Aerodynamic model of centrifugal cleaning in a once-through cyclone

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Abstract. This work examines aerodynamic modeling of the process of air cycloning in a direct-flow cyclone. The most important technological operation in the food industry is to achieve a high degree of dusty air purification. The practice of operating cyclones testifies to the discrepancy between the actual efficiency of the apparatus and the real capabilities of dust collecting installations. The modern development of industry is characterized by an ever-increasing intensification of various technological processes, which is accompanied by significant dust formation. The problem of collecting dust affects almost all branches of modern production. These are the production of building materials, metallurgy, woodworking, chemical and food industries. In this regard, the problem of maintaining the cleanliness of the air basin of cities arises, and increased requirements are imposed on dust-collecting equipment. Along with the requirement to ensure minimum dust emissions, dust-collecting equipment should be completely reliable for a long time of operation and not require large costs for installation and maintenance. For dust collection of dust, cyclones are now widely used, the principle of which is based on centrifugal separation of the mixture. In the food industry, the most widespread are cyclones of spray units "Niro-Atomizer", "VRA-4", "Nema-500", A1-ORCH. The cyclones of the listed installations differ from each other in the number of devices installed in the dust collection system, design features and aerodynamic modes of air purification.

1. Introduction

In the agro-industrial complex, cyclonic cleaning of dusty air has become widespread, in the processing industries - flour-grinding, dairy, confectionery industries, at elevators.

However, the aerodynamic processes occurring during dust collection in a cyclone, despite their apparent simplicity, have not yet been fully studied. This is also indicated by the presence of a large variety of designs of cyclone devices, the lack of scientific substantiation of the optimal number of installed devices in the cleaning system and rational aerodynamic modes of the process. All this leads to significant emissions of food dust and environmental disruption in industrial areas. According to the majority of scientists and engineers, the process of dust cleaning in a cyclone is determined by the aerodynamic situation in the apparatus [1-4].

Depending on the method of supplying air to the cyclone, cyclones with tangential and spiral air supply are distinguished. All other things being equal, cyclones with a spiral feed have a higher dust removal efficiency. Cyclones provide average air purification from dry non-sticking dust at its signifi-
cant concentration in the cleaned air. The proportion of captured fine dust in cyclones is small. Cyclones have a number of advantages - simplicity of the device, reliability in operation with relatively low capital and operating costs.

The main disadvantage of cyclones is the low fractional efficiency of the apparatus in capturing dust particles ranging in size from 5 to 10 microns. In this regard, the use of new effective designs of devices, the use of small-diameter cyclones has succeeded in increasing the fractional efficiency of cyclones.

Active scientific developments carried out recently made it possible to establish the basic laws of the dust collection process and substantiate practical recommendations for the creation of new highly efficient devices and rational aerodynamic dust cleaning modes [5-13].

2. Research objects and methods
The object of the study is the aerodynamic process of cycloning dusty air in a cyclone apparatus; the analytical-experimental method with the use of digital technologies is adopted as the basis for the study.

3. Aerodynamic process modeling
Let us consider numerical aerodynamic modeling of the process of air mass movement in a direct-flow cyclone apparatus. Let us determine the change in the value of the residual pressure (rarefaction), the air flow velocity in an arbitrary cross-section of the conical part of the cyclone, from the design parameters of the apparatus. To determine the parameters of the separation process, we will use the theoretical provisions developed by D.L. Josiah, D. Leith, L. Theodora, V. De Paola [1,2].

We assume that the air flow during rotation in the cyclone has a speed $v$, pressure $p$ and density $\rho$. The geometric dimensions of the cyclone are shown in Fig. 1.

Let us denote the axis $Z$ – the cyclone axis, let the origin be located at the base of the apparatus at the point $O$. The radius of the cylindrical part of the cyclone is denoted by $R_1$, radius of the lower base of the conical part of the cyclone – $R_2$, the height of the conical part of the cyclone – $H_c$.

Let's draw through the points ABCDM plane perpendicular to the cyclone axis, in section we have a circle with a radius $R_{st}$, Figure 1 shows that $R_{st}$ lies in the range from $R_2$ to $R_1$. The distance from the cyclone axis to point $C$ is denoted by $r$ – variable radius ($r\in[0, R_{st}]$). The height of the cross section of the cone is denoted by $Z$. The angle between the generatrix of the cone and the cyclone axis – $\gamma$.

By the triangle $\Delta ABN$ it follows:

$$tg(\gamma) = \frac{R_1 - R_2}{H_c},$$

it is also known that in a triangle $\Delta MDN$:

$$tg(\gamma) = \frac{R_{st} - R_2}{Z},$$

equating values $tg(\gamma)$ from the above relations we obtain:

$$R_{st} = R_2 + \frac{Z}{H_c} \cdot (R_1 - R_2) \quad (1)$$

Assuming that for the distribution of the tangential velocity of the spiral flow in all elements of the section, the area law (Kepler's law) is valid, we will establish the dependence of the change in the rarefaction of air in the plane of the cross section of the cyclone on the wall of the apparatus body $R_{st}$ to radius - $r$: Tangential speed $\theta_{tang} = \theta\cdot\cos(\alpha)$ spiral flow obeys the law of areas, i.e.:

$$\theta_{tang} = \frac{L}{r} \quad (2)$$
where: \( L \) – volumetric second air flow rate, \( m^3/s \);
\( f \) - elementary flow area, \( m^2 \).

The area of movement of the dusty flow is determined by the formula:

\[
\int_{0}^{f} df = a \cdot r \cdot \int_{R_{st}}^{R} \frac{dr}{r} \Rightarrow f = a \cdot r \cdot (lnR - lnR_{st})
\]  

(3)

where \( a \) - spiral flow height, m;
\( R \) – cyclone radius (\( R=R_{1} \)), m;
\( R_{cm} \) – conical radius at the wall part of the cyclone, m;
\( r \) - variable radius at an arbitrary reference point, m.

Figure 1. Geometric parameters of the direct-flow cyclone

The movement of the air flow in the closed annular space of the cyclone is a steady vortex circulating flow. Let us establish a relationship between the absolute flow rate, pressure and air density at an arbitrary point of the spiral flow, for this we use the Bernoulli integral [14]:

\[
\frac{\vartheta^2}{2} + \int_{P_{st}}^{P} \frac{dP}{\rho} - \text{const}
\]

(4)
We accept a tangential supply of air flow to the cyclone at an angle of inclination of the inlet pipe \( \alpha_1 = 0 \), consequently, \( \cos(\alpha_1) = 1 \) and \( v = v_{\text{tang}} \).

Due to the isothermal process of air purification, according to the equation of state for an ideal gas, we have:

\[
\rho = \rho_{\text{st}} \frac{P}{P_{\text{st}}} \tag{5}
\]

Substitute density \( \rho \) from expression (5) in (4) we will have:

\[
\frac{\varrho^2}{2} + \frac{P_{\text{st}}}{\rho_{\text{st}}} \cdot \int \frac{dP}{P} = C_o
\]

Calculating integral (6), we obtain:

\[
C_o = \frac{\varrho^2}{2} + \frac{P_{\text{st}}}{\rho_{\text{st}}} \cdot \ln\left( \frac{P}{P_{\text{st}}} \right)
\]

Integration constant \( C_0 \) we define from the boundary conditions

\( P = P_{\text{st}}, \ v = v_{\text{st}} \) при \( r = R_{\text{st}} \), тогда:

\[
C_o = \frac{\varrho^2_{\text{st}}}{2} \tag{8}
\]

After simple transformations, we obtain the following formula:

\[
\varrho = \varrho_{\text{st}} \cdot \frac{R_{\text{st}}}{r} \tag{9}
\]

Substituting the value of the flow rate from (9) into equation (7), we obtain:

\[
\frac{\varrho^2_{\text{st}}}{2} = \frac{1}{2} \left( \frac{\varrho_{\text{st}} \cdot R_{\text{st}}}{r} \right)^2 + \frac{P_{\text{st}}}{\rho_{\text{st}}} \cdot \ln\left( \frac{P}{P_{\text{st}}} \right)
\]

Transforming expression (10), we obtain the formula for calculating the residual pressure in the cross section of the cyclone, depending on the housing wall (\( R_{\text{st}} \)) to an arbitrary reference point (radius \( r \)).

\[
P = P_{\text{st}} \cdot \exp \left[ \frac{\varrho^2_{\text{st}} \cdot \rho_{\text{st}}}{2 \cdot P_{\text{st}}} \left( 1 - \frac{R_{\text{st}}^2}{r^2} \right) \right], \ Pa \tag{11}
\]

Let us analyze dependence (11), consider two cases.

The first, when \( r = R_{\text{st}} \), in this case \( P = P_{\text{st}} \exp (0) = P_{\text{st}} \), the pressure on the surface of the conical part is determined by the value \( P_{\text{st}} \).

The second, when approaching the radius \( r \) to the central axis of the cyclone, the pressure value in this case asymptotically approaches positive infinity, which is practically unrealizable and this state characterizes the limited application of formula (11) in the area of the axial part of the cyclone.

Taking into account equation (11), the air flow velocity in the axial part of the cyclone (the vortex core, that is, at \( r = 0 \)) will be determined by the formula:

\[
\varrho = \sqrt{ \frac{2 \cdot P_{\text{st}} \cdot \ln\left( \frac{P}{P_{\text{st}}} \right)}{\rho_{\text{st}}}} \tag{12}
\]

From formula (12) it follows that the speed in the axial part of the cyclone does not depend on the height of the cross-section \( Z \) (see fig. 1) and design parameters of the conical part of the apparatus. The core of the vortex has a constant and maximum velocity of the gas flow along the axis of the apparatus, in a stationary mode of dust cleaning.
Transforming expression (12), we have:

\[
\frac{\rho_{st} \cdot V^2}{2} = P_{st} \cdot \ln \left( \frac{P}{P_{st}} \right),
\]

We multiply the left and right sides of expression (13) by the mass of the air flow - m, we obtain an expression for calculating the kinetic energy of the flow core:

\[
\frac{m \cdot V^2}{2} = \frac{m \cdot P_{st}}{\rho_{st}} \cdot \ln \left( \frac{P}{P_{st}} \right) \Rightarrow E = V \cdot P_{st} \ln \left( \frac{P}{P_{st}} \right),
\]

Based on the Mendeleev – Clapeyron equation, the equation of state for the gas \( PV = RT \), the specific kinetic energy of the flow (at \( m = 1 \text{ kg} \)) will be:

\[
E = R \cdot T \cdot \ln \left( \frac{P}{P_{st}} \right), J
\]

where: \( R \) - gas constant \([\text{for air } R = 287 \text{ J} / (\text{kg} \cdot \text{K})]\);
\( T \) - gas flow temperature, \( \text{K} \);
\( P \) - gas flow pressure in the vortex core, \( \text{Pa} \);
\( P_{st} \) - gas flow pressure in the near-wall part of the cyclone, \( \text{Pa} \).

Formula (15) allows you to calculate the kinetic energy of the circulating flow in the cyclone at known experimental values \( P \) and \( P_{st} \).

**Tables 1.** Design parameters of cyclone VRA-4

| Parameters                               | Symbol | Parameters            |
|------------------------------------------|--------|-----------------------|
| Full height, mm                          | H      | 5575                  |
| Height of the cylindrical part, mm       | \( H_c \) | 1450                  |
| Cyclone diameter, mm                     | \( D_c \) | 1800                  |
| Exhaust pipe diameter, mm                | \( D_p \) | 1060                  |
| Diameter, mm                             | \( d_1 \) | 800                   |
| Base diameter, mm                        | \( d_2 \) | 250                   |
| Exhaust pipe height, mm                  | h      | 1200                  |
| Inlet branch pipe, mm                    | \( a \times b \) | 650×650               |
| Outlet branch pipe, mm                   | \( a_1 \times b_1 \) | 700×700               |
| Attitude                                 | H/H_c | 3.84                  |
| Froude criterion                         | Fr     | 36.7                  |
| Number of cyclones                       | –      | 2                     |

![Figure 2. Cyclone VRA-4](image)

Figure 2. Cyclone VRA-4

Figure 3. The calculation of the residual air pressure depending on the height \( Z \) and the radius in the cross section of the conical part of the cyclone, at a tangential flow velocity equal to 15 m / s. The calculation is performed in the system MathCAD-15.
Figure 3. Calculation of the residual pressure of the gas flow in the cross section of the cyclone performed in the MathCAD Pro system

With a change in the height of the cross-section (Z) and the radius in the near-wall part of the cyclone (Rst), we obtain the full range of pressure diagrams in the cross-section of the conical part of the apparatus of the VRA-4 installation.

4. Research results

Table 2 shows the results of calculating the residual pressure with a change in height (Z) and distance in the cross-section of the apparatus (r).

| Height of the reference point of pressure (Z), from the base of the cyclone, m | Distance from the central axis to the reference point r, m | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
|---|---|---|---|---|---|---|---|---|---|
| 1.8 | 1.5 | 1.2 | 1.0 | 0.5 | 0.25 | 0.1 |
| 644 | 1046 | 1579 | 1995 | 3102 | 3584 | 3814 |
| 2589 | 2923 | 3240 | 3435 | 3836 | 3977 | |
| 3350 | 3536 | 3701 | 3799 | 3990 | | |
| 3666 | 3779 | 3878 | 3935 | | | |
| 3823 | 3897 | 3962 | | | | |
| 3910 | 3963 | 3999 | | | | |
| 3999 | | | | | | |

Figures 4-6 show the visualization of the symmetric change in the residual pressure in the direct-flow cyclone of the BPA-4 installation, at different values of Z - the height of the cross-section in the device.
**Figure 4.** Air pressure change in the cross section of the cyclone at a height of 1.8 m from the base of the apparatus

**Figure 5.** Air pressure change in the cross section of the cyclone at a height of 1.2 m from the base of the apparatus
5. Results and discussion

The results of analytical and experimental studies have shown that the residual air pressure in the closed space of the cyclone changes along the height of the vortex core, the minimum air pressure is at the base of the exhaust pipe of the apparatus. At the tangential air velocity at the cyclone inlet, the residual pressure in the vortex core is 644 Pa; when the swirling air flow moves down the cyclone, the residual pressure increases. For the investigated cyclone BPA-4, this value is 3102 Pa.

The developed aerodynamic model makes it possible to assess the relationship of aerodynamic parameters - pressure and gas flow velocity with the design parameters of a direct-flow cyclone apparatus.

The kinetic energy of the vortex core in the cyclone is calculated and amounts 15 m/s.

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