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Andrii CHEILYTKO
Sergii ILIN
Zaporizhzhya National University, Ukraine

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RESEARCH OF CYCLONE CHARACTERISTICS FOR DRY CLEANING OF GASES FROM DUST

Abstract: *The development and application of new, more efficient dust collection units that will help reduce emissions and conserve some very valuable resources for production is an important area of research. With the growth of innovation in technological enterprises, the number of harmful emissions into the atmosphere is growing. Thus, the ecological condition of the environment deteriorates. The basic analytical dependences which are necessary for construction of a technique of carrying out experiments and calculations of dust catching for concrete working conditions are developed. Methods of calculating cyclones as vortex devices and research of cyclone operation for air purification from dust were investigated. On the basis of the used basic theoretical positions of heat and mass transfer and thermodynamics at carrying out analytical researches the mathematical model was offered. Calculations of new designs of modern cyclones to obtain their geometric dimensions, resistance and dust capture efficiency were presented. Modern cyclones are designed to more effectively remove dust from the air during various types of work.*

Keywords: *modern cyclone, dust collection, mathematical modelling.*

Introduction

In connection with the UN Development Strategy, one of the four main principles is ecology. In the field of thermal energy, the development and application of new, more efficient dust cleaning units, which will help reduce emissions into the atmosphere and save some very valuable resources for production, is of particular interest. Because with the growth of innovation in technological enterprises, the number of harmful emissions into the atmosphere increases. Thus, the ecological condition of the environment deteriorates.

There are several technologies for cleaning the air from dust. Particular attention is paid to cyclone cleaning. The most reliable results from various experiments can be obtained through experiments conducted on physical models. A separate experiment must be performed for each specific design. More general results are obtained using a mathematical model of hydromechanical processes of cyclones. Creating a mathematical model of the movement of dust particles in a swirling flow will assess the impact of various factors on the efficiency of dust control in cyclones.

To determine the nature of the motion of particles transported by the flow in swirling dust air streams, and their deposition on a solid surface requires the calculation of dynamic equations for turbulent flow and particles used the method of calculating gas-dynamic flows, which combines the properties of Euler and Lagrangian approaches, each is a method of “particles in a cell”. An approximation model of the motion of dust particles in the apparatus was created, with the help of which for each type of aerosol the trajectories of its motion in the apparatus are constructed theoretically, having different design parameters of the dust collector. And thus in the future select the most efficient dust collector for each specific type of technological production.

Another new cyclone installation has a relief surface with detachable zones and an upward-facing truncated cone with 2 times lower aerodynamic drag compared to smooth-walled. The reduction of the hydraulic resistance of the cyclone is facilitated by the presence of detachable zones on the relief surfaces. Simulation of turbulent gas flow in a new type of dust collector shows that the calculations of the cyclone flow pattern agree qualitatively satisfactorily with the experimental data; the decrease in the hydraulic resistance of the cyclone with the internal elements in comparison with the smooth-walled devices is due to the adjustment of the flow: a decrease in the tangential velocity with a simultaneous increase in the axial flow velocity in the cyclone.

Literature review

Industrial enterprises purify the air that is supplied not only to the shops, departments, but also removed from them into the atmosphere to prevent air pollution in the enterprise and the residential areas attached to it [1].

Dedusting devices are divided into dust collectors and filters.

Dust collectors include devices in which dust particles are deposited under the action of gravity and inertial forces with a change in speed and direction of air flow. Such devices are dust chambers, cyclones and other devices operating on the basis of centrifugal forces.

Filters are devices in which dusty air is purified by passing through mesh or porous materials (glass wool, gravel, coke, porous paper, fabric, metal mesh) [2].

Dedusting devices can be not only dry but also wet. When using wet dedusting devices, the efficiency of air purification from dust increases.

To date, both the theoretical basis for capturing dust and gas components and methods for calculating various equipment for these purposes have been developed.

Particular attention was paid to cyclone cleaning. The most reliable results can be obtained through experimental experiments conducted on physical models. But for each specific design you need to conduct a separate experiment. More general results can be obtained using a mathematical model of hydromechanical processes of cyclones. Creating a mathematical model of the movement of dust particles in a swirling flow will assess the impact of various factors on the efficiency of dust control in cyclones [3].

To determine the nature of the motion of particles transported by the flow in swirling dust air streams, and their deposition on a solid surface requires the calculation of dynamic equations for turbulent flow and particles used the method of calculating gas-dynamic flows, which combines the properties of Euler and Lagrangian approaches, each is a method of “particles in a cell”. The nature of the motion of particles is significantly influenced by the conditions of their contact with impact with the surface of the dust collector body, and at sufficiently high speeds the reflection of the particlesaw. Mathematical modeling of the separation process reflects the relationship of the motion of solid particles in the apparatus with its efficiency, it allows to obtain the trajectory of particles in different parts of the apparatus, which calculates its efficiency for each type of dust, and it allows for each type of aerosol theoretically, having different design parameters of dust collectors, choose the most efficient design for each specific type of technological production [4].

Another new cyclone installation has a relief surface with detachable zones and an upward-facing truncated cone with 2 times lower aerodynamic drag compared to smooth-walled. The reduction of the hydraulic resistance of the cyclone is facilitated by the presence of detachable zones on the relief surfaces. Simulation of turbulent gas flow in a new type of dust collector shows that the calculations of the cyclone flow pattern agree qualitatively satisfactorily with the experimental data; the numerical values of the energy of turbulent pulsations for smooth-walled and new types of cyclones agree satisfactorily with experimental data on the efficiency of dust collection of these dust collectors; reduction of hydraulic resistance of a cyclone with internal elements in comparison with smooth-walled devices occurs owing to adjustment of a current.

Dust collectors and filters are used to clean the air from the dust removed by exhaust ventilation [5].

Dust collectors include dust chambers, inertial dust collectors and cyclones. The simplest dust collector for purification of the removed air are dust-depositing chambers which work is based on deposition of dust particles of air at low speed of its movement.

In louvered dust collectors, dust is released from the gas stream under the action of inertial forces when changing the direction of gas flow. With the help of louver plates installed in the flue, the gas flow is divided into two parts.

One stream is 80-90% of the total amount of gas and is largely free of dust, the other is 10-20% and it concentrates the bulk of the dust, which is then captured in a cyclone or other, quite efficient dust collector. The movement of gas through the cyclone is due to the pressure drop on the louver.

Of the inertial devices, cyclones have become the most widespread as more efficient and less expensive dust collectors for the rough cleaning of exhaust gases. This type of dust collector differs significantly from dust chambers both in design and principle of operation.

Cyclones have become widespread and are used to trap chips, sawdust and metal dust. Dusty air is supplied by a fan to the upper part of the outer cylinder of the cyclone.

In a cyclone, the air takes a rotational motion, as a result of which centrifugal force develops, mechanical impurities are thrown to the walls, from where they roll into the lower part of the cyclone, which has the shape of a truncated cone. Purified air through the inner cylinder of the cyclone, the so-called exhaust pipe, comes out. The lower part of the cyclone is periodically cleaned.

In the LIOT cyclone, the separation of dust from the air occurs using centrifugal forces arising in the rotational flow of dusty air descending along a helical line. Dust particles are squeezed to the walls and go down. The purified air exits through the central pipe. Cleaning efficiency up to 85%.

Multicyclones are installed at thermal power plants for pre-treatment in combination with other ash capture methods.

A multicyclone is a combination in one unit of many small cyclones with a diameter of 300-400 mm with a total supply of polluted air and a common hopper for ash that has settled. Up to 65-70% of ash is retained in the multicyclone.

Of interest are wet type dust collectors, which have good efficiency. These include centrifugal scrubbers, washing cyclones, Venturi dust collectors, foam dust collectors and others.

Also worth noting are electrostatic precipitators and ultrasonic dust collectors. The principle of operation of the electrostatic precipitator is based on the fact that dust particles, passing with the air through an electric field, receive charges and, attracting, settle on the electrodes, from which they are then removed mechanically.

Ultrasonic dust collectors use the ability of dust particles under the action of a powerful sound stream to coagulate, i.e. to coagulate in a flake, which is very important for the capture of aerosols from the air [6]. These flakes fall into the hopper. The sound effect is created by a siren. The sirens which are issued can be applied in dust-cleaning installations with a productivity up to 15000 m^3/h.

Problem formulation

The described devices for air purification, shops and departments of industrial enterprises, which are removed to the atmosphere by exhaust ventilation, do not exhaust all types of dust collectors and filters used to prevent air pollution in cities.

Despite the existing variety of cleaning devices, cyclones are now the most common for cleaning gases from dust due to their low cost, simplicity and ease of operation. In this regard, the development of perforated cyclone requires research aimed at increasing the degree of dust capture from gases, which is considered in this paper.

The calculation of cyclones is reduced to obtaining their geometric dimensions, resistance and dust collection efficiency.

Currently, the most common method of calculating cyclones is the method of generalization and use of indicators obtained by testing cyclones in industrial conditions or on stands.

The method of calculating cyclones using experimental data is based on determining the diameter of the cyclone by the formula [7]:

$$D_c = \sqrt{\frac{Q_g}{900 \cdot \pi \cdot W_{\text{con}}}} \tag{1}$$

where:

Q_g – volumetric gas flow through the cyclone, m³/h;

W_{con} – conditional flow rate of gas in the cyclone, m/s.

Cyclone resistance is determined by the following equation [8]:

$$\Delta p = \xi_0 \cdot \frac{W_{\text{con}}^2 \cdot \rho}{2} \tag{2}$$

or

$$\Delta p = \xi_0 \cdot \frac{W_{\text{con}}^2 \cdot \gamma}{2g} \tag{3}$$

The speed of the gas in the inlet of the cyclone is determined by the formula:

$$W_{\text{in}} = \sqrt{\frac{2 \cdot \Delta p}{\xi_{\text{in}} \cdot \rho}} \tag{4}$$

High emissions and low efficiency of cyclones led to significant residual dust in the atmosphere, which required both the development of a new design of cyclones and new theoretical solutions and systems for dedusting of gases. Thus, the generalizing design parameter of cyclones is found in the work and its optimal value is determined, which provides the maximum efficiency of the cyclone, and the analytical dependence characterizing the length of the vortex chamber required to capture the minimum dust particles $d_{\min}$ is obtained.

$$L_{\max} = \frac{9D_c}{\varepsilon^2} \cdot \frac{\mu}{\rho_m} \cdot \frac{\sum f}{\pi \cdot R_0 \cdot R_p \cdot \cos\beta} \cdot \frac{R_c}{R_0} \cdot \frac{1}{W_0} \cdot \frac{\left(\frac{R_p}{R_c}\right)^4 \cdot \frac{1}{\cos\beta}}{\left[1 + \frac{R_p}{R_c} + \left(\frac{R_p}{R_c}\right)^3 + \left(\frac{R_p}{R_c}\right)^4\right] \cdot d_{\min}^2} \tag{5}$$

where:

D_c – inner diameter of the cyclone;

μ – coefficient of dynamic viscosity of the cleaned medium;

ρ_m – actual density of the powder;

$\sum f$ – total area of the pipes of the supply of the cleaned medium in the cyclone;

R_0 – twisting arm (distance from the axis of the supply pipe to the axis of rotation of the cyclone);

R_p – inner radius of the cyclone pipe;

W_0 – speed of the cleaning medium at the outlet of the supply pipe.

In the development of large cyclones, their ability to capture dust can be determined on a model of smaller size, but this requires dependencies, which could be converted from model to nature.

Using the dependence determine the size of the dust, which will be caught by the cyclone at the length L of its chamber:

$$d_{\min} = \frac{3D_c}{\varepsilon} \cdot \sqrt{\frac{\mu}{\rho_m} \cdot \frac{1}{W_0} \cdot \frac{\dfrac{\sum f}{\pi \cdot R_0 \cdot R_p \cdot \cos\beta} \cdot \dfrac{R_c}{R_0} \cdot \left(\dfrac{R_p}{R_c}\right)^4}{\left[1 + \dfrac{R_p}{R_c} + \left(\dfrac{R_p}{R_c}\right)^3 + \left(\dfrac{R_p}{R_c}\right)^4\right] \cdot L \cdot \cos\beta}} \tag{6}$$

The speed of movement of the cleaned environment at the outlet of the supply pipe is determined:

$$W_0 = \sqrt{\frac{2\Delta P}{\xi_{\text{in}} \cdot \rho_g}} \tag{7}$$

where:

ΔP – pressure drop on the cyclone;

ρ_g – density of the medium to be cleaned;

ξ_{in} – coefficient of resistance of the cyclone, which is determined as follows:

$$\xi_{\text{in}} = \left[\frac{\dfrac{R_0}{R_c} \cdot \cos\beta}{\phi_0 \cdot \dfrac{R_p}{R_c}\left(1 - \dfrac{\sum f}{\pi \cdot R_0 \cdot R_p \cdot \cos\beta} \cdot \dfrac{1}{4\text{tg}\alpha_1} \cdot \dfrac{1}{\varepsilon}\right) \cdot \cos\alpha_1}\right]^2 \tag{8}$$

We obtain the dependence that determines the relationship between the geometric dimensions of the cyclone and its ability to capture dust particles with a diameter of $d_{\min}$ in the following form:

$$d = \frac{3D_c}{\varepsilon \sqrt[4]{\dfrac{2\Delta P}{\rho_g}}} \cdot \sqrt{\frac{\mu}{\rho_m} \cdot \frac{\dfrac{\sum f}{\pi \cdot R_0 \cdot R_p \cdot \cos\beta}}{\phi_0\left(1 - \dfrac{\sum f}{\pi \cdot R_0 \cdot R_p \cdot \cos\beta} \cdot \dfrac{1}{4\text{tg}\alpha_1} \cdot \dfrac{1}{\varepsilon}\right) \cdot \cos\alpha_1} \cdot \frac{\left(\dfrac{R_p}{R_c}\right)^4}{\left[1 + \dfrac{R_{mp}}{R_c} + \left(\dfrac{R_p}{R_c}\right)^3 + \left(\dfrac{R_p}{R_c}\right)^4\right] \cdot L}} \tag{9}$$

For geometrically similar cyclones:

$$\frac{d}{D_c} = \frac{C}{\varepsilon} \cdot \sqrt[4]{\frac{\rho_g}{2\Delta P}} \cdot \sqrt{\frac{\mu_g}{\rho_m}} \cdot \sqrt{\frac{1}{L}} \tag{10}$$

where C = const, and

$$C = 3 \cdot \sqrt{\frac{\dfrac{\sum f}{\pi \cdot R_0 \cdot R_p \cdot \cos\beta}}{\phi_0\left(1 - \dfrac{\sum f}{\pi \cdot R_0 \cdot R_p \cdot \cos\beta} \cdot \dfrac{1}{4\text{tg}\alpha_1} \cdot \dfrac{1}{\varepsilon}\right) \cdot \cos\alpha_1} \cdot \frac{\left(\dfrac{R_p}{R_c}\right)^4}{\left[1 + \dfrac{R_p}{R_c} + \left(\dfrac{R_p}{R_c}\right)^3 + \left(\dfrac{R_p}{R_c}\right)^4\right]}} \tag{11}$$

We determine the constant C:

$$C = \frac{d}{D_c} \cdot \varepsilon \cdot \sqrt[4]{\frac{2\Delta P}{\rho_g}} \cdot \sqrt{\frac{\rho_m}{\mu_g}} \cdot \sqrt{L} \quad (12)$$

For two similar cyclones, one of which is denoted by 1, the other – 2, we obtain:

$$\frac{d_1}{D_{c1}} \cdot \varepsilon_1 \cdot \sqrt[4]{\frac{2\Delta P_1}{\rho_{g1}}} \cdot \sqrt{\frac{\rho_{m1}}{\mu_{g1}}} \cdot \sqrt{L_1} = \frac{d_2}{D_{c2}} \cdot \varepsilon_2 \cdot \sqrt[4]{\frac{2\Delta P_2}{\rho_{g2}}} \cdot \sqrt{\frac{\rho_{m2}}{\mu_{g2}}} \cdot \sqrt{L_2} \quad (13)$$

From where the proportion of dust caught in the first cyclone will be determined by the size of the captured dust of the second cyclone according to the following expression:

$$d_1 = d_2 \cdot \frac{D_{c1}}{D_{c2}} \cdot \frac{\varepsilon_2}{\varepsilon_1} \cdot \left(\frac{\Delta P_2}{\Delta P_1}\right)^{0.25} \cdot \left(\frac{\rho_{g1}}{\rho_{g2}}\right)^{0.25} \cdot \left(\frac{\rho_{m2}}{\rho_{m1}}\right)^{0.5} \cdot \left(\frac{\mu_{g1}}{\mu_{g2}}\right)^{0.5} \cdot \left(\frac{L_2}{L_1}\right)^{0.5} \quad (14)$$

since $\mu = \rho \cdot \nu$, then

$$\left(\frac{\rho_{g1}}{\rho_{g2}}\right)^{0.25} \cdot \left(\frac{\rho_{g1}}{\rho_{g2}}\right)^{0.5} \cdot \left(\frac{\nu_1}{\nu_2}\right)^{0.5} = \left(\frac{\rho_{g1}}{\rho_{g2}}\right)^{0.75} \cdot \left(\frac{\nu_{g1}}{\nu_{g2}}\right)^{0.5} \quad (15)$$

then

$$d_1 = d_2 \cdot \frac{D_{c1}}{D_{c2}} \cdot \frac{\varepsilon_2}{\varepsilon_1} \cdot \left(\frac{\Delta P_2}{\Delta P_1}\right)^{0.25} \cdot \left(\frac{\rho_{г1}}{\rho_{г2}}\right)^{0.75} \cdot \left(\frac{\rho_{m2}}{\rho_{m1}}\right)^{0.5} \cdot \left(\frac{\nu_{г1}}{\nu_{г2}}\right)^{0.5} \cdot \left(\frac{L_2}{L_1}\right)^{0.5} \quad (16)$$

or

$$\frac{d_1}{d_2} = \frac{D_{c1}}{D_{c2}} \cdot \frac{\varepsilon_2}{\varepsilon_1} \cdot \left(\frac{\Delta P_2}{\Delta P_1}\right)^{0.25} \cdot \left(\frac{P_{g1}}{P_{g2}}\right)^{0.75} \cdot \left(\frac{T_{g2}}{T_{g2}}\right)^{0.75} \cdot \left(\frac{\mu_1}{\mu_2}\right)^{0.75} \cdot \left(\frac{\rho_{m2}}{\rho_{m1}}\right)^{0.5} \cdot \left(\frac{\rho_{m2}}{\rho_{m1}}\right)^{0.5} \cdot \left(\frac{\nu_{g1}}{\nu_{g2}}\right)^{0.5} \cdot \left(\frac{L_2}{L_1}\right)^{0.5} \quad (17)$$

If under index 2 to denote a model cyclone, and under index 1 – a natural variant, the test results of a model cyclone for dust capture with a diameter of d_2 can be converted into dust capture by a natural cyclone d_1.

Results and Discussions

Thus, if the cyclone model is made reduced by 10 times compared to nature, i.e., $D_{c1} = 10 \cdot D_{c2}$, $L_1 = 10 \cdot L_2$, and the other values of the dependence were the same, in this case $d_2 = d_{2\min}$ = 20 μm, then:

$$d_{1\min} = 20 \cdot \frac{10 \cdot D_2}{D_2} \cdot \left(\frac{L_2}{10 \cdot L_2}\right)^{0.5} = 20 \cdot \frac{10}{3.16} \quad (18)$$

That is, it increases 3 times, which will reduce efficiency.

It is known that as the diameter of the cyclone increases, its efficiency decreases, as evidenced by the experimental data presented in Figure 1.

Gas density $\rho_g = \dfrac{P_g}{R \cdot T_g}$, then

$$\left(\frac{\rho_{g1}}{\rho_{g2}}\right)^{0.75} = \left(\frac{P_{g1}}{R_1 \cdot T_{g1}} \cdot \frac{R_2 \cdot T_{g2}}{P_{g2}}\right)^{0.75} = \left(\frac{P_{g1}}{P_{g2}}\right)^{0.75} \cdot \left(\frac{T_{g2}}{T_{g1}}\right)^{0.75} \cdot \left(\frac{R_2}{R_1}\right)^{0.75} \tag{19}$$

$$\varepsilon = \frac{M_{\text{Out}}}{M_{\text{in}}} = \frac{C_1 \cdot \cos\alpha_1 \cdot R_{mp}}{W_0 \cdot R_0} = \frac{C_{ump} \cdot R_{mp}}{W_0 \cdot R_0} = C_1 \cdot \cos\alpha_1 \cdot \frac{R_p}{R_0} \cdot \sqrt{\frac{\xi_{\text{in}} \cdot \rho_z}{2\Delta P}} = \\ = \frac{Q}{F_p} \cdot \frac{\cos\alpha_1}{\sin\alpha_1} \cdot \frac{R_{mp}}{R_0} \cdot \frac{\sum f}{Q} = \frac{\sum f}{F_p} \cdot \frac{R_{mp}}{R_0} \cdot \text{ctg}\alpha_1 \tag{20}$$

$$\frac{\varepsilon_2}{\varepsilon_1} = \frac{\sum f_2}{\sum f_1} \cdot \frac{F_{p1}}{F_{p2}} \cdot \frac{R_{p2}}{R_{p1}} \cdot \frac{R_{01}}{R_{02}} \cdot \frac{\text{tg}\alpha_2}{\text{tg}\alpha_1} = \frac{\sum f_2}{10\sum f_2} \cdot \frac{10F_{p2}}{F_{p2}} \cdot \frac{10R_{02}}{R_{02}} = 10 \tag{21}$$

$$\frac{\varepsilon_2}{\varepsilon_1} = \frac{\left(\dfrac{\sum f}{F_p}\right)_2}{\left(\dfrac{\sum f}{F_p}\right)_1} \cdot \frac{\left(\dfrac{R_p}{R_0}\right)_2}{\left(\dfrac{R_p}{R_0}\right)_1} \cdot \frac{(\text{ctg}\alpha_1)_2}{(\text{ctg}\alpha_1)_1} = 1 \tag{22}$$

since they are geometrically similar.

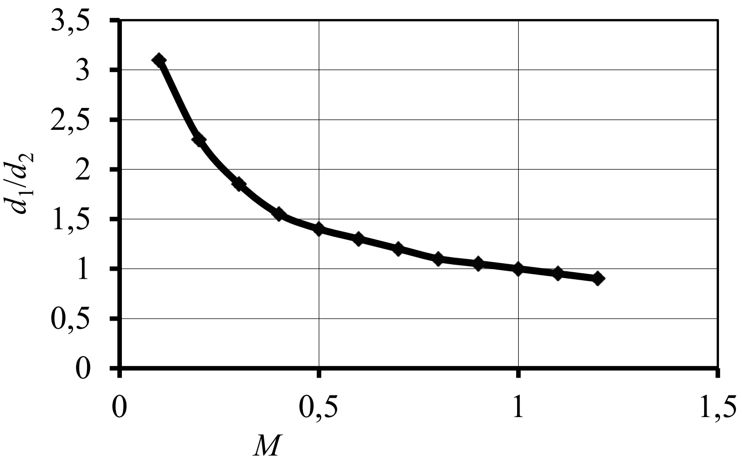

FIGURE 1. *Changing the diameter of the captured dust by a natural cyclone from changing the scale of the model cyclone*

In order for the gas to flow through the dust bypass pipe (flow) from the hopper to the entrance to the dust collector, and not vice versa, it is necessary to calculate the minimum cross-sectional area of the Venturi pipe so that the pressure in this section would be less than the hopper pressure. The movement of gas flows, the values of cross-sectional areas and pressures are showing Figure 2. Experiments have shown that it is the high pressure observed in the upper perforated chamber of the dust collector.

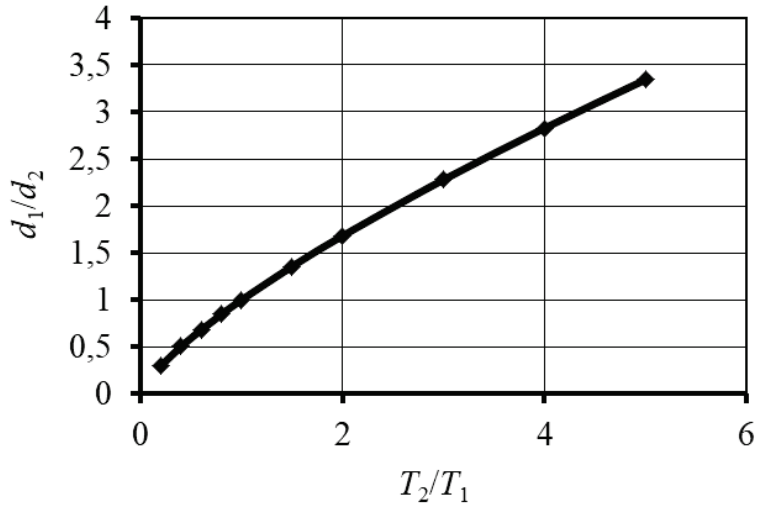

***FIGURE* 2.** *The effect of temperature changes on the diameter of the trapped dust*

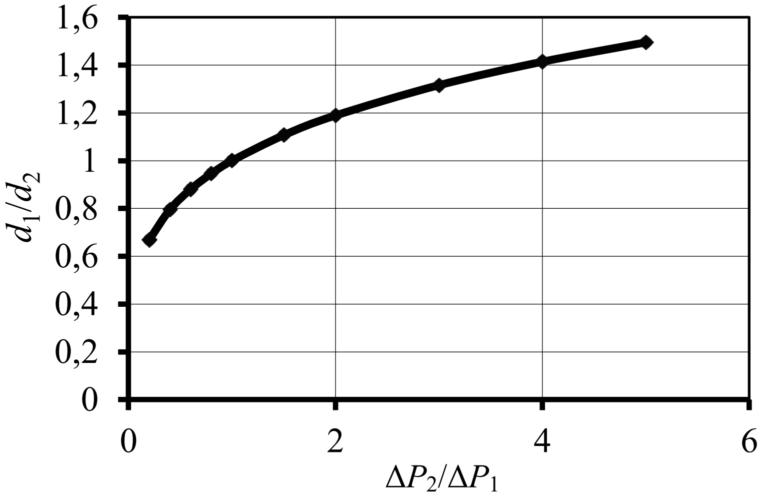

***FIGURE* 3.** *Influence of change of pressure difference on diameter of the caught dust*

Conclusions

Cyclones are widely used in industry. There is a great variety of works devoted to the study of the parameters of cyclones and are private, episodic. The great variety of the offered dependences for calculation of their parameters testifies to complexity of the solved scientific problem which does not have the unambiguous answer yet. Despite the adequacy of aerodynamic processes occurring in cyclones, there is currently no single method for calculating the characteristics of the most common in the industry cyclone-vortex devices. The lack of scientifically sound theoretical developments summarizing the large accumulated material for the study of various cyclones prevents the development of scientific and technological progress in the field of creation and improvement of existing cyclones.

As a result of the theoretical researches carried out in work analytical dependences of the basic parameters of a dust collector are defined. These dependencies make it possible to conduct experimental studies of the dust collector and build a streamlined method of calculating dust collectors of new design, which will allow you to design dust collectors with maximum efficiency for specific operating conditions.

Conflicts of Interest: The author declares no conflict of interest.

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