

*The influence of the side walls of a vibratory sieve on the motion of a loose mixture flow has been investigated. The regularities have been established of the flow motion parameters on the walls' height, the resistance of their surfaces, the length and distance between them. The condition has been defined for the occurrence, degree, character, as well as the region of the side walls' influence on the mixture motion over the entire area of a sieve.*

*Increasing the height of the walls, the length and resistance of their surfaces increases the surface density and reduces the longitudinal velocity of a mixture near the near-wall region, causing the occurrence of the transverse velocity component and the uneven distribution of the specific load of the sieve. For the wall's steady parameters, there is a threshold of distance between them, at which the near-wall regions of uneven loading begin to interact with each other, thereby enhancing their influence on the flow. There occur the under-loaded and over-loaded sites in the sieve that differ in the magnitude of deviations and area. The uneven loading area reaches 83 % of the sieve area while the magnitude of deviations in the specific loading is 26 %.*

*A condition of the influence exerted by the side walls on a flow is exceeding the minimum values of the parameters: a wall height,  $h > 4 \cdot 10^{-3}$  m; the resistance of a wall surface,  $C_z > 2$  kg/m<sup>2</sup>·s; a wall length,  $l > 0.5$  m. The side walls' influence leads to the formation of a near-wall region of the sieve's under-loaded and over-loaded sites, whose deviations and area are the same. The magnitude of the wall's region of influence increases in proportion to the sieve length and acquires the shape of a rectangular triangle.*

*To reduce the influence of the side walls, it is necessary to reduce the resistance of their surfaces, the sieve length, and to increase its width, to avoid the threshold distance between the walls and a simultaneous growth of their parameters. The patterns in the side walls' influence underlie the improvement of vibratory-sieve separators and the substantiation of their operation modes*

*Keywords: influence of side walls, mixture flow motion, distance between walls, specific loading of sieve*

# PATTERNS OF INFLUENCE EXERTED BY THE SIDE WALLS OF A VIBRATORY SIEVE ON THE MOTION OF A LOOSE MIXTURE FLOW

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## 1. Introduction

The efficiency of technological processes of bulk mixtures processing is determined by the character of relative flow movement over the entire surface area of the working body. For most processes, such as transportation, mixing, compaction, loosening, separation, drying, etc., it is important to ensure the optimum kinematic parameters of a loose mixture motion, and to provide for the uniform distribution of these parameters over the area of the working body. In a general form, working bodies for the treatment of loose mixtures take the form of a tray, container, or capacity. The volume of a mixture layer is limited to the work surface and side walls, at which boundary effects occur. In many studies, the effect of side walls on the process was considered insignificant because of the small layer thickness and considerable width, and,

therefore, was not taken into consideration. However, the ratio of the thickness to the width of a layer, when the effect of the side walls is exerted, would depend on the structural and kinematic parameters of the working body and the physical and mechanical properties of the mixture, and, therefore, would be different for particular cases. Also uncertain is the size of the zone and the extent of the impact of the walls on the flow in proportion to the distance from them. At the same time, the increase in the specific performance of modern machines leads to an increase in the load and thickness of the mixture layer, and, therefore, to the increase in the effect exerted by side walls. Consequently, there is a need to investigate the influence of the side walls on the mixture flow motion, which would affect the effectiveness of the technological process.

Particularly important is to study the side walls action in the processes of the separation of bulk mixtures on sieves.

Separating the mixtures for particle size starts in the layer, is accompanied by the movement along the sieve, by penetrating and screening through the holes. The specified components of the separation process depend significantly on the thickness of the layer, the speed and density of the mixture, the specific loading of the working surface. Changing the parameters of a loose mixture flow motion leads to a decrease in quality and productivity of the separation process. The distribution of flow parameters over the area of a sieve is uneven and, under certain conditions, is changed under the influence of the side walls. Thus, it is a relevant task to determine the influence of the side walls of a sieve on the motion of a loose mixture flow.

Research in this field would make it possible to define the conditions under which it is necessary to take into consideration the action of the side walls of a sieve, and assess their influence on the kinematic parameters of the flow, the loading and distribution of the mixture over the entire area of the working surface. These characteristics are crucial in the design of vibratory-sieve structures and for the calculation of separation modes.

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## 2. Literature review and problem statement

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To control the processes of loose materials processing, it is necessary to know the structural and physical-mechanical properties of grainy media. Paper [1] investigated the distributions of relative density, porosity, and the coordination number of the medium consisting of spherical particles of the same size. The authors developed an algorithm and the software simulating a three-dimensional packing of spherical particles in a hypothetical container with the rigid walls and bottom. They took into consideration the regions of influence of the side walls and container bottom, as well as the free packing surface on values of the investigated characteristics. It was determined that the boundary effect of the bottom and the free surface extends to a distance of 5–6 radii of the particles, and the boundary effect of the side wall of the container – to a distance larger than three radii of the particles. Thus, the existence of side walls changes the structural and physical properties of granular environment in the boundary regions.

However, the issues of side wall influence on the density and speed of a movable mixture remained unresolved. The reason for this can be objective difficulties related to the complexity of physical experiences, the high cost of equipment, and significant labor costs, which render such studies impractical. An option of overcoming such difficulties can be the use of numerical modeling methods, which are quite easily implemented using a PC. This approach is used in work [2]. The process of moving the granular environment is modeled using a transporting body in the form of two trays connected by elastic elements and forming a rectangular pipe. The unbalanced vibrators are mounted on the trays, causing the synphase oscillations of the walls in the vertical direction and the antiphase ones in the horizontal. The accepted transporting material is dry sand, which is considered to be an isotropic solid environment. For a given material, the authors adopted the condition that at the width of the layer larger than its thickness, the effect of resistance forces of the side walls on the flow dynamics is insignificant and, therefore, is not considered. Thus, at a ratio of the layer width to thickness exceeding unity, the side walls would not exert a significant impact on the mixture movement.

A problem on calculating the movement parameters of a molten polymeric material in the channel zone of a single-

screw extruder is solved in paper [3]. The employed geometric model of a screw channel is the sweep onto the plane because the depth of the channel is much less than the screw radius. The screw is considered immobile while the casing unfolds on the plane and moves at a constant speed. As a result, the problem of motion in a screw channel is reduced to the problem of movement in a rectangular channel. The numerical realization of the process model and the calculation of velocity profiles involved an iterative method by Newton. It is assumed that at a ratio of the channel width to its depth exceeding three, the flow motion in the middle longitudinal intersection can be considered disregarding the influence of the side walls. The comparative analysis of the estimated data with the results of the experiment showed minor differences proving the possibility of applying a simplified condition for a given case. Consequently, the authors established a ratio of the layer width to its depth at which the side walls would not affect motion in the middle longitudinal intersection. However, this ratio is not the same for different materials. Applying such conditions to other flow intersections was not investigated.

In work [4], the movement of a food mixture in the screw channel of an extruder is also represented as motion in a long rectangular channel whose upper wall moves. A mathematical model includes the equation of the viscous liquid movement, preservation of the mass, thermal balance, connection between the tensor of stresses and the tensor of deformation velocity taking into consideration the rheological properties. Based on the results of numerical modeling, the authors constructed the diagrams for the distribution of velocity fields of the mixture in the channel. Their analysis showed that the shape of the profile of speeds in the transverse cross-section of the channel is almost unchanged; but, at the side walls, they decrease to zero. Thus, the side walls alter the profile of velocities along the channel width, therefore, there is a certain zone of their influence on the flow, so the simplified condition and cannot be applied for all longitudinal intersections.

Experimental research into the process of the vibration mixing of loose materials is reported in paper [5]; it confirms the influence of the side walls on the process. Thus, a layer of the mixture, located in the center of the container, is more movable than near the side regions, whose motion is significantly influenced by the force of friction with walls. With increasing the width of the container, the difference in the mixture mobility in these regions increases. The action of certain modes of vibration leads to the transition of the mixture into the state of vibration boiling and mobility alignment throughout the entire layer volume. Consequently, the structural dimensions of the working body and its kinematic parameters can affect differently the degree and size of the zone of influence of the side walls. However, the theoretical justification for this influence is not given.

In order to determine the quantitative and qualitative characteristics of the field of velocities of a granular medium in a cylindrical container, work [6] applied an ultra-fast X-ray computed tomography. The authors investigated a monodisperse environment of spherical particles of two types: solid and elastic with low friction. It was established that the flow of solid particles forms the stagnant regions on the walls of the container, while the flow of elastic particles becomes homogeneous, independent from the distance to the walls. Consequently, for different environments, the influence of the walls on the flow is different.

In [7], the effect of side walls was applied to implement the process of separating a mixture by particle size. The radial

segregation of the mixture particles in a vertical drum with double lateral walls was investigated experimentally. The outer and inner walls rotate at different angular velocities and have different surface resistance. The results of experiments show that the rotation speed and the friction coefficient of the side walls significantly change the distribution of particles in the layer. At the dominating gravitational force, large particles concentrate near the outer wall while the small ones – near the inner wall. When the centrifugal force dominates, large particles concentrate inside the annular layer while the small ones – near the side walls. Consequently, the obtained results confirm the need to consider the impact of side walls on the mixture flow. However, there is no theoretical justification for the action of side walls on the flow.

A study of the turbulent movement of a viscous uncompressible liquid in a straight channel between the two parallel planes is reported in [8]. Current is described by the Navier-Stokes equations for uncompressible liquid. To simulate the action of the side walls, the right-hand part of the equations includes artificial forces forcing the liquid to stop on these surfaces. The magnitude of the mean gradient of pressure that causes movement along the channel is selected based on the condition for a fluid steady flow rate. It is established that with increasing the height of the side walls, the friction force on these surfaces increases, and at the bottom of the tray decreases. With the increase in the distance between walls, their effect on the flow decreases. However, the cited work did not elucidate how the force of friction on the side walls would affect the mixture movement.

Study [9] investigated the motion of a non-Newtonian fluid on an infinite plate between the side walls, parallel to each other and perpendicular to the plate plane. The flow of fluid is formed by the oscillations of an infinite horizontal plate. The influence of the oscillation nature and the distance between the walls on a velocity profile for a layer thickness is determined. By increasing the distance between the side walls, the fluid velocity increases. After exceeding the boundary value of the distance between the walls, their impact on the flow is not essential. However, the influence of the height, length, and the resistance of walls on the flow rate is not investigated in the cited study.

The influence of side walls on the motion of a viscous liquid caused by the fluctuations of a working surface was examined in paper [10]. The authors determined the influence of the walls on the velocity field, the time necessary to achieve a steady movement, the distance between the walls at which their action not would affect motion inside the channel. It was found that the side walls change the velocity profile with the greatest impact exerted at the initial point in time. The time required to achieve a steady movement increases with the increase in the distance between the walls. The distance between the walls, at which motion inside the channel remains constant, decreases at cosine oscillations. However, the cited paper does not take into consideration the structural parameters of the side walls; the authors determined only one characteristic of the flow – the speed of its movement.

A study of the non-stationary magnetohydrodynamic flow of viscous fluid between two parallel side walls perpendicular to the plane of the working surface is reported in work [11]. The flow movement is caused by the saw-like pulses applied to the plane of the working surface. The calculation is performed by a numerical method using the analytical solutions to a Burgers equation as a model equation of the dynamics of viscous liquid. The influence of a magnetic

field and the side walls on fluid movement is investigated. It is determined that the fluid velocity changes from zero at the side walls to the maximum value in the middle of the channel. With increasing a distance between the walls, the velocity profile magnitude increases. However, for other environments, for example, grainy, the speed on the wall would not equal zero because of the mixture sliding along its surface. Consequently, the flow characteristics under the wall action require a separate study for different environments.

Works [12–14] studied the separation on sieves by examining the movement of loose mixtures to form the optimal conditions for the separation process components – segregation and sifting. The degree of loosening the mixture by changing porosity was determined, to improve the ability of particle passing through a layer to the surface of a sieve [15]. Paper [16] determined the relative speed of movement, which ensures the penetration and passage of particles through holes taking into consideration their shape and dimensions. For the intensification of separation, vibratory oscillations of the sieve were used. The effect of vibrations transforms the forces of dry friction into a force of the type of viscous friction, and the behavior of the vibro-liquefied mixture is similar to a viscous liquid. This enables the use of hydrodynamics equations to describe the movement of a loose mixture [17, 18]. Underlying the mathematical models of the separation process are the methods from the mechanics of heterogeneous media; computational and physical experiments were performed. It was established that the range of the optimal kinematic parameters of flow movement changes in narrow limits while the process itself is very sensitive to the load change, which is determined by the speed and density of the mixture.

Studies [12–14, 18, 19] assumed that the parameters of the flow of granular loose mixtures do not change across the area of a sieve; the influence of side walls was not taken into consideration at all. In [20], to assess the error introduced by this assumption, the authors developed a theory of the motion of a mixture in a vibratory sieve of the finite width. The influence of side walls on the average flow velocity and sieve performance was determined. However, for the separation process, it is important to define the flow motion parameters throughout the entire working surface area.

The analysis of works [1–10] shows that the nature of the flow changes under the influence of side walls and requires refined studies for each individual case. The obtained results were fragmented, determined only the separate characteristics of the flow, there is no comprehensive approach to investigating a given process. Not defined are the conditions of the occurrence, the degree, character, and the zone of influence of the side walls of a vibratory sieve on the distribution of the parameters of the flow of a loose mixture over the entire area of the working surface. Therefore, there are reasons to believe that the lack of certainty regarding the influence of the side walls of a vibratory sieve on the motion of a mixture flow predetermines our research in this area.

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### 3. The aim and objectives of the study

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The aim of this study is to investigate patterns of the influence exerted by the side walls of a vibratory sieve on a loose mixture flow motion. This would make it possible to take into consideration a change in the flow parameters over the entire sieve area under the influence of the side walls when designing separators and calculating the modes of their operation.

To achieve the set aim, the following tasks have been solved:

- to establish patterns of the parameters for a mixture flow motion depending on a wall height, the resistance of their surfaces, their length, and the distance between them;
- to define a condition for the occurrence, the character, degree, as well as the region of influence exerted by the side walls of a vibratory sieve on the distribution of the parameters of a loose mixture motion over the entire area of the working surface.

**4. Methods to investigate the motion of a loose mixture flow in a vibratory sieve**

A mathematical model of the spatial movement of a loose mixture in the flat inclined vibratory sieve was applied to conduct our study; it was constructed in work [21]. The sieve has parallel side walls arranged perpendicular to its working surface. The effects of vibration on the medium are manifested by the reduction of internal friction while increasing the vibration intensity. A system of motion equations is reduced to the equations of a plane flow. The main prerequisite for this transformation is the small size of the layer thickness compared to the linear dimensions in the flow plane, and the change in the velocity components along the normal to the sieve is very low. The influence of sieving the mixture on the movement process was not taken into consideration since the magnitude of the passing fraction is much less than the descending one. The system of equations for the plane motion of a loose mixture flow in a vibratory sieve takes the following form:

$$\frac{\partial}{\partial t} \gamma + u \frac{\partial}{\partial x} \gamma + v \frac{\partial}{\partial y} \gamma + \gamma \frac{\partial}{\partial x} u + \gamma \frac{\partial}{\partial y} v = 0, \tag{1}$$

$$\begin{aligned} & \frac{\partial}{\partial t} u + u \frac{\partial}{\partial x} u + v \frac{\partial}{\partial y} u + \frac{g \cos \theta}{2} \frac{\partial}{\partial x} h + \frac{hg \cos \theta}{2\gamma} \frac{\partial}{\partial x} \gamma - \\ & - \frac{2\mu h}{\gamma} \frac{\partial^2}{\partial x^2} u - \frac{\mu h}{\gamma} \frac{\partial^2}{\partial y^2} u - \frac{2\mu}{\gamma} \frac{\partial}{\partial x} h \frac{\partial}{\partial x} u - \frac{\mu}{\gamma} \frac{\partial}{\partial y} h \frac{\partial}{\partial y} u - \\ & - \frac{\mu}{\gamma} \frac{\partial}{\partial y} \left( h \frac{\partial}{\partial x} v \right) + \frac{C_s}{\gamma} u - g \sin \theta = 0, \end{aligned} \tag{2}$$

$$\begin{aligned} & \frac{\partial}{\partial t} v + u \frac{\partial}{\partial x} v + v \frac{\partial}{\partial y} v + \frac{g \cos \theta}{2} \frac{\partial}{\partial y} h + \frac{hg \cos \theta}{2\gamma} \frac{\partial}{\partial y} \gamma - \\ & - \frac{\mu h}{\gamma} \frac{\partial^2}{\partial x^2} v - \frac{2\mu h}{\gamma} \frac{\partial^2}{\partial y^2} v - \frac{\mu}{\gamma} \frac{\partial}{\partial x} h \frac{\partial}{\partial x} v - \frac{2\mu}{\gamma} \frac{\partial}{\partial y} h \frac{\partial}{\partial y} v - \\ & - \frac{\mu}{\gamma} \frac{\partial}{\partial x} \left( h \frac{\partial}{\partial y} u \right) + \frac{C_s}{\gamma} v = 0, \end{aligned} \tag{3}$$

where  $x, y$  is the current value of the coordinate in the Cartesian system;  $u, v$  are the projections of a particle velocity onto the axes of the Cartesian coordinate system;  $\gamma$  is the surface density of the mixture;  $g$  is the acceleration of free fall;  $\theta$  is the sieve inclination angle;  $h$  is the layer thickness, counted along the normal to the sieve in the direction of the free surface;  $t$  is the time;  $\mu$  is the dynamic shear viscosity ratio;  $C_s$  is the phenomenological coefficient similar to the Shezi coefficient.

Three equations (1) to (3) contain four unknown functions  $h, \gamma, u, v$ . To close this system of equations, we adopted a kinematic boundary condition at the layer free surface:

$$\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0. \tag{4}$$

The layer of a mixture takes up the volume limited to a flat sieve, the side walls, the inlet and outlet cross-sections. From the top, the layer is limited to the surface, which changes its shape and moves in accordance with the movement of the mixture.

The equation system is supplemented by the boundary and initial conditions. On a solid wall,  $\Sigma$  is the assigned condition for non-leaking.

$$v_n|_{\Sigma} = 0, \tag{5}$$

where  $v_n$  is the normal component of mixture velocity on the wall. The tangent stress on a solid wall is determined from the Cauchy ratio.

$$\vec{p}_\tau = n_k \sigma_{ki} \tau_i \vec{e}_i = -C_s v_k \tau_k \tau_i \vec{e}_i, \tag{6}$$

where  $n=(n_1, n_2, n_3)=(n_x, n_y, n_z)$  is the single normal to the  $\Sigma$  surface with respect to the volume  $V$ ;  $\sigma$  are the components of a stress tensor;  $\tau=\{\tau_1, \tau_2, \tau_3\}$  is the arbitrary single vector tangent to  $\Sigma$ ;  $e_i$  are the basis vectors of the Cartesian coordinate system.

At the inlet cross-section of the sieve, we assigned the distributions of the density, velocity, and thickness of the mixture layer, which are derived from experimental studies.

$$\begin{aligned} \rho_0 &= \rho(t, 0, y, z), \quad u_0 = u(t, 0, y, z), \\ v_0 &= v(t, 0, y, z), \quad h_0 = h(t, 0, y). \end{aligned} \tag{7}$$

At the outlet cross-section, we set conditions in the form in which they are used in the numerical methods for solving the problems on the dynamics of viscous liquid:

$$\left. \frac{\partial u(t, x, y, z)}{\partial x} \right|_{x=l} = 0, \quad \left. \frac{\partial v(t, x, y, z)}{\partial x} \right|_{x=l} = 0. \tag{8}$$

At the free surface of a loose layer, we assign two dynamic conditions: one follows from the law of mass preservation and expresses the continuity of the mass flow over a free surface:

$$\langle \rho(v_n - W) \rangle = 0, \tag{9}$$

where  $\rho=\gamma v$  is the density of the medium considering the voids between the particles;  $v$  is the volumetric density of the medium;  $W$  is the normal component of the velocity of the medium surface gap;  $v_n$  is the normal velocity component of particles on the free surface, the angle brackets represent the corresponding function jump at this surface.

Another dynamic condition expresses the continuity of stresses during the transition through a free surface:

$$-2 \left( \frac{\partial}{\partial x} h \right) \sigma_{xz} - 2 \left( \frac{\partial}{\partial y} h \right) \sigma_{yz} + \sigma_{zz} + P_0 = 0, \tag{10}$$

$$- \left( \frac{\partial}{\partial x} h \right) \sigma_{xx} - \left( \frac{\partial}{\partial y} h \right) \sigma_{xy} + \sigma_{xz} + \sigma_{zz} \frac{\partial}{\partial x} h = 0, \tag{11}$$

$$- \left( \frac{\partial}{\partial x} h \right) \sigma_{xy} - \left( \frac{\partial}{\partial y} h \right) \sigma_{yy} + \left( \frac{\partial}{\partial y} h \right) \sigma_{zz} + \sigma_{yz} = 0, \tag{12}$$

where  $P_0$  is the pressure exerted by air on the surface of a mixture layer;  $\sigma_{ij}$  are the components of a stress tensor.

The derived system of equations was solved by a numerical method using the software package MATLAB.

**5. Patterns of a mixture flow motion in a vibratory sieve depending on the side wall parameters**

A mathematical model was used to determine the distribution of the characteristics of a loose mixture flow over the entire area of the working surface for different values of the walls height, length, the resistance of their surfaces, and the distance between them. The following process parameters were accepted for numerical calculations: the density of a loose mixture is  $800 \text{ kg/m}^3$ ; the specific loading at the sieve inlet is  $900\text{--}2,300 \text{ kg/h}\cdot\text{dm}$ ; the mixture velocity component transverse to the tray axis is  $V_0^0 = 0 \text{ m/s}$ ; the pressure at the surface layer of the mixture is  $P_0 = 20 \text{ kg/m}\cdot\text{s}^2$ ; the sieve length is  $l = 1.5 \text{ m}$ ; the sieve width is  $l_1 = 0.4\text{--}1.0 \text{ m}$ ; the sieve inclination angle to the horizon is  $\theta = 10$  degrees; the shear viscosity coefficient is  $\mu = 0.2 \text{ kg/m}\cdot\text{s}$ ; the phenomenological coefficient of the resistance of side walls and sieve, analogous to the Shezi coefficient, is  $C_2 = 2\text{--}10 \text{ kg/m}^2\cdot\text{s}$ . To exclude the influence of the uneven feed at the inlet to the sieve on the investigated process, the profile of the initial speed for the width of the sieve was assigned to be uniform.

A flow is characterized by a layer thickness, the surface density, the longitudinal and transverse components of mixture velocity, the specific loading on the working surface. These are the main characteristics that determine the efficiency of separation in sieves. Fig. 1–6 shows the distributions of the specified characteristics over the area of the sieve at different values of the resistance coefficient of the side walls  $C_2$ , the distance between them  $l_1$ , the length  $l$  and height  $h$  equal to the thickness of the layer.

At the uniform feed of the mixture across the sieve width, the layer thickness of  $h = 4 \cdot 10^{-3} \text{ m}$ , the sieve width of  $l_1 = 0.4 \text{ m}$  and length of  $l = 1.5 \text{ m}$ , the resistance of the side walls of  $C_2 = 2 \text{ kg/m}^2\cdot\text{s}$ , at the inclination angle of  $\theta = 10$  degrees, the mixture viscosity of  $\mu = 0.2 \text{ kg/m}\cdot\text{s}$ , the flow moves evenly. The main characteristics of the flow – a layer thickness, surface density, the longitudinal and transverse velocity components, specific loading – remain unchanged almost over the entire area of the working surface (Fig. 1, *a–e*).

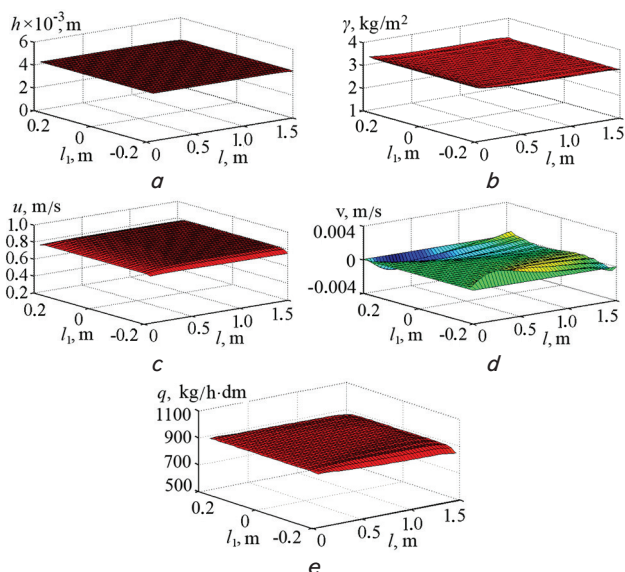


Fig. 1. The characteristics of a mixture flow at  $h = 4 \cdot 10^{-3} \text{ m}$ ;  $l_1 = 0.4 \text{ m}$ ;  $C_2 = 2 \text{ kg/m}^2\cdot\text{s}$ : *a* – a layer thickness; *b* – a mixture surface density; *c, d* – the longitudinal and transverse velocity components; *e* – specific loading

On the side walls, there is a slight deviation in the specific loading in comparison with the deviations over the area of the sieve, which gradually increases with the wall length and constitutes 3–4 %.

Increasing the resistance coefficient of the side walls starts changing the flow characteristics near their surfaces. The surface density is increased, the longitudinal velocity component decreases. There is a transverse velocity component but it is significantly smaller in magnitude compared with the longitudinal one (Fig. 2, *b–d*). The specific loading varies with a wall length (Fig. 2, *d*). To determine the nature of such a change, we performed the transverse, longitudinal intersections of a specific loading function and built the level lines (Fig. 2, *f–i*). In the transverse cross-section of the flow, near a side wall, the deviation in the specific loading  $\Delta q$  is the largest and negative (Fig. 2, *h*). As the distance from the wall grows, it is reduced to zero and then it changes its sign to positive, increases to some value, and descends to zero again.

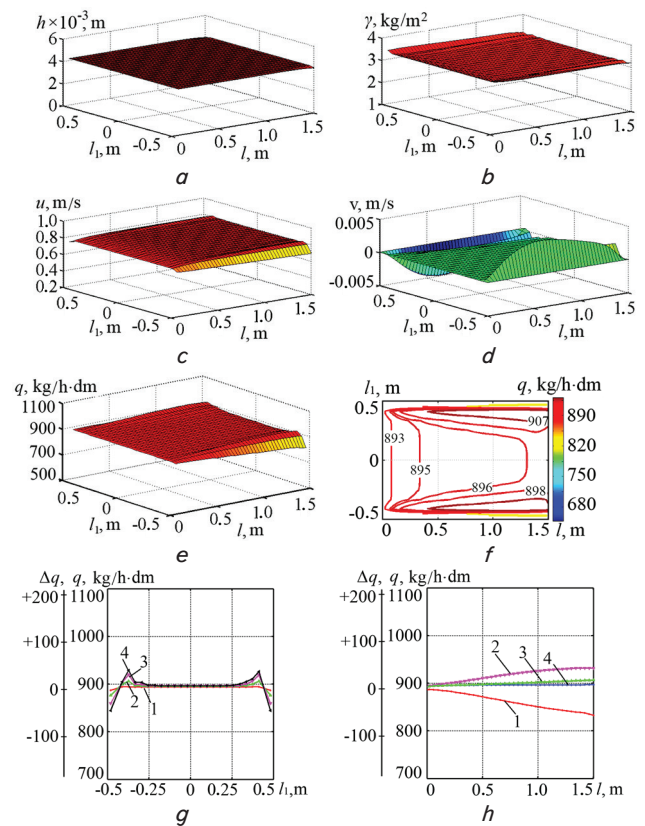


Fig. 2. The characteristics of a mixture flow at  $h = 4 \cdot 10^{-3} \text{ m}$ ;  $l_1 = 1.0 \text{ m}$ ;  $C_2 = 10 \text{ kg/m}^2\cdot\text{s}$ : *a* – a layer thickness; *b* – a mixture surface density; *c, d* – the longitudinal and transverse velocity components; *e* – specific loading; *f* – the level lines of a specific loading function; *g* – the transversal intersection of the function  $q = f(l_1, l)$ : 1 –  $l = 0.1 \text{ m}$ , 2 –  $l = 0.5 \text{ m}$ , 3 –  $l = 0.75 \text{ m}$ , 4 –  $l = 1.5 \text{ m}$ ; *i* – the longitudinal intersection of the function  $q = f(l_1, l)$ : 1 –  $l_1 = 0.5 \text{ m}$ , 2 –  $l_1 = 0.39 \text{ m}$ , 3 –  $l_1 = 0.33 \text{ m}$ , 4 –  $l_1 = 0 \text{ m}$

Thus, near a wall, there form the underloaded and overloaded regions that are the same in the deviation magnitude. This kind of change in the specific loading is due to the corresponding changes in the mixture velocity and density. In the longitudinal cross-section of the flow, near a side wall, the deviations in the specific loading increases in proportion to

length in the direction of mixture movement (Fig. 2, *i*, curves 1, 2). The level lines define the shape and area of the overloaded or underloaded sieve regions under the influence of the side walls (Fig. 2, *f*). The shape of these regions is close to a rectangular triangle and their area is almost the same. The central region of the sieve has a uniform distribution of the specific loading and its shape is close to the trapezoid. In the central region of the sieve the surface density and the components of mixture velocity remain unchanged while the thickness of the layer does not change near the side walls (Fig. 2, *a-d*).

The increasing layer thickness of a mixture changes the character of a flow motion. Thus, the longitudinal velocity component increases in proportion to the length of the sieve to a stable value, indicating the accelerated movement of the flow at the beginning of the sieve, which transfers into a uniform one (Fig. 3, *c*). The surface density of the mixture decreases in proportion to the length of the sieve to a steady value (Fig. 3, *b*). The side walls effect is evident in the reduction of the longitudinal velocity and the increased density of the mixture near their surfaces. The transverse velocity component significantly increased in magnitude but remains smaller than the longitudinal one (Fig. 3, *d*). The thickness of the layer is stable over the entire sieve area (Fig. 3, *a*). The specific loading changed more significantly near the side walls (Fig. 3, *e*).

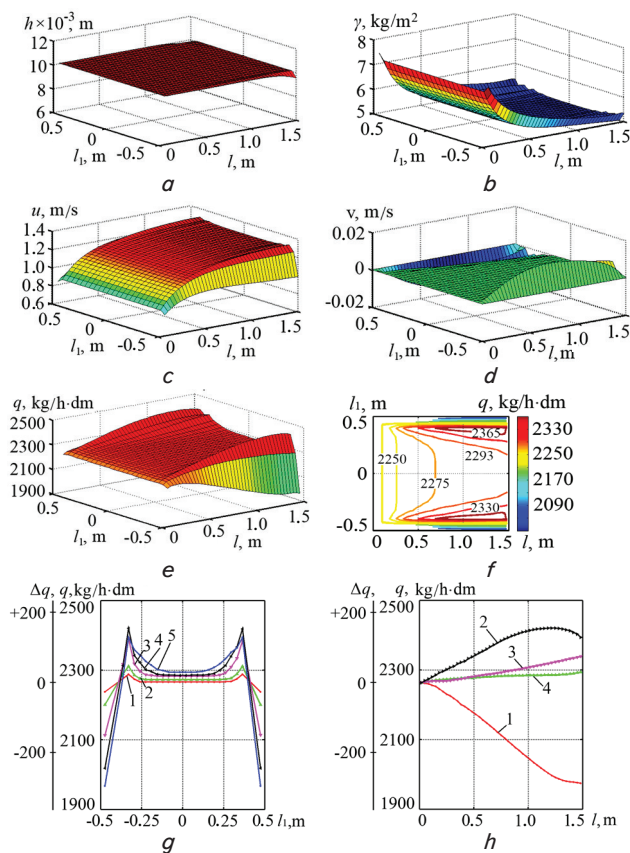


Fig. 3. The characteristics of a mixture flow at  $h = 10 \cdot 10^{-3}$  m;  $l_1 = 1.0$  m;  $C_z = 10$  kg/m<sup>2</sup>·s: *a* – a layer thickness; *b* – a mixture surface density; *c*, *d* – the longitudinal and transverse velocity components; *e* – specific loading; *f* – the level lines of a specific loading function; *g* – the transversal intersection of the function  $q = f(l_1, l_2)$ : 1 –  $l_2 = 0.15$  m, 2 –  $l_2 = 0.4$  m, 3 –  $l_2 = 0.75$  m, 4 –  $l_2 = 1.5$  m; 5 –  $l_2 = 1.5$  m; *h* – the longitudinal intersection of the function  $q = f(l_1, l_2)$ : 1 –  $l_2 = 0.5$  m, 2 –  $l_2 = 0.37$  m, 3 –  $l_2 = 0.3$  m, 4 –  $l_2 = 0$  m

The magnitude of positive and negative deviations increased and grows in proportion to the length of the sieve in the direction of mixture motion (Fig. 3, *h, i*). The area of the underloaded and overloaded regions also increased (Fig. 3, *f*) but the central region of the sieve has a uniform load distribution due to a far distance from the side walls. However, in proportion to the length of the sieve, the area of this region decreases. Thus, increasing the layer thickness of the mixture increases the effect of side walls in terms of both the magnitude of deviations of the flow parameters and the area of the influence zone.

The reduction of the distance between the side walls in the interval from 1.0 to 0.4 m, at the constant thickness of the layer  $h = 4 \cdot 10^{-3}$  m, the length  $l = 1.5$  m, and the resistance of the wall surface  $C_z = 10$  kg/m<sup>2</sup>·s, did not change the parameters of a mixture flow motion. At the distance between the side walls of  $l_1 = 0.4$  m (Fig. 4), their influence on the flow begins to differ from the previous cases (Fig. 2). The surface density is still increasing while the longitudinal velocity component is still decreasing. The transverse velocity component is less than the longitudinal and is directed to the side walls. The character of specific loading in the transverse cross-section of the flow changed (Fig. 4, *e*). The negative deviations near the side walls became larger than positive in their magnitude and are concentrated over a narrow area. The positive deviations are less than negative and concentrated over a larger remaining area of the sieve (Fig. 4, *h*). Consequently, for the steady wall parameters, there is a threshold of distance between them, at which the character of influence on a flow begins to change. Near their surfaces, there are the overloaded and underloaded regions that are different in the size of deviations and area.

In the longitudinal cross-section of the flow, near a wall, the deviation in specific loading increases in proportion to the length up to some constant value (Fig. 4, *i*, curve 1). At a distance from the wall, the magnitude of the deviation decreases (Fig. 4, *i*, curve 2). At a larger distance from the wall, the specific loading increases at the beginning of the sieve and then gradually decreases, forming a surface overload region (Fig. 4, *i*, curve 3). At the equidistant distance from the both side walls, in the central region of the sieve, there is a gradual increase in the specific loading in the direction of the outlet cross-section (Fig. 4, *f*, curve 4).

The level lines of specific loading (Fig. 4, *f*) indicate that at the beginning of the sieve the central region in the form of an isosceles triangle has the uniform load distribution. The remaining area of the sieve has an uneven load distribution. Thus, at the boundary distance between the side walls, the flow motion parameters begin to vary over a large surface area of the sieve.

In the case of a simultaneous increase in the resistance of the walls  $C_z = 10$  kg/m<sup>2</sup>·s, a reduction of the distance between them  $l_1 = 0.4$  m, and an increase in the layer thickness  $h = 10 \cdot 10^{-3}$  m, the mixture flow motion changes quite significantly over the entire sieve area (Fig. 5). The longitudinal velocity component of the mixture near a side wall remains constant in magnitude, close to the original speed, at the increasing velocity of a flow movement in the sieve (Fig. 5, *c*). The surface density decreases in proportion to the length of the sieve but, near the side walls, remains larger in magnitude than that in the center of the flow (Fig. 5, *b*). The transverse velocity component increased two-fold in its magnitude and is directed to the side walls, but remains considerably less than the longitudinal one (Fig. 5, *d*). The mixture layer thickness, similarly to the examined cases, remains unchanged throughout the entire area of the sieve (Fig. 5, *a*).

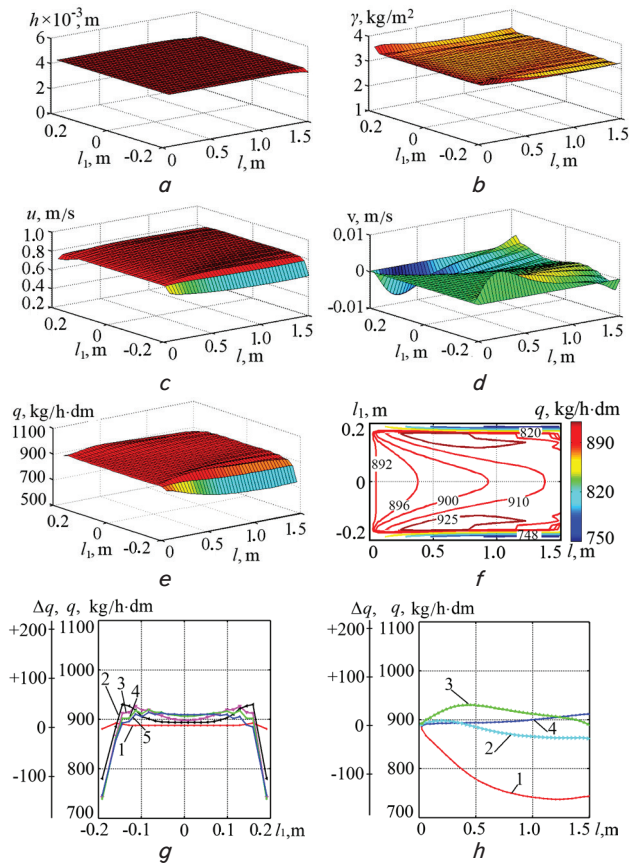


Fig. 4. The characteristics of a mixture flow at  $h=4 \cdot 10^{-3}$  m;  $l_1=0.4$  m;  $C_2=10$  kg/m<sup>2</sup>·s: *a* – a layer thickness; *b* – a mixture surface density; *c*, *d* – the longitudinal and transverse velocity components; *e* – specific loading; *f* – the level lines of a specific loading function; *g* – the transversal intersection of the function  $q=f(l_1, l)$ : 1 –  $l=0$  m, 2 –  $l=0.4$  m, 3 –  $l=0.75$  m, 4 –  $l=1.1$  m; 5 –  $l=1.5$  m; *i* – the longitudinal intersection of the function  $q=f(l_1, l)$ : 1 –  $l_1=0.2$  m, 2 –  $l_1=0.18$  m, 3 –  $l_1=0.16$  m, 4 –  $l_1=0$  m

The consequence of change in the longitudinal velocity and surface density of the mixture is the uneven distribution of specific loading over the entire area of the sieve (Fig. 5, *e*). The side regions of the sieve are underloaded while the central one is overloaded and, in the transverse cross-section, has two maxima and a minimum of loading (Fig. 5, *h*, curves 1, 2, 3). In proportion to the length of the sieve, the loading maxima are distanced from the side walls and merge in the middle near the outlet cross-section. The magnitude of negative deviations in the specific loading near the side walls reaches 26 % of the average loading, and that of the positive ones – up to 8 % over the greater central area of the sieve.

In the longitudinal cross-section of the flow, near a side wall, specific loading rapidly falls (Fig. 5, *f*, curve 1), and, in the middle of the sieve, gradually grows (Fig. 5, *f*, curve 4). When moving away from the wall, the dependence of specific loading on length has an extremum at the beginning of the sieve (Fig. 5, *f*, curve 2), which is shifted forward with a further distance from the side wall (Fig. 5, *f*, curve 3).

The underloaded side regions of the sieve are close in their shape to rectangular triangles and, in terms of area, are significantly smaller than the central overloaded region (Fig. 5, *f*). In turn, the central overloaded region has

a maximum loading in the V-shaped form, whose arrow-head is directed to the outlet cross-section (Fig. 5, *f*, level line  $q=2,444$  kg/h·dm).

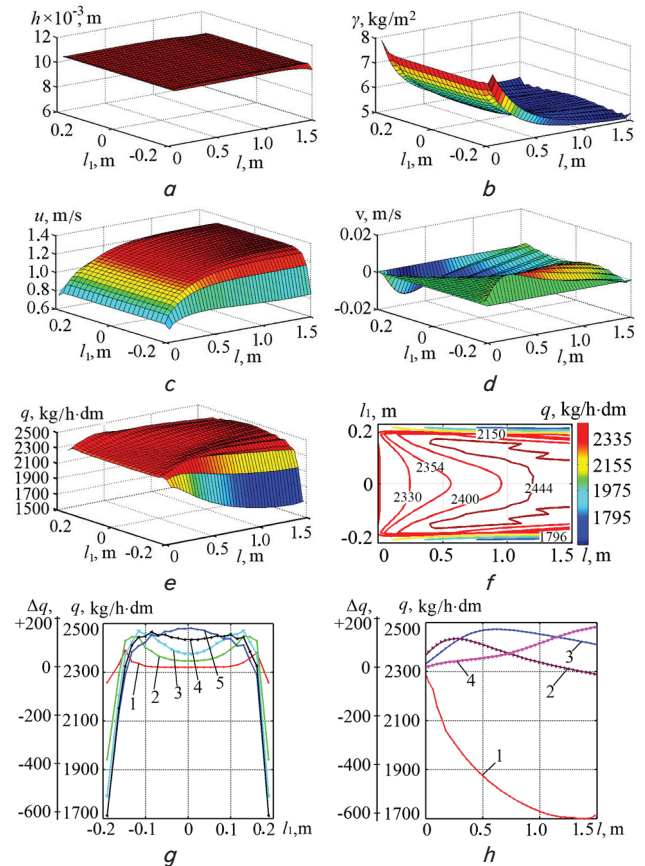


Fig. 5. The characteristics of a mixture flow at  $h=10 \cdot 10^{-3}$  m;  $l_1=0.4$  m;  $C_2=10$  kg/m<sup>2</sup>·s: *a* – a layer thickness; *b* – a mixture surface density; *c*, *d* – the longitudinal and transverse velocity components; *e* – specific loading; *f* – the level lines of a specific loading function; *g* – the transversal intersection of the function  $q=f(l_1, l)$ : 1 –  $l=0.05$  m, 2 –  $l=0.35$  m, 3 –  $l=0.75$  m, 4 –  $l=1.2$  m; 5 –  $l=1.5$  m; *i* – the longitudinal intersection of the function  $q=f(l_1, l)$ : 1 –  $l_1=0.2$  m, 2 –  $l_1=0.16$  m, 3 –  $l_1=0.13$  m, 4 –  $l_1=0$  m

**6. A condition for the occurrence, the character, degree, and a zone of the influence of the side walls on the distribution of the parameters of a mixture motion over the area of a vibratory sieve**

A condition for the occurrence of the influence of side walls on a flow movement is specific for each case. This paper has examined the impact of the side walls of a vibratory sieve on the movement of a mixture flow under the process parameters specified in the previous chapter. The sign of wall influence is a case where the deviation in specific loading near the walls would exceed the average deviation in the specific loading over the remaining sieve area, at the uniform feed at the inlet. Specific loading is a generalized flow characteristic that includes the layer thickness, the velocity and density of the mixture, so it was chosen as the sign of the side walls influence. Our numerical experiment has established the minimum values for the side walls parameters at which a deviation in the

specific loading near their surfaces would exceed the average deviation over the remaining sieve area (Fig. 1, *e*). The thickness of the layer or the wall height in contact with the mixture is  $h=4\cdot 10^{-3}$  m; the resistance of a wall surface is  $C_2=2$  kg/m<sup>2</sup>·s, which is five times less than the resistance of the working surface of the sieve; the wall length is  $l=0.5$  m. For the specified parameters, a specific loading deviation is the same in the underloaded and overloaded regions and exceeds the mean one over the remaining area of the sieve by 3–4 %. If the wall parameters are smaller or equal to the minimum value, then their impact on the flow can be ignored.

The character of the influence of the side walls remains constant at any distance between them. Near a wall area, there form the same sieve underloaded and overloaded regions, identical in the area and the magnitude of deviations. However, reducing the distance between the walls leads to that the near-wall regions of uneven loading approach each other. If this distance exceeds the limiting magnitude, the character of the effects of the walls does not change. The absolute values of deviations in the specific loading and area of the underloaded and overloaded regions of the sieve remain constant. If the distance between the walls is equal to the limiting value, the character of their influence on the flow begins to change throughout the entire area of the sieve. The longitudinal speed near a wall becomes even smaller and the density of the mixture – even greater. The underloaded and overloaded regions near the side walls become different in terms of the magnitude of the deviations and their area. The central region is gradually overloaded but maintains a uniform distribution of the specific loading at the beginning of the sieve. However, in proportion to the length of the sieve, the area of this region rapidly decreases in the direction of movement of the mixture. Thus, at the limiting distance between the walls, they begin to interact together and reinforce their influence on the flow. A sign of the interaction between the side walls is the absence of an evenly loaded central region between them (Fig. 5, *h*, curves 2, 3, 4). For the stable values of wall parameters, there is a threshold of the distance between them. Thus, at the height of the walls  $h=10\cdot 10^{-3}$  m, the resistance of their surfaces  $C_2=10$  kg/m<sup>2</sup>·s, the length of the sieve  $l=0.5$  m, the maximum distance between them is  $l_1=0.4$  m. The result of the mutual influence of the side walls is the merger of two overload maxima across the width of the sieve into one, in the middle of the working surface (Fig. 5, *g*, curve 5). The profile of specific loading in the cross-section is convex, close to parabolic, and the magnitude of deviations, both positive and negative, increases significantly. This indicates the lack of uniform loading of the sieve and a significant change in the parameters of a mixture flow motion over the entire area of the working surface, which negatively influences the efficiency of the technological process.

The magnitude of the zone of wall influence in the direction normal to its surface increases in proportion to the length of the sieve and has the shape of a rectangular triangle. At the wall height  $h=4\cdot 10^{-3}$  m, the resistance of its surface  $C_2=2$  kg/m<sup>2</sup>·s, the sieve width  $l_1=0.4$  m and length  $l=1.5$  m, the area of the influence zone of both side walls is 0.03 m<sup>2</sup>, which is 4 % of the total sieve area. Thus, for the established minimum values of the side walls, their zone of influence is so small that it can be neglected.

When increasing the resistance  $C_2=10$  kg/m<sup>2</sup>·s and the height of a side wall  $h=10\cdot 10^{-3}$  m, (Fig. 3, *e*, *f*), the area of the impact zone increases to 0.45 m<sup>2</sup>, and, for the sieve of width  $l_1=1$  m and length  $l=1.5$  m, it is already 30 % of the to-

tal area. The magnitude of deviations in the specific loading increases to 14 %. If the distance between the walls becomes boundary (Fig. 5, *e*, *f*), they begin to interact together and the area of their influence zone would increase significantly and could amount to 83 % of the total area of the sieve. The magnitude of deviations in the specific loading thus increases to 26 %.

The process when the zones of uneven loading approach each other is affected not only by reducing the distance between the walls but increasing the length of the sieve, the wall height, and the resistance of its surface. The larger the values of these parameters, the closer to the beginning of the sieve a mutual influence of the side walls on the flow would occur (Fig. 5, *f*). For a sieve of width  $l_1=0.4$  m, at the height of the wall (a layer thickness)  $h=10\cdot 10^{-3}$  m, and the resistance of side walls  $C_2=10$  kg/m<sup>2</sup>·s, their mutual influence on the flow occurs at the length of  $l=0.5$  m. If one increases the width of the sieve, that is, the distance between the walls, and reduces the resistance of their surfaces, the reciprocal influence of the walls would occur at a larger length. Therefore, in order to avoid the mutual influence of the side walls on the flow movement, it is necessary to increase the width of the sieve and reduce its length, at a constant area.

Consequently, the side walls alter the motion parameters of a loose mixture flow in a vibratory sieve at any distance between them. The extent and their zone of influence increase with an increase in the height of the wall, length, and the resistance of its surface. For the steady wall parameters, there is a threshold of distance between them, at which the impact on the flow becomes mutual and intensifies both in terms of the magnitude of deviations and the distribution area. It is therefore necessary to take into consideration the effect of the side walls in the design of vibratory sieve separators and in the calculation of their operation modes. To reduce the influence of the side walls, it is necessary to reduce the resistance of their surfaces, the length of the sieve, to increase its width at the constant area, to avoid the boundary distance between the walls and the simultaneous increase in the magnitudes of several parameters.

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### 7. Discussion of results of studying the influence of side walls influence on a loose mixture motion over the sieve area

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The analysis of our results has established patterns in the movement of a mixture flow over the area of a vibratory sieve under the influence of the side walls. The main parameters of a side wall are the height equal to the thickness of the contact layer, the length, and the resistance of its surface. Increasing the magnitudes of these parameters results in a change in the characteristics of a mixture flow. While simultaneously increasing the quantities of several parameters, the effect of the influence on the flow is greatly increased (Fig. 2, 3).

The results are explained by the derived graphic dependences of the mixture flow characteristics on the side wall parameters. Close to a near-wall region, the longitudinal velocity component of the mixture decreases while the density increases (Fig. 2, *b*, *c* – 5, *b*, *c*). In the central part of the sieve, the specified flow parameters remain unchanged. The thickness of the layer is stable over the entire sieve area (Fig. 1, *a* – 5, *a*), which corresponds to the properties of the vibro-liquefied loose mixture. There is a change in the character of specific loading in the cross-section of the



flow (Fig. 2,  $h - 5, h$ ). There forms an underloaded region near the surface of the wall and, at a distance from it, there forms a sieve overloaded region. Due to a change of loading over the width of the sieve, there is a transverse velocity component of the mixture (Fig. 1,  $d - 5, d$ ), which is directed to the side walls, in the direction of smaller loading. However, the transverse velocity component is much less than the longitudinal one in its magnitude. The underloaded and overloaded regions are the same in terms of the magnitude of deviations and area, while the central region of the sieve has a uniform load distribution (Fig. 2,  $f, i - 3, f, i$ ).

The condition of influence of the side walls on a flow is exceeding the minimum values of the following parameters: a wall height,  $h > 4 \cdot 10^{-3}$  m; the resistance of a wall surface,  $C_2 > 2$  kg/m<sup>2</sup>·s; a wall length,  $l > 0.5$  m (Fig. 1). The character of the effect of the side walls on the flow changes if the distance between the walls is equal to the threshold magnitude (Fig. 4, 5). There form the overloaded and underloaded regions of the sieve (Fig. 4,  $e, 5, e$ ), different in their area and the magnitude of deviation. The density of the mixture becomes even larger while the longitudinal velocity is even smaller close to the near wall regions. The degree and area of influence of the side walls increase in proportion to the length of the sieve and, in terms of area, take the shape of rectangular triangles (Fig. 2,  $f, i - 4, f, i$ ). The area of the central uniformly loaded region decreases in proportion to length and takes the shape of the trapezoid.

We solved the set problems by using a system of motion equations of a loose mixture (1) to (3), which makes it possible to investigate the characteristics of flow over the entire area of a vibratory sieve, taking into consideration the boundary effects on surfaces that limit its volume (4) to (12). Owing to the established changes in the flow over the sieve width and length, it was possible to determine the qualitative and quantitative influence of the side wall parameters on the motion of a mixture flow. The solution to the set problem is proven by the qualitative match between the results of our study and the findings reported in works [4, 10], as well as experimental confirmation in papers [5, 6]. The specified condition under which the effect of side walls can be neglected is also confirmed by studies [2, 3, 11–13], indicating that we have solved the set problem.

The advantage of this research is a comprehensive approach, which implies the simultaneous identification of all characteristics of the flow of a loose mixture under the influence of the side walls, over the entire area of the working surface, in contrast to works [4–6, 9, 10, 16, 19]. The application of numerical modeling makes it possible to vary the values of wall parameters and other output data in a wide range and at any ratios. This reduces the cost of research and establishes

the correlation between the flow characteristics to substantiate the components of a separation process.

Our study results could be recommended for non-perforated working surfaces and sifting and sorting sieves. The application of the results for unloading and grain sieves is limited due to the significant screening ability, which changes the loading of the working surface. For these sieves, it is necessary to change the boundary conditions on the working surface and take into consideration the patterns of sifting through the holes, which is the prospect for the advancement of our research.

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## 8. Conclusions

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1. The main parameters of the side walls are the height equal to the thickness of the contact layer, the length, and the surface resistance. Increasing the values of these parameters increases surface density and reduces the longitudinal velocity of the mixture close to the near-wall region. The consequence of the change in flow parameters is uneven loading of the sieve and the emergence of a transverse velocity component, which is directed to the side walls but is considerably less than the longitudinal velocity. The thickness of the layer remains constant over the entire sieve area. For the stable wall parameters, there is a threshold of distance between them, at which the near-wall regions of uneven load begin to interact with each other, enhancing their influence on the flow. For such wall parameters as  $h = 10 \cdot 10^{-3}$  m,  $C_2 = 10$  kg/m<sup>2</sup>·s,  $l = 0.5$  m, the maximum distance between them is  $l_1 = 0.4$  m. The area of the influence zone of the walls reaches 83 % of the total area of the sieve while the magnitude of deviations in specific loading – 26 %.

2. The condition for the occurrence of influence of the side walls on a flow is exceeding the minimum values of the following parameters: a wall height,  $h > 4 \cdot 10^{-3}$  m; the resistance of a wall surface,  $C_2 > 2$  kg/m<sup>2</sup>·s; a wall length,  $l > 0.5$  m. If the wall parameters are smaller or are equal to the minimum values, then their influence on the flow can be neglected. The influence of the side walls leads to the formation, close to the near-wall zone, of the underloaded and overloaded sieve regions, which are the same in terms of the magnitude of deviations and area. The magnitude of the wall region of influence in the direction normal to its surface increases in proportion to the length of the sieve and has the shape of a rectangular triangle. At the wall height of  $h = 10 \cdot 10^{-3}$  m, the resistance of its surface  $C_2 = 10$  kg/m<sup>2</sup>·s, the sieve width  $l_1 = 1.0$  m and length  $l = 1.5$  m, the area of the wall effect zone is 30 % of the total area while the magnitude of deviations in the specific loading reaches 14 %.

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