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ANALYSIS OF FIELD TEST RESULTS FOR THE OIL SHALE MINE VENTILATION SIMULATION

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Abstract. *Analysis of the field test results for inputs to the ventilation simulation model was performed in the conditions of an operational oil shale mine in Estonia. The oil shale mine uses a very sophisticated ventilation system to provide enough airflow to the eight operational areas with a radius of about 5–6 km. The main purpose of the field tests was to obtain data about ventilation simulation processes that could be useful for improving ventilation efficiency and optimizing related costs. Field tests included measurements of airflow and the fan pressure at different cross sections of intake air through the ventilation shaft. Measurements of airway friction factors were made during the ventilation surveys to determine characteristic friction factors for the intake airway. The results of measurements can be used for constructing the mine ventilation simulation model required to design a ventilation system in operating oil shale mines.*

Keywords: *airflow, friction factor, oil shale mine, ventilation simulation.*

1. Introduction

Mine planning typically involves estimations of the required airflow supply to the working faces. For this reason it is very important to determine all ventilation parameters.

The mine as a target of this study has been operating since 1972 and currently runs with a large footprint, approximately 12 km by 12 km. It is a large-scale room and pillar mine that produces oil shale by applying conventional drill and blast methods, followed by mucking to conveyors, which transport oil shale to the surface. The oil shale seam dips less than 1° and the overburden varies in thickness from 45 m in the north to 65 m in the south direction, giving a maximum depth to the base of the oil shale seam of approximately 70 m.

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Estonian oil shale mines do not have gas-bearing seams, thus their dilution is not considered in ventilation designing and planning processes. Nevertheless, methane gas cannot be ignored in simulation of ventilation in underground oil shale mines. Due to Estonian coastal climate and low depth of oil shale deposits, cooling mine ventilation is not necessary. However, heating ventilation is sometimes required. Based on operational experience an optimum airflow is considered to be 1.5–3.0 m/s in working stoppings and 0.4–0.6 m/s in development drifts. In the main ventilation drifts, airflow should not exceed 6–8 m/s [1].

Explosions of oil shale dust which suspends in a mine atmosphere represent a serious hazard one has to take into account. The occurrence of dust explosion depends on its concentration, calorific value, moisture content and amount. Oil shale dust is considered explosive if its volatile content is higher than 15%, calorific value > 5.3 MJ/kg and moisture content < 12%. In high-humidity conditions oil shale dust is stuck on the mine surfaces and does not spread to the air. On the other hand, if the airflow is higher than 3.0 m/s, dry dust will spread to the mine air and an explosive environment will be formed. The most hazardous dust comes from oil shale productive layers "B" and "E" because of its high calorific value and low moisture content. To prevent the accumulation of dust mine ventilation and water spraying are mainly used. However, in the conditions of Estonian oil shale mines, the dust does not spread to the mine atmosphere and become explosive, due to its high humidity and low calorific value [1].

Usually, a mine district comprises mining blocks (approximately 400 m wide and 800 m long), which are further halved into semi-blocks. The shape and size of a mining block vary depending on geological characteristics such as roof hardness, karst features, faults, joints, as well as share of waste rock in oil shale. Area development generally takes place on a territory of 5.0 to 5.5 m in width, depending on the geology of the area. The development height is dependent on the thickness of the oil shale seams, the layers that are to be mined and the roof condition, but generally ranges between 2.8 and 3.8 m. Development is carried out using drill and blast methods instead of employing mechanical excavators. Production takes place applying room and pillar methods. A typical pillar is between 50 and 55 m^2. The room height relates to the thickness of the seam to be mined and the amount of dilution from the collapse of the roof, and varies between 2.8 and 3.8 m. The room width varies according to the stability of the overlying strata, up to 7 m under favourable conditions and as low as 5 m under unfavourable conditions, and a thicker overburden. After each face is advanced, the ground support is installed. Rock bolts of two lengths (1.2 m and 2.2 m) are used based on the working height of the mine. All bolts are ungrouted anchor shell bolts. Ground supporting consists in drilling a 41 mm diameter hole and installing a 16 mm diameter rebar with a face plate and a shell anchor, and a bolting pattern of either 1.5 m × 1.5 m (favourable conditions) or 1.2 m × 1.2 m (unfavorable conditions). In areas with no geological faults or joints, the bolts are removed and up to 75% of them will be reused unless damaged, to save costs. The oil shale layers occur among the limestone interlayers. The overburden is represented by limestone. The uniaxial compressive strength of oil shale is 20–40 MPa and that of limestone is 40–80 MPa [2].

The main purpose of this paper was to examine the applicability of the field test data collected about an Estonian oil shale mine to the simulation of ventilation processes to improve ventilation efficiency and optimize relevant costs. Field test works included measurements of airflow and the fan pressure at different cross sections of intake air through the ventilation shaft. Measurements of airway friction factors were made during the ventilation surveys to determine characteristic friction factors for the intake airway. The results of measurements can be used to construct the mine ventilation simulation model required for designing the ventilation system in the conditions of oil shale mines.

2. Theoretical background

The frictional pressure drop in mine airways can be obtained from the following relationship:

$$p = f\,L\frac{Per}{A}\rho\frac{v^2}{2}, \qquad (1)$$

where ρ is the air density, kg/m^3; f is the Chezy-Darcy coefficient of friction; Per is the airway perimeter, m; v is the air velocity, m/s; A is the area, m^2; L is the length, m.

This is the form of the Chezy-Darcy (Darcy-Weisbach) equation that is applicable to circular and non-circular airways and ducts. The Chezy-Darcy coefficient of friction (dimensionless) varies with the Reynolds number, the trend of which is plotted on the typical Moody diagram. The Chezy-Darcy equation was adapted by Atkinson to give the following, commonly used Atkinson equation:

$$p = k\,L\frac{Per}{A}v^2. \qquad (2)$$

The k factor is a function of air density and is computed as the product of the Chezy-Darcy coefficient of friction and the air density, divided by a factor of two. Since the Chezy-Darcy coefficient of friction is dimensionless, the k factor is expressed in the units of density, kg/m^3. The Atkinson equation may be expressed in terms of the Atkinson resistance (R) for the airway as follows:

$$R = \frac{p}{Q^2} = k\,L\frac{Per}{A^3}, \qquad (3)$$

where R is the Atkinson resistance, Ns^2/m^8; Q^2 is the quantity of airflow, m^3/s; k is the friction factor, kg/m^3.

The left-hand side of Equation (3), relating to frictional pressure drop and quantity to resistance, is known as the Square Law. This important relationship is used to establish resistance from measured pressure and quantity data. The middle section of the Equation is used to determine resistance from typical k factor values, and known or proposed airway geometry. It should be noted that the frictional pressure drop time in the Square Law is directly proportional to air density, as is the k factor, which is the combination of the friction factor, air density and constants in the Chezy-Darcy equation. Hence, the k factor value applied must be adjusted to the actual mine air density. The k factor is not constant for a given airway, but varies with the Reynolds number. However, when designing mine ventilation, the k factor is usually assumed to be constant, regardless of the flow regime. This is because for the fully turbulent flow, which is typically the case in mine ventilation, the friction factor is a function of the relative roughness of airway only. The latter is defined as the height of the airway asperities (e) divided by the hydraulic mean diameter (d = 4 A/Per). The von Kármán equation expresses the relationship between the k factor and the relative roughness of the fully turbulent flow:

$$f = \frac{2k}{\rho} = \frac{1}{4\left[2\log 10\left(\frac{d}{e}\right)+1.14\right]^2}. \tag{4}$$

From Equation (4) it is apparent that for airways with the same surface roughness (asperity height), but different hydraulic mean diameters, the k factor should vary. Hence, as the airway hydraulic mean diameter increases and all other conditions remain the same, both the relative roughness and the k factor will decrease. One final consideration is that in modern mining methods there is a potential for the flow to be theoretically fully developed and turbulent based on the Reynolds relationships; however, we can induce local instabilities from heat sources in which the buoyancy of natural convection overrides the tendency for turbulence to maintain a fully mixed and uniform state [3].

The selection of appropriate friction factor values is critical in mine ventilation planning. Resistance values for future mine openings are determined by applying a suitable friction factor value against the proposed airway geometry.

3. Field work measurement techniques

Resistance was determined from the measured pressure and airflow data using the Square Law relationship (Eq. 3). The airflow surveys consisted in the measurement of mean air velocities and airway cross-sectional areas at predetermined locations. A rotating vane anemometer attached to an extendible rod was used to traverse the airways for measurement of the mean air velocity [3].

The airway cross-sectional areas were measured using laser distance measurement with typically three measurements of width and three measurements of height per cross section. Airway obstructions were measured, recorded and subtracted from the gross cross-sectional area. The air quantities at each station were computed as the product of the air velocity and the airway cross-sectional area. Frictional pressure drops were determined employing the gauge-and-tube technique for all lateral airways and ramps. The gauge-and-tube (or trailing hose) method allows direct measurement of frictional pressure differentials by using a digital manometer connected to the tubing, the ends of which are connected to the total pressure tappings of pitot-static tubes [3].

During the ventilation surveys the friction factor was measured. The measured frictional pressure drops and airflow data will be used to optimise the mine ventilation networks.

4. General mine ventilation system layout

The mine ventilation was carried out by a combined scheme using eight intake ventilation units located on the surface to supply fresh air to the operational areas (arranged along the long drift in Fig. 1; blue drift in the on-line version). The overall mining field was divided into four main sections (Fig. 1; green, light blue, yellow and dark blue developments in the on-line version) for ventilation-equipped operational sites. This was also assumed to be for safety reason in case of fire in mine sections. The operational development area used a U-ventilation scheme. The return air went through the ventilation drifts and was exposed to the surface through the return ventilation shafts [4, 5].

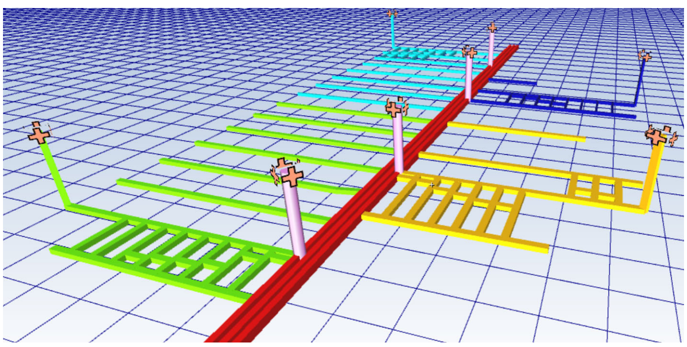

Fig. 1. The general mine ventilation system layout.

During the experimental tests the inlet volume of the tested fan VOKD-2.4 (with a 500 kW electric drive) was about 137 m^3/sec. Measurements took place in the eastern part of the mine workings.

5. Results and discussion

The experimental tests were carried out using five different modes of testing. These modes assumed closing in sequence the intake gates of four gates of ventilation shafts, each of which had a different cross-sectional area (Table 1). Thus, the overall cross-sectional area of ventilation shafts could be decreased and the airflow for each mode was measured.

The fan pressure in the five modes of testing was also determined. This data can be used to analyze the dependence of fan efficiency on the proposed cross-sectional area of a new shaft. The airflow for each cross section is shown in Figure 2.

As can be seen from the figure, the area is critical when the shaft cross-sectional area is smaller than 4 m^2 and airflow lower than 95 m^3/s.

Table 1. Ventilation system test results in different modes of testing

Mode	Shaft cross section, m^2	Air volume, m^3/min	Air volume, m^3/sec	Fan pressure, Pa
1	7.76	6527	109	1128
2	6.63	6350	106	1228
3	5.50	6174	103	1324
4	4.37	5998	100	1422
5	3.39	5380	90	1912

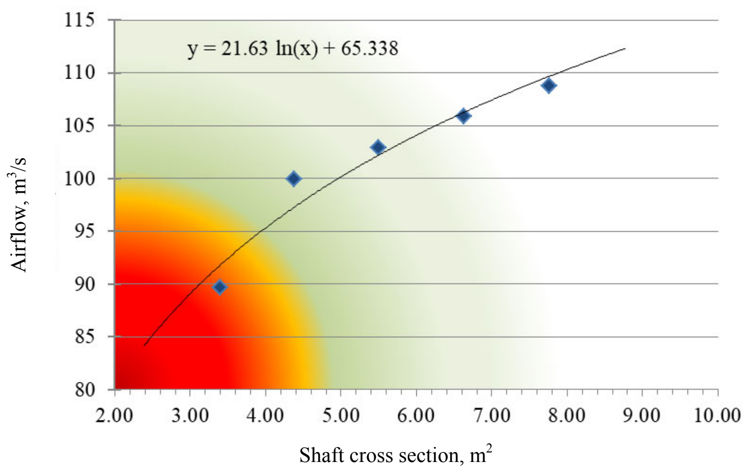

Fig. 2. Airflow for each shaft cross section.

The measured fan pressure and related airflow are shown in Figure 3. The area is critical when the fan pressure is higher than 1650 Pa and airflow lower than 95 m^3/s.

The airflow for five different shaft cross sections was determined. This data can be used to estimate costs of designing a new shaft in case of sinking and providing necessary airflow in the future mining production.

A schematic layout of ventilation shafts and the ventilation drift at experimental airflow velocities is shown in Figure 4.

The airway friction factor values obtained during the ventilation surveys can be used to determine characteristic friction factors for the intake airway. The intake airway was defined as a clean rectangular entry with roof bolts (Table 2).

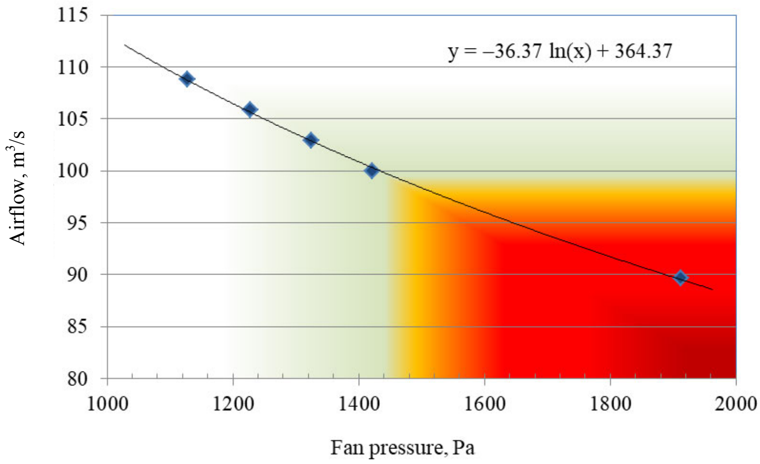

Fig. 3. Airflow related to the fan pressure.

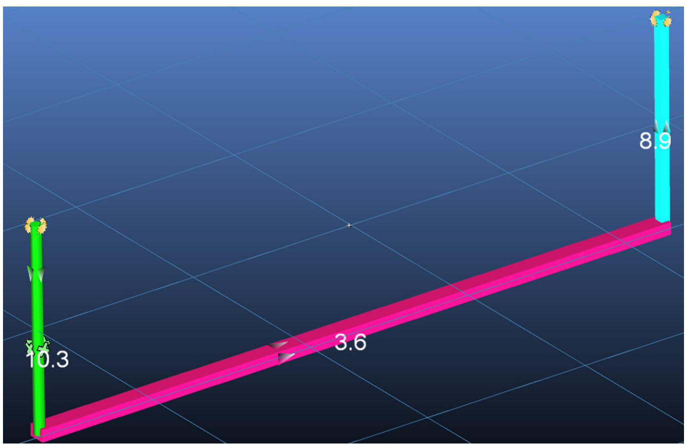

Fig. 4. A schematic layout of ventilation shafts and the ventilation drift.

Table 2. Friction factors

Name	Drift #1	Drift #2
Width, m	6.9	3.5
Height, m	4.2	2.2
Section, m²	29.0	7.7
Mean velocity, m/s	3.6	8.8
Friction factor, kg/m³	0.00812	0.00834

The measurements showed the mean friction factor value for intake airways to be 0.0082 kg/m^3, which might be used in future mine ventilation planning.

6. Conclusions

The airflow for five different intake modes was determined. Under the current mine conditions the airflow of about 100 m^3/s was sufficient to supply fresh air to the operational mining areas. Data analysis showed that the cross section of a shaft less than 4 m^2 might not be enough to obtain a sufficient airflow for the current mine workings. Also, in case of said cross section, the fan efficiency dropped drastically. This data can be used to estimate costs of designing a new ventilation shaft in case of sinking under conditions of a given mine.

During the ventilation surveys the airway friction factor was measured to determine its optimum value for the intake airway. The mean friction factor for the intake airway was 0.0082 kg/m^3 which could be made use of in future ventilation planning. The results of measurements can be applied to construct a mine ventilation simulation model required for designing a ventilation system in conditions of oil shale mines.

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