Modernization of two-stage main fans at the end of the service life

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Abstract. The authors analyze air velocities in the inlet of the installation composed of two-stage axial fans (aerodynamic design OV-84 of the Central Aerohydrodynamic Institute) and in the inlet elements of the fan. It is shown that air flow is considerably nonuniform at the fan inlet, and the nonuniformity reduces in the air passage of the fan. The fan can be modernized by replacing the two-stage rotor by a high-rate single-stage rotor as per the inlet guide vanes–impeller–flow straightener design. This modification allows the required uniformity of air flow at the impeller inlet and ensures a longer service life of the rotor bearing assembly owing to considerable decrease in the weight of the rotor.

1. Introduction
Underground mines, subways and transport tunnels need much air to ensure life activity of personnel and passengers [1, 2]. Fan installations in coal and ore mines consume approximately 1.5% of the total power generated in Russia. Airing of a mine takes to 30% of the total power consumed by the mine [3–5]. The cost of ventilation can reach 20% of the cost of produced mineral [4]. Underground mines are supplied with fresh air using main ventilation fans (MVF). The capacity of such fans can reach 600 m³/s, and their drive motors can have capacity of 5000 kW. MVF are expensive equipment, and their service life is over 20 years. During this long period of time, fan assemblies spend their operational life and need increasingly often preventive and running repairs. Furthermore, with increasing depth of mining with higher production equipment, air demands grow, and old fans are no more capable to ensure the wanted capacity. Most of outdated axial fans belong to the series of two-stage axial fans (VOD in Russian). Ventilation systems of underground mines, transport tunnels and air-conditioning workshops of metallurgical works in Russia operate more than 50 fan installations composed of VOD series fans (Figure 1a). This aerodynamic design was developed at the Central Aerohydrodynamic Institute in the 1960s [6] and engineered by the Dongiprouglemash Institute in the 1970s. These machines have worked out their service lives three times and reached obsolescence by the early 21st century. Replacement of these fans by new machines requires much investment as it is necessary to replace all mechanical equipment and control, and need partial reconstruction of the fan installation, namely, its foundation, inlet and outlet elements, etc. The task of the current day is to update the obsolete fans.

The aim of this research is to validate the modernization approach to the series VOD two-stage axial fans based on the analysis of air flow velocities in the inlet line of the main fan installation and in the inlet elements of MVF.
2. Research methods
Mathematical modeling of air flow structure in the inlet elements of main ventilation fans used the Navier–Stokes equation and finite element method in ANSYS [7]. The data of the computational experiments were processed using the methods of mathematical statistics.

One of the ways of the fan remodeling is the replacement of the assemblies which are worn or off the currently effective standards without replacement of the assemblies and parts which remain serviceable (housing of fan, spinner, collector, diffuser, lubricant system, etc.). In this case, the built structure of the fan installation, including its foundation, is preserved, and the terms of the modernization activities are reduced.

In the last 30 years the mine ventilation engineering has undergone appreciable advance due to achievements in computational aerodynamics. New aerodynamic configurations allow creation of high-capacity axial fans for main ventilation, and the new single-stage fan machines possess characteristics earlier only achievable in two-stage fans [8]. Mostly, this is achieved owing to higher rotation speed of impellers.

3. Structure of air flow velocity field at the fan inlet
Let us discuss the influence of the real structure of the ventilation channel on the air flow velocity field in the inlet cross-section of a fan. Then, we are going to compare the findings with the modeling data of air flow in the ventilation channel structure recommended by the Central Aerohydrodynamic Institute [6] and assumed as the baseline version.

The studies were carried out on a standard design installation of fan series VOD-30 (Figure 1a) in a mine of SUEK. The input data were 3D model of ventilation line 9 in the form of *.igs surface mesh obtained after volumetric scanning.

![Figure 1. Main fan design: (a) fan series VOD; (b) modernization of fan series VOD-30; 1—motor; 2—coupling; 3—transmission shaft; 4—support; 5—shaft fan; 6—first-stage flow straightener; 7—impeller; 8—second-stage flow straightener; 9—air passage.](image1)

![Figure 2. Flow lines in the inlet elements of main fan: 1—zone of nonuniformity; 2—zone of vortex.](image2)
A 3D model connected with VOD-30 fan elements was used to study air flow through the elements of the fan installation (Figure 2). It was revealed that in such configuration, a parasitic vortex appeared behind the ring-shaped diffuser of the fan, which caused extra pressure waste in the fan installation. At the fan inlet, the flow was nonuniform though without significant vortexes.

For the comparison, we analyzed air flow in the ‘goose-neck’ air passage and in the fan elements configured as per recommendations of OV-84 designers from the Central Aerohydrodynamic Institute [6]. The said configuration is assumed as the baseline design. For this design, a 3D model is constructed and the air flow dynamics is studied on this model by analogy with the real fan configuration.

For the analysis of the air flow velocity field nonuniformity, a few representative cross-sections are chosen in the two models (Figure 3). These cross-sections are located at different distances from the collector inlet: 1—collector inlet (distance 0 m); 2—at the inlet of the first impeller II (distance 0.6 m); 3—inlet of the first impeller II (distance 1.2 m); 4—inlet of the straightener–guiding vanes (SGV) (distance 1.7 m); 5—inlet of the second impeller I2 (distance 2.4 m); 6—inlet of the straightener S (distance 2.9 m); 7—outlet of the straightener S (distance 3.6 m).

The velocity fields in cross-sections 3, 5 and 7 for the baseline and real designs are reduced to the common range of velocities. According to Figure 3, the velocity field nonuniformity in the real design considerably lowers as air flows along the air passage of the fan, i.e. with the increasing distance from the fan inlet.

For the evaluation of the nonuniformity, we use a ratio of the maximum air flow velocity to the average flow velocity in a cross-section. The value of this ratio in a perfectly uniform flow is one; in the real conditions of a straight inlet to a fan (straight-through air passage), this ratio is 1.03–1.06. Table 1 gives the values of the nonuniformity ratio for the mentioned representative cross-sections.

| Cross-section | 1 collector inlet | 2 in front of II | 3 inlet of II | 4 inlet of SGV | 5 inlet of I2 | 6 inlet of S | 7 outlet of S |
|---------------|------------------|----------------|--------------|---------------|--------------|------------|-------------|
| Distance from collector inlet, m | 0 | 0.60 | 1.20 | 1.7 | 2.4 | 2.90 | 3.60 |
| Nonuniformity ratio (real design) | 1.49 | 1.28 | 1.20 | 1.17 | 1.14 | 1.13 | 1.13 |
| Nonuniformity ratio (baseline design) | 1.56 | 1.17 | 1.12 | 1.13 | 1.13 | 1.13 | 1.14 |

In the real design fan, the nonuniformity at the collector inlet is 1.49 and rapidly decreases with the distance from the fan inlet. In the baseline design, the nonuniformity lowers faster and reaches permissible values in cross-section 3 in the inlet of K1. Starting from cross-section 5 (inlet of I2, 2.4 m away of the
At the collector inlet, the air flow velocity nonuniformity reduces to 1.14 and remains almost constant up to the outlet of the straightener. The nonuniformity value of 1.14 insignificantly differs from the nonuniformity in the baseline design and, accordingly, slightly influences the aerodynamic parameters of the fan. In the acting fan VOD-30, at the inlet of I1 (cross-section 3), the nonuniformity ratio is 1.20; for this reason, the aerodynamic characteristic of the fan disagrees with the plant characteristic.

Thus, VD series fans can be modified by means of replacement of the I1–S–I2–S configuration by the IGV–I–S configuration, i.e. by withdrawal of the first impeller I1 from the design, where IG is the inlet guiding vanes. Such modification can eliminate the adverse influence of the nonuniformity of the impeller aerodynamics due to manufacturing errors of the air passage as against the baseline design. In this case, air flow in the flow passage up to the impeller I2 lowers the velocity field nonuniformity down to the permissible values.

4. Aerodynamic design of fans

The modernization method of series VOD fan, with removal of the first impeller is illustrated in Figure 1b in terms of main ventilation fan VOD-30 with rotation speed of 500 rpm. The bold lines mark the assemblies to be replaced by new assemblies. The post-modification aerodynamic parameters are: capacity 143.2 m$^3$/s; static pressure 3160 Pa. With the outlet diffuser diameter of 4.3 m, the dynamic pressure is 85.8 Pa at a preset air flow rate; consequently, the total fan pressure, with regard to the approximate local air loss ratio of 1.25–1.30 in the diffuser is around 3320 Pa.

The calculation used operating mode computation module ANSYS SFX. The geometry of the blades of impellers I1 and I2 were selected in accordance with OV-84 configuration, with 12 blades on each impeller; for the first and second stage straighteners, with regard to the fan reversibility, we selected 14 blades in accord with S-54 configuration of the Central Aerohydrodynamic Institute [6]. The main angle of blades AB of I1 and I2 was 35 deg. The diffuser sizes were taken from the standard drawings.

First, we compared with aerodynamic parameters of the single-stage IGV–I–S design with adjustable AB with the two-stage I1–S–I–S design at the same rotation speeds of 600 rpm (blade tip speed 94 m/s). The reason for that was that straightener S-54 was planned to be used in the modified fan as inlet guiding vanes.

![Figure 4. Aerodynamic parameters of VOD-30 fan with modified aerodynamic configuration:](image)

| Curve | Description |
|-------|-------------|
| 1     | design Q-point of fan (required parameters) |
| 2     | manufacturer’s design I1 + S + I2 + S, AB of I1 and I2 35°, 600 rpm |
| 3     | design without I1, IGV + I2 + S, AB of I2 35°, AB of IGV 70°, 600 rpm |
| 4     | design with optimized AB of IGV 100.6°, IGV + I2 + S, 600 rpm |
| 5     | new design IGV + I1 + S, 750 rpm |

Removal of the first-stage impeller I1 at the preserved angle of blades of 70 deg in S, which is now IGV, results in the drop in the aerodynamic parameters of the fan (Figure 4, curve 3 as IGV spins air flow in line of I2 rotation rather than in the opposite direction. For this reason, the angle of blades of the inlet guiding vanes was optimized by the total pressure criterion of 3320 Pa at the air flow rate of 143.2 m$^3$/s with achievement of the maximum efficiency at the rotation speed of 600 m/s. The computational experiments determined the angle of blades AB of the inlet guiding vanes IGV as 100.6 deg. Curve 4 in Figure 4 shows that the aerodynamic parameters fulfill the requirements but the Q point is situated nearby
the zone of unstable operation of the fan. It can be concluded that the one-stage fan configuration with adjustable AB of IGV is efficient but it is necessary to change the blade profile geometry on impeller I2 to ensure stable operation of the fan. It is required that the blade profile has a pressure margin of 5% at the least, which has been implemented. The computational experiment determined aerodynamic parameters of the modified fan with a blade having a new profile which totally satisfied the required air flow rate and pressure (curve 5 in Figure 4).

Thus, we have developed an aerodynamics design procedure for modernization of mine fans. The axial main ventilation fans of series VOD (aerodynamic configuration OV-84 of the Central Aerohydrodynamic Institute) are modified by means of transition from the I1–S–I2–S design to the IGV–I–S design and replacement of a two-stage rotor by the high-capacity single-stage rotor. Such modification allows higher uniformity of air flow at the inlet of the impeller and extends the service life of the rotor bearing assemblies owing to much lighter weight of the rotor.

5. Conclusions
It is possible to enhance efficiency of main ventilation installations equipped with two-stage axial fans which are at the end of the service life in underground mines by redesigning of the rotor group of the fans. The modernization of two-stage axial fans of series VOD (aerodynamic configuration OV-84 of the Central Aerohydrodynamic Institute), with an impeller and guiding vanes at each stage, consists in replacement of the two-stage rotor by the higher capacity single-stage rotor in the new inlet guiding vanes–impeller–straightener design which ensures the required uniformity air flow at the inlet of the impeller.

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