Numerical simulation of single-stage axial fan operation under dusty flow conditions

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Abstract: Assessment of the aerodynamic efficiency of the single-stage axial flow fan under dusty flow conditions based on a numerical simulation using the computational package Ansys-Fluent is proposed. The influence of dust volume fraction on the dependences of the air volume flow rate and the pressure drop on the rotational speed of rotor is demonstrated. Matching functions for formulas describing a pressure drop and volume flow rate in dependence on the rotor speed and dust content are obtained by numerical simulation for the single-stage axial fan. It is shown that the aerodynamic efficiency of the single-stage axial flow fan decreases exponentially with increasing volume content of dust in the air.

1. Introduction
It is known that the standard practice for an axial fan characterization are the engineering techniques with the following using of the available experimental database for obtaining the correction coefficients allowing one to precise the specific fans characteristics [1-3].

As a rule, the creation of such an experimental database for new type of fans requires the carrying out a series of experiments that is a resource and wasteful action.

Availability of the present-day computational software [4] allows one to carry out the direct numerical modeling of fans operation and to predict adequately its characteristics that leads to the essential reduction of material costs [5].

One of important characteristics of an axial fan is the aerodynamic efficiency representing a ratio of the air flow power produced by the fan to the power of the moment of forces acting on blades of the fan wheel (rotor). The investigation of the influence of rotational speed of rotor and angle of blades position in relation to a fan hub for dusty-free air on the aerodynamic efficiency of the axial fan was carried out in [6].

Wide use of axial fans for ventilation of coal mines excavations requires the research of influence of dust content in air on the main characteristics of such fans.

In this paper the research of influence of coal dust content in air on the aerodynamic efficiency of the single-stage axial fan with the straightening device is carried out with using of numerical modeling on the basis of Ansys-Fluent Software.

2. Physical model of the axial fan
The axial fan, fig. 1 consisting of the rotor 1, the straightening device (SD) 2, the directing hub of rotor 3, the directing blade SD 4 and the casing 5 has been considered. The directing blades of the rotor and SD have the identical radius $R_1$. The external shroud is a pipe with radius $R_2$. The blades (in quantity $N_r$) are disposed on the rotor with a constant step and their height is equal to $R_2 - R_1$. The angle between a circumferential direction and a chord of rotor blade profile is equal to $\alpha$. Length of a
rotor blade chord is equal to \( b \). The directing blades (in quantity \( N_s \)) with their profile chords (length \( b_s \)) are parallel to the directing blade of SD are disposed on the SD with a constant step. Shapes of rotor blades and SD are given in the paper [6]. Rotor blades rotate at angular speed \( \omega \), providing the air movement in the direction parallel to the generatrix of hub and increasing the total pressure of air [3, 7, 8].

![Image](image1.png)

**Figure 1.** Axial fan

As the fan studied corresponds to the mine fan of local ventilation then, because of low values of Mach number, we neglect the effect of compressibility, and we suppose that a flow is isothermal.

3. **Mathematical model of the axial fan**

As the rotor and SD free for air mass have periodically repeating parts (angles of periodicity are \( 2\pi/N_r \) and \( 2\pi/N_s \) for rotor and SD respectively), then we research the flow in the domain represented in the fig. 2.

![Image](image2.png)

**Figure 2.** Geometry of domain

1 – rotor blade; 2 – SD blade; 3 – directing rotor hub; 4 – directing SD hub; 5 – shroud; 6 – entrance surface of a rotor; 7 – output surface of a rotor; 8 – entrance surface of SD; 9 – output surface of SD.

The approach of the interpenetrating continua was applied for modeling the dusty air flow via the axial fan. The system of the governing equations written down in the rotating frame of reference consists of the mass conservation equations for air and dust, the momentum conservation equations for air and dust, the equation of turbulent kinetic energy for mixture and the equation of dissipation rate of turbulent kinetic energy for mixture.

Boundary conditions for the system of governing equations were set as follows. At the inlet in the domain the volume fraction of dust particles was set and the total atmospheric pressure of air was specified. At the outlet from the domain the atmospheric static pressure of air was specified. On walls
of the shroud, rotor and SD no-slip conditions were set. Turbulent parameters of the flow on walls and in near wall region were defined according to classical k-ε model of turbulence [4].

4. Solution method of the system of governing equations

Ansys Fluent Software was used for solving the problem. The system of the governing equations was solved numerically with use of the Patankar method. Convective terms of the equations were approximated by means of the upwind scheme of the second-order accuracy. Velocity-pressure coupling was carried out using the algorithm SIMPLE on the staggered grid.

For SD the system of the equations was solved in the mixed coordinate system (ω=0), and for a rotor – in the rotating coordinate system with an angular speed ω relatively longitudinal axis. Recalculation of parameters from an output surface of a rotor on an inlet surface of SD was done on the basis of the concept "mixing plain interface" realized in Ansys-Fluent. According to this concept the profiles of average parameters of total pressure, the directing angle cosines of velocity vectors in the radial, tangential and axial directions, turbulent kinetic energy and turbulent dissipation rate are transferred from the area of the rotor to the SD area which then are used as entrance boundary conditions for the SD area.

The calculation domain was meshed with 340 thousand hexahedral cells. Calculation accuracy was controlled by balance of mass flows. The grid was refined near blades of the rotor and the SD.

5. Results of numerical modeling of the axial fan operation

Calculations of axial fan parameters were carried out under the following parameter values:

- $\mu = 1.8 \cdot 10^{-5}$ Pa·sec;
- $\rho_{\text{air}} = 1.225$ kg/m$^3$;
- $\rho_{\text{coal}} = 1600$ kg/m$^3$;
- $R_1 = 225$ mm, $R_2 = 350$ mm, $b_r = 67$ mm; $b_s = 80$ mm; $L_1 = 400$ mm; $L_2 = 100$ mm; $L_3 = 600$ mm; $N_r = 15$, $N_s = 12$.

Rotational speed of the rotor was varied from 500 rpm to 5000 rpm, the dust volume fraction $\beta$ was varied from $10^{-5}$ to $10^{-3}$. The size of dust particles was equal 10 microns. The value of an orientation angle of a working rotor blade $\alpha$ was equal $30^\circ$. As it was shown earlier [6], in case of such a value $\alpha$ the maximum of fan aerodynamic efficiency for dust-free air is reached.

The results of calculation of static pressure drop between input and output of the fan depending on rotational speed of the rotor and the volume content of dust in air are shown in fig. 3.

![Graph](https://example.com/graph.png)

**Figure 3.** Dependence of the air volume flow rate on a rotor’s rotation frequency

1 – $\beta=10^{-5}$, 2 – $5 \cdot 10^{-4}$, 3 – $10^{-3}$.  

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It is clear that the increase of rotational speed of the rotor and the decrease of dust content leads to the growth of static pressure drop. Approximation of calculation results using the least-squares method shows that the pressure drop is proportional to a square of a rotor’s rotation frequency, i.e. $\Delta P \propto n^2$.

The increase of a rotor’s rotation frequency leads to the growth of the volume flow rate, $Q \propto n$, fig. 4. Results of numerical modeling for dependence of the air volume flow rate on a rotor’s rotation frequency and a volume content of dust can be fitted by the correlation $Q = A \cdot n \cdot \exp[-B(n)\beta]$ with the mean error, which is not exceed 2%. In the given formula the flow rate $Q$ has dimension $m^3/sec$, and rotation frequency – rpm, $B(n) = 59.345 \cdot \ln(n) + 68.744$, $A = 3.43 \cdot 10^{-3}$.

![Figure 4. Dependence of pressure drop on rotational speed of rotor](image)

One of the important characteristics of the fan is the dependence of pressure drop on the air volume flow rate. From fig. 5 we can see that the increase of dust content reduces the air volume flow rate under the given pressure drop. All set of calculated data are fitted by a formula close to that, which results from Bernoulli’s equation: $\Delta P = \frac{\rho}{2S} \cdot Q^2 \cdot (1+1303.34 \cdot \beta)$, where $\rho$ – density of air, and $S$ – the square of fan cross section.

Another important characteristic of the fan is the power of flow created by a rotor. Its value can be defined as a product of the air volume flow rate and pressure drop: $N_p = Q \cdot \Delta P$. It follows from fig. 3-5 that the power of air flow increases with the growth of the rotational speed of rotor and with reduction of dust content in air. When the rotor rotates, the dust-air flow exerts pressure on the working blades and the moment of forces relatively to longitudinal axis arises. The power of resistance forces, at which the fan has aerodynamic characteristics required, is defined as $N_v = M_v N \cdot 2\pi n/60$.
Figure 5. Dependence of pressure drop created in the fan on the air volume flow rate

\[ 1 - \beta = 10^5, 2 - 5 \cdot 10^4, 3 - 10^3. \]

Aerodynamic efficiency of the fan can be defined as the ratio of the power of air flow created by the fan to the power of fan rotor resistance forces, \[ \eta = \frac{N_p}{N_v} \times 100\%. \]

Figure 6. Dependence of fan efficiency on the volume content of dust.
Calculation results of the efficiency expressed in % are given in fig. 6. It is clearly that with the growth of the dust content from $10^{-5}$ to $10^{-3}$ the aerodynamic efficiency of the fan exponentially decreases from 70% to 20%. At the same time it is necessary to notice that for rotational speed of a rotor higher than 1000 rpm the efficiency of the fan practically remains constant under determined volume dust particles fraction. The value of the aerodynamic efficiency expressed in percentage can be described by a formula $\eta = A \cdot \exp(-B \cdot \beta)$, where $A = 66.29$, $B = 1347.6$ (a continuous curve on fig. 6).

6. Conclusions
On the basis of numerical simulation with Ansys-Fluent software the dependence of single-stage axial fan aerodynamic efficiency on the volume fraction of coal dust in air varied from $10^{-5}$ to $10^{-3}$ is derived.

The dependence of the pressure drop along the fan on the volume air flow rate with taking account of the dust content is obtained.

The formula for the volume dust-air flow rate vs the rotational speed and the volume fraction of coal dust content fits numerical results with the mean error, which is not exceed 2%.

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