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TRANSPORT OF PARTICULATE SOLIDS THROUGH A HORIZONTAL GRID UNDER GAS COUNTERFLOW

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1. Introduction. The present paper deals with the problem of transport of granular material through a permeable horizontal grid from dense or fluidized bed material into a free space under gas counterflow. This problem is of both practical and theoretical significance. In practice, the process in question takes place in devices with moving and pseudofluidized beds [1, 2], in sectioning elements, in units distributing solids and gas, and elsewhere. What makes this problem interesting from the theoretical standpoint is that its solution provides a foundation for understanding the regularities of solid circulation and heat transfer in a baffled fluidized bed when a fluidized bed exists both above and under the grid.

Only a few experimental works deal with the problem of transport of particles through a horizontal permeable grid [3–5].

A number of features typical of the process of particle passage through a grid from the upper section into a free space can be pointed out on the basis of data published.

1. In the absence of a gas flow, each hole functions as a single one, and the total passage of the granular material through the grid can be determined by summing up the identical passage over all holes.

2. As the gas velocity increases, the passage of the solid particles through the grid decreases.

3. The limiting gas velocity averaged over all holes at which the efflux of particulate solids ceases exceeds substantially the limiting gas velocity in the case of a single hole.

The experimental data in [4, 5] contain not only the general features outlined above but also some crucial qualitative inconsistencies. In particular, it is noted in [4] that there is a dependence of the limiting gas velocity on the diameter and density of the particles, while no such dependence is found in [5]. At the same time, dependence of the solid flow on the height of a pseudofluidized bed on the grid is noted in [5], though it is not found in [4].

These discrepancies allow us to conclude that the results of [4, 5] are not indisputable. Another thing that makes it difficult to use those results is that [4] does not present the primary data, and the values derived from the relations presented therein defy common sense (for example, the calculated gas velocity for the particles with $d_s = 1$ mm amounts to 113 m/sec).

On the other hand, although [5] presents the primary data, the magnitudes of solid flow through the grid shown in the graphs are, in all appearance, erroneous, since there is no correspondence between the data in different figures under the same conditions.

It should also be noted that the mechanism and physical features of efflux of granular material through a grid under the gas counterflow have been not considered in the literature.

In this paper, a physical model of the observed process is presented. On the basis of this model an approximate theory of solid efflux is developed that allows one to obtain relations for calculating the solid passage through the grid and the limiting gas velocity when solid flow ceases. The relations do not contain any new empirical constants.

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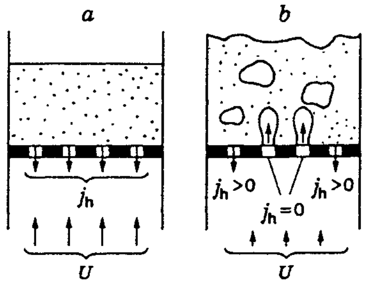

Fig. 1

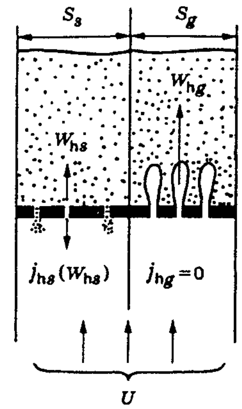

Fig. 2

2. Efflux of Granular Material at Small Gas Velocities. Analysis of both the published data and the experimental results of the present work allows one to single out the main regimes of solid flow through a grid: the fixed bed regime, corresponding to the small gas velocities (Fig. 1a), and the bubbling regime, corresponding to the large gas velocities at which a fluidized bed on the grid occurs (Fig. 1b).

We consider sectioning grids or nets with identical, uniformly placed holes. The particulate flow through such grids in the nonbubbling regime is characterized by uniform distribution of the gas among the holes. The consumption $j_{\rm h}$ of the particulate solids at each hole will be the same, as is the case when the gas flow through the grid is equal to zero [4].

When the distributions of the gas flow and particulate flow over the holes are uniform, the total consumption of particles per unit of hole area can be expressed as

$$j = j_{\rm hs}\varphi, \tag{2.1}$$

where $j_{\rm hs} = j_{\rm h}/S_{\rm h}$ is a mass flow of particles per unit of hole area ($S_{\rm h}$ is the area of the hole). The value of $j_{\rm hs}$ can be determined from the relationship for a single hole under conditions of counterflow of gas and particles [6, 7]

$$j_{\rm hs} = K\,\rho_d\left(\frac{(\pi\, d_s^3\rho_s g - 6F_g)d_{\rm h}}{\pi d_s^3\,\rho_s}\right)^{1/2}(1 - d_s/d_{\rm h})^{5/2}. \tag{2.2}$$

From this point on

$$K = \frac{4((1-\varepsilon)/3)^{3/2}/(1-\varepsilon_0)}{\ln(\exp(3\,(2-2^{1/2})(1-\varepsilon)/2) - \exp(3\,(2-2^{1/2})(1-\varepsilon)-1)^{1/2})};$$

$$F_g = 12.5\,\pi\,(1-\varepsilon)\,d_s\rho_g\nu_g W_{\rm h}/\varepsilon^3 + 7.29\cdot 10^{-2}\pi\, d_s^2\,\rho_g W_{\rm h}^2/\varepsilon^3; \quad W_{\rm h} = U/\varphi;$$

ρ_g, ρ_d, and ρ_s are the densities of the gas, fixed bed, and particles [$\rho_d = (1-\varepsilon_0)\rho_s$]; ε_0, and ε are the porosity of the fixed bed and arch; d_s and $d_{\rm h}$ are the particle and hole diameters; ν_g is the kinematic viscosity of the gas; U and W_0 are the gas velocity before the grid and in a hole; φ is the fractional free cross-sectional area of the grid.

It is obvious that formula (2.1) must be valid in the range of gas velocities not exceeding the limiting velocities U_1 above which the efflux regime of the holes is not uniform.

Indeed, if the distribution of the gas flow among the holes remains uniform, the particulate flow must cease at the gas velocity $U = W_{\rm h\,cr}\varphi$ in the device, where $W_{\rm h.cr}$ is the critical gas velocity in a single hole.

The relation for calculating this velocity has the form [6, 7]

$$W_{\text{h.cr}} = \frac{4\text{Ar}\,\nu_g/d_s}{150\,(1-\varepsilon)/\varepsilon^3 + ((150(1-\varepsilon)/\varepsilon^3)^2 + 4\text{Ar}\,1{,}75/\varepsilon^3)^{1/2}} \tag{2.3}$$

[$\text{Ar} = d_s^3\rho_s g/(\rho_g\nu_g^2)$ is the Archimedes number]. This, however, as has been noted above, does not occur. The flow of particles through the grid stops at average gas velocities U_2 that are many times higher than the value of $W_{\text{h.cr}}\varphi$. This indicates that under conditions of elevated gas velocities there is a special mechanism of solid efflux through the grid, which is due to irregularity in the operation of the holes.

3. Transport of Granular Material at $U > U_1$. *Physical Model.* The practically observed flow of granular material through the grid at gas velocities exceeding $W_{\text{h.cr}}\varphi$ can be explained by making an assumption that a redistribution of the gas flow among the holes occurs at elevated gas velocities, starting with some velocity U_1.

The distributions of the flows of gas and particles are shown schematically in Fig. 2, where S_s and S_g are portions of holes of the s and g types, $W_{\text{h}s}$, $W_{\text{h}g}$, $j_{\text{h}s}$, and $j_{\text{h}g}$ are mean gas velocities and particulate flow per unit hole area in the holes of s and g types, respectively. It is assumed that the grid has only two types of holes, g and s, the characteristic gas velocities in the holes being $W_{\text{h}g}$ and $W_{\text{h}s}$, and $W_{\text{h}g} > W_{\text{h.cr}}$ and $W_{\text{h}s} < W_{\text{h.cr}}$. Obviously, in this case the g-type holes are blocked by the gas flow ($j_{\text{h}g} = 0$), while the s-type holes are not blocked ($j_{\text{h}s} > 0$). The mean gas velocity in the s and g holes can be higher than $W_{\text{h.cr}}$, and still, owing to the s-type holes, the particles will be transported from the upper to the lower section through the grid. Such a redistribution of the gas is quite possible in the case of formation of gas bubbles on the grid (when there is a fluidized bed above the grid).

Indeed, in the absence of gas bubbles at a given pressure drop on the grid, the gas velocity in the hole is determined to a large extent by the hydraulic resistance caused by gas efflux from the hole into the fixed covering. With formation of a bubble on the hole (change of the s-type hole to a g-type hole), this resistance decreases abruptly. Owing to this, the gas velocity increases in the given hole and decreases in the s-type holes. With a further increase in the gas feed under the grid, gas bubbles will form on additional holes which have the smallest hydraulic resistance and the highest gas velocity.

Under these conditions, as the gas velocity increases, the portion of the s-type holes will decrease, and that of the g-type holes will increase. In the case when $a \ll H_b$ (a is the distance between adjacent holes and H_b is the height of the bed), those holes s which are closest to the g-type holes (those adjoining with g holes) may serve as such. If $a \simeq H_b$, the change of regime will happen first at the holes for which the bed height is minimal. Below we consider the case when $a \ll H_b$.

From the above reasoning we can assume that the physical mechanism of solid transport when there is a fluidized bed on the grid ($U > U_1$) consists in the following:

— Redistribution of the gas flow between the holes occurs due to formation of gas bubbles on the grid;

— There are two main types of holes: ones that let the particles pass (small gas velocities, s-type holes) and ones that do not let them pass (large gas velocities, g-type holes);

— The gas velocity in the holes is determined by their hydraulic resistance, including the component connected with distribution of the particles above the hole;

— The flow of granules through the grid is determined by the specific particulate flow $j_{\text{h}s}(W_{\text{h}s})$ through the s-type holes and by the portion S_s of these holes at a given gas velocity;

— The gas velocity U_1 at which a transition from uniform to nonuniform operation of holes occurs must correspond to the maximum velocity under which $S_s = 1$;

— The limit gas velocity U_2 at which the particulate flow stops corresponds to the condition of transition of all holes of the grid to the g regime, i.e., $S_g = 1$;

— In the velocity range U_1–U_2, the operation of each hole is characterized by periodic alternation of the regimes, while the total number of holes of each type at a constant gas velocity remains unchanged.

Within the framework of the suggested model, there are two major problems of calculating the flow of solids through the grid and limiting gas velocities U_1 and U_2: determination of the gas velocities in the holes and determination of the number of holes of each type at a given gas velocity in the apparatus. These

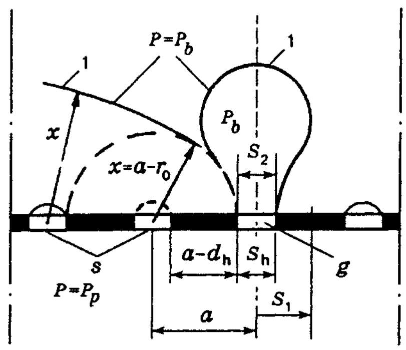

Fig. 3

characteristics, in turn, depend to a great extent on the pressure differential on the grid.

Pressure Drop on the Grid. The qualitative pattern of the gas-pressure distribution near the grid is shown in Fig. 3, where curve 1 and the surface of the bubble are isobars corresponding to the pressure P_b in the bubble. We denote the gas pressure under the grid by $P_{\rm g}$. We must find the pressure drop

$$\Delta P = P_{\rm g} - P_b.$$

Considering the gas flow through an s-type hole, we get

$$\Delta P = \Delta P_{gs} + \Delta P_{ss}.$$

Here, ΔP_{gs} is the pressure drop immediately at the s-type hole; ΔP_{ss} is the drop in the fixed bed on the segment x from the hole to isobar 1. Assuming that $W_{{\rm h}s} \ll W_{{\rm h}g}$, we have $\Delta P_{gs} \ll \Delta P_{ss}$ and

$$\Delta P \approx \Delta P_{ss}. \tag{3.1}$$

Using the views on formation of a dynamic arch of particles with a radius $r_{\rm h} - r_s$ ($r_{\rm h}$ and r_s are radii of the hole and particle) above the hole [6, 7] due to efflux of solids from a single hole, one can estimate the quantity ΔP_{ss} for $H_b \gg a$ from the relation

$$\Delta P_{ss} \simeq \Delta P(x) = \int\limits_{r_{\rm h}-r_s}^{x} P_e(x)\,dx, \tag{3.2}$$

where $P_e(x)$ is the pressure drop per unit of fixed bed height. The pressure drop is determined on the basis of the Ergan equation [8]

$$P_e(x) = A_1 U_s(x) + B_1 U_s^2(x). \tag{3.3}$$

Here

$$A_1 = 150\,\frac{(1-\varepsilon_0)^2}{\varepsilon_0^3\, d_s^2}\,\rho_g \nu_g, \quad B_1 = 1.75\,\frac{1-\varepsilon_0}{\varepsilon_0^3\, d_s^2}\,\frac{\rho_g}{d_s} \tag{3.4}$$

(U_s is the filtration rate at the point under consideration).

Assuming that the gas flow near the s-type hole is spherically symmetric, we get

$$U_s(x) = W_{{\rm h}s} r_{\rm h}^2/(2x^2).$$

Having integrated (3.2) and taking into account (3.3) and (3.4), we have

$$\Delta P(x) = A_1 \frac{W_{{\rm h}s} r_{\rm h}^2}{2}\Big(\frac{1}{r_{\rm h} - r_s} - \frac{1}{x}\Big) + B_1 \frac{W_{{\rm h}s}^2 r_{\rm h}^4}{12}\Big(\frac{1}{(r_{\rm h} - r_s)^3} - \frac{1}{x^3}\Big). \tag{3.5}$$

To determine $\Delta P_{ss} = \Delta P(x)$, one has to know the quantities $W_{{\rm h}s}$ and x for at least one s-type hole. Their determination can be based on physical considerations, if one takes into account the following. Under stationary conditions, the number of holes of each type on the grid remains constant. At the same time, the operation of each hole, as observations show, is periodic. A periodic alternation of the operation regimes of the holes takes place in the course of time: at some of the holes, the operation regime switches from g to s, and at others, the other way around. This tells us that at each moment there exist s-type holes which are in a critical state, i.e., the gas velocity in these holes is equal to the critical gas velocity $W_{\text{h.cr}}$ determined by relation (2.3). This is the maximum possible velocity for holes of the s type.

On the other hand, since $\Delta P_{ss} \simeq$ idem for all holes, it follows that in the case $H_b \gg a$, as seen from (3.5), the maximum gas velocity must be realized at those holes where the value x is minimum. Obviously (Fig. 3), the minimum values of x are characteristic of s-type holes which are adjacent to g-type holes. For adjacent s-type holes, we can let $x = a - r_{\text{h}}$. Assuming thus that for s-type holes adjacent to g-type holes $x = a - r_{\text{h}}$ and $W_{\text{h}s} = W_{\text{h.cr}}$, and substituting these values into (3.5), we get an equation for the pressure drop on the grid

$$\Delta P = \Delta P_{ss} = A_1 \frac{W_{\text{h.cr}} r_{\text{h}}^2}{2} \left(\frac{1}{r_{\text{h}} - r_s} - \frac{1}{a - r_{\text{h}}} \right) + B_1 \frac{W_{\text{h.cr}}^2 r_{\text{h}}^4}{12} \left(\frac{1}{(r_{\text{h}} - r_s)^3} - \frac{1}{(a - r_0)^3} \right). \tag{3.6}$$

Typical Gas Velocity in s-Type Holes. It has been assumed above that the gas velocity $W_{\text{h}s}$ is equal to $W_{\text{h.cr}}$ for s-type holes adjacent to g-type ones. However, there must be a relatively small number of such holes, since in practice holes of types g and s are distributed nonuniformly over the grid at each moment of time. There is a tendency to form continuous patches containing only holes of a single type. Under these conditions, it can be assumed for most s-type holes that $x \gg a$. Taking this condition into account, we can rewrite (3.5) in the form

$$\Delta P(x) = A_1 \frac{W_{\text{h}s} r_{\text{h}}^2}{2} \left(\frac{1}{r_{\text{h}} - r_s} \right) + B_1 \frac{W_{\text{h}s}^2 r_{\text{h}}^4}{12} \frac{1}{(r_{\text{h}} - r_s)^3}.$$

From this, with (3.1) taken into account, we find

$$W_{\text{h}s} = \frac{-A_1/2 + (A_1^2/4 + \Delta P_{ss} B_1/(3(r_{\text{h}} - r_s)))^{1/2}}{B_1 r_{\text{h}}^2/(6(r_{\text{h}} - r_s)^2)},$$

where ΔP_{ss} is determined by relation (3.6).

Gas Velocity in g-Type Holes. For g-type holes, the expression for the pressure drop under consideration has the form

$$\Delta P = P_{\text{g}} - P_b = \Delta P_g = \zeta_g \frac{\rho_g W_{\text{h}g}^2}{2}.$$

Here, ζ_g is the coefficient of hydraulic resistance. It depends on how the gas inlet and outlet are implemented [9].

In particular, in the case of a flat grid (Fig. 3), a hole can be deemed as a diaphragm for which the ratio of the hole section and inlet section S_{h}/S_1 is equal to φ, and the ratio S_{h}/S_2 of the hole area to the outlet section is equal to 1, because the space outside the bubble above the grid is filled with particles. Given the values of S_{h}/S_1 and S_{h}/S_2, one can determine the quantity ζ_g from the pertinent tables (see [9, p. 196], for example).

Taking into account that $\Delta P_g = \Delta P = \Delta P_{ss}$, we obtain an expression for $W_{\text{h}g}$ in the form

$$W_{\text{h}g} = \left(\frac{2 \Delta P_{ss}}{\zeta_g \rho_g} \right)^{1/2}.$$

Portions of the Holes of s and g Types. Since there are two types of holes in the grid,

$$S_s + S_g = 1. \tag{3.7}$$

On the other hand, knowing the gas velocities in the holes of each type, one can write the equation of gas-consumption balance

$$S_s W_{\text{h}s} + S_g W_{\text{h}g} = U/\varphi. \tag{3.8}$$

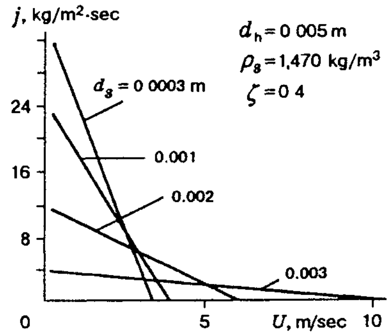

Fig. 4

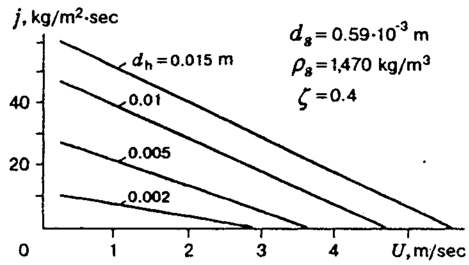

Fig. 5

Solving (3.7) and (3.8) together, we find

$$S_s = \frac{W_{\mathrm{h}g} - U/\varphi}{W_{\mathrm{h}g} - W_{\mathrm{h}s}}; \tag{3.9}$$

$$S_g = \frac{U/\varphi - W_{\mathrm{h}s}}{W_{\mathrm{h}g} - W_{\mathrm{h}s}}. \tag{3.10}$$

Solid Consumption Through the Grid. Since the flow of granular material through a single hole depends only slightly on how high and encumbered the dense bed above the hole is (only if the height of the free dense bed above the hole exceeds its diameter), it can be assumed that regularities of solid efflux both through a solitary hole [6, 7] and through s-type holes are the same. The flow through the grid is determined by summing the flow rates over all s-type holes. Knowing the velocity $W_{\mathrm{h}s}$ in the s-type hole, we determine the flow $j_{\mathrm{h}s}(W_{\mathrm{h}s})$ of particles per unit of this hole's area on the basis of relation (2.2). One does this by substituting W_{h} for $W_{\mathrm{h}s}$. In this case, the total flow of particles per unit grid area

$$j = j_{\mathrm{h}s}(W_{\mathrm{h}s})\,\varphi S_s = j_{\mathrm{h}s}(W_{\mathrm{h}s})\,\varphi\left(\frac{W_{\mathrm{h}g} - U/\varphi}{W_{\mathrm{h}g} - W_{\mathrm{h}s}}\right). \tag{3.11}$$

Limiting Gas Velocities U_1 and U_2. The gas velocity U_1 at which the change of the efflux regime on the grid occurs corresponds to the maximum velocity at which $S_s = 1$. This value can be obtained by substituting U_1 for U on the right-hand side of (3.9) and letting the left-hand side be equal to unity

$$U_1 = W_{\mathrm{h}s}\varphi.$$

The limiting gas velocity at which transport of particles through the grid stops can be found if, in (3.10), one assumes $S_g = 1$, or, in (3.11), $j = 0$. We then have (replacing U with U_2)

$$U_2 = W_{\mathrm{h}g}\varphi = \varphi\left(\frac{2\Delta P_{ss}}{\zeta_g \rho_g}\right)^{1/2}.$$

4. Analysis of the Results Obtained. Analysis of the relations obtained shows that both the magnitude of flow of the granular material through the grid and the critical gas velocity at which the efflux of particles through the grid ceases depend on a great number of parameters: gas viscosity, densities of the gas and particles, diameters of the hole and particles, free cross-sectional area of the grid, and hydraulic resistance of the orifice.

Figure 4 presents calculated curves reflecting the influence of the gas velocity and particle diameter on the flow of granular material through the grid. It is seen that the particulate flow decreases as the gas velocity increases. With a decrease in particle diameter, the solid flow at low gas velocities increases, but this is accompanied by decrease in the limiting gas velocity U_2 at which efflux of granular material through the grid ceases.

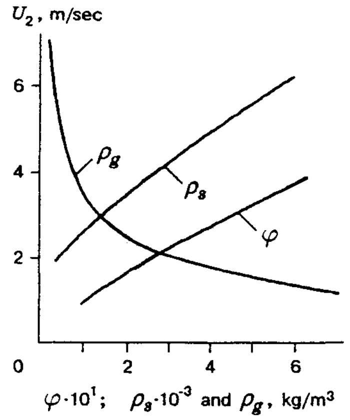

Fig. 6

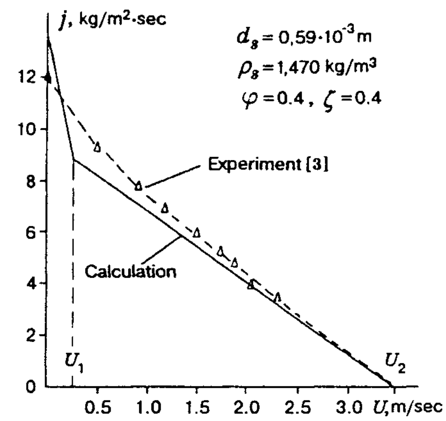

Fig. 7

The calculations show that the particulate flow through the grid can vary depending on the hole diameter, the fractional cross-sectional area of the grid being the same (Fig. 5). Both the solid flow of the granular material and the critical gas velocity U_2 increase as the hole diameter increases. Solid flow also grows with increases in the fractional free cross-sectional area section of the grid and in density of the particles. Figure 6 shows the influence of gas and particle density as well as the free cross-sectional area of the grid on the limit gas velocity. The curves $U_2(\rho_g)$ and $U_2(\rho_s)$ are calculated for $d_{\rm h} = 5.0 \cdot 10^{-3}$ m, $d_s = 0.1 \cdot 10^{-3}$ m, $\varphi = 0.4$; $U_2(\varphi)$ for $d_{\rm h} = 2.35 \cdot 10^{-3}$ m, $d_s = 0.59 \cdot 10^{-3}$ m, $\rho_s = 1{,}470$ kg/m. It is seen that U_2 decreases with an increase in the gas velocity and increases (not proportionally) with an increase in particle density and in the free cross-sectional area of the grid.

On the whole, there is a qualitative agreement with the regularities of change of U_2 and j observed in practice [4]. Because of the absence of necessary information, only a qualitative comparison can be made with the experimental data [3] (Fig. 7). A sectioning baffle with an even hole distribution $\varphi = 0.4$ was employed in [3]. Assuming (see above) $S_{\rm h}/S_1 = \varphi = 0.4$ and $S_{\rm h}/S_2 = 1$ and using the table for hydraulic resistance of the diaphragm [9, p. 196], it can be established that for the case in hand $\zeta_g = 0.4$. The magnitude ε of the arch porosity is taken to be equal to 0.5, as is justified in [7].

It is seen from Fig. 7 that the discrepancies between the results of experiments (in dots) and those of calculations (in solid curves) do not exceed 10% in the entire range of the gas velocities. Extrapolation of the experimental data up to the velocity at which particle efflux ceases allows us also to obtain a value of the critical velocity U_2 which is close to the experimental value.

It is interesting to note that a slight qualitative difference between the experiment and theory shows itself in the region of small gas velocities. The results of calculations demonstrate an abrupt decrease in the flow of particles in a very narrow range of small gas velocities ($0 < U < U_1$). This range corresponds to the uniform efflux regime. Such an abrupt decrease in particle flow is not observed in experiments. Here, the range of velocities is extended. These inconsistencies can be easily explained if we suppose that in practice the assumption we accepted in the model about the uniformity of gas distribution over the holes in the region of small velocities does not hold strictly. This can be caused, for instance, by defects in manufacturing the grid or by making the density of the fixed bed above the grid nonuniforn with respect to the volume of the bed. In a situation like this, a change in the operation regime of the holes takes place earlier at some part of the grid, owing to which the tempo of the decrease in j slows down. If the velocity increases further, fluidization of the disperse material will occur and nonuniformity of the fixed bed density will have no effect.

5. Conclusion. The suggested model of solid efflux through a grid under gas counterflow allowed to obtain relations for calculating both the flow of granular material and the limiting velocity at which the passage of particles through the grid ceases. The relations contain no new empirical coefficients and agree well with the experimental data. For narrow ranges of parameters, these relations can be brought to a simpler form. This can be accomplished, for example, when one of the terms in the Ergan equation can be neglected. The suggested theory also allows to estimate local characteristics of the process, such as the pressure drop on the grid, the mean gas velocities in holes operating in different regimes, the proportions of these holes, etc. The formulated approach to analysis of solid transport through a grid under gas counterflow can be applied to the process of transport of a granular material through a grid with slot holes under a given law of distribution of the hole parameters over the grid section (this problem arises, for example, in designing devices with a given circulation of particles in the space of the bed and in other cases) as well as in determining conditions for excluding entry of the granular material into the supporting space of the gas-distributing grid in fluidized-bed devices. Good agreement between the results of calculation and the experiments on solid transport through the grid can also be regarded as additional confirmation of the elementary theory of efflux of granular material through a single hole under gas counterflow [6, 7]. The main concepts and results of this theory have been used in this paper.

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