FEASIBILITY STUDY OF MIXTURE TRANSPORTATION AND STIRRING PROCESS IN CONTINUOUS-FLOW CONVEYORS
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ТЕХНІКО-ЕКОНОМІЧНЕ ОБГРУНТУВАННЯ ПРОЦЕСУ ТРАНСПОРТУВАННЯ ТА ЗМІШУВАННЯ СУМІШЕЙ ТРУБЧАСТИМИ КОНВЕЄРАМИ

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ABSTRACT

The article presents a research technique on the process of simultaneous transporting and stirring of mixture components by a continuous-flow conveyor. Kinematic motion parameters of loose materials in the main characteristic route segments have been substantiated. Experimental studies have been conducted in order to determine the drag force in set route segments and the stirring rate of mixture components. The obtained results provide a mean of choosing cost-effective operating modes of a conveyor-mixer, whereby the specified quality of mixtures is achieved.

РЕЗЮМЕ

В статті представлена методика дослідження процесу транспортування та одночасного змішування компонентів сумішей трубчастим скребковим конвеєром. Проведено обґрунтування кінематичних параметрів руху сипкого матеріалу на основних характерних ділянках траси. Виконані експериментальні дослідження для виявлення сил опору на встановлених ділянках траси та ступеня змішування компонентів сумішей. Отримані результати дають можливість обирати економічно доцільні робочі режими конвеєра-змішувача, за яких досягається задана якість сумішей.

INTRODUCTION

Continuous-flow conveyors are widely applied when transporting loose materials. Considering their power inputs and ecological safety *(Dziadykevych Y.V., 2016)*, these conveyors are the most effective, since they transport materials in closed environments. They are widely applied for feeding, but there are certain difficulties providing simultaneous transporting and stirring of loose components, especially on a large scale. In addition, it is advantageous to make sectional traction elements and beaded operating elements with a central opening in order to provide spillage and stirring of feed mixture.

The analysis of recent researches *(Hryshova and Lebedev, 2015; Hevko M.R. and Vitrovyi A.O., 2016; Hevko R.B. and Klendiy O.M., 2014; Hevko R.B. et.al., 2016; Loveikin et.al., 2010; Loveikin and Rogatynska, 2011; Lyashuk O.L. et.al., 2015; Pylypaka S.F. and Klendiy M.B., 2016; Rogatynska, 2010; Rogatynska O. et.al., 2015; Rohatynskyi et.al., 2016; Shynkaryk et.al., 2014)* shows that the main disadvantages of the existing traction elements and operating elements of continuous-flow conveyors are the following: their high material capacity and low maintenance ability as well as limited functionality, which provides only transporting of loose materials without providing mixture homogeneity.

MATERIAL AND METHODS

In order to improve the effectiveness of continuous-flow conveyor operation, a flow sheet of simultaneous transporting and stirring of mixture components which can provide their transporting and the attainment of the required homogeneity has been developed.

The technological lane of a continuous-flow conveyor is spatial and consists of certain set segments: rectilinear, curvilinear concave, vertical, curvilinear convex and so on.

Figure 1 shows the technological lanes of such segments.

The procedure of transporting and stirring is the following. In the first stage (Fig.1a) a conveyor casing is fed with the first mixture component with a certain filling coefficient of inter-scraper space, which is picked by scrapers with a central opening and is transported along the route.

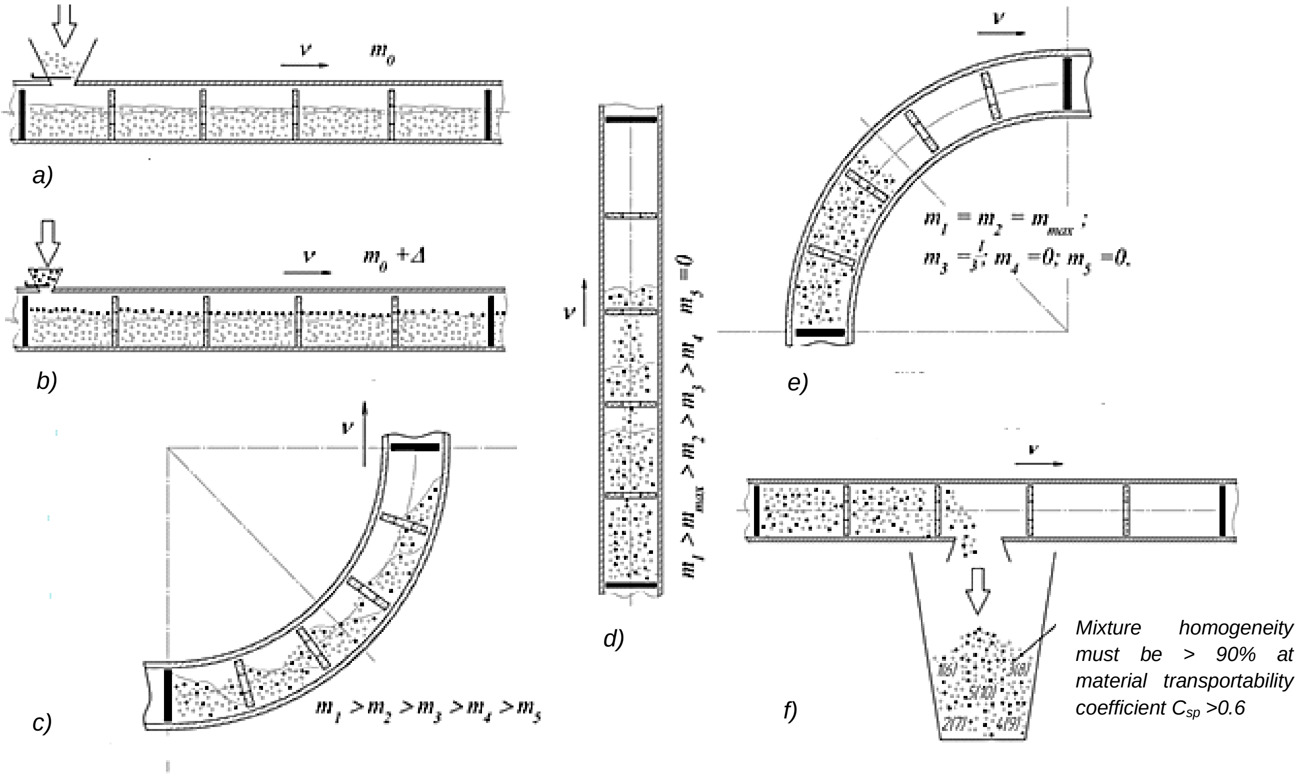
In the second stage, a certain batch of the second component is fed through a special hopper (Fig.1b). As a rule, this component is situated on the surface of a load layer, which is to be transported.

In the third stage (Fig.1c), a load placed between continuous scrapers, when being transported along the route, begins to spill through central openings of beaded scrapers.

In the fourth stage (Fig.1d), when transporting the load, which is situated between continuous scrapers, in vertical route segments there is effective spillage and stirring of mixture components.

In the fifth stage (Fig.1e), the load is transported in a curvilinear vertical segment, where mixture fills certain space between beaded scrapers and load is stirred in continuous flow.

In the sixth stage (Fig.1f), mixture is unloaded and when it is spilled into a container, the mixture is entirely stirred.



Mixture homogeneity must be > 90% at material transportability coefficient C_{sp} >0.6

Fig. 1 - Flow sheets of simultaneous transporting and stirring of mixture components

a – I stage – feed of the main component; b – II stage – feed of the second component;
c – III stage – partial stirring of components; d – IV stage – main stirring of components;
e – V stage – transportation of components; f – VI stage – unloading with entire stirring of components

In order to provide proper homogeneity, it is necessary to determine the influence of technical and design parameters, namely: speed of transportation, diameter of a pipe-line, pitch of scrapers, diameter of scrapers, diameter of an opening etc. on load parameters of the process and mixture homogeneity.

In order to substantiate kinematic motion parameters of loose material with elementary mass dm_c in vertical segments of a technological lane, possible cases of the motion of a variable-mass body vertically upwards (Fig. 2a) have been considered:

- separation from a scraper surface 1 of elementary mass particle Δdm_C;
- simultaneous attachment to a scraper surface 2 and separation from its surface of elementary mass particle Δdm_C;
- attachment to a scraper surface 3 of elementary mass particle Δdm_C.

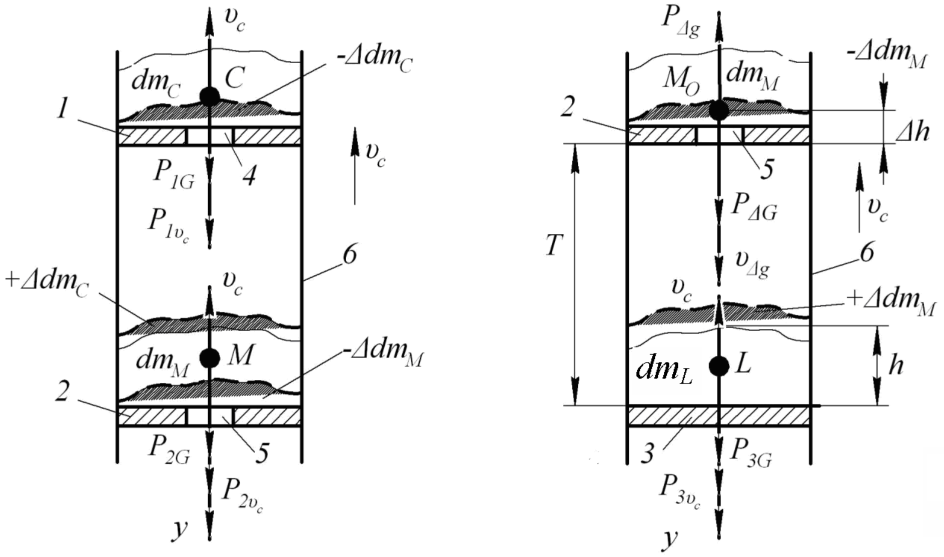
A change in elementary mass dm_i on operational surfaces of relative scrapers over a period of time Δt_c is determined using the following system of equations:

$$\left.\begin{aligned}\Delta dm_C &= dm_C\left(t_c\right) - dm_C\left(t_c + \Delta t_c\right);\\ \Delta dm_M &= dm_M\left(t_c\right) + \Delta dm_C - dm_M\left(t_c + \Delta t_c\right);\\ \Delta dm_L &= dm_L\left(t_c\right) + \Delta dm_M\left(t_c + \Delta t_c\right)\end{aligned}\right\} \tag{1}$$

where Δdm_C – separated or attached elementary mass particle Δdm_M ; Δt_c – period of time for separation and attachment of elementary mass particle Δdm_C and Δdm_M .

Based on energy conservation law, momentum Q_C of elementary mass particle dm_C in case of separation, simultaneous attachment and separation, attachment of elementary mass particle Δdm_C at instant of time t_y , respectively, equals:

$$Q_C\left(t_y\right) = \left(dm_C + \Delta dm_C\right)\vartheta_y - \Delta dm_C\vartheta_1\text{, } Q_M\left(t_y\right) = dm_M\vartheta_c + \Delta dm_C\vartheta_1 - \Delta dm_M\vartheta_2\text{, } Q_L\left(t_y\right) = \left(dm_L + \Delta dm_M\right)\vartheta_y + \Delta dm_M\vartheta_2\text{.}$$



a) ***b)***

Fig. 2 - Design diagrams of kinematic motion parameters of loose materials

Applying Meshchersky's equation with regard to (1) and resultant force exerted on elementary mass dm_i , we have obtained a differential equation for the motion of loose material in a vertical route segment of an operating element for the three cases of behaviour at instant of time t_y taking into account the aerodynamic drag force of aerial environment:

$$dV_C\psi\frac{d^2y_C}{dt_C^2} = dV_C\psi\left[g + p\left(\frac{dy_C}{dt_c}\right)^2\right] + \frac{d\left(dV_C\psi\right)}{dt_c}\left(\frac{dy_1}{dt_c} - \frac{dy_C}{dt_c}\right) \tag{2}$$

$$dV_M\psi\frac{d^2y_M}{dt_C^2} = dV_M\psi\left[g + p\left(\frac{dy_M}{dt_c}\right)^2\right] - \frac{d\left(dV_C\psi\right)}{dt_c}\left(\frac{dy_1}{dt_c} - \frac{dy_C}{dt_c}\right) + \frac{d\left(dV_M\psi\right)}{dt_c}\frac{dy_2}{dt_c} \tag{3}$$

$$dV_L\psi\frac{d^2y_L}{dt_C^2} = dV_L\psi\left[g + p\left(\frac{dy_L}{dt_c}\right)^2\right] + \frac{d\left(dV_L\psi\right)}{dt_c}\left(\frac{dy_3}{dt_c} - \frac{dy_L}{dt_c}\right) \tag{4}$$

where dV_C , dV_M , dV_L – voluntary unit of elementary mass dm_C , dm_M , dm_L ; ψ – specific load weight; y_C , y_M , y_L – *C*, *M*, *L* point coordinates of the mass centre of constant elementary mass dm_C , dm_M , dm_L ; y_1 , y_2 , y_3 – point coordinates of the mass centre of variable elementary mass dm_C , dm_M , dm_L .

A differential equation of elementary mass motion Δdm_M (Fig. 2b) vertically downward under gravity and taking account of aerodynamic drag force of aerial environment is the following:

$$\Delta dm_M \frac{d^2\left(T-h+\Delta h\right)}{dt_c^2} = \Delta dm_M g - p\Delta dm_M \vartheta_{\Delta g}^2 = \Delta dm_M \left(g - p\vartheta_{\Delta g}^2\right) \tag{5}$$

where T – pitch of scrapers; h – initial height of loose material hopper relative to the work surface of a scraper; Δh – height, which takes into account scraper thickness 3 and centre-of-mass coordinate *M* relative to work surface of a scraper.

In order to determine the speed or obtain the equation of elementary mass downward motion Δdm_M it is necessary to eliminate time t_c, applying a substitute method (5). Then, the differential equation (5) becomes the following:

$$\frac{d\left(T-h+\Delta h\right)}{dt_c} = \int_0^{t_c}\left(g - 2p\frac{\vartheta_{\Delta g}}{dt_c}\right)dt_c = gt_c - 2p\vartheta_{\Delta g} \quad \text{or} \quad \int_0^{\vartheta_{\Delta g}} \frac{d\left(T-h+\Delta h\right)}{\dfrac{gt_c}{p} - 2\vartheta_{\Delta g}} = p\int_0^{t_c} dt_c. \tag{6}$$

In order to eliminate random time integration constant we shall take the defined integral, remaining upper and lower limits of variable integration. For lower limits $t_c = 0$, $\vartheta_{\Delta g} = 0$. After the separation of variables, integration and transformation (6), the following can be deduced:

$$\int_o^{T-h+\Delta h} d\left(T-h+\Delta h\right) = \sqrt{g/p}\int_0^{t_c} \ln\left(t_c\sqrt{gp}\right)dt_c; \qquad y_{\Delta M} = T-h+\Delta h = \frac{1}{p}\ln\left(t_c\sqrt{gp}\right). \tag{7}$$

The dependence (7) describes a law of vertical downward motion of elementary mass particle Δdm_M taking into account aerodynamic drag force of aerial environment, and can be used for the substantiation of the parameters of an operating element by determining the time and the distance needed to fill the inter-scraper space volume of the last scraper and their pitch to capacity.

A pilot plant used for the determination of the drag force in set route segments and the stirring rate of mixture components (Fig.3) contains horizontal *5* and *14*, curvilinear *9* and *11* and vertical *10* segments, where there is a traction operating element with scrapers *6*. In loading and unloading area there is a hopper *7*, component additives feeder *8*, an unloading port *12* and a load tank *13*.

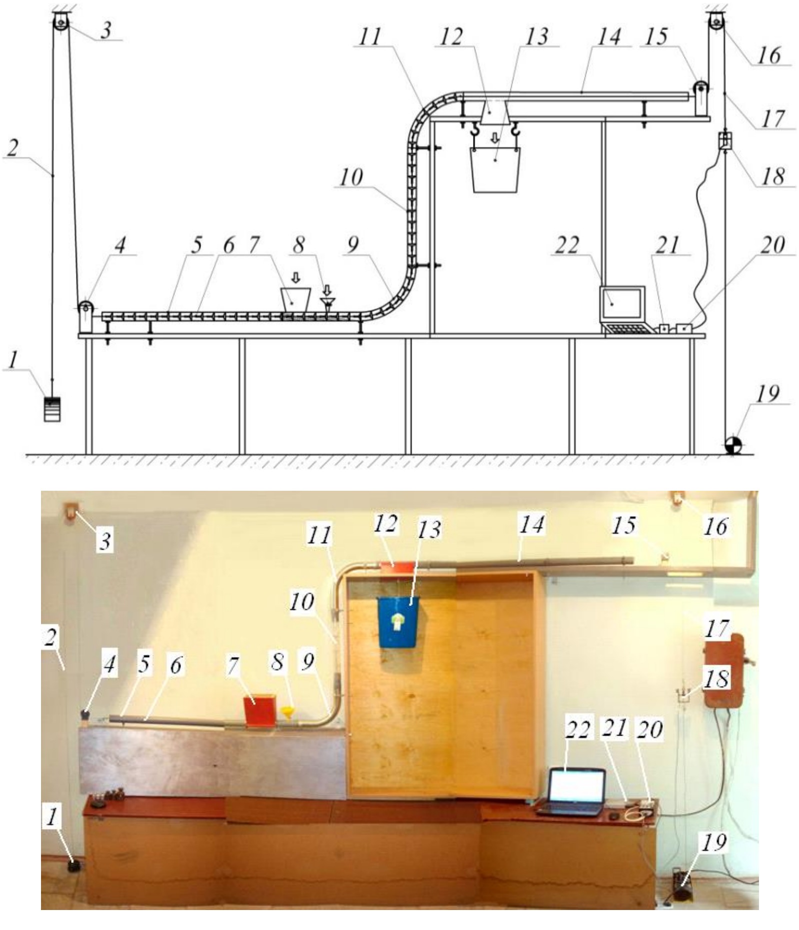


Fig. 3 - Installation diagram and overview of a pilot plant of a continuous-flow conveyor with the designed scrapers

A traction operating element interacts with cables *2* and *17*, which are weighted by load *1* via guide blocks *3,4,15* and *16* and are coupled to an electric drive *19*. The tension force of a driving part of a cable *17* was recorded on PC monitor *22* via an inductive sensor *18* (JA12SSVD10/N2P), a switch and a power supply unit of a measuring system *20*, an analog-to-digital adaptor *21* (ADA-1406).

The length of a cable from a sensor *18* to an electric drive *19* was divided into segments, which corresponded to a horizontal segment of a casing in the area of hoppers arrangement, a curvilinear segment and a vertical segment as well as a curvilinear area, which transforms into a horizontal one in the area of loose mixture unloading.

The change of a drag force was recorded on a PC monitor in each segment of the technological lane.

RESULTS

Experimental studies in order to determine the spillage rate of loose materials in a curvilinear route segment through the openings in beaded scrapers were conducted using a test stand. A curved bend, which had 5 sections, was fed with loose material with the weight of 100…150 g, which corresponded to space filling coefficient ψ = 0.6...0.9. After opening a flap, the flow of loose materials pressed a lever pedal, which turned the timer on. The flow quantity was weighed by an electronic balance. Bend sections with beaded scrapers arranged at angles of α_1=75º, α_2=6º, α_3=45º, α_4=3º were used. The diameter of the central openings of beaded scrapers was 12, 14, 16, 20 and 24 mm, and the outside diameter of washers was d_w = 45 mm.

The overview of the process of transporting and stirring of mixed fodder in a transparent guide pipe in a vertical route segment is shown in Figure 4.

Fig. 4 - A beaded operating element and the process of transporting and stirring of mixed fodder in a vertical route segment of a technological lane

The rate (coefficient) k_{tr} of the transported material, which was unloaded into the tank, was determined with the help of the dependence $k_{tr} = \left(m_{tr} / m_{\Sigma}\right) \cdot 100\%$, where m_{tr} is the mass of the material transported; m_{Σ} is the total mass of the material, which was picked by five scrapers.

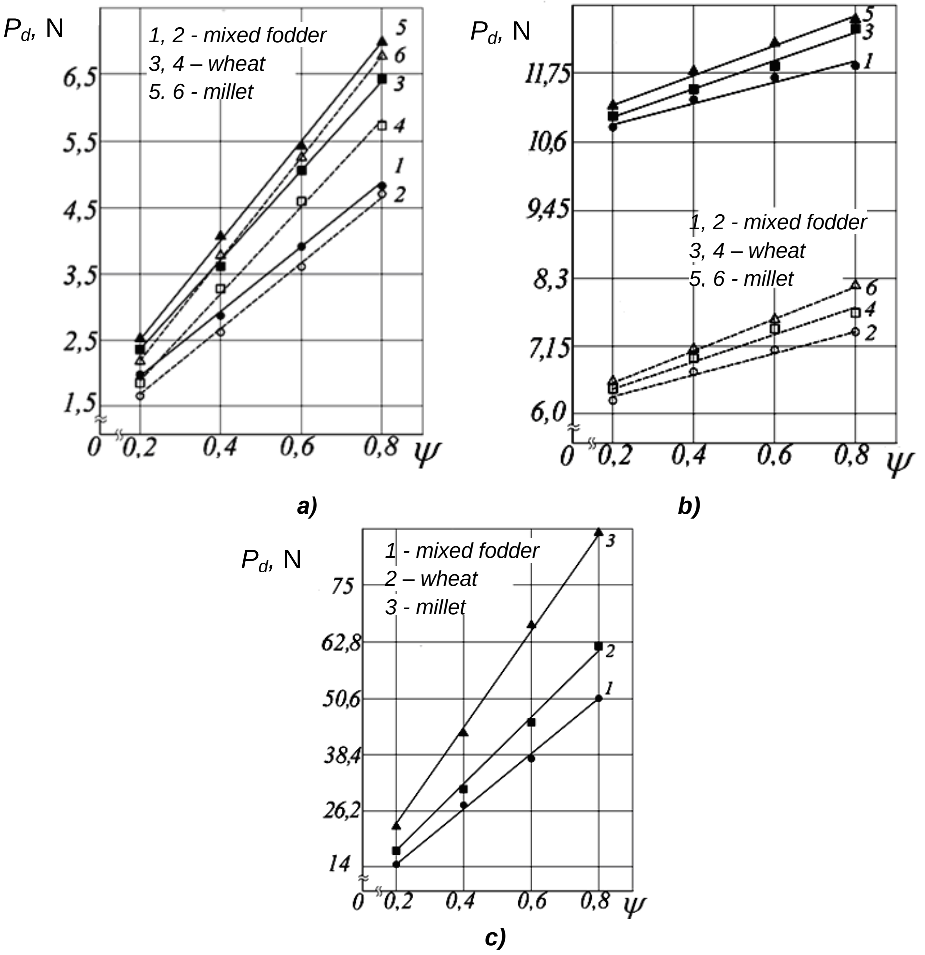
It has been stated that the greatest force increment P_d (Fig. 5) for the transportation of materials in all the route segments is observed during transporting corn seeds at ψ = 0.8. In a curvilinear segment, the friction coefficient in scraper-guide pipe pair has the maximum influence on the force P_d (steel-steel – solid lines, steel-polycarbonate – cross hatching lines).

As a result of data processing for a complete factorial type experiment CFE 3^2 we have obtained the regression equations in actual values, which specify the change in the mass m of loose materials spilled by washers in a curvilinear segment of the lane depending on the diameter of the opening d_{op} and the washer angle α relative to the horizon:

$$\left.\begin{aligned} m_{mf} &= -35.61 + 4.71 d_{op} + 2.81\alpha - 0.42 \cdot 10^{-2} d_{op}\alpha - 0.04 d_{OT}^2 - 0.05\alpha^2; \\ m_w &= 130.78 + 1.29 d_{op} - 1.35\alpha + 0.12 d_{op}\alpha - 0.11 d_{op}^2 - 0.02\alpha^2; \\ m_m &= 488.76 + 0.73 d_{op} - 47.58\alpha - 0.13 d_{op}\alpha + 0.01 d_{op}^2 + 1.67\alpha^2 \end{aligned}\right\} \tag{8}$$

where m_{mf}, m_w, m_m is the mass of spilled mixed fodder, wheat, millet.

Statistical significance evaluation of the coefficients of the regression equation and model validity for actual experimental data file was conducted using Student's test and Fisher's test. According to (8) the response surface of the mass-change of spilled material from d_{op} and α has been defined, Fig. 6.



a) b)

c)

Fig. 5 - The dependence on the change of the force P_d, needed to transport materials with the help of ten scrapers (1 rm) on loading coefficient of the guide pipe ψ:

a) horizontal; b) curvilinear; c) vertical route segment

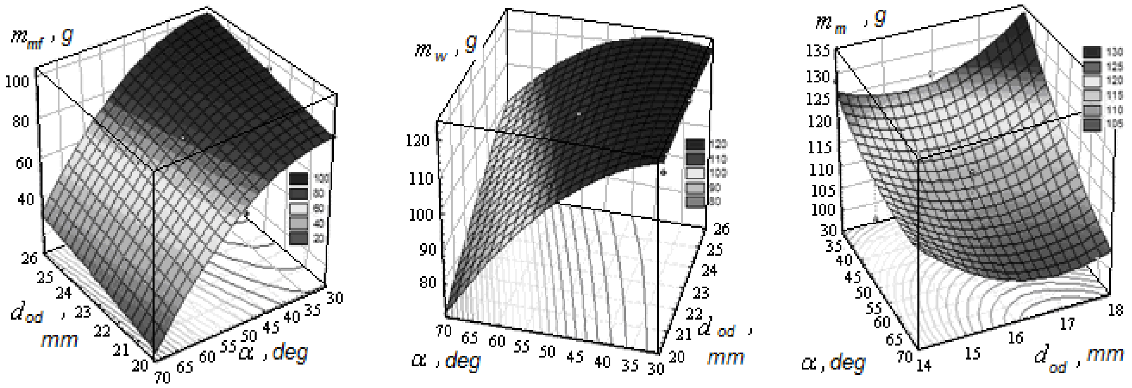


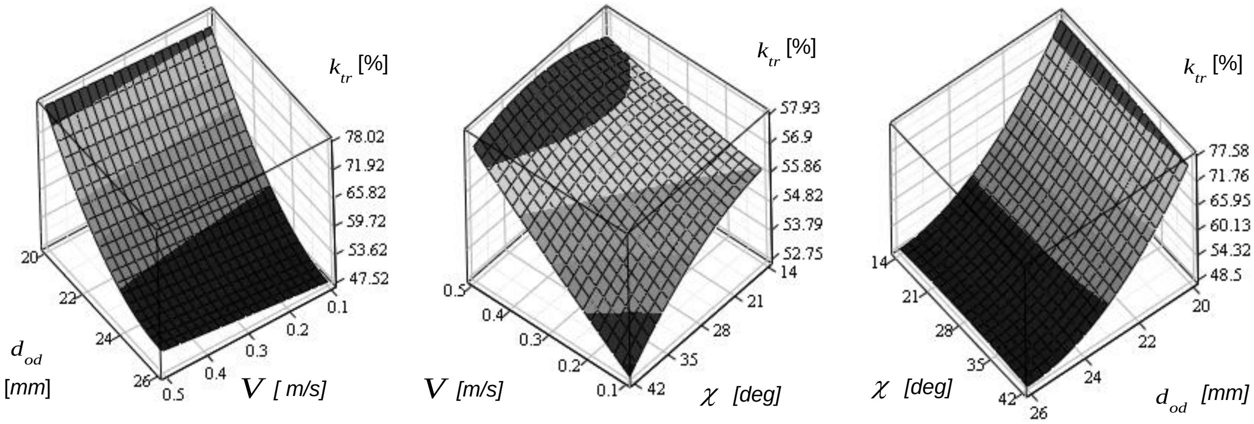
Fig. 6 - Response surface of spilled material mass from d_{op} and α

It has been determined that the change in the diameter of a washer opening from 10 up to 25 mm causes an increase in the mass of spilled material m_i, and the increase of a washer angle α relative to the horizon is of the opposite pattern.

A regression equation of the dependence of the change in the coefficient of transported material k_{tr} on the speed of scraper movement ($0.1 \le V \le 0.5$ m/s), the diameter of the internal opening ($20 \le d_{od} \le 26$ mm) and a cone angle ($14 \le \chi \le 42$ degrees) have been obtained:

$$k_{tr} = 576.749 - 23.020V - 40.118 \cdot d_0 - 0.217\chi + 0.875Vd_0 + \\ +0.305V\chi + 1.079 \cdot 10^{-2} d_0\chi + 2.425 \cdot V^2 + 0.756d_0^2 - 3.128 \cdot 10^{-3}\chi^2. \qquad (9)$$

It has been determined that the dominant factor, which influences the coefficient of the transported material k_{tr} is the diameter of the internal opening d_{op} of scraper washers (Fig.7). The change in the speed of movement V and the cone angle χ of a washer within the limits of 14-28 (degrees) does not influence the increase of the coefficient k_{tr} significantly, but the increase of the angle χ to 42 degrees causes the decrease of the coefficient k_{tr} due to material jamming.



a) *b)* *c)*

Fig. 7 - Response surface of change the coefficient k_{tr} as functionality

a) $k_{tr} = f(V, d_{od})$; b) $k_{tr} = f(V, \chi)$; c) $k_{tr} = f(d_{od}, \chi)$

For the in-process testing, which is connected with the determination of the productivity of the scraper conveyor-mixer, the quality of the process and simultaneous stirring of the components of microgranulated mixed fodder depending on the design and kinematic parameters of the operating elements, a pilot plant has been designed and constructed. Its general view is shown in Fig.8.

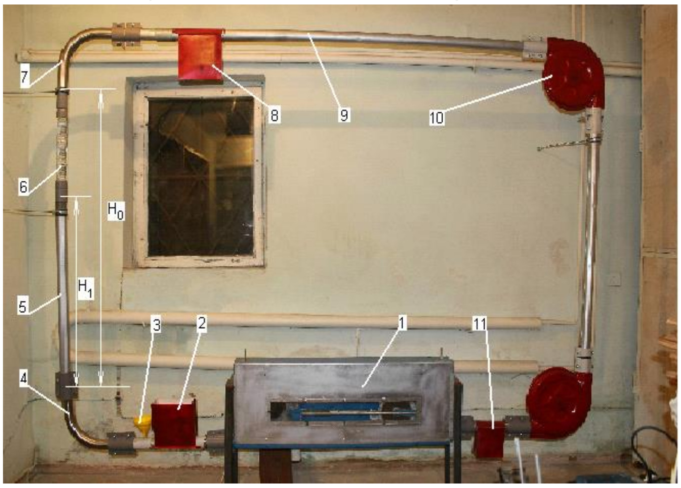


Fig. 8 - Pilot plant

1 – power-drive station; 2 – loading hopper; 3 – bunker for micro additives; 4 – concave curvilinear route segment;
5 – vertical route segment; 6 – vertical transparent route segment; 7 – convex vertical segment;
8 – unloading port; 9 – horizontal segment; 10 – swivel block; 11 – unloading port for material remains

The plant contains a power-drive station *1*, where there are horizontal *9*, vertical *5*, curvilinear (concave *4* and convex *7*) sections of pipe technological lanes attached about a closed path. Inside the lanes there are the designed scraper operating elements arranged. In the left side of the vertical lane there is a section *6* of a vertical transparent route segment mounted. Its length is $H_0 - H_1$ = 0.5 m, which corresponds to five scraper sections of the operating element connected with each other.

In the area of the material intake there is a loading hopper *2* for the main component of microgranulated mixed fodder and a hopper *3* for the control component.

During the in-process testing, the efficiency of a scraper conveyor-mixer depending on variable design and kinematic parameters of the operating element as well as on the stirring quality of feed components was determined.

When determining the effectiveness of the scraper conveyor-mixer, microgranulated mixed fodder was applied. Forward speed of the operating element of the conveyor changed within the range of V = 0.1...0.5 m/s. In the process of the investigation, scrapers with skid-washers with the internal diameter d_{in} = 18, 20 and 23 mm were used. The results of the conducted experiments are shown in Table 1.

Table 1

Forward speed of the operating element *V*, m/s	**Effectiveness of a conveyor-mixer *E*, t/h**		
	d_{in} = 18 mm	**d_{in} = 20 mm**	**d_{in} = 23 mm**
0.1	0.392	0.365	0.338
0.2	0.785	0.733	0.637
0.3	1.172	1.098	1.026
0.4	1.561	1.469	1.362
0.5	1.998	1.838	1.711

The investigation aimed at defining the dependence of mixture heterogeneity H_m on the coefficient of the transported material k_{tr}. For the experimental studies microgranulated mixed fodder with bulk density being 500 kg/m^3 and with particle size being 1...1.5 mm and rape seeds with bulk density being 654 kg/m^3 were chosen. A rape seed was chosen to be the control component and it was stirred with microgranulated mixed fodder at the ratio of 1:8. The indicated component was fed from the side of the loading branch pipe. Mixture quality was determined from the degree of distribution of the control component in the mass of microgranulated mixed fodder.

In the process of experimental studies the spot sampling method was applied. Sampling from the container was done at regular intervals with the help of a special sampler.

The minimum sample mass is calculated using the following formula:

$$G_M = \frac{10^4 \pi d^3 \rho}{c_0 + 1.5c_0} \approx \frac{1.26 \cdot 10^4 d^3 \rho}{c_0} = \frac{1.26 \cdot 10^4 \cdot 0.1^3 \cdot 0.5}{0.125} = 50.4\ g \tag{10}$$

where d – diameter of mixture particles, [cm];

ρ – bulk density of mixture particles, [g/cm^3];

c_o – value of the specified concentration of the main component.

Thus, let us assume sample mass $G \geq G_M \geq 50$ g.

The number of samples is 9; the repetition of the testing is triple. The main component content of rape seeds in the samples was determined using a quantitative analysis of samples. In order to do this, they were weighed using a second type balance like compensatory analytical balance VLKT-500g-M and they were consecutively separated on sieves, since the use of a gravimetric method is possible when all the particles of the control component form a fraction without any particles of other components. After their separation on sieves, the seed mass of the main component (rape seeds) and its concentration in a sample were determined. Having obtained a number of concentration values of the main component in samples c_i, the coefficient of mixture heterogeneity (variations) H_m for a certain coefficient value of the transported material k_{tr} is defined applying the following formula:

$$V_c = \frac{100}{\bar{c}} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (c_i - \bar{c})^2}, \%, \tag{11}$$

where $\bar{c}$ – arithmetic mean value of the main component in the samples, [%]; c_i – value of the main component concentration in the *i*-sample, [%]; n – a number of samples analysed.

Based on the obtained experimental data by means of the regression analysis in Microsoft Office Excel environment, the empirical data were approximated by theoretical curves, the results of which are shown in Fig. 9.

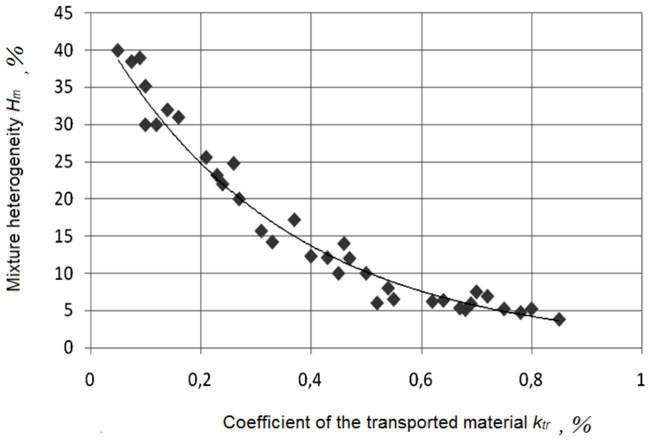


Fig. 9 - The dependence of mixture heterogeneity H_m on the coefficient of the transported material k_{tr}

The obtained results enable to choose such operating modes of the conveyor-mixer at which the specified mixture quality can be attained.

In order to determine economic efficiency, an experimental example of a continuous-flow conveyor-mixer has been designed and has undergone in-process testing.

We have suggested the methodology for determining economic results of the application of the designed conveyor-mixer compared to the basic example, which was taken from the best foreign prototype (that is the decrease of the material capacity of the operating element as well as the decrease of power inputs into the process of transportation). Besides, in the process of transportation, stirring of mixture components of loose materials takes place.

CONCLUSIONS

Having analysed scientific researches, a new flow sheet of simultaneous transportation and stirring of loose material components has been suggested.

The dependencies which define a motion law of an elementary mass particle vertically downward in the process of attachment and separation of loose material or its stirring have been obtained, the analysis of which enables to determine the time and the way needed for filling to capacity inter-scraper space volume, scraper pitch and the amount of transported loose material.

Test stands have been designed and constructed in order to conduct experimental studies.

It has been determined that the greatest force increment P_d needed for material transportation in all the route segments is observed during transporting corn seeds at loading coefficient being $\psi = 0.8$ for steel scrapers, the force P_d is 12.4 and 6.8 greater than in a rectilinear route segment and in a curvilinear one.

Maximum demand of traction force F_D change when the block of beaded scrapers is moved can be observed in a vertical route segment, where F_D for solid scrapers is in 1.1...1.15 times greater than for scrapers with openings and the change in motion speed within the limits of 0.15...0.3 m/s does not influence the force F_D significantly.

Based on the conducted laboratory research, it has been determined that the change in the diameter of a scraper opening from 20 to 25 mm causes the decrease in the time of mixed fodder spillage from 3.3 to 2.25 s, if the angle of washer arrangement is $\alpha = 30^0$; in the process, there is spillage of 84.6% and 96.1% of mixed fodder out of the loaded mass respectively. If the angle is $\alpha = 75^0$ the time of mixed fodder spillage decreases from 4.9 to 3.2 s, the spillage of mixed fodder is 17.3% and 30.8% respectively.

The dominant factor, which influences a coefficient value of transported material $k_{tr,}$ is the diameter of the internal opening d_{op} of scraper washers and the change in the speed of movement and the cone angle of an operating surface within the limits of $0.1 \le V \le 0.5$ (m/s). $14 \le \chi \le 28$ (degrees) does not cause a significant increase of the coefficient k_{tr}, but further increase of the angle χ to 42 degrees causes the decrease of the coefficient k_{tr}. It has been determined that the effectiveness of the conveyor-mixer, when the internal opening of a washer is changed from 18 to 23 mm, decreases from 2.0…1.7 t/h at forward speed of the operating element being 0.5 m/s and the best homogeneity of mixed fodder mass is achieved at the coefficient k_{tr} from 0.55...0.6 and above.

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