УДК 621.929:664
UDC 621.929:664

Dudarev I., Hunko Yu.
Lutsk National Technical University, Lutsk, Ukraine

DETERMINING THE ADVANTAGES OF THE GRAVITATIONAL MIXER OF GRANULAR AND BULK MATERIALS

In the food industry, the batch and continuous drum mixers of various designs are used for mixing of granular and bulk materials. The drum mixers have low productivity because they are typically batch and have considerable energy costs for the mixing process, as energy is consumed not only for the dosing, loading and unloading of components and mixtures, but also energy is consumed directly for the mixing process, which involves the rotation of the drum and workers bodies and surfaces. The gravitational mixers have several advantages over the drum mixers. As a rule, in the gravitational mixers the mixing process takes place without energy consumption, which significantly reduces the specific energy consumption for mixing. The results of the comparative calculation of the productivity of the drum mixer and proposed gravitational mixer and the specific energy consumption for the mixing process in these mixers indicate the benefits of the gravitational mixer, which has higher productivity and lower specific energy consumption. Analysis of the possible trajectories of movement of the particles of granular and bulk materials in the mixer section leads to the conclusion that their contact with the walls of the section body is possible, which does not directly affect the flow of the mixing process, but may cause damage to the components. The theoretical study allowed obtaining a condition for determination of the design parameters of the mixer section taking into account the physical and mechanical properties of the components. In the gravitational mixer with these design parameters, the components particles will not contact with the walls of the section body and accordingly will not be damaged.

Keywords: mixing process, mixer, bulk and granular components, mixer productivity, mixer energy consumption.

INTRODUCTION

The batch and continuous drum mixers are used to mix bulk and granular components in the food industry [1 – 4]. The batch drum mixers are the most common (Fig. 1). This is due to the peculiarities of food production technology and the duration of individual technological processes. Most of the batch drum mixers are additionally equipped with work bodies and work surfaces that intensify the mixing process, but also cause damage to the components of the mixture. During component loading and unloading, the batch drum mixer does not work, causing poor productivity. In the batch drum mixers, energy is consumed by the drum drive and equipments of components loading and mixture unloading. However, the gravitational mixers are gaining ground in various industries, since gravitational mixers consume energy only for components loading. Thus, the gravitational mixers have advantages over the batch drum mixers and these mixers are more suitable for granular and bulk materials mixing process in the food industry.

LITERARY DATA ANALYSIS AND PROBLEM STATEMENT

A large number of publications in the scientific literature are devoted to the study of the bulk and granular materials mixing process and determination of the mixer designs [5 – 9].

In describing the mixing process, the mixer hardware is only one of several components, because the mixing process also includes component dosing method, the loading method, the unloading method, the mixing time, and the mixing energy [10]. The method of dosing components and the design of the dispenser is selected taking into account the physical and mechanical properties of the components. The loading method includes the order of loading the constituents into the mixer and also the duration of the loading period. The components are loaded together before mixing or added one at a time to the mixer during the mixing process. In addition, for continuous mixers, the height of the component layer in the mixer is important, since the mixing quality depends on it.

The mixing time is defined as the time elapsed between the loading of the first component to the final unloading of the mixture or as the time between the loading of all components and the beginning of mixture unloading [10].

Unloading a mixture of granular and bulk components from the mixer, as a rule, occurs by gravity without the use of special equipment. The unloading time must be kept to a minimum so that the quality of the mixture does not deteriorate due to caking.

The energy needed to mix is determined by the duration of dosing and loading of components, the immediate duration of the mixing process and the duration of unloading the mixture, if this equipment is used. In addition, the power consumption depends on the design of the mixing equipment and its performance.

Thus, it is important to compare the productivity and energy costs of the mixing process for different mixers. Comparison of the mixer designs will allow offering the best mixer design for granular and bulk materials.

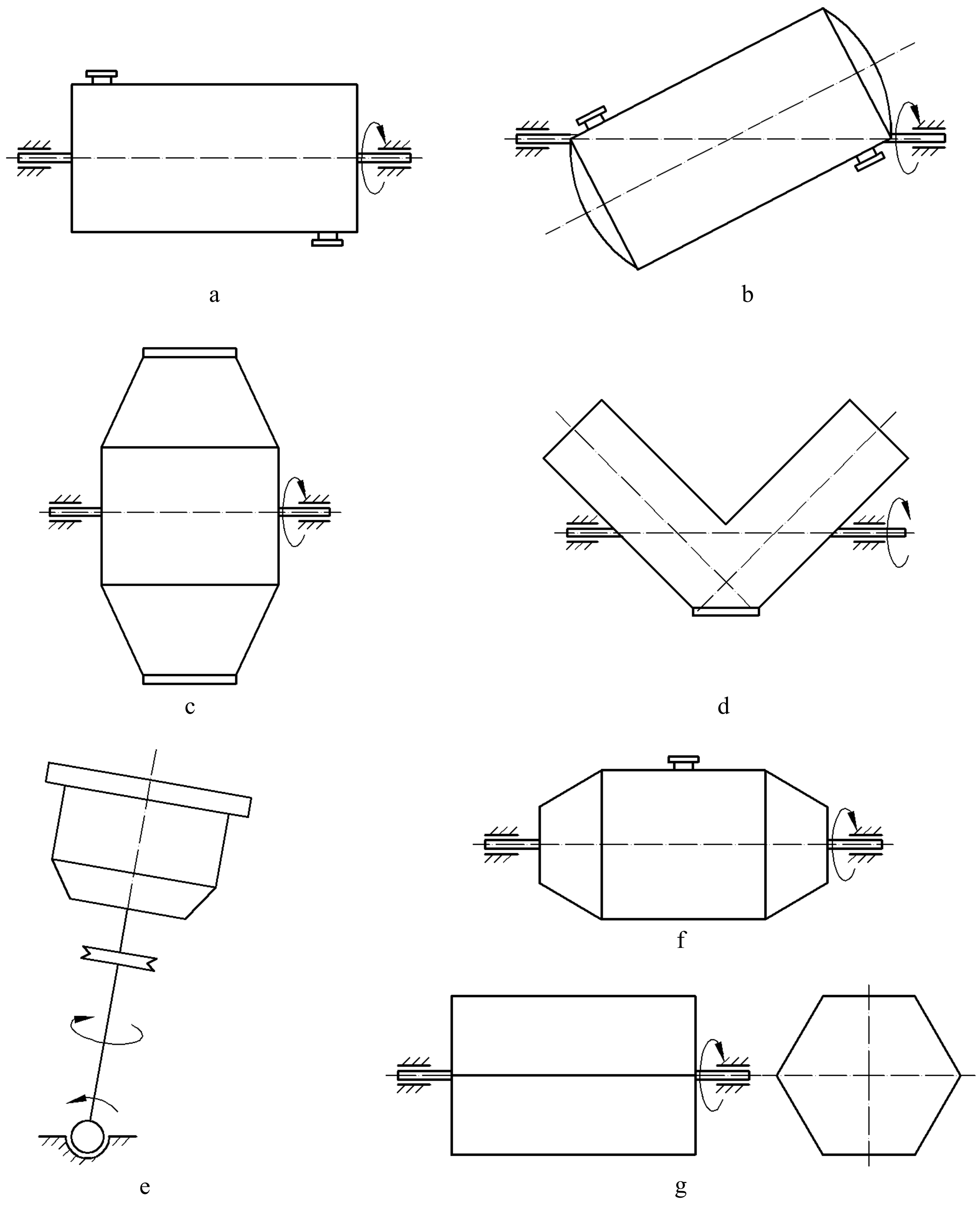


Figure 1 − Schemes of the batch drum mixers of bulk and granular materials:
a – the horizontal mixer; b – the inclined mixer; c – the vertical inclined; d – the V-mixer;
e – the vibration mixer; f – the conical mixer; g – the multifaceted mixer

THE GOAL AND OBJECTIVES OF THE RESEARCH

The goal of the research is to determine the design of the mixer of granular and bulk materials for the food industry, which ensures high mixing process productivity and low energy consumption for the mixing process, and does not cause damage to the components of the mixture.

To achieve the goal of the research it is very important to solve the following tasks:

− to determine the theoretical productivity of the batch drum mixer and the gravitational mixer;

− to determine the specific energy consumption of the batch drum mixer and the gravitational mixer;

− to analyze the trajectories of possible movement of the particles of components in the gravitational mixer and to determine the mixer design parameters of the, which do not generate the damage of the mixture.

RESULTS AND DISCUSSION

The proposed gravitational mixer consists of sections of the same design installed one above the other (Fig. 2). Sections are rotated relative to each other by an angle $\pi/2$ (rad) in the horizontal plane. The section is formed by the body, inside which two vertical partitions are fixed, delineating the section into three parts. Moreover, the part between the vertical partitions is not operational, and the part between the vertical partitions and body is operational. From the operational parts of the section to each vertical partition are attached the combiner and the separator. They are correspondingly designed to combine flows of the components and to divide flow of the mixtures of the components. Each combiner and separator is formed by two plates. Under the bottom section there are four containers designed to collect the finished mixture. The component flows and the flows of the mixtures formed by the components are repeatedly combined and separated in the mixer, which leads to mixing of the components.

Before mixing the components, the components are always dosed and loaded into the mixer. As a rule, the processes of dosing and loading of components are combined, performed by one device. Accordingly, in addition to the energy costs of mixing, energy is spent on the dosage and loading of components. Thus, when choosing a mixer design, it is necessary to compare, in addition to the productivity of various mixers, also the energy costs for dosing, loading and mixing of components.

To obtain multicomponent mixtures in the food industry, the drum mixers of various designs are mainly used. These are the batch mixers. The productivity of such mixers is determined by the equation:

$$Q = \frac{V k_V \rho}{t_l + t_m + t_d}, \tag{1}$$

where Q – the productivity of the batch mixer, kg·h^{-1};

V – the volume of the working chamber of mixer, m^3;

k_V – the coefficient of filling the mixer chamber (it is recommended $k_V \le 0.5$);

ρ – the density of the mixture, kg·m^{-3};

t_l – the duration of dosing and loading of components into the mixer, h;

t_m – the duration of mixing of components in the batch mixer, h;

t_d – the duration of unloading the mixture from the batch mixer, h.

The total energy consumption for dosing, loading and mixing of components in the batch drum mixer is determined by the equation (provided that the equipment is not used for unloading the mixture):

$$N_\Sigma = \frac{1}{t_l + t_m + t_d}(t_l N_l + t_m N_m), \tag{2}$$

where N_Σ – the total energy consumption for dosing, loading and mixing, W·h;

t_l – the duration of dosing and loading of component into the mixer, h;

N_l – the power of equipment for dosing and loading of component, W;

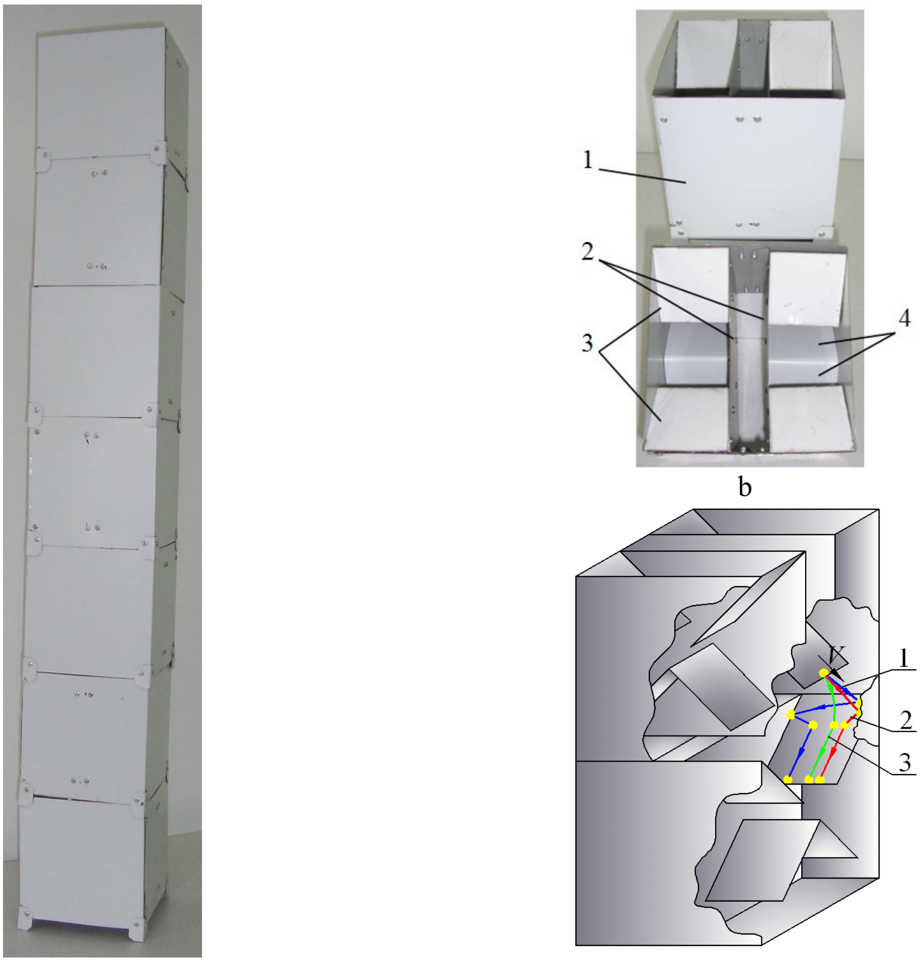
N_m – the power of the batch drum mixer for mixing components, W.

The productivity of the proposed gravitational mixer is determined by the equation:

$$Q = \sum_{i=1}^{4} Q_i, \tag{3}$$

where Q – the productivity of the gravitational mixer, kg·h^{-1};

Q_i – the weight of the component i that is loaded into the mixer in one hour, kg·h^{-1}.



a

Figure 2 – The gravitational mixer of bulk materials (a), and the internal structure of its section (b) (1 – the section body; 2 – the vertical partitions; 3 – the plates of the combiner; 4 – the plates of the separator), and the trajectories (c) of the component particles within the transition from section to section of the mixer (1, 2, 3 – the trajectories of the component particles)

The mass of each of the components that are loaded into the gravitational mixer in one hour can be determined by the equation:

$$Q_i = \frac{lsh\rho_i}{t} = 3600sh\rho_i\sqrt{\frac{gl(\sin\alpha - f\cos\alpha)}{2}}, \qquad (4)$$

where Q_i – the amount of component i what is loaded into the mixer, kg·h^{-1};
l – the length of the plate of the combiner, m;
s – the width of the plate of the combiner, m;
h – the height of the layer of the component i on the plate of the combiner of upper section, m;
ρ_i – the density of component i, kg·m^{-3};
t – the time of movement of the component i along the plate of the combiner of the upper section, h;
g – the acceleration of gravity (g = 9.81 m·s^{-2}), m·s^{-2};
α – the angle of the plate of the combiner to the horizon, rad;
f – the coefficient of friction of the component on the surface of the plate of the combiner.

Time t in the equation (4) is determined by solving the system of equations of movement of the component particle on the surface of the combiner (assuming that the particle slides the surface) (Fig. 3a):

$$\left.\begin{aligned} m\ddot{x} &= mg\sin\alpha - F; \\ m\ddot{y} &= N - mg\cos\alpha, \end{aligned}\right\} \qquad (5)$$

where m – the mass of the component particle, kg;

$\ddot{x}$, $\ddot{y}$ – the acceleration of the component particle along the x and y axes, m·s^{-2};

F – the friction force, N;

N – the normal reaction of the surface of the combiner, N.

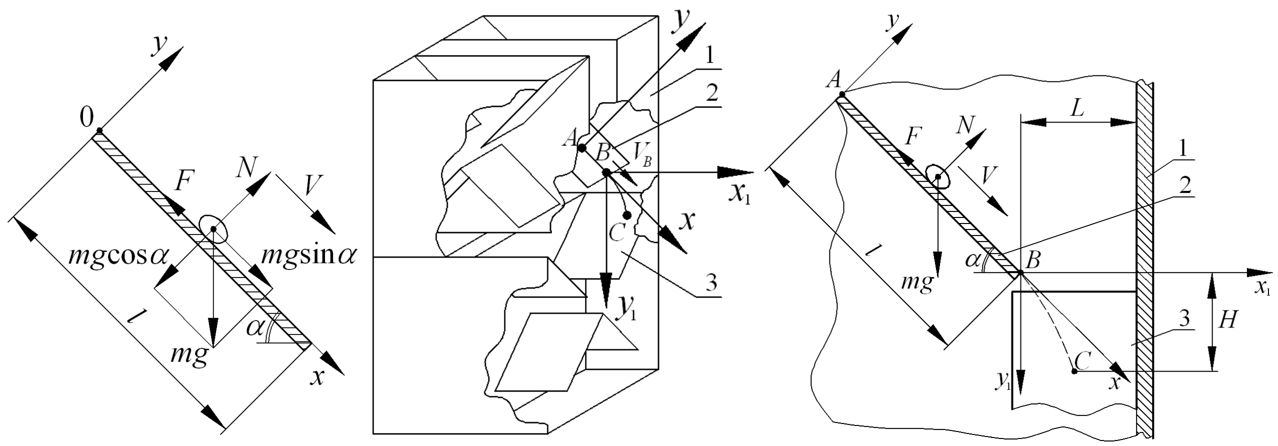


Figure 3 – The scheme (a) of forces acting on a component particle during its movement by the plate of the combiner of the upper section and the schemes (b, c) of component particle movement from the plate of the separator to the plate of combiner
(1 – the section body; 2 – the plate of the separator; 4 – the plate of the combiner)

Let us solve the system of equations (5) and determine the time t for what the component particle moves along the plate of the combiner of the upper section by the distance l ($x = l$). In this case, the initial conditions are $t_0 = 0$, $\ddot{y} = 0$, $\dot{y}_0 = 0$, $y_0 = 0$, $\dot{x}_0 = 0$, $x_0 = 0$ and also the friction force is $F = f{\cdot}N$:

$$x = \frac{gt^2}{2}(\sin\alpha - f\cos\alpha), \tag{6}$$

$$t = \sqrt{\frac{2l}{g(\sin\alpha - f\cos\alpha)}}. \tag{7}$$

The total energy consumption for dosing, loading and mixing of components in the proposed gravitational mixer is determined by the equation (energy consumption for the mixing process is $N_m = 0$):

$$N_\Sigma = 4N_l t_l, \tag{8}$$

where N_Σ – the total energy consumption in the proposed gravitational mixer, W·h;

N_l – the power of equipment for dosing and loading components, W;

t_l – the duration of dosing and loading of component into the mixer, h.

The specific energy consumption for obtaining 1 kg of mixture for mixers of any design:

$$N_p = \frac{N_\Sigma}{Q}, \tag{9}$$

where N_p – the specific energy consumption for 1 kg of mixture, W·h/kg.

Let us compare the specific energy consumption for the drum mixer and the proposed gravitational mixer on the example of mixing of four components in a ratio of 0.25:0.25:0.25:0.25.

After calculations, the following parameters were obtained (calculations were carried out for the drum mixers at: V = 0.05–0.3 m^3; k_V = 0.5; ρ = 720 kg·m^{-3}; t_l = 0.1 h; t_m = 0.25 h; t_d = 0.25 h; N_m = 0.5–2.2 kW;

N_l = 0.4 kW; for gravitational mixer at: t_l = 1 h; ρ = 720 kg·m^{-3} (all components have the same bulk density); s = 0.05 m; h = 0.005 m; l = 0.07 m; $\alpha = \pi/4$ rad; f = 0.35):

– for the drum mixers: the productivity – Q = 45–270 kg·h^{-1}; the total energy consumption – N_Σ = 0.41–1.48 kW·h; the specific energy consumption – N_p = (5.5–9.1)·10^{-3} kW·h/kg;

– for the proposed gravitational mixer: the productivity – Q = 1030 kg·h^{-1}; the total energy consumption – N_Σ = 1.6 kW·h; the specific energy consumption – N_p = 1.6·10^{-3} kW·h/kg.

The results of calculating the productivity of the drum mixer (Q = 45–270 kg·h^{-1}) and the proposed gravitational mixer (Q = 1030 kg·h^{-1}) show that the productivity of the gravitational mixer is higher. The specific energy consumption of the mixing process, including component dosing, component loading, component mixing and component unloading, for the drum mixer (N_p = (5.5–9.1)·10^{-3} kW·h/kg) is higher than for the proposed gravitational mixer (N_p = 1.6·10^{-3} kW·h/kg). Thus, according to the basic performance of the mixer (productivity, specific energy consumption for the mixing process), the proposed gravitational mixer is better than a drum mixer. This is due to the fact that no energy is directly consumed by the mixing process in the gravitational mixer.

During the movement of the components particles by the sections of the gravitational mixer, their contact with the walls of the mixer body is possible. When the particles of the components fall from the plate of the separator, different trajectories of their movement are possible. The trajectories depend on the initial velocity V of the particles, the direction of the initial velocity, which depends on the angle α of installation of the plate of the separator, and the distance L between the plate of the separator and the mixer body. We analyse the possible trajectories of the components particles within the transition from section to section of the mixer:

1. The movement of the components particles along the trajectory 1 (Fig. 2c) is possible in the case when the initial velocity V of the particles and its direction are such that the particles reach the wall of the mixer body, are reflected from it and fly to the vertical partition. After reaching the vertical partition, the particles are reflected from it and fall on the plate of the combiner of the next section. The plate of the combiner directs the particles to the mixing zone.

2. The movement of the components particles along the trajectory 2 (Fig. 2c) is possible in the case when the initial velocity V of the particles and its direction are such that the particles reach the wall of the mixer body, are reflected from it and fly in the opposite direction. The particles do not reach the vertical partition and fall on the plate of the combiner of the subsequent section. The plate of the combiner directs the particles to the mixing zone.

3. The movement of the components particles along the trajectory 3 (Fig. 2c) is possible in the case when the initial velocity V of particles and its direction are such that the particles do not reach the wall of the body, but fall on the plate of the combiner of the next section. The plate of the combiner directs the particles to the mixing zone.

Regardless of the trajectory of the component particles during the transition from section to section, the particles continue to move in the same flow. Moreover, this flow of particles within the transition from section to section is not mixed with other flows. This phenomenon is due to the design features of the gravitational mixer, since the transition of the component particles from the flow to the flow can occur only after their descent from the plates of the combiners. Thus, there is no negative effect on the mixing process from the possible collision of particle flows with the walls of the body and vertical partitions. In addition, no matter what was the trajectory of the particles of the components at the transition between the sections, the particles are on the plate of the combiner, in the fall from which three cases, which were considered above, are possible.

It is not desirable for the component particle to contact with the wall of the section body, as the component particle may be damaged. Therefore, it is necessary that the component particle falls from the separator plate to the combiner plate. This is only possible with a certain installation angle α of the separator plate and the distance L. Knowing the trajectory of the component particle flight, the distance L between the separator plate and the section body of the mixer can be determine. This distance L will only cause the component particle to fall to the combiner plate. The movement of the component particle by the separator plate (trajectory section AB in the Fig. 3b and Fig. 3c) can be described by equations (5). The velocity of the component particle at the moment when it reaches the end of the separator plate (state B in the Fig. 3b and Fig. 3c) can be determined by solving equations (5):

$$V_B = \sqrt{2lg(\sin\alpha - f\cos\alpha)}\,. \tag{10}$$

The free fall of the component particle was investigated in the trajectory section *BC* (Fig. 3b and Fig. 3c). The particle of the component begins to fall with the initial velocity V_B. The force *mg* of gravity acts on the component particle during a fall. The resistance of the air was neglected during the study. The movement of the component particle on the trajectory section *BC* is determined by the following equations:

$$\left.\begin{aligned} m\ddot{x}_1 &= 0; \\ m\ddot{y}_1 &= mg. \end{aligned}\right\} \tag{11}$$

The coordinates of the component particle movement are obtained by solving the system of equations (11) with the initial conditions $t_0 = 0$, $\dot{x}_{10} = V_B \cos\alpha$, $\dot{y}_{10} = V_B \sin\alpha$, $x_0 = 0$, $y_0 = 0$:

$$\left.\begin{aligned} x_1 &= V_B t \cos\alpha; \\ y_1 &= \frac{gt^2}{2} + V_B t \sin\alpha. \end{aligned}\right\} \tag{12}$$

For the case $x_1 = L$, the time t is determined from the first equation of the system (12):

$$t = L/(V_B \cos(\alpha)), \tag{13}$$

From the second equation of the system (12), the coordinate of the component particle movement is determined:

$$y_1 = L\left(\frac{gL}{2V_B^2 \cos^2\alpha} + \mathrm{tg}\alpha\right). \tag{14}$$

The component particle will not contact with the body section of the mixer if the condition is implemented:

$$H = y_1 < L\left(\frac{gL}{2V_B^2 \cos^2\alpha} + \mathrm{tg}\alpha\right). \tag{15}$$

To prevent component damage, the number of component particle contacts with the body section of the mixer must be reduced. Equation (12) was obtained to determine the trajectory of particles movement along the mixer section. Condition (15) was obtained from equations (12). This condition allows substantiating the design parameter *H* of the mixer section, taking into account the physical and mechanical properties of the component. The particles of the components will not contact with the body of the section and the components will not be damaged if the parameter *H* will be obtained from the condition (15).

CONCLUSIONS

The proposed gravitational mixer is very useful equipment for mixing process of granular and bulk materials and it can be use by producers in the food industry for mixing different raw materials and finished products. The design of the gravitational mixer can be used in the food industry to mix two, three or four bulk materials. The advantage of the gravitational mixer is the lack of energy consumption for the mixing process. The presence of such mixer will reduce the cost of food production. In addition, during the mixing there is no damage to the materials, which is extremely important for the food industry. The gravitational mixer provides good mixing quality. Also, the gravitational mixer has a compact design and is easy to operate.

Comparing the specific energy consumption of mixing in the drum mixers of different volume and the proposed gravitational mixer, we conclude that in the gravitational mixer the specific energy consumption is 3.4–5.7 times less than in the drum mixers.

The analysis of the trajectories of the possible movements of the components particles in the proposed gravitational mixer allowed us to determine that the particles continue to move in the same flow regardless of the trajectory of the component particles during the transition from section to section. In addition, condition

(15) was obtained, which allows us to substantiate the design parameters of the mixer section. With these parameters, the particle component will not contact with the body of the section. In this case, the components of the mixture will not be damaged.

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Дударєв І.М., Гунько Ю.Л. **Визначення переваг гравітаційного змішувача сипких та гранульованих матеріалів.**

У харчовій промисловості для змішування сипких та гранульованих матеріалів використовуються в основному барабанні змішувачі періодичної та неперервної дії різних конструкцій. Барабанні змішувачі мають низьку продуктивність, оскільки вони, як правило, періодичної дії, та значні енерговитрати на процес змішування, оскільки енергія затрачається не лише на дозування, завантаження і вивантаження компонентів і суміші, але й безпосередньо на процес змішування, що передбачає обертання барабана та/або робочих органів і поверхонь. Гравітаційні змішувачі мають низку переваг у порівнянні з барабанними. Як правило, безпосередньо процес змішування у них відбувається без енерговитрат, що суттєво знижує питомі витрати енергії на змішування. Результати здійсненого порівняльного розрахунку продуктивності барабанного змішувача і гравітаційного змішувача запропонованої конструкції, а також питомої витрати енергії на процес змішування у цих змішувачах вказують на переваги гравітаційного змішувача, що має вищу продуктивність та нижчу питому витрату енергії. Аналіз можливих траєкторій руху частинок сипких та гранульованих матеріалів у секції змішувача дозволяє зробити висновок, що можливий їх контакт із корпусом секції, який не впливає негативно безпосередньо на перебіг процесу змішування, але може спричинити пошкодження компонентів. Теоретичне дослідження дозволило отримати умову для обґрунтування конструктивних параметрів секції змішувача із урахуванням фізико-механічних властивостей компонентів, за яких частинки компонентів не будуть контактувати з корпусом секції гравітаційного змішувача, і, відповідно не будуть пошкоджуватися.

Ключові слова: процес змішування, змішувач, сипкі та гранульовані компоненти, продуктивність змішувача, енерговитрата змішувача.

ДУДАРЄВ Ігор Миколайович, доктор технічних наук, професор, професор кафедри технологій і обладнання переробних виробництв, Луцький національний технічний університет, i_dudarev@ukr.net. https://orcid.org/0000-0002-2016-5342

ГУНЬКО Юрій Леонтійович, кандидат технічних наук, доцент, доцент кафедри технологій і обладнання переробних виробництв, Луцький національний технічний університет, iuriy.hunko@gmail.com. https://orcid.org/0000-0002-1441-9625

Igor DUDAREV, Doctor of Technical Sciences, Professor of Department of Technologies and Equipment of Processing Industries, Lutsk National Technical University, i_dudarev@ukr.net. https://orcid.org/0000-0002-2016-5342

Yurii HUNKO, PhD (Techn.), Associate Professor of Department of Technologies and Equipment of Processing Industries, Lutsk National Technical University, iuriy.hunko@gmail.com. https://orcid.org/0000-0002-1441-9625