ELEVAÇÂO DA EFICIÊNCIA DE TRABALHO DE MÁQUINAS MISTURADORAS

THE INCREASING OF WORK EFFICIENCY OF MIXING MACHINES

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ РАБОТЫ СМЕСИТЕЛЬНЫХ АППАРАТОВ

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RESUMO

Este trabalho descreve a eficácia de um aparelho de misturador de aditivos alimentares para animais com um dispositivo de mistura horizontal e vertical. As características da interação de partículas com uma lâmina misturadora são consideradas. A análise da trajetória das partículas durante seu contato com a lâmina. Os processos de obtenção de uma mistura líquida multicomponente em dispositivos com eixo de lâmina horizontal e vertical são considerados. As principais características do processo são apresentadas na forma de critérios de similaridade. Equações empíricas para a dependência dos parâmetros do processo de mistura nos fatores foram obtidas. Os resultados do estudo são apresentados sob a forma de gráficos. Os parâmetros ótimos do aparelho com um dispositivo mecânico de mistura são indicados, proporcionando um modo de operação de economia de recursos, mantendo ao mesmo tempo a eficiência do processo de mistura. Os fatores do processo de mistura que afetam o consumo de energia foram determinados.

Palavras-chave: *misturador, propriedades físicas e mecânicas, processos hidrodinâmicos, turbulização, consumo de energia*.

ABSTRACT

The article describes the effectiveness of the mixing apparatus of feed additives for animals with a horizontal and vertical mixing device. The characteristics of the interaction of a particle with a mixer blade are considered. The analysis of the trajectory of the particle during its contact with the blade. The processes of obtaining a multicomponent liquid mixture in devices with horizontal and vertical blade shaft are considered. The main characteristics of the process are presented in the form of similarity criteria. Empirical equations for the dependence of the parameters of the mixing process on the factors are obtained. The results of the study are presented in the form of graphs. The optimal parameters of the apparatus with a mechanical mixing device are indicated, providing a resource-saving mode of operation while maintaining the efficiency of the mixing process. The factors of the mixing process that affect the amount of energy consumption are determined.

Keywords: *mixer, physical and mechanical properties, hydrodynamic processes, turbulization, energy consumption.*

АННОТАЦИЯ

В статье рассмотрена эффективность работы смесительных аппаратов кормовых добавок животным с горизонтальным и вертикальным перемешивающим устройством. Рассмотрены характеристики взаимодействия частицы с лопастью смесителя. Выполнен анализ траектории перемещения частицы при контакте ее с лопастью. Рассмотрены процессы получения многокомпонентной жидкой смеси в аппаратах с горизонтальным и вертикальным лопастным валом. Основные характеристики процесса представлены в форме критериев подобия. Получены эмпирические уравнения зависимости показателей процесса перемешивания от факторов. Результаты исследования представлены в виде графиков. Указаны оптимальные параметры аппарата с механическим перемешивающим устройством, обеспечивающие ресурсосберегающий режим работы с сохранением эффективности процесса перемешивания. Определены факторы процесса перемешивания, оказывающие влияние на величину энергозатрат.

Ключевые слова: *смеситель, физико-механические свойства, гидродинамические процессы, турбулизация, энергозатраты.*

INTRODUCTION

Mixing is one of the main processes in the technology of preparation of a multi-component liquid mixture of nutritious feed additives for animals, fertilizer solutions for plants, etc. (Braginsky *et al.*, 1984; Ibrahim and Nienow, 1996). Despite the wide distribution, the mixing process due to its big complexity remains insufficiently studied (Pezzini *et al.*, 2016). The essence of this process is determined by the connection between the amount of energy consumed and the mixing efficiency that achieved in this case (Vasiltsov and Ushakov, 1979; Chapman *et al.*, 1983). This connection is established on the basis of experimental data, using the method of the theory of similarity, which has become widespread. At the same time, the results of the study of a single phenomenon could be generalized and transferred to a wide range of similar phenomena (Kafarov, 1962; Vieth *et al.*, 1963; Akita and Yoshida, 1974).

The qualitative characteristics of a multicomponent mixture are determined by the degree of its homogeneity when the energizing to a unit of the volume that is mixing. Under the concept of energy is understood as the working power that expanded on the formation of vortices in a liquid that is mixing.

When mixing inhomogeneous fractions, mechanical mixers are most widely used, which ensure the creation of homogeneous solutions and the intensification of heat and mass transfer processes (Strenk, 1975; Estanek *et al.*, 1981; Deckwer *et al.*, 1974). To this mixers impose the following requirements (Ibrahim and Nienow, 1996; Strenk, 1975; Kokieva *et al.*, 2016a; Tur and Kuznetsov, 1978; Chernetskaya and Shaposhnikov, 2010; Bruijn *et al.*, 1974; Shah *et al.*, 1982):

• uniform and fully distribution of particles of fractions by volume of the mixture, which determines the quality of mixing;

• metal and energy intensity of the structure in combination with high performance;

• tightness and reliability of the mixer constructions;

• the simplicity of the device and convenience of maintenance.

These requirements are determined by a combination of a large number of factors, including the mode and the type of mixing; the nature of the impact on the fractional environment; the shape and location of the mixer; physicomechanical properties of the mixing materials, etc.

The task of the scientific question is to study the mixing process of heterogeneous fractions with the establishment of mutual connection between the hydraulic and mass transfer sides of this process, while ensuring resource-saving mode of operation with the preserving of the efficiency of the mixing process, as well as the choice of a rational design of mixing devices.

MATERIALS AND METHODS

The task of the scientific question is to study the mixing process of heterogeneous fractions with the establishment of mutual connection between the hydraulic and mass transfer sides of this process, while ensuring resource-saving mode of operation with the preserving of the efficiency of the mixing process, as well as the choice of a rational design of mixing devices. The dynamics of the interaction of a particle of a fractional mixture and a blade of a mixer are shown in the scheme (Figure 1), which is represents the relative motion of a particle along the surface of a blade during rotation of the mixer (Shaposhnikov *et al.*, 2012; Shaposhnikov and Chernetskaya, 2014).

In the scheme of a paddle stirrer, the following coordinate systems are indicated: motionless - $K_0(0\xi\eta\varsigma)$, associated with the axis of rotation of the shaft, and movable- $K_1(0xyz)$, associated with the paddle. The particle motion (M)is a relative in the system K_1, moving with the paddle, and absolute to the system K_0. The position of the point M is determined by the radius-vector ($\vec{r}$) in the coordinate system x, y, z (Equation 1).

The interaction dynamics of the particle at the point of connection of the blade and the shaft is determined by the initial time of reference (t).On a particle, in the point of a contact with the paddle, operate the forces: P – the weight of the particle; N – the reaction of the surface of the blade; F_T – the friction force of the particle on the surface of the blade; Φ_c – Coriolis inertia force; Φ_i – relative inertia force. The equation of motion of a point in the initial conditions for the coordinates $y=0$ and $\dot{y}=0$ have the form (Shaposhnikov *et al.*, 2012; Shaposhnikov and Chernetskaya, 2014) – Equation (2).

The system of differential equations was solved by the Runge-Kutta method of the 4th order using a computer system of mathematical calculations. The result of the calculations was the coordinates of the particle on the blade $x(t)$ and $z(t)$, the projections of the particle velocity $\frac{dx(t)}{dt}$ and $\frac{dz(t)}{dt}$ on the coordinate axes, the absolute velocity $V(t)$ and the path of motion $S(t)$. Wherein, the values of the angular velocity (ω) of the shaft, the angle (φ) of the paddle inclination to the plane of rotation and time (t) were varied.

RESULTS AND DISCUSSION:

2.1. Dynamics of the interaction of a particle with a paddle of an agitator

The analysis of the performed calculations of the interaction of the particle with the paddle showed that the rational angular velocity of rotation of the shaft lies in the range from $\omega = 6{,}28$ rad/s to $\omega = 10{,}47$ rad/s. In this working range, the particles are in contact with the paddle when the shaft turns to the angle $\varphi = 200^\circ$ and is subsequently captured by the rotating medium. The above model provides high-quality mixing of the solid fraction with a liquid medium and contributes to the effective dissolution of the particles (Chernetskaya and Shaposhnikov, 2010; Shaposhnikov *et al.*, 2012; Shaposhnikov and Chernetskaya, 2013).

Conducted studies of the dynamics of the interaction of a particle with a paddle revealed the following features of the process:

1. The change $S(t)$ of the particle is directly proportional depends from the angular velocity (ω) of the shaft and inversely proportional to the angle magnitude (φ), which corresponds to a change φ from 0° to 90°. A further increase of φ does not affect to $S(t)$. The growth of the frequency of rotation of the shaft increases $S(t)$ and ensures its contact with the paddle.

2. Particles move on the paddle along the trajectory, which is close to straight lines, with a deviation opposite to the direction of rotation of the shaft. The particle leaves the paddle at different moments in time. Depending on the angular velocity, a particle descends from the

paddle (Figure 2).

• at $\omega = 6{,}28$ rad/s through $t = 0{,}1$ min, in the angles φ from 60° to 90°;

• to $\omega = 10{,}47$ rad/s the lower border of the range of the angle φ expands to $\varphi = 40^\circ$.

3. The absolute velocity of a particle is changing directly proportion to the value ω and inversely proportional to the value φ:

• at $\omega = 10{,}47$ rad/s, $V(t)$ increases by 23%, to $V(t) = 1{,}38$ m/s ($\varphi = 0^\circ$);

• by increasing the angle φ from 10° to 90° leads to a decrease $V(t)$ in the particle, also decreases the percentage of its growth with increasing ω;

• at $\varphi = 90^\circ$ particle moves with low speed $V(t) = 0{,}78$ m/s, and does not depend on ω, in the considered range. Consequently, with the greatest contact between the particle and the paddle, the velocity will take on a value $V(t) = 0{,}78$ m/s.

4. The maximum value of the contact of the particle with the paddle is set at $\varphi = 90^\circ$, wherein $V(t)$ and $S(t)$ the particles will be the smallest.

2.2. Experimental Mixers

To solve the problem of searching for an energy-saving mode of obtaining a homogeneous mixture with water while preserving the efficiency of the mixing process, we investigated mixing devices of horizontal and vertical types (Kokieva *et al.*, 2016a; Shaposhnikov and Chernetskaya, 2013; Rosenberg and Brun, 1990)

The horizontal mixer (Figure 3) has a capacity with U-shaped in the cross-section, inside of which the vane shaft is placed (Chernetskaya and Shaposhnikov, 2010). The paddles on the shaft are set at an angle to the plane of rotation, which will ensure axial movement of the fractional mixture. During the operation of the mixer, the radial circulation of the liquid prevails.

The paddles on the shaft of the mixer installed along the screw line. The length of the paddle is not less than 90% of the radius of the base of the tank; the width of the paddle is equal to the diameter of the shaft of the mixer. The paddles are evenly distributed by the length of the shaft, with the possibility of changing their number and angle (φ) the paddle inclination to the plane of rotation. During rotation, the paddle of the shaft moves in a certain volume equal to the diameter of the mixing tank and the width of the paddle.

The particles of the fractional mixture are in contact with the surface of the blade, moving along a certain trajectory, further, when they descend from the paddle, they are carried away by the flow of liquid and fall into the other blade. The mixing process continues until the full dissolution of the particles and the formation of a homogeneous mixture (Chernetskaya and Shaposhnikov, 2010).

A vertical type mixer (Kokieva *et al.*, 2016a; Kokieva *et al.*, 2016b; Shilov *et al.*, 1976; Danilin *et al.*, 2015; Danilin *et al.*, 2016) is a structure (Figure 4), in which the shaft is mounted vertically, the blades at an angle of the plane of rotation, what provides axial mixing of particles of the fractions of the medium. The mixer has a paddle three-tiered mixing device, which creates greater turbulence of the flow of liquid, and ensures the mixing of the medium throughout the volume of apparatus. Such a constructive execution intensifies the mixing process and improves product quality. The installation works as follows, the mixture fractions are fed through the branch pipe 11 and 12. The shaft of the agitators is driven from the gearbox 13 and the electric motor, and the air is supplied through the hollow shaft 2 for a barbotage.

The mixers that are investigated provide a complete and uniform distribution of particles throughout the volume of the mixing medium, simplicity, convenience, and tightness of the construction. The main task of the study is to identify the effective mode of operation of the mixer.

2.3. Modes of operation and mixer parameters

The parameters of the mixer operation process are the power (N), spent on the mixing process, the specific productivity (k) of the process, time (t) of a mixing, which depend on the rotation frequency (n) of a mixer, paddle setting angle (α) to the plane of rotation, section (f) of the paddle, the number (z) of the paddles. We present the parameters and factors of the mixing process in the form of dimensionless criteria, what will allow distributing the received results to a similar phenomenon.

Detailed view of the criteria of dependencies (Shaposhnikov *et al.*, 2012; Shaposhnikov and Chernetskaya, 2014):

1. The expenses of the capacity have expressed through the Euler criterion (Eu) (Equation 3).

2. The quality of the mixture – by the Dyakonov criterion (Di) (Equation 4).

3. The expenses of the time – a dimensionless criterion (T) (Equation 5).

4. The frequency of rotation of the agitator – Reynolds criterion (Re) (Equation 6), where d – stirrer diameter; ρ – solution density; η – dynamic viscosity of an aqueous solution.

Experimental studies and processing of the results were carried out using the planning theory methods. The following levels and the intervals of the variation of factors were applied with research (Shaposhnikov *et al.*, 2012):

- $X_1 = \mathrm{Re}$ – ranging from $6.35 \cdot 10^5$ to $10.6 \cdot 10^5$, with the intervals of the variation $2.12 \cdot 10^5$;

- $X_2 = \alpha$ – ranging from 10° to 90°, with the interval 40°;

- $X_3 = f$ – ranging from 0.24 to 0, with the interval0.12;

- $X_4 = z$ – ranging from 8 до 24, with the intervals of the variation 8.

According to the results of the regression analysis, when removing insignificant regression coefficients and checking the model for adequacy, the following dependencies were obtained (Shaposhnikov *et al.*, 2012; Shaposhnikov and Chernetskaya, 2014) (Equations 7-9). Equations (7, 8, 9) with the values of the coefficients corresponding to the actual values of the process factors are as follows – Equations (10-12).

From equations (7, 8, 9) it can be seen that the Reynolds criterion associated with the frequency of rotation of the shaft of the mixer, effects all process parameters. However, the number of paddles affects the specific performance, and the mixing time does not affect the power expended in mixing. The specific productivity of the mixer depends on the working section of the paddle. Graphic dependences of the parameters of the process of mixture formation are presented in Figures 5 and 6 (Shaposhnikov *et al.*, 2012).

The dependence of power (Figure 5) on the frequency of rotation of the mixer, the angle of setting of the paddle to the plane of rotation and the number of blades is expressed in the dimensionless form (Eu from Re). The dependence of the time criterion (T) on the Reynolds criterion (Re) is shown in Figure 6. The results were obtained for various combinations of factors.

CONCLUSIONS:

The process of mixture formation is best realized when the angular velocity of rotation of the beam $\omega = 10{,}47\ \mathrm{rad/s}$ and with the angle of inclination of the blade to the plane of rotation $\varphi = 90^\circ$. The given mode of mixture formation and the constructive execution of the paddle shaft provide an effective trajectory of a particle movement and contribute to its maximum contact with the paddle. Thus, the particles of the fractions are evenly distributing throughout the volume, dissolve and form a homogeneous mixture.

The meaning of power that required for mixing depends on the frequency of rotation of the mixer and the number of blades. Changing the angle of the paddle setting to the shaft and the magnitude of its working section slightly affect the amount of power consumption. The duration of the mixture formation decreases with increasing frequency of rotation of the stirrer, which is true for mixers with different numbers and designs of paddles.

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$$\vec{r} = \vec{i}\,x + \vec{j}y + \vec{k}z \qquad (1)$$

$$\begin{cases} m\ddot{x} = -f|N|\dfrac{\dot{x} + \omega\cos\varphi z}{\sqrt{(\dot{x} + \omega\cos\varphi\, z)^2 + (\dot{z} - \omega\cos\varphi\, x)^2}} + \\ \quad + m\omega^2\cos^2\varphi\; x \text{-} 2m\omega\cos\varphi\,\dot{z} \\ |N| = -m\omega^2\sin\varphi\cos\varphi\; x + 2m\omega\sin\varphi\,\dot{z} \\ m\ddot{z} = -mg - f|N|\dfrac{\dot{z} - \omega\cos\varphi x}{\sqrt{(\dot{x} + \omega\cos\varphi\, z)^2 + (\dot{z} - \omega\cos\varphi\, x)^2}} + \\ \quad + m\omega^2 z + 2m\omega\cos\varphi\,\dot{x} \\ x = x_0;\ \text{-}r \le x_0 \le r \\ z = \sqrt{r^2 - x_0^2\cos^2\varphi} \\ \dot{x}_0 = \omega\cos\varphi\, z_0 \\ \dot{z}_0 = -\omega\cos\varphi\, x_0 \end{cases} \qquad (2)$$

$$Eu = \frac{N}{d^5 n^3 \rho} \qquad (3)$$

$$Di = \frac{k}{n} \qquad (4)$$

$$T = tn \qquad (5)$$

$$\mathrm{Re} = \frac{d^2 n\rho}{\eta}, \qquad (6)$$

$$Y_1 = 97.165 - 61.193X_1; \qquad (7)$$

$$Y_2 = 0.190 - 0.033X_1 + 0.012X_4; \qquad (8)$$

$$Y_3 = 1819.792 + 357.292X_1 - 24.792X_3 - 40.208X_4 \qquad (9)$$

$$Eu = 341.217 - 3\cdot 10^{-4}\,\mathrm{Re}; \qquad (10)$$

$$Di = 0.3 - 4\cdot 10^{-7}\,\mathrm{Re} + 1.5\cdot 10^{-3} z; \qquad (11)$$

$$T = 615.731 + 1.7\cdot 10^{-3}\,\mathrm{Re} - 165.278f - 5.026z. \qquad (12)$$

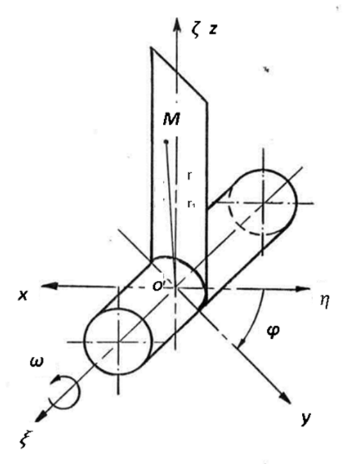

***Figure 1**. Scheme of the dynamic interaction of a particle with a paddle*

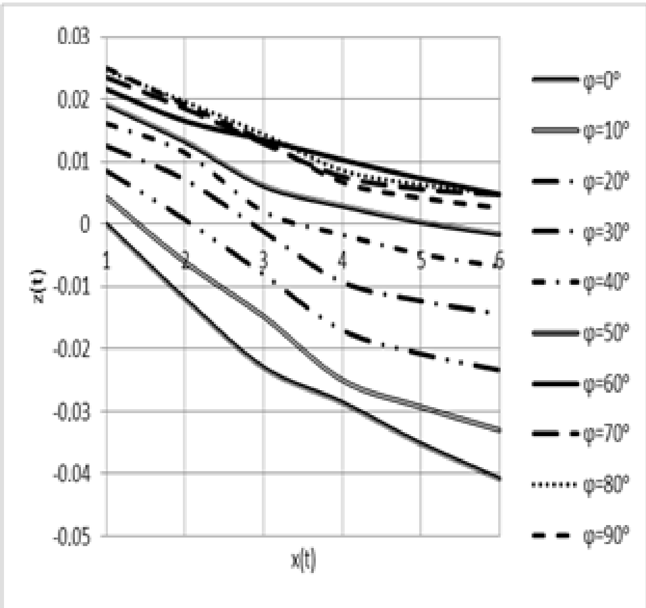

***Figure 2**. The trajectory of the particle during the time* $t = 0{,}1$ min *and* $\omega = 10{,}47$ rad/s

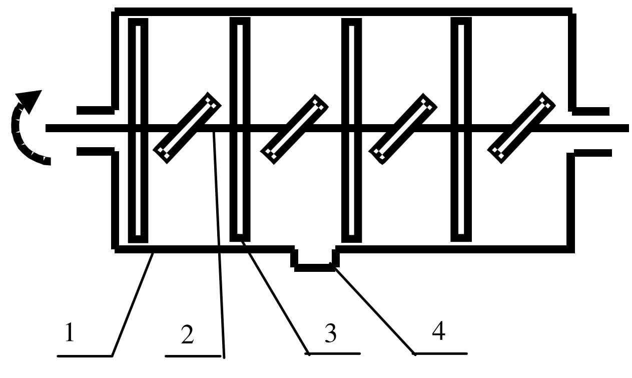

***Figure 3**. Scheme of a horizontal mixer: 1 – capacity; 2 – agitator shaft; 3 – paddles; 4 – exhaust channel*

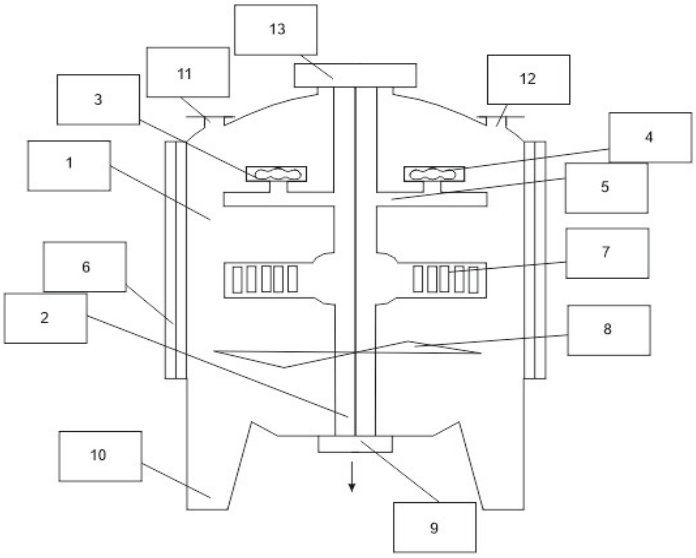

***Figure 4**. Scheme of a vertical mixer: 1 – body; 2 – shaft; 3 – scapula; 4 – slotted in the paddles; 5 – top mixer; 6 – heat exchange shirt; 7 – central stirrer; 8 – bottom stirrer; 9 – unloading branch pipe; 10 – base; 11, 12 – branch pipes; 13 – reduction gear*

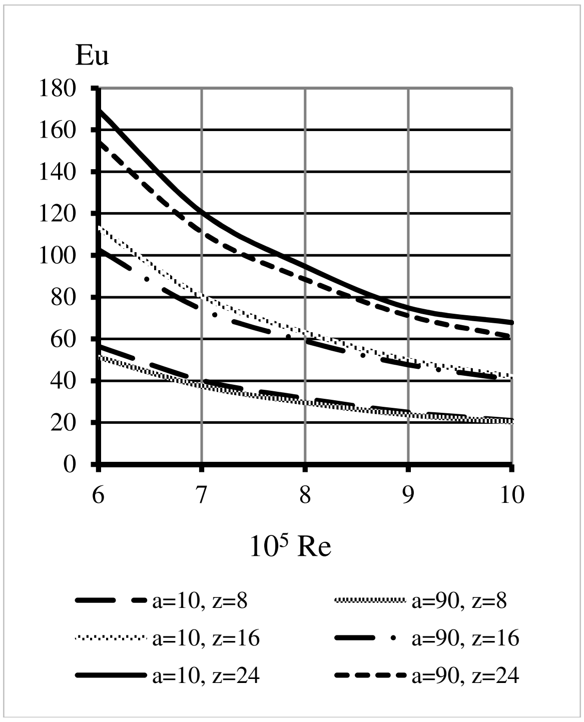

***Figure 5**. The dependence of the Euler criterion on the Reynolds criterion*

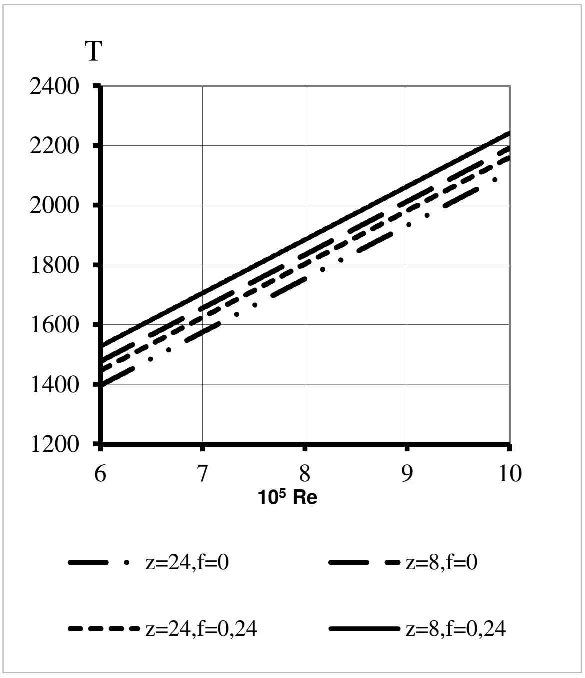

***Figure 6**. Dependence of the criterion T on the Reynolds criterion)*