Calculating Shock Losses in Mine Ventilation Networks

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Abstract. In this paper, we investigate the relative contribution of shock losses to the total pressure drop in a mine ventilation network. It is shown that for a specific class of mines it is necessary to consider the shock losses of mine airway junctions. This class includes mines with large airway cross-sectional areas and extended work areas. A comparative analysis of existing literature on methods to calculate shock losses is conducted using ventilation system with parallel airways. Existing methods are compared with the results of 3D numerical simulation of airflow through junctions. Several existing methods for shock loss calculation incorrectly assume airways being symmetrical with uniform airflow distribution of airflow in parallel airways This symmetry is physically incorrect, and asymmetric methods are identified to more accurately calculate shock losses underground.

Keywords: Mine Ventilation, Air Distribution, Shock Loss, Airway Junction, Airway Split, Numerical Simulation.

1 Introduction

Modern mining operations with large production and quick advances result in rapid expansion and increased complication of mine ventilation system. Calculation of air distribution becomes more complicated or almost impossible without numerical modeling. Calculating mine ventilation networks are becoming increasingly important considering an increasingly complicated ventilation system.

The efficiency of computational model is determined at least by two factors:

1. Speed of the model construction.
2. Accuracy of forecasting made by the model.

The first factor assumes decrease of the total time spent on development of accurate working model using data from ventilation surveys. The second factor means stable accuracy of the model predictions when air distribution in mine is changed. Computational model of ventilation network based on one set of experimental data achieved for one ventilation mode, should give adequate forecast of air flows for other possible ventilation modes.

Usually, formulation of mine ventilation network models is based on the first and the second laws of Kirchoff. In this example, airflow distribution in mine ventilation network can be found by solving nonlinear equations with unknown airflows and pressure drops in each mine airway [1].

Mine ventilation network including only straight airway resistances (or Atkinson resistances) may result in less accurate result when airflow distribution varied sufficiently comparing to the initial state. Mainly, it is concerned with the influence of shock losses at bends and junctions of mine airways, changes in its' cross-sectional area etc. [2, 3]. Decrease of accuracy occurs even when shock losses are considered using equivalent length approach [3]. It is concerned with sufficiently different functional relation between pressure loss and airflow in case of straight airways and in case of bends and junctions [2, 4]. Therefore, when the airflow distribution in mine is changed, there is disproportional pressure response in straight airways, in bends and junctions.

It leads to more complicated redistribution of airflows in mine ventilation network after changing the ventilation mode. These redistributed airflows and pressure losses does not satisfy the former system of equations representing the first and the second laws of Kirchoff with only Atkinson resistances determined from ventilation survey at one specified ventilation mode. One can observe it particularly during the main fan reversal [2].

2 Estimation of the Relative Contribution of the Shock Losses

The relative contribution of shock losses depends on airway cross-sectional areas, air velocity magnitudes, air inlet angles at junctions etc. The relative contribution of the shock losses depends on the specific features of the mine.

A simple estimation of the shock losses contribution can be made using the following criteria *K*, which represents the relative fraction of shock losses in total pressure loss in the network:

$$K = \frac{P_S}{P_S + P_A}, \tag{1}$$

where P_S is total pressure drop across an airflow path due to shock losses and P_A is the total pressure drop across the same airflow path in straights airways (due to Atkinson resistance).

The value of the criteria (1) also depends on the specific features of the mine. It's primarily reflected in the properties of the airflow path, which is different for each specific mine. The simplest way to estimate the average properties of the airflow path is to use integral characteristics of a mine or of a district – average cross section area S and perimeter P, remoteness of work areas L, total airflow Q etc. These characteristics allow us to consider two simplified idealized districts of a mine corresponding to two commonly used ventilation layouts: (a) U-tube ventilation district and (b) through-flow ventilation district (see Fig. 1).

We assume that intake and return airways have infinite number of equally-spaced air connections with each other. Junction angle for each air connection is 90°. Resistances of air connections are determined in such a way as to divide the flow into equal parts. The total airflow through the district is Q. The length of each airways is L. Cross-sectional area of each airways is S and cross-sectional perimeter is P.

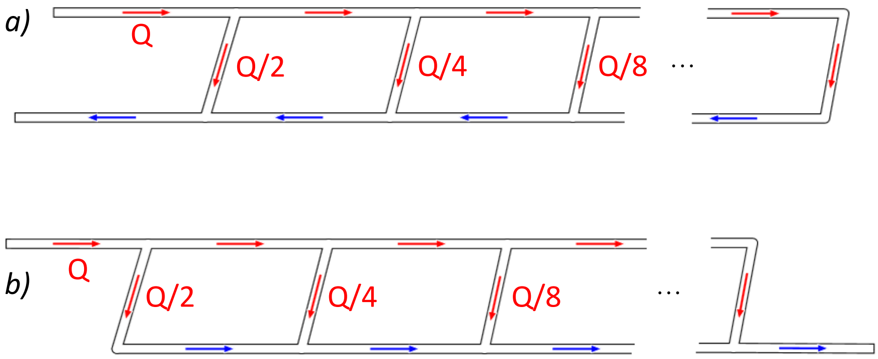

Fig. 1. Two simplified districts of a mine corresponding to two ventilation layouts: U-tube ventilation district (a) and through-flow ventilation district (b).

The districts may be chosen in a variety of ways: with other proportions of the airflows in connections, other junction angles, additional parallel intake and return airways etc. But in this paper, we pay our attention to this simple case.

In this case the pressures P_A and P_S are determined as follows:

$$P_A = 1.64\frac{\alpha PL}{S^3}Q^2, \tag{2}$$

$$P_S = 4.1\frac{\rho Q^2}{S^2}. \tag{3}$$

Here $\alpha = 0.5\rho f$ is the coefficient of air resistance, kg/m^3; ρ is air density, kg/m^3, f is roughness coefficient [3].

Calculation of pressure P_A is based on the Darcy equation, while calculation of the shock losses P_S is accomplished using empirical formula for right-angled junctions given by Mokhirev [4].

The criteria (1) takes on values from 0 to 1 and represents relative fraction of the shock losses in total pressure drop across the airflow path. Fig. 2 shows isogram of the criteria in case of airways with circular cross section $P = \sqrt{4\pi S}$ and coefficient of air resistance $\alpha = 0.007$ kg/m^3. The value of α corresponds to arc wall steel lining. The zones corresponding to different types of mines are also shown in Fig. 2.

As follows from Fig. 2, there is a class of mines with sufficiently great relative fraction of shock losses (more than 20 %). This class includes mines with large cross-sectional areas of airways and small remoteness of work areas. It is recommended to take into account shock losses when calculating air distribution in this class of mines.

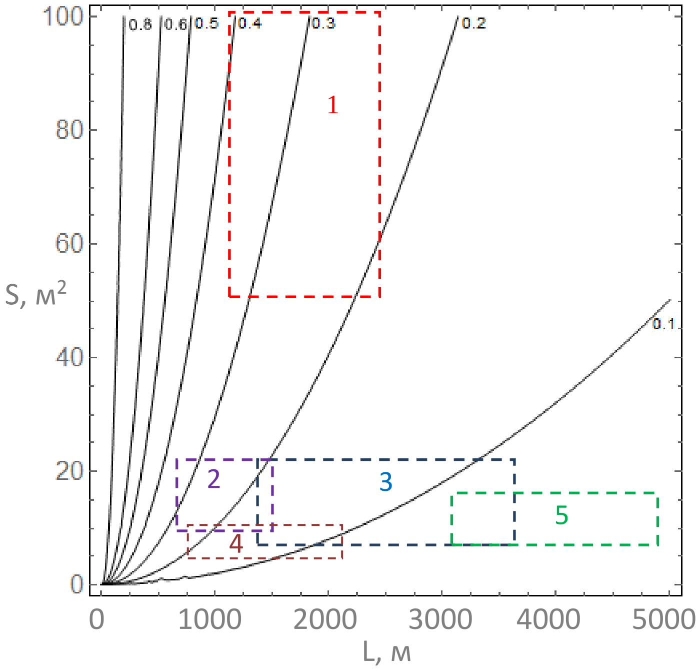

Fig. 2. Isogram of criteria (1), relative fraction of the shock losses from different types of mines: 1 — gypsum mine of “Gypsum Knauf Novomoskovsk”, 2 — diamond mines of “Alrosa” company, 3 — head rock mines of “Norilsk Nickel” company, 4 — oil mines of “Lukoil” company, 5 — potash mines of “Uralkali” and “Belaruskali” companies.

3 Methods for Shock Loss Calculation

Nowadays, a number of methods for calculating pressure differential produced by the shock loss at junctions are described in the literature. The simplest method is the equivalent length method [3, 6]. According to it, shock losses are considered as an additional term R_S in air resistance of the branch:

$$R_S = \frac{\rho X}{2S^2}, \tag{4}$$

where X is empirical coefficient (shock loss factor), which depends on the type of airways junction.

According to [3], shock losses resistance R_S should be assigned to the side inflow branches and to the all outflow branches. The specific value X can be determined with the help of tables and nomographs summarizing complex experimental studies [3, 5, 6].

The similar method was introduced in the seminal work on mine ventilation in the USSR [7]. The values of coefficient X are presented in case of right-angled splits and junctions of three airways. At that, shock loss resistances are recommended to include only for side branches. Thus, straight airflow has not any additional resistances. Physically it is not correct. Described methods, which are based on formula (4), give results sufficiently different from results of 3D numerical modeling and experimental study of airflow [8].

More complex approach to shock losses modeling is presented in [4, 9]. The monograph [4] contains a number of empirical functions of shock loss calculation in right-angled junctions of three airways. Additional air resistances are included both in inlet and outlet branches.

The monograph [9] presents a universal method for calculating shock losses in T-junctions in case of any angle between the branches.

Shock loss at splits:

$$P_{S_i} = X\frac{\rho}{2}\left(V_i^2 - 2V_1V_i\cos\delta_1 + V_1^2\right),\ i = 2,3. \tag{5}$$

Shock loss at junctions:

$$P_{S_i} = X\frac{\rho}{2}\left(V_i^2 - 2V_3\left(\frac{Q_1}{Q_3}V_1\cos\delta_1 + \frac{Q_2}{Q_3}V_2\cos\delta_2\right) + V_3^2\right), \quad i = 1,2. \tag{6}$$

Here X is empirical friction coefficient, which varies from 1 (smooth concrete lining) to 2 (rough walls without lining), V_i is the average velocity in i-th branch, δ_i is the angle between i-th branch and horizontal axis (see Fig. 3).

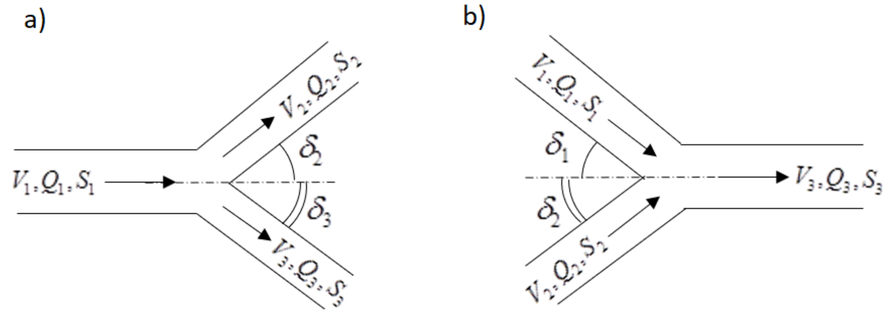

Fig. 3.T-junctions: (a) airflow split and (b) airflow junction

The above-mentioned studies are devoted to bends and junctions of maximum three branches. Study on shock loss in junctions of an arbitrary number of branches was conducted in paper [10]. An analytical formula for shock loss determination was derived as a generalization of Borda–Carnot equation.

$$P_{S_i} = \sum_j \frac{Q_i Q_j}{Q_\Sigma^2} \frac{\rho\left(V_i - V_j\right)^2}{2}. \tag{7}$$

Here Q_Σ is total airflow through the junction, index “i" is referred to the outlet branches, while index “j” is referred to the inlet branches. Number of inlet and outlet branches may be selected in an arbitrary way.

Derivation of the formula (7) assumes several simplifications:

1. Energy loss due to airflow turn is not considered.
2. Variable friction factor is not considered.
3. Pressure loss$P_{S_i}$is a part of air resistances of outlet branches, while inlet branches have no summands corresponding to the shock loss.

The influence of shock loss factor was also carefully studied in hydraulics. The handbook [11] offers a number of models and methods to calculate shock losses (or minor losses) in pipe networks. The methods for calculation shock losses are formulated in general terms and can be applied for any fluids. The friction factor, which has a great importance in mine airways, is sufficiently smaller in smooth pipes, therefore the accuracy of these methods can be low in case of rough walls without lining when blasting technique is used.

In the present paper authors attempted to combine existing methods (5) – (7) of shock loss calculation. The 1D mathematical model of airflow junction with arbitrary physical and geometry properties was formulated according to 1D conservation laws and experimental data. The following expression for shock loss was derived

$$P_{S_{ij}} = X\sum_s \frac{Q_s}{Q_\Sigma}\frac{\rho\left(V_s - V_j\right)^2}{2} + X\sum_j \frac{Q_s}{Q_\Sigma}\frac{\rho\left(V_i^2 - V_s^2\right)}{2} + X\sum_j \frac{Q_s}{Q_\Sigma}\rho(V_i - V_s) + 2X\sum_j \frac{Q_s}{Q_\Sigma}\rho V_s V_j \sin^2\left(\delta_{sj}/2\right). \quad (8)$$

Here X is friction coefficient; $P_{S_{ij}}$ is pressure drop due to the shock loss between i-th inlet branch and j-th outlet branch, Pa; Q_s is the volume airflow in s-th branch, $m^{3/}s$; V_s is the average velocity in s-th branch, m/s; ρ is air density, kg/m^3; δ_{sj} is the angle between s-th inlet stream and j-th outlet stream, °; indices "i"and "s" are referred to inlet branches, while index "j" is referred to outlet branches.

Formula (8) was implemented numerically using mesh current method for calculation of air distribution in mine ventilation networks in software application "AeroSet" [12].

4 Comparative Study of Existing Methods

The comparative study of existing methods is conducted in the context of solving air distribution problem for the following system of mine airways (see Fig. 4). This system consists of four branches and clearly demonstrates the shock loss influence on air distribution in parallel branches.

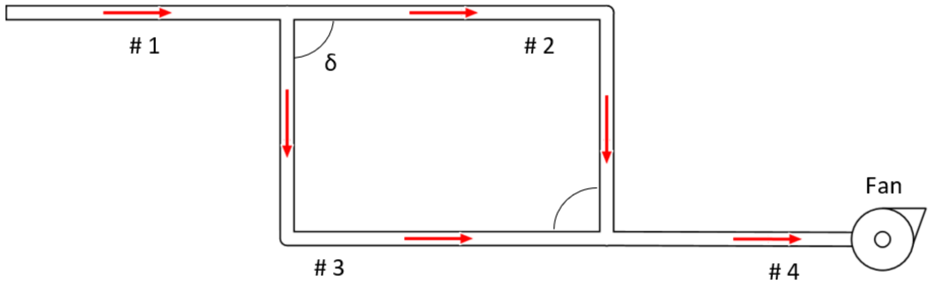

Fig. 4. System of mine airways

It is assumed that all branches have the similar physical and geometry properties: length L, cross-sectional area S and perimeter P, air resistance coefficient α. Air moves from the left to the right due to depression of a fan.

The classical approach of solving air distribution problem using only straight airway resistances in Kirchhoff's circuit laws results in the wrong solution with equal airflows in the branches No. 2 and No. 3. At that, results of 3D numerical simulation of steady-state turbulent airflow in ANSYS CFX show that the airflows in two parallel branches are sufficiently different. The discrepancy between airflows strongly depends on angle δ of junction and coefficient of air resistance α.

Fig. 5 shows the results of 3D numerical simulations using the following parameters of the problem: L = 50 m, S = 7 m^2, P = 8 m, V_1 = 2 m/s. Coefficient of air resistance αtakes on the values from 0.005 (concrete lined airways) to 0.05 (unlined airways when blasting technique is used). Angle δ of junction varies from 20° to 120°. As the result, the ratio between airflows in parallel branches varies in a wide range. In case of δ = 90°it ranges from 1.5 to 3 (see Fig. 5). The greater airflow is observed in the branch No. 2. This fact has the following explanation. At the airflow split, shock loss of the straight flow is much lesser than shock loss of the flow in side branch. While shock losses at airway junction are roughly the same for straight flow and side flow.

When airflow in the system is reversed, the situation changes dramatically. The new reversal airflow ratio in the parallel branches become reciprocal to the old value. This example shows principal asymmetry of shock losses in relation to the change of airflow direction.

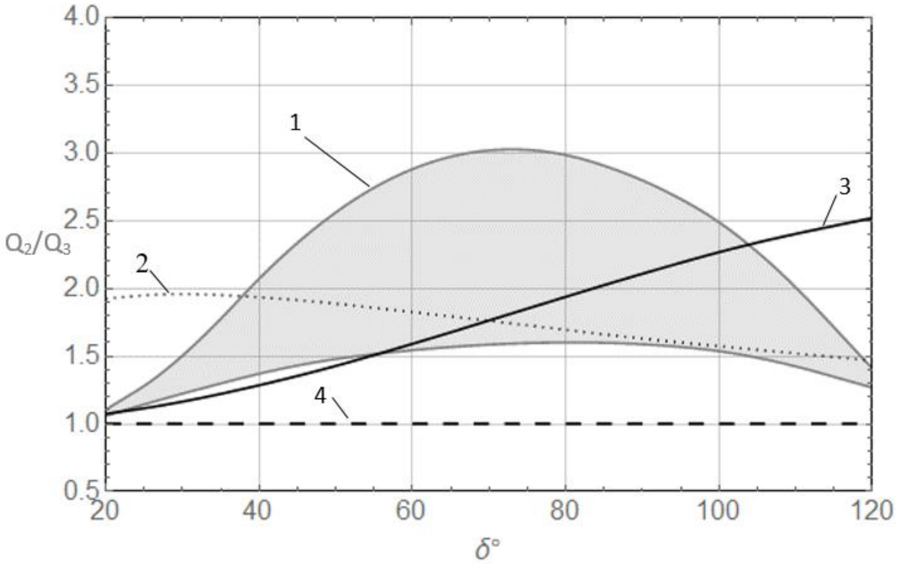

Fig. 5. The ratio between airflows in parallel branches as a function of junction angle δ: 1 – results of 3D numerical simulation in ANSYS CFX for values of wall roughness in the interval [0.005, 0.05], 2 –hydraulic method, described in [11], 3 – model proposed by authors, 4 – a class of symmetric shock losses methods proposed in monographs [3, 4, 9, 10].

Fig. 5 also shows the ratios between parallel airflows calculated using methods, which were described above. Most methods predict the equal airflow distribution in parallel airways. These methods can be ranged in a class of symmetric shock losses in relation to airflow reversal.

Asymmetric air distribution in parallel airways was achieved by means of two methods – hydraulic method [11] and method (8) proposed by the authors. These two methods both correspond to the results of 3D simulation on qualitative level, but in terms of quantity each method has its own limitations.

The results of 3D simulation show the following scenario of airflow ratio change. At first, the airflow ratio grows up with the increasing of junction angle δ from 20° to 75°. It is caused by increasing of shock loss in side branch flow at the split of parallel airways. At that, shock loss of the straight flow at the split remains the same relatively small value. When the junction angle δ becomes greater than 75°, decreasing tendency of the airflow ratio is observed. It is concerned primarily with the increasing influence of shock loss at the junction of parallel airways. The air stream from the side branch No. 2 enters the junction at a high angle>75°. It leads to formation of a large stagnant wake in the branch No. 4 right after the junction, which is energetically unfavourable and leads to decrease of airflow in the branch No. 2.

Hydraulic method of calculation shock losses [11] predicts only decreasing of airflow ratio, while proposed model (8) describes only the process of airflow ratio growth.

Considering high inaccuracy of experimental data used for creating mathematical models of mine ventilation networks, quantitative deviations of the methods [11] and (8) are not crucial. Usually, the mine is designed in such a way that airflow turns by the angles lesser than 90°. From this point of view, the physical process of airflow ratio growth on parallel airways is more important.

It should be added that method (8) is universal and applicable for arbitrary airway junctions, when the hydraulic method consists of many formulae, which are applicable only for specific splits or junctions and hardly suitable for implementation in mine ventilation network models.

5 Conclusion

The results of the study allow formulating recommendations for mine ventilation design. The procedure of creating a mathematical model of mine ventilation network should include the following steps:

1. Determine the influence quantity of the shock loss factor for the network using Fig. 2.
2. In case of sufficient shock loss factor, calculate airflow distribution in mine using formula (8) for pressure drop due to the shock losses.

3. In case of complex geometries at the specific junctions, where the airflow is sufficiently nonuniform and pressure loss is conceivably great, use 3D numerical simulation for determination of pressure losses (junction of fan drift and mine shaft).

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