DETERMINATION OF DUCT PARAMETERS FOR AUXILIARY VENTILATION IN QUANG NINH UNDERGROUND MINE

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Abstract

Ventilation when driving roadways is one of the most important considerations in coal underground mines. Ventilation efficiency depends on fan performance and ventilation ducting system. In recent years in Vietnam, ducts have often been produced domestically. However, parameters of the duct as duct leakage, duct resistance for designing auxiliary ventilation system are referenced from abroad handbook. This lead to inaccurate design results and needs to adjust efficiency of auxiliary ventilation during driving roadways. Determination of duct resistance; air leakage in ducting system have been undertaken. The research result has been used to optimize the auxiliary ventilation system.

Keywords: air leakage, auxiliary ventilation, duct resistance.

Introduction

In each country, ducts are manufactured from different materials and technologies, so the resistance coefficient and air leakage of the ducts are not the same. Studies on duct resistance and air leakage began to be carried out in the middle of last century. In recent years, the number of these works is not much, while the material quality of the duct is higher than before.

In developed mining countries such as Russia, Ukraine, Germany, Poland, The United Kingdom. The United States, Japan, etc. ... since the middle of the last century, they have carried out research on duct parameters. The results of these studies can refer to the works of scientists from some countries with a traditional background in mining, such as institutes, universities. Among the typical scientists, the scientists in former Soviet Union can mention such as: A.T. Ayruni, A.S. Buchakov, A.A Bobrov, A.B. Braitsev, I.I. Medvedev, S.V Yanko, S. Tkachuk, L.F. Bazhenov, V.E. Eliseev, V.B. Komarov A.A. Eremenko, V.I. Golinko, I.I. Lebedev, L.A. Puchkov, O.A. Mukha, P.I. Mustel and K.Z. Ushakov.

In Australia, scientists Barret and Wallman, Jones and Rodgers determined the frictional resistance and air leakage for duct different materials. British scientist Vutukuri has proposed to solve the air leakage problem by assuming a number of discrete leakage paths and treating the leaky duct as a ventilation network.

Scientists D.A. Telyakovsky, V. Komarov pointed out that if the effects of aerodynamic factors on air leakage are not fully taken into account, the results of air leakage level are determined almost higher than in reality.

Contrary to the results of the studies in the former Soviet Union countries, in the United States, according to survey of Mine Ventilation Services Inc. the friction coefficients referenced from textbooks and documents are larger than that measured at the field under the same conditions. This problem can be explained as follows: these data were published decades ago while at present, materials, as well as duct technology are much different.

In Vietnam, studies on an auxiliary ventilation mainly aimed at finding solutions to improve the ventilation efficiency when mining roadways driven in coal mines. The number of these works is not much, especially there is no research on the resistance and air leakage in ducting system being used in coal mines.

In the past, due to flexible ducts were often imported from abroad, parameters of the duct as duct leakage, duct resistance were referenced from abroad handbook to design the auxiliary ventilation system. However, currently, flexible ducts have often been produced domestically, determination of a relationship of the duct leakage and the duct aerodynamic characteristic must been undertaken.

1. Literature review on the air leakage and resistance of ducting system

1.2. Literature review on determination of duct resistance

Moving the air in the ducting system often result in loss of certain energy (pressure). There are two types of resistance: friction resistance and local resistance. For the ducting system kept tight, straight during experimental procedures, the energy loss on the ductwork is caused by frictional resistance.

In mine ventilation, characteristic quantities for frictional resistance are:

r - specific resistance per unit duct length, (km/m);

α - Friction factor, KgF s^2/m^4;

λ - Friction coefficient, dimensionless; $\lambda=65,4\alpha$

The values for published values of the friction factors by authours as shown in Table 1.1.

Table 1.1

Quoted friction factors α for flexible duct

No	Friction Factor α, KgF, s^2/m^4	Reference
1	0,00054	Telyakovsky and Komarov, 1969
	0,00046- 0,00048	Burtrakov and Ushakov
2	0,00030	Le Roux, 1979
3	0,00037- 0,00046	Hartman and Mutmanski, 1982
4	0,00051	Baret and Wallman, 1983
5	0,00023	Jones and Rodgers, 1983
6	0,00038	Vutukuri V., 1983

G.V. Levin show the resistance per 100 m of duct as in table 1.2

Table 1.2

The resistance per 100 m of duct, (kμ)

D, mm / Type of duct	300	400	500	600	700	800	900	1000
M	128	31,0	10,0	4,0	1,8	0,9	0,5	0,3
Tekctovinnite	56	10,8	3,3	1,2	0,5	0,25	0,13	0,08

However, G.V. Levin noted that the resistance value are as in the table 1.2 when ducting system was installed well. If ducting system was not installed tight, straight these values could increase more 25%.

1.3. Methods of determination of duct air leakage
Experimental method

Experimental methods are mainly performed on the model with the ducts and fans used in field.

Semi-experimental method

Dzidziguri and Cholikidze (1977) proposed a method for the summation of discrete leakage paths for calculating the total air losses in long air ducts. Assuming that air leakage in the first l meters of a duct is ΔQ m³/s, and the initial quantity of air beyond the fan is Q_0 m³/s, then a leakage coefficient can be described as $\delta = (\Delta Q/Q_0) \times 100$, (%). Summing the air leakages over the entire duct and simplifying, an equation for the total air losses over the entire duct length is given by

$$\sum \Delta Q_n = n.\delta.\frac{Q_o}{100} \left\{ 1 - \frac{\delta.(n-1)}{100.2!} + \frac{\delta^2.(n-1)(n-2)}{100^2.3!} - \frac{\delta^3.(n-1)(n-2)(n-3)}{100^3.4!} + \cdots \right\}.$$

Sufficient accuracy can be obtain by considering only the first five to six terms, and for low values of δ (0,4-1,0%) three terms are sufficient.

From the above equation, the air leakage coefficient - p, the efficiency of the air delivery of duct length L- η can be obtained by the following equations

$$p = Q_q / (Q_q - \Delta Q_n) \text{ and } \eta = 1/p.$$

Vutukuri Mathematical Solutions

Vutukuri (1983) proposed that analysing flow in a leaky duct is possible by assuming a number of discrete leakage paths and treating the leaky duct as a ventilation network. In Fig. 1, air enters the duct and leaves either through leaky joints or via the exit of the ducting.
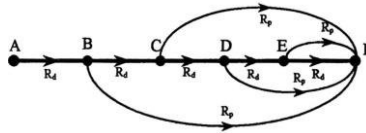

Fig. 1.1. Vutukuri's network analysis for leaky duc

A number of assumptions have been made as: Leakage paths have some resistance and the resistance coefficient of leakage paths (R_p) is the same.

• The resistance coefficients of all duct sections are the same R_d.

• The pressure outside the duct is assumed to be the same along the airway.

So that: $Q_{BF}=Q_{AB}-Q_{BC}$ and because these are in parallel

$$R_{BF} \cdot Q_{BF}^2 = R_{BC} \cdot Q_{BC}^2 .$$

From that the leakage from *B* to *F* can be found. Vutukuri found that the air leakage depends on flow rate, the length and the diameter of duct.

Some researchers gave the results of the air leakage coefficient in the form of tables or graphs for certain types of duct.

1.4. Literature review on results of the air leakage coefficient

The results of the air leakage coefficient shown in the form of tables or graphs for certain types of duct are as:

V. Komarov and D. Telyakovsky gave the results of the air leakage of the duct per 100 m of the ducting system. According to G.V. Levin, the air leakage coefficient p of the flexible duct with length *L*(m), when ducting system installed well, have values as shown in Table 1.3.

Table 1.3

Coefficient and percent of air leakage of flexible duct M

Duct length, m	200	400	600	700	800	1000
Air leakage coefficient,	1,21	1,33	1,45	1,50	1,54	1,64
Percent of air leakage , %	17,4	24,8	31,0	33,3	35,1	39,0

If using TV synthetic flexible (tektovinnite) duct, the air delivery efficiency increases and the air leakage decreases quite significantly (Table 1.4).

Table 1.4

Air delivery efficiency η and air leakage p of flexible duct TV (tektovinnite)

Diameter (m)	Coefficient	Duct length, *L* (m)							
		100	200	300	400	500	600	700	800
0,5	η	0,98	0,95	0,91	0,87	0,83	0,77	0,72	0,70
	p	1,020	1,053	1,099	1,149	1,205	1,299	1,389	1,429
0,6	η	0,8	0,97	0,93	0,90	0,87	0,84	0,79	0,76
	p	1,020	1,031	1,075	1,111	1,149	1,190	1,266	1,316
0,7	η	0,99	0,97	0,95	0,92	0,90	0,87	0,84	0,79
	p	1,010	1,031	1,053	1,087	1,111	1,149	1,190	1,266
0,8	η	0,99	0,98	0,96	0,94	0,92	0,90	0,87	0,84
	p	1,010	1,020	1,042	1,064	1,087	1,111	1,149	1,190

Formula of determination of duct air delivery efficiency

The research work of K.Z. Usakov show that for flexible ducts, air leakage per a section is approximately 1% (with the first 20 duct sections); each subsequent section is equal to 0,5%. Therefore, air delivery efficiency can be calculated by the following expressions

For duct length L≤20l

$$\eta = \frac{1}{1 + 0,01 \cdot n} \, .$$

For duct length L>20l

$$\eta = \frac{101}{1 + 0,05 \cdot L} \, .$$

where L total length of ducting system; n: number of ducts; l:length of a duct.

According to the authours F.A. Kozhanov, I.S. Rodkin, air leakage coefficient is determined by the formula

$$p = 1 + \frac{f}{3} L - \frac{5f^2}{6} L^2 \, ,$$

where

$$f = \sqrt[3]{\frac{tk^2}{2}} \dot{v}ak = k_y \frac{D_\dot{o}}{L} \, ,$$

k - Specific coefficient of air leakage (level of air leakage per 1 m when pressure 1 kG/s²);

k_y - Local coefficient of air leakage;

$D_\dot{o}$ - Duct diameter.

However, the above formulas did not take into account the influence of factors such as air flow, duct diameter.

Authour Bogomolov (Ukraine) shown that, air leakage flow through the joints connecting duct depends linearly on static pressure loss: $\Delta Q = B \cdot H$ (m³/s);

where B: Constant was determined experimentally for each duct type;

H - Static pressure loss, mm H_2O.

Analyses the literature, the findings suggest that:

The resistance and air leakage of duct the usually are determined by experimental methods.

The values of the resistance and air leakage of ducts have different due to different technology and materials made duct. At present materials, as well as duct technologies are much different from before, therefore determination of air leakage and resistance of auxiliary ventilation ducting must be updated. In Vietnam, ducts are

now produced by higher quality materials than previously imported ducts.

Literature review on duct parameters, some researchers often showed results of air leakage and resistance of duct in the form of tables or graphs for certain types of duct. Some analytical expressions given are unreliable and do not took into account the relationship between the duct parameters.

The determination of the duct resistance is carried out by the experimental method through the duct diameter, head loss and flow rate on the test duct. The level of air leakage is estimated from the relationship between the geometrical and aerodynamic parameters of the duct.

2. Fundamental basis of determining resistance and air leakage of the duct in Quang ninh coal mine

2.1. Fundamentals of airflow

Moving the air in the ducting system often result in loss of certain energy (pressure). Pressure loss is due to as follows:

- Pressure loss is due to overcome viscosity of the air moving in a straight duct and a constant cross-section. It is the energy loss due to friction resistance and is proportional to the duct length and diameter.

- Pressure loss is due to overcome local resistance, as well as deformation of duct. This energy loss depends on the directions and values of airflow velocity.

In practice, air leakage through in ducting system flows in turbulent flow mode. In turbulent flow mode, airflow energy loss for overcoming viscosity of the air due to turbulent vibrations. Pressure loss due to frictional resistance in a round duct is determined by

$$\Delta P = H = \lambda \frac{L}{D} P_v, \qquad \text{Or } \frac{\Delta P \cdot D}{P_v L},$$

where

ΔP - Pressure loss (head loss) due to frictional resistance in duct L long, mm H_2O;

P_v - Velocity pressure in duct, mm H_2O;

λ - Friction coefficient, dimensionless coefficient;

L - Distance between two cross sections of duct, m;

D - Diameter of the duct, m;

However, at present, there is no expression for calculating friction coefficient in turbulent flow mode. It has been determined experimentally.

Theoretically, for the short ductwork, the static pressure loss between the two cross-sections of duct is negligible, so the total pressure loss can be considered to be the velocity pressure loss.

In laminar flow mode, coefficient λ is usually higher than turbulence mode (due to small airflow velocity) and depends linearly on airflow velocity approximately,

2.2. Factors affecting on resistance and air leakage of duct

Currently, many studies have been showed the results of air leakage and resistance of the duct depending mainly on the length, materials and diameter of the duct. The results of these parameters are often presented in the form of tables or graphs. Thesis will focus on factors that mainly affect duct leakage and from that derive analytical expressions to calculate air leakage coefficient based on these factors.

Ducts of different sizes and diameters

Air leakage of the ducting system is affected by the length of duct. Obviously, when the duct length is longer, the ducting system requires more joints. For flexible ducting system, air leakage through these joints cannot be avoided. The degree of the air leakage in the ducting system depends on duct diameter; if the duct diameter - D is larger, the degree of the leakage is smaller due to the resistance of the duct that is inversely proportional to D^5.

Aerodynamic parameters

Air volume is one of the important factors to consider when estimating air leakage through ducting system into the face. Regarding the pressure in the duct, studies on the level of airflow to the face give the following remarks: the variability of the pressure values inside ducting system is not much that influences air leakage level about 1-2%.

Duct system resistance

Duct system resistance affects the degree of air leakage when the joints are of poor quality, but in the case of good installation practices, local duct resistance in ductwork has small.

The resistance and air leakage of duct depend on working life, installation and maintenance of ducting system.

2.3. The duct used in underground

Auxiliary ventilation systems in underground used is the force system, in which the fresh air is led to the face through the duct. Flexible ducts and different types of fans are used for the auxiliary ventilation system. There are various types of ducts: rigid, semi-rigid and flexible. Depending on the different types of duct, there are different advantages and disadvantages.

In practice, in Quang Ninh mines, PVC coated fabric duct is suitable for high power fan in order to reduce level of the air leakage and increase durability of the ducting system, especially at site where a duct connects to the fan.

2.4. The basis for determining duct resistance

A relationship between pressure loss and flow velocity in the duct is given by

$$\frac{P_1 - P_2}{L} = \frac{\lambda}{D} \cdot \frac{\rho}{2} v^2,$$

where
P_1 - Pressure of air at section 1;
P_2 - Pressure of air at section 2;
ρ - Air density, kg/m^3;
V - Average velocity at the duct cross-section, m/s.

In laminar flow mode, friction coefficient depends on Reynolds number and smoothness of the duct material. Duct resistance coefficient can be determined by A.D. Altsul's formula

$$\lambda = 0,11 \cdot \sqrt[4]{68 / \text{Re} + k / D},$$

where k - Roughness of the duct wall material;

However, using this formula could be difficulties to take into account roughness of the duct wall material.

In turbulent flow mode, there is currently no analytical formula for calculating the coefficient λ. A relationship between λ and Re is often determined experimentally.

2.5. Theory of leaky duct

When air flow is moved in ducting system, air leakage is always presented. Air leakage is a complicated aerodynamic phenomenon. If there is not air leakage through the duct, the pressure of the fan

generated and the air flow throughout the ducting system can be described by a model quite accurately.

Air leakage can be described in the following two physical models:

+ Discrete - air leakage leaks through joints of ductwork

+ ontinuous - randomly distributed outlets along the ductwork walls.

According to Goodfellow, H.D. Tähti, the process of movement of the airflow in the duct is described by the conservation equation of energy and mass usually solved with the following conditions:

- The air flow in the duct is turbulence flow;

- The density of the air is a constant;

- Local resistance can be calculated as the additional factor to frictional resistance.

The authour B.I. Medvedev show that air leakage occurs along the ducting system. Depending on the leakage flow, the air permeability through the wall of the duct will be turbulent flow (if the leakage is large) or laminar flow (if the leakage is small). The authours A.A. Myasnikov, I.A. Kamyshansky investigated that: the variability of the pressure values inside flexible ducting system is not much that influences air leakage level about 1-2%. From Experimental results, authours I.A. Shvyrkov, F.S. Klebanov show that at the end of ducting system, flow rate, as well as the pressure decreases while level of air leakage through the ducting system decreases quite significantly.

The authour Sh.P. Khangeldyan pointed out that, if the ducting system is installed straight, the local resistance can be calculated as the additional factor with frictional resistance.

In conclusion:

Auxiliary ventilation systems in coal underground mine used is the force system, in which the fresh air is led to the face through the duct. Flexible ducts produced by different materials with diameter of 0,5-1,0 m are often used. Duct is available in various lengths, generally in 10-20 m lengths. At present, flexible ducts manufactured by Vinacomin - Cam Pha Materials Trading JSC are one-sided or double-sided PVC coated duct. These ducts have a smaller resistance and a longer working life than fabric ducts produced before.

In laminar flow mode, duct resistance coefficient can be determined by the A.D. Altsul formula. However, using this formula could be difficulties to take into account roughness of the duct wall material.

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Air through in ducting system in turbulent flow mode, the expression for determining Atkinson's resistance as $H=RQ^2$ (also called Square Law because the pressure drop is proportional to the square of the volume of airflow rate). In turbulent flow mode, duct resistance coefficient has to be determined experimentally.

3. Determination of duct resistance coefficient

3.1. Fundamentals of duct resistance

Air leakage through in ducting system flows in turbulent flow mode. In turbulent flow mode, airflow energy loss for overcoming viscosity of the air due to turbulent vibrations, so this level of energy loss is much higher than that in laminar flow.

Pressure loss due to frictional resistance in a round duct is determined by

$$\Delta P = H = \lambda \frac{L}{D} P_v = 32,25 \cdot \alpha \cdot \frac{L}{D} \rho \cdot v^2$$

where

ΔP - Pressure loss (head loss) due to frictional resistance in duct L long, mm H_2O;

P_v - Velocity pressure in duct, mm H_2O;

λ - Friction coefficient, dimensionless coefficient;

L - Distance between two cross sections of duct, m;

α - Friction factor for the duct, $KgF, s^2/m^4$;

D - Diameter of the duct, m;

ρ - Air density, kg/m^3;

V - Average velocity at the duct cross-section, m/s.

A relationship between pressure loss and friction factor in duct is given by

$$\frac{H}{L} - \frac{P1 - P2}{L} = 65,4 \cdot \frac{\alpha}{D} \cdot \frac{\rho}{2} v^2,$$

where

P_1 - Pressure of air at section 1;

P_2 - Pressure of air at section 2,

However, at present, there is not expression for calculating friction factor α. It has been determined experimentally,

3.2. Method of determination of duct resistance coefficient

One of the most basic ventilation equations describes a relationship between pressure loss and airflow volume in a duct is

$$H = \Delta P = R \cdot Q^2 = R \cdot (v \cdot S)^2$$

Therefore, friction resistance in ducting system can be obtained by the following equation

$$R = \frac{H}{v^2 S^2},$$

where

R - Friction resistance, kµ;

S - Cross sections of duct, m^2,

From equation above, the specific resistance - r and friction factor of the duct can be found

$$r = R / L.$$

And friction factor α is determined by

$$\alpha = 0{,}25 \cdot \frac{H \cdot D}{v^2 \cdot L}$$

### 3.3. Experimental model for determination of duct resistance

Laboratory set-up: Experimental model for determination of duct resistance was set up at Institute of Mining Science and Technology - Vinacomin (IMSAT), Uong Bi, Quang Ninh.

Fig. 3.1. Experimental apparatus for determination of duct resistance

Fig. 3.2 shows the schematic diagram for determination of duct resistance.

Fabric duct was connected to the test setup. Fabric duct was connected directly to rigid steel ducting and carried as straight in the horizontal direction. The fan had the capability to blow the airflow into the duct.
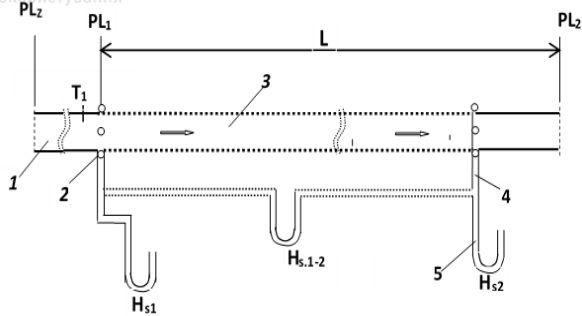
Fig. 3.2. Schematic diagram for determination of duct resistance: *1* - rigid steel ducting; *2* - holes for measurement; *3* - flexible fabric ducting; *4* - pitot-tube; *5*- U tube

According to the authours H.D. Goodfellow et al, the process of movement of the airflow in the duct is described by the conservation equation of energy and mass. For determination of duct resistance, assuming that:

- The air flow in the duct is turbulence flow;
- The density of the air is a constant.

Experimental model set up the conditions which must be satisfy the conditions as follows:

- The ducting system must be kept tight, straight during experimental procedures. Hence, the pressure loss on the ductwork was caused by frictional resistance, Since the duct from PL_1 to PL_2 has no joints, local resistance does not appear.
- The test duct length shall be required to arrive at a fully developed turbulent flow.

For the model to determine the resistance of the duct with diameter $D=0,6$ m and air flow $Q=3,4$ m³/s, the velocity in the duct is as

$$v = 3,4 : \left[\pi * \left(\frac{D}{2} \right)^2 \right] = 12,02 \ \text{m/s}$$

Reynolds number

$$R_e = \frac{v.D}{v} = \frac{12.02 * 0.6}{14.4 * 10^{-6}} = 500833$$

where v is the viscosity coefficient of the air, $v=14,4\times10^{-6}$

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Duct length between two cross sections of duct section must be satisfied

$$L = 0.639 * R_e^{0.25} * D = 10,2 \text{ (m)}$$

Thus, for the duct with diameter D=600 mm, test duct length is set 15 m.

For the duct of 0,7-1 m diameter, test duct length have calculated as the same above.

- The system had a fan to supply air flow. The variable speed control unit of the fan was used to obtain a fine adjustment of airflow under 12 m³/s.

- Microclimatic conditions during experimental procedures was: temperature 26°C and humidity 62%.

The average velocities in the ducts were obtained using the following method:

Velocity v at the center of each section was measured by a pitot tube. The cross sectional area of the duct was equally divided into four areas, 16 points traverse as shown in Fig. 3.3.
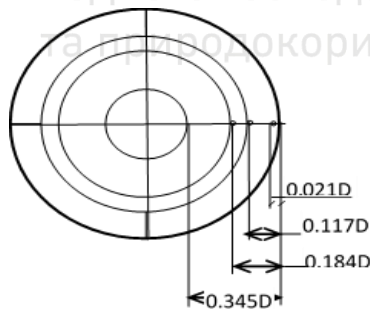

0.021D
0.117D
0.184D
0.345D

Fig. 3.3. Diagram position of traverse points in a circular measurement section for 4 - area, 16 point traverse

The average velocity *V* in the duct was calculated from the arithmetical mean value of *v*. From that the average velocities at the measuring of the pressure drops along the ducts can be estimated.

At the same time, the pressure difference between the pressure PL_1 and PL_2 was measured and related with the average velocity *V*.

Fig. 3.4. shows cross sectional area for the pressure measurement
and pitots in practice

3.4 Results of determination of duct resistance

Experimental data for determining duct resistance R, specific resistance r and friction factors are shown in Table 3.1 by Phuong Thao Dang, Z. Malanchuk, et al.

Average values of the resistance R, specific resistance r and friction factors calculated for test ducting are as

$$\bar{R} = 0.4041 \text{ k}\mu; \; \bar{r} = 0.0269 \; k\mu. \, m^{-1};$$
$$\bar{\alpha} = 0.00030 \text{KgF}. \, s^2. m^{-4}$$

The values for the measured friction factor is small compare with published values calculated by others as shown in Table 1.1- Chapter 1.

The measured friction coefficient (0,0003 kgF·s^2/m^4) is much smaller with the value using the auxiliary ventilation design in Vietnam (0,00048 kg·F·s^2/m^4).

Table 3.1

Experimental data and results for determining duct resistance

Measurement	1	2	3	4	5
Airflow Q, m^3/s	7,33	7,42	7,42	7,42	7,43
Pressure at section PL_1, Pa	785	784	781	780	777
Pressure at section PL_2, Pa	558	569	553	564	555
Resistance R, kμ	0,4224	0,3902	0,4138	0,3921	0,40201
Specific resistance r, kμ/m	0,02816	0,02602	0,02759	0,02610	0,02680
Friction factor α KgF,s^2/m^4	0,00034	0,0031	0,00033	0,0003	0,00032

In Conclusion

- An experimental study was conducted to evaluate duct resistance. Experimental model set up the under controlled conditions in order to ensure reliability results.

- The measured friction coefficient (0,0003 kgF·s^2/m^4) is factor is small compare with the value using for designing the auxiliary ventilation in Vietnam (0,00048 kgF·s^2/m^4). Therefore, accurately estimating the friction coefficient is thus crucially important to design auxiliary ventilation in underground mine.

- The results of the duct resistance are to contribute to basis in the design and calculation auxiliary ventilation in Vietnam.

4. Determination of a relationship of duct leakage and parameters of ducts

4.1. Model for duct leakage

Study was conducted to investigate duct leakage along auxiliary ventilation ducting systems in Quang Ninh mine. Experimental data are made on 0,7 m, 0,8 and 1 m diameter ducts over sections of ducts installing towards the working face in Quang Ninh mine. Linear regression analysis fit these experimental data can derive the relationship between the air leakage coefficient, the quantity of the air in the ductwork and the ducting length.

It is shown how to derive the function indicating a relationship between leakage coefficient p and ducting length L(m), airflow in ducting system Q (m^3/s) supplied to the working face for different diameters of the duct by Phuong Thao Dang, Vu Chi Dang

$$p = f(L, Q) \tag{4.1}$$

Accordingly, assuming that air leakage coefficient in the duct-work can be described to be in the form of

$$p = 1 + c * L^a * Q^b \tag{4.2}$$

where p Leakage coefficient;

L - Duct length, m;

Q - Quantity of airflow in the ducting system, m^3/s;

a,b,c - constants,

The way to linear the equation (4.2) is to use the natural logarithm equation (4.2)

$$\ln(p - 1) = lnc + alnL + blnQ \tag{4.3}$$

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The experimental data are made on 0,7 m and 1 m diameter ducts over sections of ducts installing towards the working face in actual field conditions in Q_{uang} ninh coal mine.

Each set of data: $\ln(p_i)$, $\ln(L_i)$ and $\ln(Q_i)$ under given data – duct diameter, with $i=1, 2…n$.

With ducting length L_i, the quantity of airflow in the ducting system Q_i is measured; the air leakage coefficient p_i is calculated as

$$p_i = \frac{Q_0}{Q^i} \ ;$$

where Q_0 the quantity of airflow beyond the fan, m³/s;

Q_i the quantity of airflow reaching the end of the ducting length - L_i:

y_i, x_{i1}, x_{i2} and b_0 are denoted as: $\ln(p_i-1)$, $\ln L_i$, $\ln Q_i$ and $\ln C$ respectively.

Equation (4,3) can be rewritten

$$y_i = b_0 + b_1 x_{i1} + b_2 x_{i2} . \tag{4.4}$$

Using linear regression analysis to fit these experimental data can derive the relationship between the air leakage coefficient, the quantity of the air in the ductwork and the ducting length, Least-squares regression is chosen coefficients $b_0, b_1…$ and b_k such that the sum of squared residuals is minimum:

Multiple regression model with k independent variables

$$L = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (y_i - \hat{y_i})^2 = \sum_{i=1}^{n} (y_i - b_0 - \sum_{j=1}^{k} b_j x_{ij})^2 \quad \to min \tag{4.5}$$

$i= 1,2,...n; j=1,2,...k$

$\to$ Least-squares must satisfy

$$\frac{\partial L}{\partial b_o} = -2[y_i - (b_0 + \sum_{j=1}^{k} b_j x_{ij})]^2 = 0 \tag{4.6}$$

and

$$\frac{\partial L}{\partial b_j} = -2[y_i - (b_0 + \sum_{j=1}^{k} b_j x_{ij})]^2 x_{ij} = 0 \tag{4.7}$$

The least squares normal Equations

$$\sum_{i=1}^{n} y_i = nb_0 + b_1 \sum_{i=1}^{n} x_{i1} + b_2 \sum_{i=1}^{n} x_{i2} + \cdots + b_k \sum_{i=1}^{n} x_{ik}$$

4.8)

$$\sum_{i=1}^{n} x_{i1} y_i = b_0 \sum_{i=1}^{n} x_{i1} + b_1 \sum_{i=1}^{n} x_{i1}^2 + b_2 \sum_{i=1}^{n} x_{i1} x_{i2} + \cdots + b_k \sum_{i=1}^{n} x_{i1} x_{ik}$$

(4.9)

…………………………………………………………...................

$$\sum_{i=1}^{n} x_{ik} y_i = b_0 \sum_{i=1}^{n} x_{ik} + b_1 \sum_{i=1}^{n} x_{ik} x_{i1} + b_2 \sum_{i=1}^{n} x_{ik} x_{i2} + \cdots + b_k \sum_{i=1}^{n} x_{ik}^2$$

(4.10)

The solution to the normal equations are the least squares estimators of the regression coefficients $b_0, b_1, \ldots, b_k,$

Multiple regression model with two independent variables

Convert above system of linear equations to matrix form as:

$$\begin{vmatrix} \sum_{i=1}^{n} x_{i1}^2 & \sum_{i=1}^{n} x_{i1} x_{i2} \\ \sum_{i=1}^{n} x_{i1} x_{i2} & \sum_{i=1}^{n} x_{i2}^2 \end{vmatrix} \begin{vmatrix} b_1 \\ b_2 \end{vmatrix} = \begin{vmatrix} \sum_{i=1}^{n} x_{i1} y_i \\ \sum_{i=1}^{n} x_{i2} y_i \end{vmatrix}$$ (4.11)

Use Cramer's Rule to find the values of b_1, b_2 and $b_0,$

4.2. Goodness of fit in linear regression

Total sum of squares - SS_{tot};

Residual sum of squares - SS_{reg};

Model sum of squares: SS_{model},

$$SS_{tot} = \sum_{i=1}^{n} (y_i - \bar{y})^2 \; ; \; SS_{model} = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2; \; SS_{reg}$$
$$= \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

$$SS_{tot} = SS_{model} + SS_{reg}$$
$$\triangleright \quad R^2 = \frac{SS_{model}}{SS_{tot}} = 1 - \frac{SS_{reg}}{SS_{tot}}$$

So R^2 called "*coefficient of determination*" $0 \leq R^2 \leq 1$. If $SS_{reg}=SS_{tot}$ then $R^2=0$ and model is not useful. If $SS_{reg}=0$ then $R^2=1$ and model fits all points perfectly. Almost all models will be between these extremes.

Test of hypothesis on individual regression coefficients

Step 1: *Set up hypotheses:* (are all the coefficients really equal to zero?) H_0: $a=b=0$

H_1:H_0 is untrue $a \neq b \neq 0$

Step 2*:* Calculate test statistic F

$$F = \frac{R^2 / k}{(1-R^2)/(n-k-1)}$$

Step 3: F_c (the critical F) can be found on the F-table with k df for the numerator and n-k-1 degrees of freedom for the denominator.

Step 4 Set decision rule: if $F \geq F_c$ then reject H_0.

4.3 Analyses data

Analyses data for the duct of 0,8m diameter measured at Ha Lam Coal mine Phuong Thao Dang, V.D. Bui.

Linear regression analysis to fit these experimental data can derive the relationship between the air leakage coefficient, the quantity of the air in the ductwork and the ducting length. Therefore, the air leakage coefficient for the ductwork of 0,8 m diameter can be estimated based on the experimental data at Ha Lam Coal mine by the regression method.

As a result obtained from Stata software, the air leakage coefficient for the duct of 0,8 m diameter can be found based on data at Ha Lam Coal mine

$$p = 1 + 1.3013 * 10^{-5} * L^{1.482658} * Q^{0.450381}.$$

Critical F was found on the F-table $F_{0,05}(2,19)=3,52$ with $\alpha=0,05$, F calculate: $F(2, 19)=78,17$

L_{max}: Duct length total

So: $F > F_c$ 0,05 then reject H_0, This value would imply that the regression parameters are nonzero and the regression equation does have some validity in fitting the data.

For the duct of 0,6-1 *m diameter at Quang Ninh Coal mine have been analyzed as the same above.*

For duct of 0,6 m

$$p = 1 + 3.127.10^{-6} * L^{1.906} * Q^{0.5351}$$

For duct of 0,7 m

$$p = 1 + 2.0042048 \cdot 10^{-4} * L^{1.051706} * Q^{0.677522}$$

For duct of 1,0 m

$$p = 1 + 2.554 \cdot 10^{-5} * L^{1.164} * Q^{0.686}$$

Table 4.1

Experimental data for the duct of 0,8 m diameter measured at Ha Lam Coal mine

Face	S, m^2	Local fan	Q_o m^3/s	Q_{Face} m^3/s	Values of p_i correspond to ductwork length L_i (m) when extending driven roadways					
					L_{max} p	L_1 P_1	L_2 P_2	L_3 P_3	L_4 $P4$	L_5 P_5
Vent, Roadways of Longwall 1011-3-T-15 Area III, Seam 11	9,4	FBDN-6,0/2×22	6,8	5,4	380	60	120	240	380	–
					1,259	101	1,015	1,079	1,2592	–
Vent, Haul Roadways level -270÷ -250 Area III-Seam 10	9,4	FBDN-6,0/2×22	6,8	5,2	482	100	180	286	360	452
					1,316	1,03	1,0625	1,1333	1,214	1,308
Ven, Roadways level -50 Area VI- Seam 10	14,3	FBDN-6,7/2×30	8,6	6,6	590	140	220	320	410	560
					1,303	1,062	1,117	1,1467	1,229	1,303
Ven, Crosscut level -70÷ -60 Area II- Seam 10	15,3	FBDN-6,7/2×30	8,6	7,0	452	100	180	240	340	410
					1,223	1,062	1,103	1,117	1,147	1,212

In conclusion

- Factors such as duct size and diameter, aerodynamic parameters of duct influencing on duct air leakage have been examined.

The leakage coefficient of the ductwork can be determined based on the general evaluation of the influence of the factors, in which the duct length and diameter, airflow in the ductwork are very important.

A conceptual prediction model has been proposed based on the experimental data at Quang Ninh Coal mine. Using linear regression analysis to fit these experimental data can estimated the air leakage coefficient in the ducting systems in coal underground mines.

Also, the research result has been used to design mine auxiliary ventilation system, especially optimization of parameters of duct and fan in the auxiliary ventilation system.

The results of leakage coefficient contribute to data in the design and calculation of ventilation during the construction of the tunnel and underground works. Methodology in the thesis is the basis for finding multivariable functions in mine ventilation in particular and mine design in general.

Conclusion

In Quang Ninh, coal underground mines have high methane content and total length of new driven roadways is large for expanding mining areas and growing coal output. Ventilation is one of the most important considerations in coal underground mines.

In Viet Nam, in the past, due to flexible ducts were often imported from abroad, parameters of the duct as duct leakage, duct resistance were referenced from abroad handbook to design the auxiliary ventilation system.

However, currently, flexible ducts have often been produced domestically, investigation of air leakage and resistance of auxiliary ventilation ducting system in underground mine in Quang ninh has been undertaken.

Level of air leakage is mainly influenced by the following factors: total length, diameter of the ducting and airflow in the ducting system.

Deriving analytical expressions of a relationship between air leakage coefficient and duct parameters is done by semi-experimental methods.

Multivariable function: $p=f(L,Q,D)$ has been determined according to the linear regression method based on experimental data.

The measured friction coefficient ($0{,}0003$ kgF·s^2/m^4) is much smaller with the value using the auxiliary ventilation design in Vietnam ($0{,}00048$ kgF·s^2/m^4).

Accurately estimating the friction coefficient is thus crucially important to design auxiliary ventilation in underground mine.

Therefore, it is necessary to determine the resistance all types of the ducts being used in auxiliary ventilation when mining roadways driven in coal mines, specially, for a duct produced in Viet Nam.

Suggestions for further research

Based on the method applied in the thesis, it is recommended that institutes and manufactures carry on determination of the air leakage coefficient for all diameter of duct, as well as choose suitable materials to produce duct to avoid air leakage and resistance.

Suggesting Vietnam national coal - mineral industries holding corporation limited apply the research results on the resistance and air leakage coefficient to calculate the ventilation to ensure save cost and energy.

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