 kg/m^3; flour of the first grade M_1=0.570 kg, r_1=581 kg/m^3; flour of the second grade M_2=0.260 kg, r_2=506 kg/m^3; grain shells M_3=0.015 kg, r_3=808 kg/m^3 [4]. The boundary values of regulated parameters are p_0=1.2-3.0 kPa, p_p=0–4.0 kPa, p_u=0–4.0 kPa at a=2° for flour of the first grade.

A system of differential equations represents the mathematical model of separation of this heterogeneous mixture. Equations determine dependent (controlled) trajectories and component redistribution by coordinates:

– equation of motion for free vortex zone (Fig. 1)

$$\left.\begin{aligned}
&w_r\frac{\partial w_r}{\partial r}+w_z\frac{\partial w_r}{\partial z}+\frac{w_\phi^2}{r}=\frac{1}{\rho}\frac{\partial p}{\partial r}+v\left(\begin{gathered}\frac{\partial^2 w_r}{\partial r^2}+\frac{\partial^2 w_r}{\partial z^2}+\\+\frac{1}{r}\frac{\partial w_r}{\partial r}-\frac{w_r}{r^2}\end{gathered}\right);\\
&w_r\frac{\partial w_\phi}{\partial r}+w_z\frac{\partial w_\phi}{\partial z}+\frac{w_r w_\phi}{r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+v\left(\begin{gathered}\frac{\partial^2 w_\phi}{\partial r^2}+\frac{\partial^2 w_\phi}{\partial z^2}+\\+\frac{1}{r}\frac{\partial w_\phi}{\partial r}-\frac{w_\phi}{r^2}\end{gathered}\right);\\
&w_r\frac{\partial w_z}{\partial r}+w_z\frac{\partial w_z}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+v\left(\begin{gathered}\frac{\partial^2 w_z}{\partial r^2}+\frac{\partial^2 w_z}{\partial z^2}+\\+\frac{1}{r}\frac{\partial w_z}{\partial r}\end{gathered}\right),
\end{aligned}\right\}\quad(1)$$

where w, ρ, v are linear velocity, density and kinematic viscosity in a micro volume of a heterogeneous mixture, respectively; p is the pressure, which perceives a micro volume along a flow line; r, z, φ are coordinates of a cylindrical system;

– equation of integrity

$$\frac{\partial(\rho_r w_r)}{\partial r}+\frac{\partial(\rho_z w_z)}{\partial z}=0; \quad (2)$$

– equation of retaining the amount of vortex motion

$$\left.\begin{aligned}\rho_r\frac{\partial w_r}{\partial\tau}&=-\frac{\partial p_r}{\partial r};\\ \rho_\phi\frac{\partial w_\phi}{\partial\tau}&=-\frac{\partial p_\phi}{\partial\phi};\\ \rho_z\frac{\partial w_z}{\partial\tau}&=-\frac{\partial p_z}{\partial z},\end{aligned}\right\} \quad (3)$$

where $\partial\tau=\frac{1}{6n}\cdot\partial\phi$, n is the frequency of vortex rotation;

– equation of change in the amount of motion of components with external disturbances directed along a flow line

$$\left.\begin{aligned}\rho_r\frac{\partial w_r}{\partial\tau}+\rho_{r_2}\frac{\partial w_{r_2}}{\partial\tau}&=-\frac{\partial p_r}{\partial r}-\frac{\partial p_{r_2}}{\partial r_2};\\ \rho_\phi\frac{\partial w_\phi}{\partial\tau}+\rho_{\phi_2}\frac{\partial w_{\phi_2}}{\partial\tau}&=-\frac{\partial p_\phi}{\partial\phi}-\frac{\partial p_{\phi_2}}{\partial\phi_2};\\ \rho_z\frac{\partial w_z}{\partial\tau}+\rho_{z_2}\frac{\partial w_{z_2}}{\partial\tau}&=-\frac{\partial p_z}{\partial z}-\frac{\partial p_{z_2}}{\partial z};\end{aligned}\right\} \quad (4)$$

– equation of change in the concentration of components

$$\left.\begin{aligned}\rho_r\frac{\partial c_r}{\partial\tau}+\rho_r\overline{w}\,grad\,c_r&=I_r-div(\rho_r c_r w_r);\\ \rho_\phi\frac{\partial c_\phi}{\partial\tau}+\rho_\phi\overline{w}\,grad\,c_\phi&=I_\phi-div(\rho_\phi c_\phi w_\phi);\\ \rho_z\frac{\partial c_z}{\partial\tau}+\rho_z\overline{w}\,grad\,c_z&=I_z-div(\rho_z c_z w_z),\end{aligned}\right\} \quad (5)$$

where c, ρ are the concentrations and densities of i-th components, respectively; I is the velocity of mass increment of i-th component by coordinates;

– energy equation

$$\begin{aligned}&\rho c_p\left(w_r\frac{\partial T}{\partial r}+w_z\frac{\partial T}{\partial z}\right)=w_r\frac{\partial p}{\partial r}+w_z\frac{\partial p}{\partial z}+\\ &+v'\left\{2\left[\left(\frac{\partial w_r}{\partial r}\right)^2+\left(\frac{w_r}{r}\right)^2+\left(\frac{\partial w_z}{\partial z}\right)^2\right]+\right.\\ &\left.+\left(\frac{\partial w_r}{\partial r}+\frac{\partial w_z}{\partial z}\right)^2+\left(\frac{\partial w_\phi}{\partial r}-\frac{w_\phi}{r}\right)^2\right\}-\\ &-\frac{2}{3}v'\left(\frac{\partial w_r}{\partial r}+\frac{w_\phi}{r}-\frac{\partial w_z}{\partial z}\right)^2,\end{aligned} \quad (6)$$

where v' is a coefficient of kinematic viscosity at turbulent flow with high frequency external perturbation from a pulsator;

– equation of state by coordinates

$$\frac{\partial p}{\partial n}=RT\frac{\partial\rho}{\partial n}, \quad (7)$$

where n – r, z, φ.

Kinematic density, as for a two-phase flow

$$v=\frac{\mu}{\rho},$$

where

$$\mu=\frac{b}{24}(\zeta\rho w)\ \text{and}\ \zeta=\frac{24}{w\cdot b},$$

because

$$12\mu(2H)\frac{w}{b^2}=\zeta\frac{2H}{b}\frac{\rho w^2}{2},$$

where H is the head; b is the movement of a micro volume.

Velocities of separated components vary from w_{ij} to 0 during separation, hence flow density changes in coordinates and time, therefore, in Euler equations, values of flow viscosity changes even without changes in a sum of forces $\sum F_i$ and concentrations $\frac{\partial C}{\partial j}\neq 0.$ As follows from the above, it is advisable to use the Euler equations instead of Navier-Stokes for the zone of forced vortices. Such an approach to the development of the theory of gas-dynamic separation is also valid for heterogeneous and homogeneous mixtures, since the sum of forces, which act on a component of variable mass, volume, density etc., does not remain constant for any form of energy fields (high-speed fields, sound pressure fields, electromagnetic ones, etc.), i. e.

$$\sum F_{i_{r,\varphi,z}}=f(r,\varphi,z,\tau).$$

Features of the algorithm for calculation of the mathematical model of the vortex motion (1)–(7) with a spiral-deformed trajectory are as follows:

– determination of coordinates of i-th component goes at its velocities along r and φ axes in a plane along the normal to z axis at each stage of integration, on $\Delta\tau$ small interval, in accordance with the theorem on the average value for integral calculation by τ, φ, z coordinates;

– we define full acceleration of a micro volume as a sum of the normal, the tangential and Coriolis by variable r radius from the initial values to the finite ones equal to or greater than the radius of a vortex tube;

– we determine velocity of growth of mass of i-th component by the trajectory of motion from coordinate to coordinate by the diffusion coefficient in dependence on mass of a diffused component, total density of a flow and densities of individual components;

– we take into account parameters of a state and concentration at the inlet to a vortex separator and external perturbation, as well as a change in density by vortex r radius and z coordinate for individual components with densities ρ_i=const in estimation of density of a heterogeneous vortical flow;

– at the beginning of calculation at $\tau=0-\tau_i$, we do not include systems (4) and (5) to the calculation until the moment when z_i coordinate for a separated volume reaches a value equal to $z=2r$, that is, until complete formation of a free vortex;

– determination of forces, which act on i-th component in the separated micro volume goes for each coordinate as a sum of vectors of forces of aerodynamic resistance, static lift, gravity, centrifugal force, propulsion force and Coriolis force. It is acceptable to neglect static lift and gravity because their vectors are almost equal and act oppositely for a micro particle of a small size, not taking into account velocity circulation, that is, relative velocity of carrier fraction and carried fractions is equal to 1.

Physical modeling of separation processes proved validity of the proposed mathematical model by comparing the results of the calculation with the experimental data.

We used the vortical gas-dynamic semi-industrial separator for sifting the flour (Fig. 2). It had the following parameters: a length of vortex zones (along the z axis) $l_{I,III}=1d_t$, $l_{II}=3d_t$; an angle of an inlet of a heterogeneous mixture (velocity vector) into the free vortex zone $a=\pm4$ degrees; pressure at the inlet to the zone of free vortices $p_0=0.6-3.8$; pressure of external perturbation (pulsator) $p_e=0.8-4.5$ kPa; operation pressure inside a separator averaged over the zones, $p_p=0.4-1.2$ kPa. The proposed separator had a pulsator with six outgoing longitudinal cuts of a changing section and a control reactor set to a minimum value of an adjacent layer, which we considered as equal to zero.

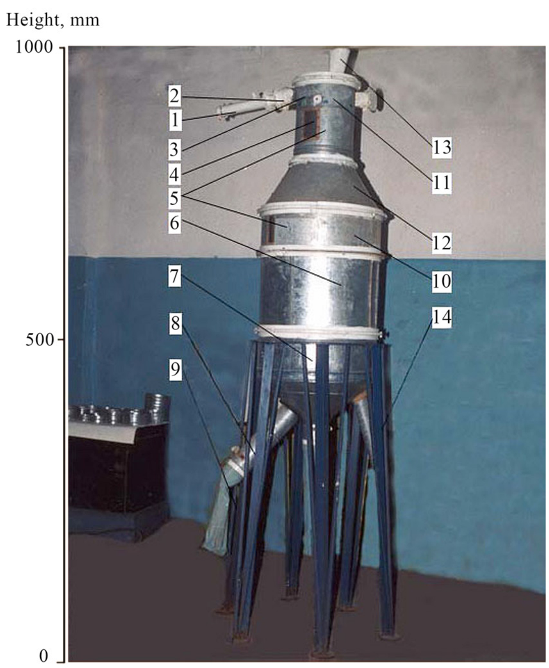

Fig. 2. Gas-dynamic vortical separator: 1 — tangential gas inlet (air); 2 — loading entry of a mixture; 3 — flow control reactor; 4 — free vortex zone; 5 — windows for a laser beam; 6 — zones of forced and potential vortices; 7 — zone of accelerators of fractions; 8 — gas flow regulator (air); 9 — sleeves of the selected fractions; 10 — shell for increasing a zone of potential vortices; 11 — introduction of measuring pressure probe; 12 — pulsator zone; 13 — pulsator; 14 — receivers of fractions

We calculated geometric parameters of the semiconductor separator for the productivity $q=1{,}500$ kg/h, over the zones of vortices, which do not exceed values along the z axis: I – 100–140 mm; II – 120–360 mm; III – 100–260 mm, and at the diameter of the separator $d=300$ mm. We can ignore a change in humidity of a component during the passage of zones, while the relative error of the analysis of three samples of 100 g per 1 m^3 of separated flow did not exceed 2.5–3 %.

We accepted p_0, p_e, p_p as variable regulated parameters and estimated final results by:

– a coefficient of separation efficiency h_e

$$\eta_5 = \frac{M_i'}{\sum_{i=0}^{i=4} M_i}, \qquad (8)$$

where M_i' is the separated i-th mass (finished product), $i=0$, 1, 2, 3; $\sum M_i$ is the mass content of starting mixture;

– a coefficient of separation precision h_s

$$\eta_G = \frac{M_i}{\sum_{i=0}^{3}\left(M_1 + M_2 + M_3\right)}. \qquad (9)$$

Partial test methodology methods for separation of flour provided variance for one passage. We obtained confirmation of the received discrete values of efficiency and precision (8), (9) by variance of the initial composition of flour on control caproic sieves of the quality laboratory at Kulindorovsky Bakery Plant (Odessa, Ukraine).

5. Results of studying the vortex separator

The aim of the analysis of obtained results was evaluation of the operation process of gas-dynamic vortical separation and a magnitude of a change of trajectories of components from variable parameters. We performed the analysis for adjusting of the mathematical model (1)–(7) and for determination of a limit of a change in regulated parameters of a separator design as parameters of quality control and distribution precision.

Changes of trajectories after the control reactor went according to the magnitude of a run (spiral length) through a change in coordinates of the location li of receiving windows of fractions 7, 8, 9 (Fig. 1), the initial sections 50–53 remained as control ones at steady values $a=a_0=0$, p_0, p_p etc. and the stationary position of reactor control 2. Thus, we found that the concentration of heterogeneous components is evenly distributed over the cross section in the zone of free vortices. The law of the change in circular velocity obeys the law of rotation of a solid, and there is already a redistribution of concentrations by density on a length of one caliber l_i in the zone of forced vortices. The heterogeneous carried component with air after the Laval nozzle, control reactor 2, is a uniformly distributed mist-like mixture (aerosol), that is, as a natural gas-vapor mixture, but with a density difference of components (Fig. 1). Components of lower density go first along the radius to collector 9 under the action of forces in a vortex flow and external perturbation, and then the next ones with a greater density – to pickers 7, 8. The heaviest fractions go to the periphery and the outlet at the end of the zones of forced vortices to carried phase 15. This is evident from the system (3), there are additional expenditures on flows 8, 8, 7 (Fig. 1) with the decrease of pressure along the z axis and preservation of consumption. Increasing the consumption through pulsator 3 does not restore loss of pressure at a given velocity of vortices. A change a within the range of ±4 degrees changes density of vortices turns without causing changes in flow velocity along the radius. This change increases or reduces time of adjustment of an input plane flow into rotational movement only. In this case, relative trajectories of individual components along r radius r remain unchanged (4). Hence, it becomes obvious from the solution to the entire system (1)–(7) that the determining arguments for the separation of heterogeneous vortex mixtures are the total pressure of a mixture at the inlet to a vortex separator, operation pressure inside a separator and pulsator pressure as external perturbation. Linear angular velocity at the inlet to the zone of forced vortices determines vortex velocity. A number of perturbation flows and p_e pressure of pulsator determines frequency and amplitude of perturbation, that is, the effect of redistribution of the increase in concentrations of components of various densities ρ_i (4), (5) at a given energy (6).

Determination of limits of a change of regulated parameters was necessary to find maximums of efficiency and precision of separation at a constant mass composition of an initial mixture and mass flow. We had no aim to increase productivity, since the separator is just a model. Although this excludes some independent variables. Complexity of the approximation η_e and η_s to the maximum remains to the maximum even with Chebyshev approximation, since some parameters influence opposite directions. Let us consider a partial case of such a change on the example of calculation results (Fig. 3), when the input pressure ρ_0 changes only.

6. Discussion of results of studying the separation processes

The demonstrated results present extreme modes. It is not possible to accept η_e and $\eta_ч$ maximum values for absolute by all variables. Since η_s value at p0, which is equal to 3.5 kPa, changes the sign to the opposite. In addition, η_e value reached 0.88–0.9 % in the range p_0=2–3 kPa, this does not mean that η_e range is absolute and boundary, since an influence of amplitude-frequency perturbations is not definitely determined here. The above information gives the right to find values of the variables as the most advantageous based on the grid method for multi-parameter tasks only (Fig. 3).

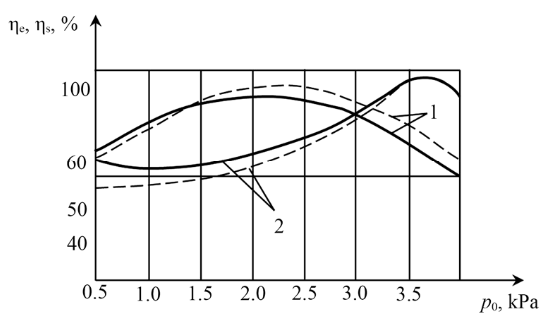

Fig. 3. Results of separation of a flour mixture in a vortex separator: 1 — separation efficiency he; 2 — separation precision; ——— — calculation; - - - - — experiment

If we consider he and hs as a metric, then we can approximate any variable (first he or second hs) anyhow precisely to the boundary one (100 %). We can perform this by a linear combination of variables of the coordinate system. In other words, combining, we can determine an influence of extremums of functions on a metric by combination of extremums of functions, for example:

$$\left\| \eta_e\left(p_0, p_e...\right) - \sum c_i\left(p_0, p_e...\right) \right\| < \left|\eta_e\right|_e \tag{10}$$

or

$$\left\| \eta_A\left[p_0, p_e... - \sum c_i p_i\right] \right\| \le \left|\eta_e\right|_e, \tag{11}$$

then

$$\left|\eta_e\right| \le \frac{\left\| \eta_e\left[\eta_A\left(p_0, p_e... - \sum c_i p_i\right)\right] \right\|}{\sqrt{\sum \eta_e\left(p_0, p_e...\right)}}, \tag{12}$$

where c_i are the coefficients of deviations of the desired function from the approximation.

Based on equations (10)–(12) and the solution to system (1)–(7), it is possible to construct a series of values, which correspond to the condition (12), but it is not possible to choose the best of n variables. One way or another, we need to know also experimental values of η_e and η_s as boundary metrics. Accordingly, it is necessary to construct theoretical and experimental curves of is efficiency $\eta_e=f(p_0, p_e, p_p)$ and is precision $\eta_s=f(p_0, p_e, p_p)$ of separation. Approximations of real η_e and η_s to absolute necessary values by any independent adjustable parameter will occur based on these curves. We can take in to account such discrete values as recommendations for a design and improvement of vortex gas-dynamic separators.

The relationships shown between p_0, p_e, p_p and η_e and p_i and η_s are in the logical connection (Fig. 4), since we assume calculated values by boundary changes p_i. The values do not violate physical separation processes calculated by system (1)–(7). We explain the behavior of the obtained results below (Fig. 4).

We consider the obtained region $A_1A_{3\Pi}A_2A_6A_1$ as a space that corresponds to necessary values of the condition (12), and averaged values $A_1A_4A_2$ – η_e, $A_1A_5A_3A_2$ – η_s as:

$$\eta_e\left(\eta_s\right) = f\left(\delta\left(p_0\right)\delta\left(p_e\right)\delta\left(p_p\right)\right), \tag{13}$$

where $\delta(p_0)$; $\delta(p_e)$; $\delta(p_p)$ is the change in pressure at the inlet to the zone of free vortices, external disturbance (pulsator), and the working pressure inside the separator, respectively.

We can consider η_e and η_s as reliable characteristics for a separated mixture.

We can construct such areas based on a change of other variables similarly, for example, for $\Delta\rho$, Δw, $\Delta l_{\text{I–III}}$ etc., which we can take as outputs for a design of necessary separator structures by productivity, energy consumption, economy, etc.

Changes in $M_{0\text{-}3}$ along a length of vortex forced zones and potential zones correspond to physical processes, the lightest components are allocated firstly to their absolute value at the smallest spiral turns. We can explain the obtained out-boundary A_{OB} values in the experiment by the resonance mode, that is, the coincidence of individual frequencies of an input flow and a flow of external perturbation at p_e=2.4 kPa and p_0=2 kPa. The average η_s value ($A_1A_5A_3A_2$ curve) below 50 % is due to the excessive pe value, which includes admixtures, and grain shells non separated in the initial mixture. And, most important, a region of actual experimental he and hs values is greater than theoretical ones. We can explain this by the fact that assumptions made during calculation do not take into account a number of arguments not excluded in the experiment.

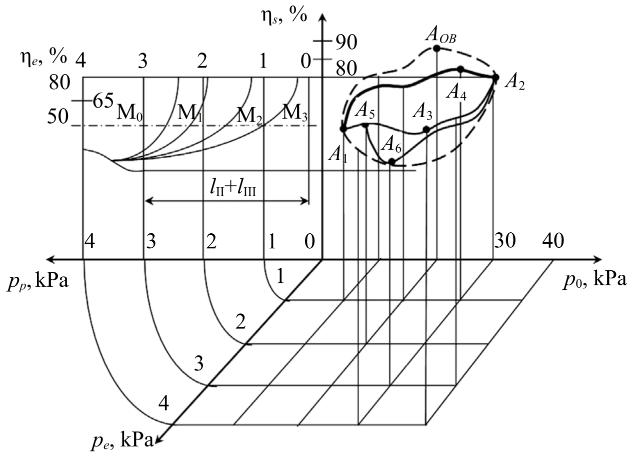

Fig. 4. Separation results of a flour mixture: $A_1A_{OB}A_2A_6A_1$ region – η_e, $=f(p_i)$ change; $A_1A_4A_2$ – averaged values of η_e; $A_1A_5A_3A_2$ – averaged values of η_s; M_0, M_1, M_2, M_3 – mass separation in zones of forced and potential vortices; ———— – calculation; ·– – – – – experiment

Efficiency of separation of a mixture depends mainly on a total concentration, productivity, humidity, operation pressure inside a device and expenditures of a carrier medium. We did not take into account changes in the humidity of components during passage through the zones, which explains discrepancy between experimental values and theoretical values of η_e and η_s. It is necessary to consider this in further scientific research.

The main feature of the methodology of the experiment and data processing was a one-time passage of the initial mixture through a separator. It is necessary to repeat the passage of a secondary product through a vortex device to improve separation of final product.

A promising solution is the creation of mobile vortex gas-dynamic separators for direct separation of grain mix on plantations. The proposed separators are less energy-intensive compared to modern machines, they have no moving nodes and parts, expensive calibrated sieves, and they have smaller dimensions. A semi-industrial separator installed on a car with a productivity of 1,500 kg/h has dimensions of 0.60.3×0.3 m and a weight of 60 kg.

7. Conclusions

1. We proved the possibility to control a change in the gas-dynamic parameters that influence a trajectory of individual components in vortex flows during interaction with external influences based on the developed mathematical model of separation of heterogeneous mixtures in vortex separators. Gas-dynamic parameters of a free vortex zone controlled by a throttle and an angle of an input determine angular velocity (frequency) and density of the initial product depending on the performance, and an angular control reactor at the inlet to a potential vortex region to a pulsator determines and an amplitude of disturbances. Thus, the resultant force with a certain amplitude operates at the point of intersection of velocity vectors of a main vortex flow and a change in velocity from an impulse of a pulsator force per unit mass, by the density of components of a mixture.

We obtained amplitude-frequency characteristics controlled by angular frequency (energy of a vortex field) and energy of secondary air flows from a pulsator for a heterogeneous mixture at the constants: linear flow velocity of a mixture was 12 m/s; frequency of a vortex flow of 1,450 min^{-1} and frequency of perturbation of a pulsator was 5,800 Hz.

2. The solution of the system of differential equations for determination of geometric dimensions of separators based on the grid method accelerates development of such devices greatly. It is more economical than other ways to improve technological processes of separation.

3. We determined boundaries of changes in adjustable parameters that affect efficiency and precision of separation for a flour mixture. The boundaries of changes in adjustable control parameters are: p_0=1.2–3.0 kPa, p_p=0–4.0 kPa, p_e=0–4.0 kPa, at a=2° for the flour of the first grade. In this case, η_e=88 % and η_s=0.91 values correspond to the final variance results on vibrating sieve units with electric drives. Owing to the experimental research, we take the obtained values of the coefficients of efficiency and density as the limit at this stage of development of the new vortex technological processes. They are also the starting point for designing and studying energy-saving vortex separators without calibrating sieves or any moving system. It simplifies both a device and a technology and improves the environmental performance (during production of cements, lime, and chalk) because they operate in a closed cycle.

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