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ТЕОРЕТИКО-ЭКСПЕРИМЕНТАЛЬНЫЙ АНАЛИЗ ЗАВИСИМОСТИ ЭФФЕКТИВНОСТИ ПРЯМОТОЧНОГО ЦИКЛОНА ОТ ГЕОМЕТРИИ РАЗДЕЛИТЕЛЬНОЙ КАМЕРЫ

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Для оценки эффективности работы прямоточного циклона найдены аналитические решения для тангенциальной, радиальной и продольной составляющих скорости газа в его разделительной камере. С учетом полученных решений рассмотрены траектории частиц пыли в камере, что позволило оценить время их пребывания в камере, а также время подлета частиц к внешней стенке разделительной камеры. Сравнение указанных времен дает возможность определить предельный размер частиц, которые в принципе могут быть уловлены данным циклоном. Кроме того, получено выражение для средней скорости частиц в радиальном направлении, которая является мерой интенсивности конвективного механизма переноса частиц твердой фазы. В результате решения нестационарного уравнения конвективной диффузии получен явный вид зависимости концентрации частиц в потоке газа от времени по мере их движения в камере. Следствием указанной зависимости является соотношение, позволяющее оценить влияние расхода газа, размера частиц пыли и основных геометрических параметров разделительной камеры на эффективность очистки запыленного газа. С целью проверки адекватности предложенной математической модели и полученных на ее основе решений проведены экспериментальные исследования на установке с конструкцией завихрителя прямоточного циклона, профиль лопастей которого обеспечивает безударный вход газовзвеси. Полученные результаты показали хорошую сходимость расчетных и экспериментальных значений степени очистки газовой фазы при различных режимах работы циклона и угла закрутки лопастей, а также геометрических параметров циклона. Результаты статьи позволяют построить методику расчета циклона на стадии проектирования, а также методику расчета оптимальной скорости запыленного газа на стадии эксплуатации.

Ключевые слова: прямоточный циклон, эффективность очистки, геометрические параметры разделительной камеры

THEORETICAL AND EXPERIMENTAL ANALYSIS OF DEPENDENCE OF EFFICIENCY OF DIRECT-FLOW CYCLONE ON GEOMETRY OF SEPARATING CHAMBER

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The efficiency is one of the most important technological characteristics of its operation of a direct-flow cyclone. High efficiency allows to capture more solid phase, which, as a rule, can be disposed of to obtain useful products. As a result not only the amount of waste released into the atmosphere, but also solves the problem of resource conservation. To evaluate the efficiency of the cyclone, the analytical solutions have been obtained for the tangential, radial and longitudinal components of the gas velocity in the separation chamber of the direct-flow cyclone. Taking into account the obtained solutions, the trajectories of dust particles in the chamber are considered, that made it possible to estimate the time of their stay in the chamber, as well as the time of the particles' approach to the outer wall of the separation chamber. Comparison of these times allowed us to determine the limiting particle size that, in principle, can be captured by this cyclone. In addition, an expression is obtained for the average velocity of particles in the radial direction, which is the convective mechanism intensity measure of solid phase particles transfer. As a result of solving the nonstationary equation of convective diffusion, we obtain an explicit form of the dependence of the particles concentration in the gas flow on time as they move in the chamber. To assess the adequacy of the proposed mathematical model and the obtained solutions, experimental studies were carried out on an installation with a design of a direct-flow cyclone swirler, the blade profile of which provides a shock-free gas suspension inlet. The obtained results showed a good convergence of the calculated and experimental values of the gas phase purification degree at different cyclone operating modes and the angle of blade twist, as well as the geometric parameters of the cyclone. The adequacy of the obtained solutions, dependencies, and conclusions is experimentally confirmed.

Key words: direct-flow cyclone, cleaning efficiency, geometric parameters of the separation chamber

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INTRODUCTION

Cleaning gas emissions from dust using cyclones is the most common method. The captured dust is usually disposed to obtain useful products, for example, in the production of quartz sand, chalk, limestone and other bulk products. Therefore, a very important issue is the development of cyclones that are compact and have high cleaning efficiency. Such cyclones undoubtedly include direct-flow cyclones [1-4]. When cleaning large volumes of industrial gas emissions, direct-flow cyclones have a number of advantages over other types of dust collectors [5, 6]. This should include a high degree of purification in a wide range of gas flow rates and dispersed phase concentrations, relatively low hydraulic resistance, reliability and simplicity of design. However, their main advantage is the ability to work at high operating gas velocities without reducing efficiency. This fact was the reason for intensive study of separation process in direct-flow cyclones in recent years [7-14]. To date, a large number of various designs of direct-flow centrifugal and vortex separators have been developed and investigated. They differ from each other in the way of organizing the swirling flow and the device of the phase separation unit. Attempts are made to adequately describe the motion of gas suspensions in swirling flows and to construct mathematical models of centrifugal dust collection [15-23]. However, so far it has not been possible to offer reliable methods for calculation of direct-flow cyclones that predict the degree of gas purification at the known gas flow rates and characteristics of dust particles dispersion. Nevertheless, the results of the conducted studies allowed us to establish two indisputable facts. First, the efficiency of dust collection is mainly determined by the geometric parameters of the separation chamber, which must be taken into account when designing cyclones. Secondly, in the operation of cyclones there is always an optimal gas velocity in terms of cleaning depth. It depends on the geometric parameters of the chamber and the characteristics of the dust [24-26].

The purpose of this article was to determine the influence of the geometry of the separation chamber of a direct-flow cyclone on the efficiency of its operation, as well as to develop a method for choosing the optimal gas velocity that ensures maximum dust collection. The results are obtained on the basis of solving the hydrodynamic equations and analyzing the trajectories of dust particles inside the separation chamber. Fig. 1 shows a typical diagram of a direct-flow cyclone used in practice. When leaving the swirler blades, the gas moves in a spiral, dragging particles along with it. The movement of the dispersed phase is determined by hydrodynamic interaction with gas and centrifugal forces. Due to the installation of the central pipe, the turbulent trace is shifted inside the nozzle for the purified gas that significantly increases the cleaning efficiency [28].

THEORETICAL RESEARCH

Let us consider the flow of a dusty gas in a swirling flow region. If we assume that the presence of particles in the flow has little effect on the gas velocity field, then the problem is divided: first, it is possible to determine the velocity field of the gas phase, and then - the nature of particle motion.

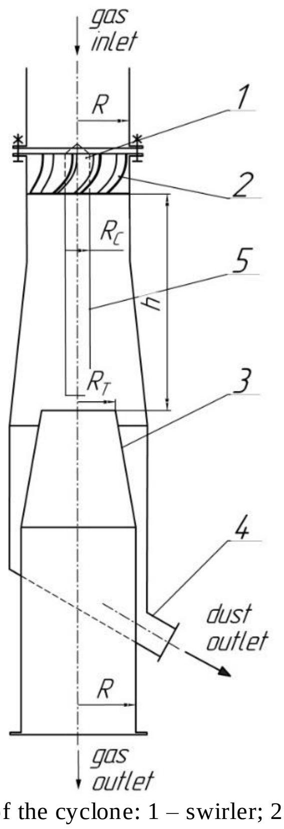

Fig. 1. Diagram of the cyclone: 1 – swirler; 2 – swirler blades; 3 – nozzle for the outlet of purified gas; 4 – nozzle for the outlet of dust; 5 – central pipe

Рис. 1. Схема циклона: 1 – завихритель; 2 – лопасти завихрителя; 3 – патрубок для выхода очищенного газа; 4 – патрубок для выхода пыли; 5 – центральная труба

Let us compose the equations of gas motion, assuming that the motion is stationary, the medium is incompressible, the fields of all hydrodynamic quantities are axisymmetric, and the gas moves under the action of inertial forces, centrifugal forces, Coriolis force and pressure forces. Under the assumptions made, the system of equations describing the gas phase motion has the form:

$$w_r \frac{\partial w_r}{\partial r} + w_z \frac{\partial w_r}{\partial z} = -\frac{w_\varphi^2}{r}; \qquad (1)$$

$$w_r \frac{\partial w_\varphi}{\partial r} + w_z \frac{\partial w_\varphi}{\partial z} = -\frac{w_\varphi w_r}{r}; \qquad (2)$$

$$w_r \frac{\partial w_z}{\partial r} + w_z \frac{\partial w_z}{\partial z} = -\frac{1}{\rho}\frac{dp}{dz}. \qquad (3)$$

Here $w_r (r,z)$, $w_\varphi (r,z)$, $w_z (r,z)$ – are the radial, tangential and axial components of the gas velocity, respectively, m/s; $p(z)$ – pressure, Pa. We neglect the dependence of pressure on the radial coordinate, assuming that the pressure gradient in the radial direction is small.

Let us now formulate equations of motion of the particle considering that its motion is determined by interaction force with gas, centrifugal force and Coriolis force. In cylindrical coordinates these equations have the form:

$$\frac{\partial v_r}{\partial t} = f(w_r - v_r) + \frac{v_\varphi^2}{r}; \qquad (4)$$

$$\frac{\partial v_\varphi}{\partial t} = f(w_\varphi - v_\varphi) - \frac{v_r v_\varphi}{r}; \qquad (5)$$

$$\frac{\partial v_z}{\partial t} = f(w_z - v_z). \qquad (6)$$

Here $v_r (r,z)$, $v_\varphi (r,z)$, $v_z (r,z)$ – are the radial, tangential and axial components of the particle velocity, respectively, m/s.

The coefficient $f = 18\mu/\rho_p d^2$, s^{-1}, that corresponds to the Stokes gas flow around the particle. In this ratio μ – coefficient of dynamic viscosity of the gas, P·s; ρ_p – particle density, kg/m^3; d – is its characteristic size, m.

To determine the trajectory of a particle depending on its size according to equations (4)-(6), it is necessary to use equations (1)-(3) to find an explicit form of the dependencies $w_r (r,z)$, $w_\varphi (r,z)$, $w_z (r,z)$. These equations are solved in the zone of the apparatus between the swirler and the cross-section corresponding to the output of the purified gas. Let the coordinate z = 0 for the entrance to this zone, and $z = h$ for the exit. The polar angle φ varies from 0 to 2π.

The radial coordinate varies from R_c to R, where R_c – is the radius of the central pipe, m, R – is the radius of the separation chamber, m (see Fig. 1). Let us compose the boundary conditions for equations (1)-(3). The radial component of the gas velocity $w_r (r, z)$ must vanish on the wall of the separation chamber (the condition of no flow through the wall):

$$w_r (r,z) = 0, \quad r = R \text{ at any } z. \qquad (7)$$

The tangential component of the gas velocity $w_\varphi\,(r,z)$ at $z = 0$ must be equal to the projection of the total gas velocity vector V onto the tangential direction when the flow leaves the swirler blades, i.e. $w_\varphi\,(R_c,0) = V\cos\beta$, where β is the angle between the vector V and the tangential direction at the blade edge. The condition on the longitudinal component of the velocity $w_z\,(r,z)$ follows from the assumption that the flow is stationary. In a stationary flow, at any value of the z coordinate, the volumetric gas flow rate Q is constant:

$$Q = \iint_S w_z(r,z)ds = const \tag{8}$$

where S – is the cross section of the flow region. It follows from this condition that the longitudinal component of the velocity depends only on the radial coordinate: $w_z = w_z\,(r)$. Let the pressure drop within the separation chamber be Δp. Then the pressure gradient $\frac{dp}{dz} \approx \frac{\Delta p}{h}$. In this case, it can be seen from equation (3) that the radial component of the gas velocity is also a function of only the radial coordinate: $w_r = w_r\,(r)$. Finally, equation (1) can be fulfilled only if the tangential component of the gas velocity does not depend on the longitudinal coordinate: $w_\varphi = w_\varphi\,(r)$.

Taking into account the assumptions made and their consequences, equation (2) is easily integrated. Its solution satisfying the boundary condition formulated above is a hyperbola:

$$w_\varphi(r) = \frac{R_c V\cos\beta}{r} \tag{9}$$

Equation (1) allows us to determine the profile of the radial component of the gas velocity:

$$w_r(r) = R_c V\cos\beta\sqrt{\frac{1}{r^2} - \frac{1}{R^2}} \tag{10}$$

The gas velocity component along the z axis is determined from equation (3). Its solution satisfying condition (8) is the function:

$$w_z(r) = \frac{Q}{S} + A\left(\frac{2}{3}\sqrt{R^2 - R_c^2} - \sqrt{R^2 - r^2}\right) \tag{11}$$

where $= \frac{R\Delta p}{\rho h R_c V\cos\beta}$, – the cross-sectional area of the chamber, m^2.

From the obtained expression it can be seen that the longitudinal component of the velocity is minimal in the vicinity of the central pipe, and reaches maximum values near the chamber wall. Fig. 2 shows the profiles of the tangential, radial and axial components of the gas velocity.

For known gas velocity fields, the trajectories of dust particles obey equations (4)-(6). In order to analyze the cyclone efficiency, it is necessary to know the explicit form of the time dependences of the radial $r_p(t)$ and axial $z_p(t)$ coordinates of the particles. These dependencies must satisfy the equations:

$$\frac{d^2 r_p}{dt^2} = f\left[w_r(r_p) - \frac{dr_p}{dt}\right] + \frac{1}{r_p}(v_\varphi)^2, \tag{12}$$

$$\frac{d^2 z_p}{dt^2} = f\left[w_z(r_p) - \frac{dz_p}{dt}\right]. \tag{13}$$

Here $w_r(r_p)$ and $w_z(r_p)$ are the radial and longitudinal components of the gas velocity at the point of the flow where the particle is currently located. In accordance with the solutions obtained earlier, these functions, which are implicitly time-dependent, have the form:

$$w_r(r_p) = R_c V\cos\beta\,\frac{\sqrt{R^2 - r_p^2}}{r_p R},$$
$$w_z(r_p) = \frac{Q}{S} + A\left(\frac{2}{3}\sqrt{R^2 - R_c^2} - \sqrt{R^2 - r_p^2}\right).$$

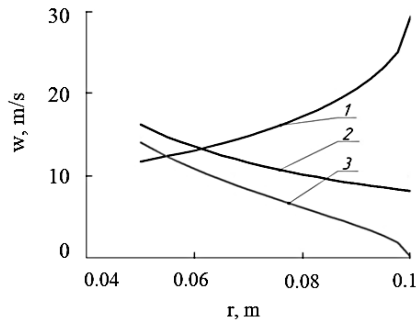

Fig. 2. Profiles of the longitudinal (1), tangential (2) and radial (3) components of the gas velocity in the separation chamber of the cyclone (volumetric gas flow Q = 960 m^3/h). Cyclone separation chamber diameter – 200 mm

Рис. 2. Профили продольной (1), тангенциальной (2) и радиальной (3) составляющих скорости газа в разделительной камере циклона (объемный расход газа Q = 960 м^3/ч). Диаметр разделительной камеры циклона – 200 мм

Equations (12) and (13) are a system of interrelated nonlinear differential equations that can be solved numerically using MathCad or analytically, but after some simplifications. Evaluating the terms in equation (12) in order of magnitude, it is easy to see that the force of the hydrodynamic interaction is significantly less than the other two (the centrifugal force and the inertia force) when the particle moves in the radial direction. Ignoring this force, we come to the equation:

$$\frac{d^2 r_p}{dt^2} = \frac{1}{R}(v_\varphi)^2 = const \tag{14}$$

Here, the variable r_p is replaced by the radius of the separation chamber. From the point of view of calculation, this will lead to a certain underestimation of the cyclone efficiency in comparison with the real value. As the initial conditions for equation (14), we take:

$$r_p(0) = R_c;\ \frac{dr_p(0)}{dt} = w_r(R_c) = \frac{V}{R}\cos\beta\sqrt{R^2 - R_c^2} \tag{15}$$

The above conditions mean that all particles enter the separation chamber at the greatest distance from its wall, and their initial velocity does not differ from the gas velocity. These conditions are also the worst in terms of the release of particles from the gas stream.

The solution of equation (14), satisfying the initial conditions (15), is the function:

$$r_p(t) = R_c + Rln\frac{R}{R-t\,w_r(R_c)}. \quad (16)$$

The resulting expression makes it possible to determine the time T_r, for which the particle, when moving in the radial direction, will reach the chamber wall:

$$T_r = \frac{R}{w_r(R_c)}\left(1 - e^{-\frac{R-R_c}{R}}\right). \quad (17)$$

Hence, as well as from condition (15), it can be seen that the time required to remove the particle from the flow depends solely on the geometric parameters (R, R_c, β) and the gas flow rate.

From the relation (16) it is not difficult to determine how the radial velocity of the particle changes with time:

$$v_r(t) = \frac{Rw_r(R_c)}{R-t\,w_r(R_c)}. \quad (18)$$

Using this ratio and the ratio (17), it is possible to determine how much the particle velocity changes during the time T_r. Really

$$\frac{v_r(T_r)}{v_r(0)} = \frac{\frac{Rw_r(R_c)}{R-w_r(R_c)\,T_r}}{w_r(R_c)} = e^{\frac{R-R_c}{R}} \quad (19)$$

Thus, when colliding with a wall, the particle velocity increases by $e^{\frac{R-R_c}{R}}$ times. The average particle velocity over the time interval (0, T_r) is:

$$\langle v_r\rangle = \frac{R-R_c}{T_r} = \frac{R-R_c}{R}w_r(R_c)\left(1 - e^{-\frac{R-R_c}{R}}\right)^{-1} \quad (20)$$

When analyzing the mass movement of dust particles in the separation chamber, the value of this velocity is a measure of their convective transport in the radial direction.

Let us now determine the time T_z in which the particle, in its longitudinal motion, will reach the exit from the separation chamber. The change in the longitudinal coordinate in time obeys equation (13). To its analytical solution on the one hand and preserving acceptable accuracy on the other replace function $w_z(r_p)$ value of the longitudinal velocity at $r = R_T$, considering the fact that in changing the radial coordinate from the R_c to the R_T value of the longitudinal velocity increases slightly (see Fig. 2). Then the equation for finding the dependence of $z_p(t)$ will take the form:

$$\frac{d^2z_p}{dt^2} + f\frac{dz_p}{dt} = fw_z(R_\text{T}). \quad (21)$$

As the initial conditions for this equation, we take:

$$zp(0) = 0;\ \frac{dz(0)}{dt} = w_z(R_c) = \frac{Q}{S} - \frac{1}{3}A\sqrt{R^2 - R_c^2}. \quad (22)$$

The second condition means that when stripping off the swirler blades, the velocities of the particles and gas coincide. The solution of equation (21) satisfying the initial conditions (22) is the function:

$$z_p(t) = w_z(R_T)t - \frac{1}{f}[w_z(R_T) - w_z(R_c)](1 - e^{-ft}). \quad (23)$$

The time T_z is found from the condition $z_p(T_z) = h$, which leads to a transcendental equation with respect to the target value:

$$T_z = \frac{h}{w_z(R_\text{T})} + \frac{1}{f}\left[1 - \frac{w_z(R_c)}{w_z(R_\text{T})}\right]\left(1 - e^{-fT_z}\right). \quad (24)$$

The solution of the inequality $T_z > T_r$, which includes all the geometric parameters of the cyclone and the volumetric gas flow rate Q, makes it possible to determine the minimum size of particles that, in principle, can be captured by this cyclone. In addition, the time T_z can be considered as the average residence time of particles in the separation chamber.

To assess the efficiency of the cyclone, depending on its geometric parameters and gas flow rate, we will follow the change in the concentration of dust particles in the elementary layer of the gas suspension as it moves in the chamber.

The concentration of particles in the layer under consideration depends on the time and the radial coordinate. In this case, the particle concentration changes due to two mechanisms: convection at a speed of $\langle v_r\rangle$ in the direction of the chamber wall and reverse mixing due to turbulence, particle collision and possible secondary entrainment of particles that have already reached the wall. Thus, the concentration of particles $C(t,r)$ in the layer obeys the equation of nonstationary convective diffusion, in which the variables t and r change at intervals (0, T_z) and (R_c, R), respectively:

$$\frac{\partial C}{\partial t} + \langle v_r\rangle\frac{\partial C}{\partial r} = D_{ef}\frac{\partial^2 C}{\partial r^2} \quad (25)$$

Here D_{ef} is the effective particle backmixing coefficient. The initial condition for this equation is: $C(0, R_c) = C_н$, where the latter value is equal to the concentration of particles in the initial flow.

It is not difficult to make sure that the solution of equation (25) satisfying the initial condition is the function:

$$C(t,r) = C_\text{н}exp\left\{\frac{1}{2}Pe_{ef}\frac{(r-R_c)}{R} - \frac{\langle v_r\rangle^2}{4D_{ef}}t\right\} \quad (26)$$

The Pe_{ef} number is calculated through the effective backmixing coefficient and the average particle velocity in the radial direction: $Pe_{ef} = \frac{\langle v_r\rangle R}{D_{ef}}$. Then the degree of purification F can be estimated by the value of the ratio:

$$F = \frac{C_\text{н} - C(T_z,R_c)}{C_\text{н}} = 1 - exp\left(-\frac{\langle v_r\rangle^2 T_z}{4D_{ef}}\right) \quad (27)$$

Here $C(T_z, R_c)$ is the concentration of particles in the gas leaving the separation chamber through the outlet pipe for the purified gas.

The ratio (27) allows us to trace the dependence of the cyclone efficiency on the geometric parameters of the separation chamber, the size of dust particles and the gas suspension flow rate. In this case, the value $\langle v_r \rangle$ is calculated using the ratio (20), and the time T_z is calculated using the ratio (24). The value of the effective mixing coefficient can be determined at the stage of preliminary experiments by matching the experimental and calculated data.

EXPERIMENTAL PROCEDURE

To assess the adequacy of the proposed mathematical model and the obtained solutions, experimental studies were carried out on the installation with a direct-flow cyclone and swirlers, the blade profile of which provided a smooth, shock-free gas suspension inlet [30]. The angle of blade twist in the swirlers was 600, 450 and 300. The gas suspension flow rate varied in the range of 270 to 1270 m^3/h. Quartz flour with a dispersion of 15 μm, 20 μm, 30 μm and 50 μm was used as the solid phase. The concentration of the solid phase in the air flow was kept constant and amounted to 100 g/m^3.

RESULTS AND ITS DISCUSSION

The obtained results showed a good convergence of the calculated and experimental values of the gas phase purification degree at different cyclone operating modes and the angle of blade twist, as well as the geometric parameters of the cyclone. Figures 3 and 4 illustrate the dependences of the cyclone efficiency on the gas velocity at various values of the twist angle and the ratio between the radii of the central pipe and the separation chamber. It is not difficult to obtain similar dependences on other geometric parameters of the cyclone. The D_{ef} coefficient depends both on the velocity of the gas suspension and on the twist angle. Therefore, the method for calculating the efficiency of a cyclone at a given flow rate and geometric parameters assumes its preliminary determination. So, at a twist angle of 60° and a gas velocity of 12 m/s, the coefficient D_{ef} = 0,224 m^2/s. The dependences shown in the figures have a pronounced maximum corresponding to the optimal gas velocity in the separation chamber. When operating cyclones, the value of the optimal speed is easily determined using the obtained relations.

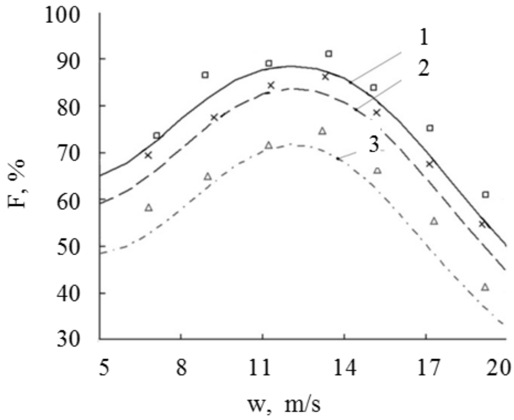

Fig. 3. Dependence of the cleaning efficiency on the gas velocity at twist angles β: 1 – 600, 2 – 450, 3 – 300; Δ, ×, □ - experimental data

Рис. 3. Зависимость эффективности очистки от скорости газа при углах закручивания β: 1 – 600, 2 – 450, 3 – 300; Δ, ×, □ - опытные данные

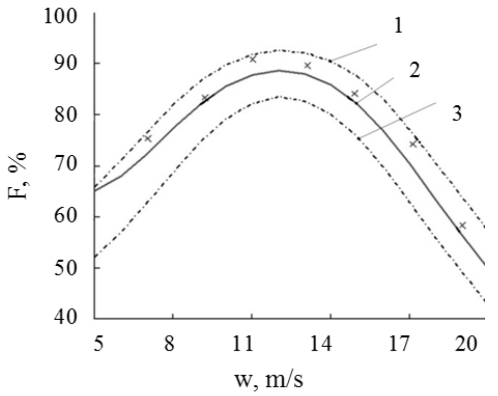

Fig. 4. Dependence of the cyclone efficiency on the ratio between the inner and outer radii of the separation chamber: 1 – R_c/R = 0.467, 2 – R_c/R = 0.667, 3 – R_c/R = 0.867; × – experimental data at R_c/R = 0.667

Рис. 4. Зависимость эффективности циклона от соотношения между внутренним и наружным радиусами разделительной камеры: 1 – R_c/R = 0,467, 2 – R_c/R = 0,667, 3 – R_c/R = 0,867; × – опытные данные при R_c/R = 0,667

CONCLUSIONS

The ratios obtained in the work, linking the geometric parameters of the cyclone with its efficiency and the most important hydrodynamic characteristics, allow us to build a method for calculating the cyclone at the design stage, as well as a method for calculating the optimal speed of dusty gas at the operation stage.

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