Improvement of auxiliary ventilation efficiency in underground workings

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Abstract. The article discusses the current research and development projects realized by KOMAG within the European INESI project, the aim of which is to increase the effectiveness of auxiliary ventilation in underground mines. They mainly focus on improving the fan operational parameters by modification of rotor’s blades. Modification of the blades by 3D printed and stuck inserts with supporting role of CFD modelling are discussed. The results of testing the fan before and after modification, are presented.

1. Introduction
Auxiliary ventilation is used in dead end workings, where forced air circulation is required. For this purpose ventube fans are used, operating in suction or pumping mode, connected to elastic or rigid ventube. Air supplied in such a way ventilates and dilutes harmful gases especially methane. The mining law [1] defines the basic parameters of ventilation, including the minimum air flowrate in methane roadways which is 0.3 m/s. When the required air flowrate and length of the workings is known, the flow resistance is calculated, and then the proper fan is selected. Improvement in ventilation efficiency should be sought mainly on improving the fan operational parameters while in the fan itself, the rotor is the main component responsible for transferring the energy needed to overcome the flow resistance. Generally, single thickness blades are made of bent metal sheet. Low production costs, satisfactory durability and reliability, as well as possibility of use in underground coal mines are the main advantages of this type of blades. However, this design solution results in less fan efficiency and narrowing of the angle of attack for which the fan's operation is effective. Professional literature on fans and design of rotor blades [11, 12, 16, 17] refers mainly to structures with advanced aerodynamic shape and complex manufacturing process intended for compressor rotors, turbines, industrial fans, where the cost of one blade can be several hundred times higher than the cost of a blade made of bent metal sheet. The work carried out under the INESI project allows for prototyping of the rotor blades using such computational tools as FEM and CFD. As part of the design work, 3D scanners and incremental methods based on 3D printing are used. The application of state-of-the-art numerical technologies in the project made it possible to predict the forces acting on the rotor at the designing stage. Thanks to the use of 3D printing, supplementary overlay were made without the necessity of making the rotor blades by machining, which would significantly increase the cost of making prototype rotors to carry out bench tests. The main objective of the work is to increase the efficiency of the fans by about 10% through the use of aerodynamic profile, for example NACA type.
2. Direction of fan modification

Blades made of bent metal sheet are usually used for construction of mine fans for auxiliary ventilation. In any cross-section they have a constant thickness, so they are called "single-thickness" profiles in contrast to the "aerofoil" profiles, cross-sections of which have a shape similar to cross section of an airplane wing. Efficiency of fans equipped with single thickness blades is lower than the efficiency of fans equipped with aerofoil blades. In the case of single-thickness blades, air flowing along both sides of the blade has in theory the same distance to overcome, but on lower side air runs not close to bent surface but along the straight line, what can be observed during wind tunnel tests. That enable generation the lift force even in the case of single-thickness, but their effectiveness is less than effectiveness of aerofoil blades. In addition, single-thickness blades in only a small range of the attack angle, show correct operation.

In KOMAG, some attempts were made to implement aerofoil blades in the mine fans, including the plastic blades. However the effects were ineligible in relation to the increased cost of fans purchase. Hence, these solutions have not been approved by the users who had to their disposal the fan solutions verified in operation. Based on the experience of fan tests and the opinions of manufacturers who use different blade solutions, it can be assumed that as a result of improving the shape of the fan blades, the energy effectiveness can be increased by 5 to 15%. In aerofoil type profiles, for example of the NACA type, the airflow distance is different on both sides of the blade (figure 1), and the divided air stream combines again behind the blade edge. The air on the convex (upper) side accelerates, as the airflow distance is longer, therefore the static pressure on this side is smaller than on the lower side. As a result, the lift force marked as “L” is generated.

![Figure 1. Scheme of aerodynamic forces of the NACA blade type [2].](image)

Air thinning on upper side of the blade creates under pressure, necessary for air sucking which results in the airflow. The next blade sweeps the air with the bottom surface and simultaneously its upper side generates under pressure. Direction of air stream flowing into the blade, shown in the (figure 1), results from a flow rate of air passing the fan and the rotor peripheral speed. The rotating blade as a result of under pressure on upper side generates lift force L. Simultaneously also the drag force D is generated. Lift-to-drag ratio L/D, which should have the greatest value, is an important factor of the fan blade design, especially in the scope of its nominal operation. Comparison of the aerodynamic properties of a single-thickness blade 417a, tested by the Institute for Aerodynamics and Flows in Göttingen [3] (figure 2) and aerofoil blade NACA 6512, (figure 3), is presented (figure 4), where aerodynamic coefficients $C_L$, $C_D$ and L/D ratio of these two types of blades are given.
The above diagrams confirm that the blade should have a aerofoil type shape, like the wing of an airplane or wind turbine blade. The recommended shape is an asymmetric profile, with a lower surface, slightly concave on 2/3 of the length, like in the example of the NACA 6512 profile.
(figure 3). The profile has a rounded front part, to enable work with different angle of attack and a tapered back section, to create a sharpened trailing edge. The upper surface is definitely convex, and the lower is slightly concave. The air stream generated by the rotating blades should have the same speed at each blade height. Together with increasing of the blade height, the linear speed is increasing, what should be compensated by the shape of the blade. As a result, the blade should be gradually twisted, as a function of distance from the rotation axis. The resulting shape of the blade twist should be closely related to the rotational speed of the rotor and the axial velocity of air flow. For the proper selection of the above blade twist, resultant air velocity vectors at different heights should be calculated based on the assumed fan capacity and the assumed rotational speed of the drive. The angle of attack, having a significant impact on the flow efficiency of the fan, should also be properly selected.

In load conditions, larger than nominal, the fan can work with the effect of the so-called "pumping". A similar effect, called "stall", can take place on the plane wings, when the pilot will excessively increase the angle of attack at insufficient power. Insufficient power causes reduction of speed, what further increases the angle of attack and the wings will lose their lift force. In the case of a fan, this effect consists in the separation of the air stream from the blade surface, what causes turbulent flow, as a result of which the fan emits different sound and its efficiency decreases significantly. Unstable fan operation mode causes pulsations of air stream, vibrations of the fan, its work becomes louder, what results of much lower efficiency [5]. To eliminate this, the load of the fan should be carefully selected, taking into account the assumed ventilation capacity as well as the diameter and length of the ventube. For the safety reasons, during designing the fan, the load should be increased by 30%.

The rotor of the fan, apart from the motor’s parameters, has a significant impact on fan’s characteristic (pressure [Pa], output [m$^3$/min], efficiency [%]). The rotor can be optimized in terms of its geometrical features, mainly by selecting the right shape of the blades and their number. In order to develop an effective modification technique by using 3D printed pads, it was decided to carry out tests on the WLE Φ630 fan, with power equal to 18.5 kW and 10-blade rotor of the speed of 3000 rpm.

The step by step analysis of the WLEΦ630 fan original blade and rotor design is illustrated (figure 5). Analysis of the 3D form of the blade, made of ITAMID, showed that its attacking edge has an ambiguously formed outline and its trailing edge does not have a definite sharpened shape. In addition, analysing the peripheral speed of the blade, it was found that its thickness, measured at 1/3 of its chord length, is too small, comparing to the thickness of NACA profile blades. Therefore, operation of such blade is similar to the operation of single-thickness blade made by bending metal sheets. At the beginning of the development work within INESI project, strength of the adhesive connection between the printed material (ABS) and the modified blade was tested. For this purpose, two small sheets 3D printed of ABS were glued onto two opposite blades. The tests were conducted at a speed of 3000 rpm for 1 hour and the glued sheets remained intact. After this positive test, the overlays for all blades were developed and manufactured, and after gluing them, the blades got the shape characteristic for aerofoil profiles. The work began with testing the original fan, without glued overlays, on the test bench for type "C" ventube ventilators according to the PN-EN ISO 5801: 2008 Standard. In order to compare the fan parameters before and after the modification, the characteristics of pressure, efficiency and power in a function of output were determined for nominal speed n = 3000 rpm/min. In the next step, the rotor blades were scanned (figure 5) using a 3D scanner. The obtained data were processed in the 3DS MAX program in order to convert them into a solid block, using the Autodesk Inventor program. The overlays were modelled on the base of asymmetric NACA 6412 profile, where the maximum thickness was in the range of 35-70% of the chord. The NACA aerofoil profile is characterized by effective generation of lift due to favourable L/D coefficient, maximally laminar flow and low resistance. In the computer optimization of the shape, 6 cross sections were identified in the blade, depending on their distance from the blade base. For each of them an aerofoil geometry was developed.
3. CFD modelling

The developed model of the blade was analysed by Computational Fluid Dynamics method (CFD). The OpenFOAM program, which is an open source software written in C++ language, was used for the analysis. The OpenFOAM processor solves partial differential equations using the finite volume method. The calculations allow simulations using multiple processors due to the ParDict decomposer, which divides the numerical model into individual domains. The calculation time is then acceptable, even when calculating large models. The discretised model of a blade was made in the Salome software. The discretised model (figure 6) of a blade placed in a cylinder of diameter 0.7 m and length of 0.5 m, was densely meshed around the blade and in the space behind the blade to obtain more accurate results.

In the simulation of the turbulent flow and for the given air speed, the following simulation parameters were assigned:

- epsilon – dispersion of turbulence
  \[ \varepsilon = 0.09^{3/4} \cdot \frac{k^{3/2}}{l} \]  
  where:
  \( k \) – kinetic energy of turbulent flow,
  \( l = 0.07L \) (L – diameter of inlet),

- \( k \) – kinetic energy of turbulent flow
  \[ k = \frac{3}{2}(u \cdot I)^2 \]  

Figure 5. (a) blade analyzing, (b) scan of 3D, (c) model, (d) model of rotor before modification [7].

Figure 6. Mesh generated in Salome program [7].
where:
\( u \) – inlet air speed,
\( I \) – turbulent factor,

- \( I \) – turbulence factor

\[
I = 0.16 \cdot Re_{dh}^{-1/8}
\]  

(3)

- \( Re \) – Reynolds number

\[
Re = \frac{ul}{\nu}
\]  

(4)

where:
\( u \) – inlet air speed,
\( l \) – diameter of inlet,
\( \nu \) – fluid kinematic viscosity.

Sample results for air speed of 9 m/s are shown in figure 8, in a form of contour maps of the air stream lines and pressure distribution on the surface of the blade using the ParaView software.

Figure 7. Turbulence of air stream and speed distribution around the blade [7].

4. Modification of the fan – bench testing and further work directions
Based on the results of the CFD analysis, specially designed overlays were optimized and printed, then glued onto the blades (figure 8), and the trailing edge was thinned to extend the laminar flow along the profile.

Figure 8. Blade of the rotor before and after sticking the correction overlay [7].
The modified rotor was balanced and re-installed in the fan, which was tested on the test bench. The graph (figure 9) shows the fan characteristics before and after the rotor modification. Continuous lines illustrated results after modification. The red line shows a significant increase of pressure of 8%, in the range of the optimal operating point, as well as a slight improvement in efficiency in the range of stable fan operation. The power consumption increased slightly and the sound power level did not change. Its value was 118.0 ± 3.0 dB during stable fan operation.

The tests confirmed that the method of sticking the overlays give the positive results in terms of strength, which allows development of the Ф800 fan of improved characteristics. Currently, the development work is carried out regarding the design of the target rotor with variable angle of attack of blades. The possibility of changing the angle of attack and the specially developed profile of the blade will allow to obtain a favourable rotor aerodynamic index (L/D), i.e. the maximum “lift to drag force” ratio [8]. In the rotor and the guide vane system, even a small change of the blade angle of attack (α) should result in rise or decrease of the pressure and efficiency. The concept of the rotor shows blades with adjustable angle by means of a threaded spigots and a nuts (figure 10).

**Figure 9.** Comparison of fan characteristics before (dotted lines) and after modification (continuous line) of the rotor blades [7].
5. Conclusions
The presented of R&D work was realized as part of the implementation of the European INESI project co-financed from the RFCS fund. The following results were obtained:

- A methodology for designing and 3D printing of overlays intended for sticking to the blade base frame was developed and verified.

Thanks to the use of a 3D scanner, the geometry of the modified blade was recreated. An overlay was designed for the model prepared in a way to obtain a profile with improved aerodynamic features. Thanks to the CFD and FEM analysis, the design assumptions in terms of strength and aerodynamics were verified. The next step was to make prototype overlays, fix them to the old type blades and then to balance the rotor.

- Modified fan of diameter 630mm, with an increased generated pressure by about 8%.

The modified profile of the blade gave measurable effects in the form of increased air pressure as well as widened effective range of the fan. The "flattening" of the fan efficiency curve allows it to operate at different airflows without a significant increase power consumption.

- The rotor with an adjustable blades for testing the target fan Ф800 was pre-designed.

After constructing the fan test stand, it was required to build a prototype impeller with adjustable angle of attack in order to make trials with different blades settings to determine their most favourable setting.

The next stages of work related to the fan will be as follows:

- CFD modelling of Ф800 fan rotor operation and final correction of the blades shape,
- construction of an experimental rotor for the target fan Ф800 with the possibility of changing the blades angle of attack,
- testing the fan in the testing rig for different angles of attack of the blades.

6. References
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