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A METHOD OF DESIGNING MEMBRANE SCREENS

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A model of screening granular materials on a membrane screen is presented in this study. A device which was a subject of research is an experimental frame screen with a membrane sieve used to screen very fine materials. The proposed design method can be used to assess sieve dimensions suitable for the process conditions. Screening efficiency is one of the elements taken into account in the method. A mathematical description of screening is proposed in the form of the simple equation and coefficients of this equation are specified.

Key words: membrane sieve, separation, screening efficiency, mathematical model

INTRODUCTION

The subject of this study is the membrane screens with vibrating sieves. The work is a next step of the research project dealing with the screens that is carried out in the Department of Process Equipment, Lodz Technical University. In general, the project covers two areas: dynamics of membrane sieve motion, and screening of fine granular materials on this sieve. The present study refers to the latter one, i.e. ability to screen granular media. It is a basis for drawing capacity-efficiency diagrams which are used to determine the efficient screening output at basic process parameters.

The authors propose a process description using mass balance equations for individual control volumes into which the granular layer, moving and screened on the membrane sieve, has been divided. The aim of this research was to determine an efficiency function, i.e. a relation that describes changes of screening efficiency along the membrane sieve length. Knowing this function for particular independent variables specific for a given screening case, we can assess and design the membrane sieve surface in a given case.

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EXPERIMENTAL MEMBRANE SCREEN

The research was carried out in the lab at the Department of Process Equipment, Technical University of Lodz. The tested machine was an experimental frame screen with a membrane sieve, designed and built in the Department of Process Equipment, Technical University of Lodz. It was used to screen fine and very fine materials. The machine was mounted in the experimental set-up shown schematically in Fig. 1.

Supporting structure 1 is the frame of the machine. Riddle 2 with sieve 3 is placed in the frame at different angles. The riddle remains motionless during the screen operation. In the experiments a standard woven wire screen was used. It has rectangular mesh with side length: l = 0.63 mm. Flat springs 4 are mounted on the riddle and on these springs drive frame 5 is located. The drive frame is connected to electrovibrators 6. An electromagnetic vibrator or vibrators can also be applied. The drive frame is connected to the sieve by means of rigid push rods 7. Feed is supplied to the screen from tank 8 with valve 9 that controls the inlet size. Oversize fraction is collected in container 10, while undersize fraction goes to container 11. The tested sieve dimensions were L = 1250 mm and B = 480 mm. The angle of screen inclination to the level is adjusted within the range from 0 to 45°, but the tests were performed at the inclination equal to 15°, 20° and 25°. These are typical angles of sieve inclination used in industrial machines. The side of rectangular mesh of the sieve is 0.63 mm long. In the case of fine screening, this is a typical industrial screen scale. Such are sieve surfaces of the machines applied in fine and very fine screening.

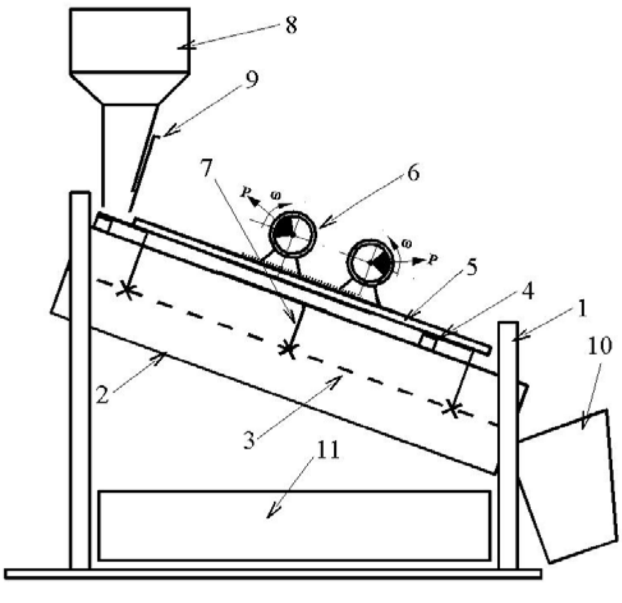

Fig. 1. Schematic diagram of the experimental set-up

Container 11 is divided into 12 sections. In each section there is a tank to collect undersize fraction corresponding to the present sieve length during the screening process, due to which the process can be carried out continuously. Feed is supplied to the sieve from the second section. Once the particles from each section had been weighed, masses of these fractions were obtained which were then converted to the height of material layer on the sieve.

The screen was driven by two electrovibrators operating in backward self-synchronisation. Such a drive system guarantees linear trajectory of vibrations. The trajectory is perpendicular to the sieve surface. The maximum exciting force is P = 2.574 kN. Centrifugal forces can be adjusted by changing the location of unbalanced mass on the vibrator shaft.

EXPERIMENTAL MATERIAL

The aim of research carried out at the Technical University of Lodz is to find a relationship between the shapes of particles constituting the screened materials and the process of screening. In general, three different particle shapes considered as model ones, were identified:

- spherical particles (a),
- irregular particles (b),
- sharp-edged particles (c).

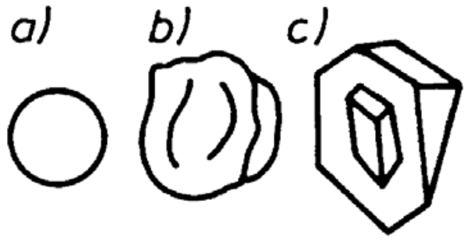

Fig. 2. Model particle shapes

In the experiment, spherical particles, i.e. agalite, irregular – pit sand and sharp-edged particles, i.e. marble aggregate, were screened.

The experimental material was in dry state only, without transient moisture. The material was not used earlier, and as such it was free from industrial contaminants and organic residues; other impurities were insignificant.

ASSUMPTIONS TO THE MODEL OF SCREENING ON A MEMBRANE SIEVE

In the continuous process feed in the form of a granular stream of flow rate Q [g/s] or q [g/s·m^2] is supplied to the beginning of the sieve. In this place thickness of the layer on the sieve is H_P and this is the initial material layer height. On the whole, sieve length L at which the final product of predetermined parameters can be obtained, the process of screening proceeds until reaching the final layer height H_K at the end of the sieve. The initial granular material is composed of two main particle fractions: K_G – oversize fraction, and K_D – undersize fraction. The material is directed to the sieve and divided into two streams: undersize fraction Y and oversize fraction X. Hence, the equations of basic mass balance are as follows:

$$Q = X + Y \tag{1}$$

$$Q = K_G + K_D \tag{2}$$

Assuming full process efficiency, we would have:

$$X = K_G \text{ and } Y = K_D \tag{3}$$

At the end of the sieve two granular streams are observed: K_G – the stream containing the entire oversize fraction and K_D' – the stream containing unscreened part of the undersize fraction, which altogether form the oversize fraction X. Hence, the whole oversize fraction that was in the feed at the beginning of the process, and part of the undersize fraction which did not pass through the sieve and remained in the oversize fraction, fall down from the sieve.

Just this part of the undersize fraction determined screening efficiency which is defined as:

$$\eta = \frac{amount\ of\ undersize\ fraction\ which\ passed\ through\ the\ sieve}{amount\ of\ undersize\ fraction\ in\ the\ feed} \tag{4}$$

or in the symbol notation

$$\eta = \frac{K_D - K_D'}{K_D} = \frac{Y}{K_D} \tag{5}$$

Here, we assume that the oversize fraction from the layer on the sieve does not pass through the sieve. This assumption holds in the case when mesh size has been adjusted to the intended size distribution and when the sieve is not damaged. In other cases the process of screening is incorrect, and such situation may occur in industrial practice.

The undersize fraction can be screened off only from the near-to-sieve layer which is included in the whole layer – the bed of granular material, moving along the sieve. This is a “discharge” layer. Its characteristic feature is that at every vibration cycle identified with a screening period (process period), the undersize fraction flows out of it totally. The height of this layer depends on many parameters specific for the screening process description (such as particle shape, moisture content and particle size distribution in the material, dynamic factor and others). In this sense of the process mechanism, screening consists of subsequent discharge of the undersize fractions from the discharge layer and completing the particle size composition each time with smaller portions of undersize fraction which cyclically "flows down" from higher parts of the particle layer. Significant in this process is the earlier mentioned segregation in the bed on the sieve. The rate of this segregation, i.e. the rate at which big particles move from the sieve and small particles move toward it, is of basic importance for the process efficiency. Hence, segregation is a process which causes mixing of particles in the discharge layer.

BALANCE MODEL OF SCREENING

To investigate the rate of changes in the whole material layer thickness on the sieve and shape of the upper edge of the layer, we should consider mass balance of the elementary sieve surfaces (sieve sections). Such a balance is shown in Fig. 3.

According to symbols presented in this Figure, we obtain the height of the layer at the end of the i-th section:

$$Q_i = H_i \cdot B \cdot \rho_n \cdot u_m \Rightarrow H_i = \frac{Q_i}{\rho_n \cdot B \cdot u_m} \tag{6}$$

where:
Q_i [kg/s] – the rate of flow of the layer from the i-th section,

$$Q_i = Q_{i\text{-}1} - Q_{KDi} \tag{7}$$

$Q_{i\text{-}1}$ [kg/s] – the rate of flow to the i-th section,

$$Q_{KDi} = \frac{m_{Di}}{t_{p1}} \tag{8}$$

Q_{KDi} – flow rate of undersize fraction from the i-th section [kg/s],
m_{Di} [kg] – mass of undersize fraction screened in time t_{p1} from the i-th section[kg],
t_{p1} [s] – process time,
H_i [m] – height of the layer on the sieve at the end of the i-th section,
B [m] – sieve width,
ρ_n [kg/m^3] – bulk density of the layer,
u_m [m/s] – mean layer velocity calculated from the relation:

$$u_m = \frac{L}{t} \tag{9}$$

L [m] – sieve length,
t [s] – time in which material passes along the sieve length.

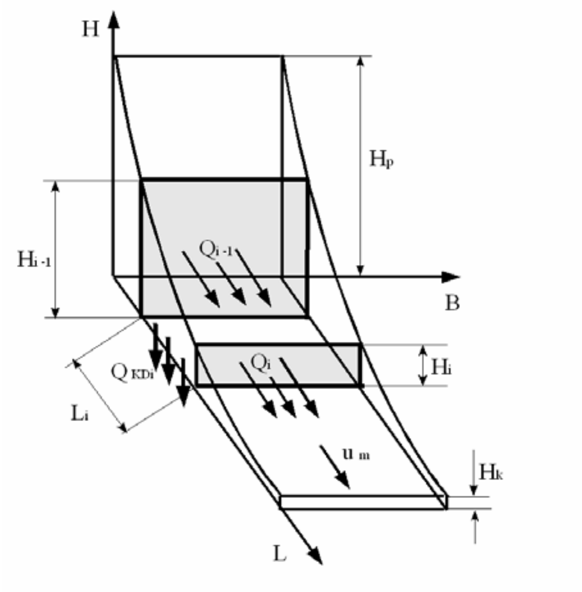

Fig. 3. Mass balance of particular sections of the screen

Here, some values need a comment. Process time t_{p1} is the time in which the feed flows to the screen (the time of feeding material onto the screen). Such definition of this value is related to the assumption that material over each section resides as long as the process takes place. On the other hand, the process lasts as long as feed is supplied to the sieve. This assumption corresponds to the statement that the process is carried out in the steady state at constant values of particular streams. The whole process of screening is always considered as continuous, i.e. lasting infinitely long. In laboratory investigations, however, the process lasts always for some specified period. Hence, it is necessary to introduce some simplifications that would enable interpretation of the process duration as the time in which screening takes place in steady-state conditions. Another value that requires explanation is the mean velocity of material on the sieve (Eq. 10). It can be calculated from available equations presented in literature, but it is most suitable to determine it experimentally for a given screen.

Coming back to the main considerations, the mass balance for the whole screen is given by the formula:

$$Q_0 = \Sigma Q_{KDi} + Q_K \tag{10}$$

where:
Q_K [kg/s] – flow rate from the last section, equal to the stream of oversize product,
Q_0 [kg/s] – flow rate of the feed.

Basing on the feed stream Q_0, the initial layer height H_P can be determined:

$$Q_0 = H_p \cdot B \cdot \rho_n \cdot u_m \Rightarrow H_p = \frac{Q_0}{\rho_n \cdot B \cdot u_m} \tag{11}$$

Applying further this procedure, a subsequent height of the layer (on next sections, from i=1 to k) is determined by the relations:

$$Q_1 = H_1 \cdot B \cdot \rho_n \cdot u_m \Rightarrow H_1 = \frac{Q_1}{\rho_n \cdot B \cdot u_m} \tag{12}$$

where: $Q_1 = Q_0 - Q_{KD1}$, $Q_{KD1} = \dfrac{m_{D1}}{t_{p1}}$ similarly to 6.28 and 6.29,

and next:

$$Q_2 = H_2 \cdot B \cdot \rho_n \cdot u_m \Rightarrow H_2 = \frac{Q_2}{\rho_n \cdot B \cdot u_m} \tag{13}$$

$$Q_2 = Q_1 - Q_{KD2}, \qquad Q_{KD2} = \frac{m_{D2}}{t_{p1}}$$

layer height at the end of the last section:

$$Q_K = H_K \cdot B \cdot \rho_n \cdot u_m \Rightarrow H_K = \frac{Q_K}{\rho_n \cdot B \cdot u_m} \tag{14}$$

$$Q_K = Q_{K-1} - Q_{KDK}, \qquad Q_{KDK} = \frac{m_{DK}}{t_{p1}}$$

where:
Q_{KDK} [kg/s] – rate of flow of the undersize fraction from the k-th (last) section,
m_{DK} [kg] – mass of undersize fraction screened in time t_{p1} from the k-th section [kg].

Final height of the layer on the sieve H_K is closely related to the screening efficiency. On this basis we can estimate whether the process lasted long enough (the sieve length was sufficient) to achieve the expected screening effect, i.e. the desired total stream of undersize fraction.

The above considerations were a starting point to carry out process research, whose aim was to find the relation $H=H(L)$ or $H=H(t)$. This relation is a basis for a mathematical model of the screening process on the frame screen with a membrane sieve. On the basis of this model, and assumed independent variables, we can attain information on process conditions in order to achieve the desired product quality.

SCREENING OF MODEL MATERIALS ON A MEMBRANE SIEVE

In a continuous process, feed in the form of a granular stream Q [g/s] or q [g/s·m^2] is supplied to the beginning of the sieve (the place of material input on the sieve). In this place, the layer on the sieve has thickness equal to H_P and this is the initial height of material layer. Along the whole sieve length L, where the final product with determined parameters can be obtained, the process of screening takes place until reaching final layer height H_K at the end of the sieve. Initially, the granular material was composed of two basic fractions: K_G – oversize fraction, and K_D – undersize fraction, and when supplied to the sieve it is divided into two streams: undersize Y and oversize X. If the process efficiency was full, then the whole undersize fraction would be equal to the oversize stream, while the whole oversize fraction would be equal to oversize stream. However, this is not so and we have efficiency of screening process called also effectiveness, accuracy of separation, etc. It is defined by the formula:

$$\eta = \frac{amount\ of\ undersize\ fraction\ which\ passed\ through\ the\ sieve}{amount\ of\ undersize\ fraction\ in\ the\ feed} \tag{15}$$

The undersize fraction can be screened off from the near-to-sieve layer which is in the structure of the entire layer – a bed of granular material moving along the sieve. This is a "discharge" layer. Its characteristic property is that at each vibration cycle of the screen, which is identified with the screening period, the undersize fraction flows out of it totally.

The efficiency of screening process is closely related to the thickness of material layer on the sieve, strictly speaking not on the thickness, but a change of this thickness along the sieve length. To investigate the rate of changes of the whole material layer thickness on the sieve mass balance of elementary sieve surfaces (sieve sections) should be considered. Such balance is shown in Fig. 3.

The final layer height on the sieve H_K is strictly related to the assumed (technological) efficiency of screening. On this basis we can assess if the process was long enough (the sieve length was appropriate), to obtain the desired screening effect, i.e. the assumed total stream of undersize fraction. When analysing results of studies on the mass of screened material over subsequent sieve sections and converting them to process efficiency over these sections, we can find that the efficiency changes according to the following relation:

$$\eta = \eta_k - \frac{\eta_k}{1 + \left(\frac{L}{L_0}\right)^p} \tag{16}$$

where: η - screening efficiency [-],

η_k - final efficiency (assumed) [-],

L - sieve length [m],

L_0 - sieve length at which process efficiency reaches 50% η_k [m],

p - coefficient [-].

Process efficiency η is an independent variable which determines screened product quality. The final efficiency η_k is assumed according to material type, and actually the fact if the material is easy or difficult to screen. Parameters L_0 and p are the values that determine how far efficiency η is close to the desired efficiency η_k. Hence, they are the function of independent variables in the process, i.e. particle shape (material type), process yield, and particle size distribution of the screened material.

In this connection the function determined in equation 16 has the form η=f(L), i.e. it determines the sieve length at which the efficiency of screening process is satisfactory. The parameters:

$$L_0 = \text{f(particle shape, } y, x_t, \alpha, Q), \tag{17}$$

$$p = \text{f(particle shape, } y, x_t, \alpha, Q), \tag{18}$$

where: y – percentage of undersize fraction in the feed,
x_t – percentage of particles hard to screen in the feed,
α – angle of sieve inclination,
Q – feed flow rate.

Below, only some values of coefficients L_0 and p are compared for particular process conditions for agalite. Similar coefficients were obtained also for other tested materials. Results were obtained using calculations made with the help of Mathcad version 11.0a (Mathsoft Engineering & Education, Inc.). The results are presented as follows:

- type of tested material, angle of sieve inclination, feed flow rate,
- the table presents determined values of L_0; rows represent constant values of undersize fraction in the feed, while columns – constant content of hard to screen particles in the feed,
- the table shows determined values of p, the method of presentation is the same as that given above.

Table 1. Agalite, $\alpha = 25^{\text{o}}, \text{Q} = 0.5\frac{\text{kg}}{\text{s}}$

Lo [mm]		x_t			p		x_t		
		0.1	0.5	0.9			0.1	0.5	0.9
y	0.1	362	442	541	y	0.1	2.116	2,129	1.828
	0.3	326	374	469		0.3	2.310	2,334	1.958
	0.5	299	366	479		0.5	2.390	1.942	1.792
	0.7	341	401	479		0.7	2.582	2.221	1.797
	0.9	367	483	673		0.9	2.107	1.934	1.611

CONCLUDING REMARKS

The main aim of this study was to propose a model of fine screening on a frame screen with membrane sieve. In this section a mathematical description of screening is proposed (Eq.16), and values of the coefficients in equation 16 are presented. Coefficient L_0 represents the sieve length on which the screening process can be treated as a steady-state one. Since that moment screening proceeds according to the model with discharge function. On the other hand, parameter p shows the rate at which assumed product quality parameters are achieved, i.e. the desired screening efficiency is reached. Both L_0 and p depend on initial process parameters, i.e. type of material, particle size distribution and process conditions.

The proposed model holds for the tested dynamic factor, which determined dynamics of the screening machine, and consequently, the rate of material transport along the sieve. Further research on this model should focus on its verifications for other values of dynamic process parameters.

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Niniejsza praca przedstawia model przesiewania materiałów drobnoziarnistych na przesiewaczu membranowym. Urządzeniem, które było przedmiotem pracy badawczej, jest doświadczalny przesiewacz ramowy z sitem membranowym, zaprojektowanym i zbudowanym w Katedrze Aparatury Procesowej Politechniki Łódzkiej. Służy on do przesiewania materiałów drobno i bardzo drobno uziarnionych. Zaproponowana metoda projektowania pozwala oszacować użyteczne wymiary sit (długość i szerokość) dla zadanych warunków procesu w celu osiągnięcia założonych efektów. Metoda ta uwzględnia między innymi skuteczność (efektywność, sprawność) procesu przesiewania, a więc punktem wyjścia do obliczeń jest końcowa zawartość klasy dolnej w produkcie nadsitowym. Jest to ważne dlatego, że technologia procesów przeróbczych zakłada „z góry" dopuszczalne zawartości klas ziarnowych innych, niż właściwe dla danego produktu. W niniejszym opracowaniu został zaproponowany opis matematyczny zjawiska odsiewania w postaci prostego równania, jak również przedstawiono wartości współczynników tego równania. Występujący w równaniu podstawowy parametr L_0 wskazuje nam długość sita, powyżej której proces przesiewania możemy traktować jako proces ustalony. Od tego momentu przesiewanie odbywa się zgodnie ze znanym modelem z funkcją odsiewu. Natomiast bezwymiarowy parametr p wskazuje nam szybkość osiągnięcia założonych parametrów jakościowych produktu, czyli osiągnięcia zadanej sprawności odsiewu. Zarówno L_0, jak i p zależą od parametrów wejściowych procesu, czyli rodzaju materiału, składu ziarnowego oraz od warunków prowadzenia procesu. Zaproponowany model jest słuszny dla określonych, stosowanych w czasie badań wskaźników podrzutu, które określają dynamikę maszyny przesiewającej, a co za tym idzie szybkość transportu materiału po sicie przesiewacza. Dalsze prace badawcze nad tymże modelem powinny iść w kierunku zbadania jego słuszności dla innych wartości parametrów dynamicznych prowadzenia procesu.