

## Derivation and Verification Analysis of Local Ventilation Resistance Formula of the Section Gradual Reduction Roadway

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### Abstract

The gradually reduced section of the roadway is a transitional section connecting two different roadways, which plays an important role in reducing the local ventilation resistance of the mine ventilation system. To reveal the local ventilation resistance characteristics of the roadway, the flow dynamics model of the roadway was built, the formula of the local ventilation resistance of the section gradual reduction roadway was deduced, and the formula was verified by the measured data. Results show that the local resistance coefficient, local ventilation resistance, and local air resistance of the gradually reduced section of the roadway are reduced by 5.71, 1.59, and 1.52 times of that of the suddenly reduced section of the roadway, respectively, which indicates that section gradual reduction roadway is in a lower energy consumption state. The conclusions obtained in the study are of great value to direct the design and construction of the similar engineering practice.

*Keywords:* Section optimization, Ventilation resistance, Local resistance coefficient, Shrinkage angle

### 1. Introduction

The section gradual reduction roadway and the section sudden reduction roadway are two transition forms of the roadways with different cross-sections. The local ventilation resistance of the roadway in the transition section is an important factor that contributes to the total ventilation resistance of the mine. The local ventilation resistance of the roadway often accounts for 10-20% of the total ventilation resistance in mines, and which can even account for 50% of the total ventilation resistance in some mines [1]. So, it is an urgent problem to solve the safety and energy consumption by analyzing the characteristics of local ventilation resistance in the different transition sections of the roadways.

The section sudden reduction roadway is to connect the different cross-section roadways in transition section directly, there is a right-angle turn on the cross-section, which can produce the problems of gas entrapment, eddy current and high energy consumption. But for the section gradual reduction roadway, it cancels the right angle on the cross-section, which makes the roadway transition section smoother. The existing analytical formula of local ventilation resistance of the sudden reduction roadway is not suitable for the section gradual reduction roadway. Zhang et al. made corresponding contributions to the solution of ventilation resistance from various aspects such as energy exchange, energy loss and different resistance losses [2-7]. Guo et al. found that there was the influence of local ventilation resistance on the long-distance ventilation of the

tunnel construction [8].

Therefore, to build the fluid dynamics model and solve the local ventilation resistance of the section gradual reduction roadway, which has important reference significance for the design and construction of the different transition sections of the roadways.

### 2. State of the art

To reduce the local ventilation resistance of roadway is directly related to reducing energy consumption of mine. Recently, some scholars have carried out related studies on improving ventilation efficiency and reducing ventilation resistance. For examples, Li et al. studied the various characteristics of ventilation resistance under different air speeds without considering the effect of eddy current on energy loss [2]. Zhang deduced the calculation formula for the local ventilation resistance coefficient and local ventilation resistance of the section sudden reduction roadway, although the influence of roadway roughness and eddy current effect on local ventilation resistance was mentioned, the calculation of local ventilation resistance was not suitable for the section gradual reduction roadway [3]. Zhou conducted theoretical analysis on the local ventilation resistance of the section sudden reduction roadway [4]. Deng and Liu obtained the total resistance formula of the roadway ventilation system, but they did not consider the influence of ventilation resistance on the transition forms of the roadways with different cross-sections [5]. Niu and Xu deduced the formula of ventilation resistance for mine by using

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thermodynamics theory and their work promoted the development of mine ventilation [6].

The local ventilation resistance in the transition section of the roadway is often disturbed by many factors and variables. With the development of computer technology, many scholars have studied the characteristics of ventilation resistance. Bruceet and Koenning summarized the ventilation resistance values of some typical roadways through the calculation of ventilation resistance in various modes by using the improved computer programs [9]. Gao et al. converted the ventilation resistance coefficient inversion problem into a nonlinear optimization problem and adopted the genetic algorithm to solve the ventilation resistance coefficient [10-11]. Song et al. [13] adjusted the ventilation simulation model through computational feedback and proposed the influences of the open area of the wind window on the regulation of ventilation resistance [12-13].

Since there are few studies on the local ventilation resistance of the section gradual reduction roadway, no matter from the aspects of theoretical parameters correction or numerical simulation, in addition, it is rarely reported to conduct comparative analysis on the local ventilation resistance of the section sudden reduction roadway and section gradual reduction roadway.

In this study, by building a fluid dynamics model, the local ventilation resistance formula of the section gradual reduction roadway was deduced and the formula was verified by the field measurement data. The rest of this study is organized as follows: Section 3 describes the research method and formula derivation of the local ventilation resistance. Section 4 quantitatively analyzes and verified the derived formula. Section 5 provides the relevant conclusions.

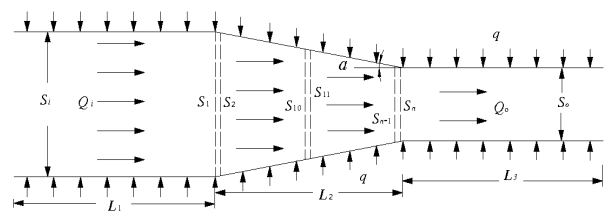
### 3. Methodology

#### 3.1 Building fluid dynamics model

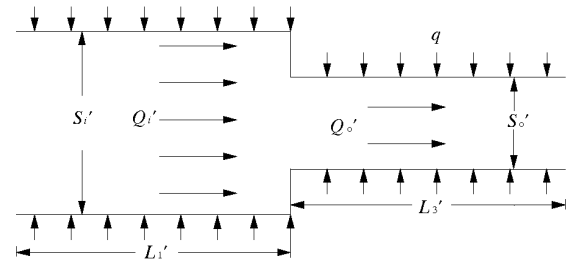
Based on the air flow changing characteristics of the section sudden reduction roadway and the section gradual reduction roadway, the fluid dynamics models are shown in Fig 1.

Assuming that the two types of roadways are surrounded by uniform load  $q$ , and the existence of the load will not cause the deformation of the roadway.  $L_1$  and  $L_1'$  are the lengths of the air volume at the entrance of the section gradual reduction roadway and the section sudden reduction roadway, respectively.  $L_2$  and  $L_2'$  are the lengths of the air volume at the outlet of the section gradual reduction roadway and the section sudden reduction roadway, respectively.  $L_3$  and  $L_3'$  are the lengths of the air volume at the entrance and exit of the section gradual reduction roadway, respectively.  $S_i$  and  $S_i'$  are the inlet cross-section areas of the section gradual reduction roadway and the section sudden reduction roadway, respectively.  $S_o$  and  $S_o'$  are the outlet cross-section areas of the section gradual reduction roadway and the section sudden reduction roadway, respectively.  $Q_i$  and  $Q_o$  are the air volumes at the entrance and exit of the section gradual reduction roadway, respectively.  $Q_i'$  and  $Q_o'$  are the air volumes at the entrance and exit of the section sudden reduction roadway, respectively.  $S_1$  and  $S_2$  are inlet cross-section areas of the normal section and the section gradual reduction roadway, respectively.  $S_o$  and  $S_n$  are outlet cross-section areas of the normal section and the section gradual reduction roadway, respectively.  $\alpha$  is the shrinkage angle of the section gradual reduction roadway. All of other factors are the same in both types of roadways except for the

gradual reduction of cross-section changes in the roadway.



(a) The section gradual reduction roadway



(b) The section sudden reduction roadway

Fig. 1. The fluid dynamics models of two kinds of roadways

Other conditions are as follows:

- (1) The roadway can not produce deform significantly under stress field, the wall of roadway is smooth and the air flow through each cross-section is constant.
- (2) On the premise of equal air volume, the air speed in the roadway is increasing through the section gradual reduction roadway, using  $Q/S$  to express the air speed when the air passing through each section-element.
- (3) It is assumed that  $S_i \approx S_1, S_o \approx S_n$ , and in addition to the change of cross-section, there is no effective section of the roadway occupied by other structures or mine cars.

#### 3.2 Local ventilation resistance of the section gradual reduction roadway

##### 3.2.1 Local ventilation resistance coefficient of the section gradual reduction roadway

When the empirical formula is used to analyze the local ventilation resistance coefficient of the section gradual reduction roadway, the sections of large and small roadways are directly connected, and the connection length can be regarded as a unit length. Therefore, the influence of length on the ventilation resistance coefficient can be ignored analyzing the local ventilation resistance of the section sudden reduction roadway, without considering the influence of surrounding rock fissures, mine cars and other structures on the air volume loss. The local ventilation resistance coefficient is only related to the large and small ratio of the roadway sections that the airflow goes through.

The traditional empirical formula of the local ventilation resistance coefficient  $\xi$  is [3]:

$$\xi = 0.5(1 - S_2/S_1) \tag{1}$$

where  $S_1$  and  $S_2$  are large and small sections of the roadway, respectively.

Different from the section sudden reduction roadway, the local ventilation resistance coefficient of the section gradual reduction roadway is mainly determined by two geometric parameters: the shrinkage ratio and the shrinkage angle of the section. The most important factor affecting the local

ventilation resistance coefficient of the roadway is the shape of the local section.

From the geometric point of view, there are variables  $L_2$  and  $a$  in the section gradual reduction roadway compared with the sudden reduction roadway. This study only analyzes the influence of  $L_2$  on the local ventilation resistance coefficient. Then

$$\varepsilon = \frac{1}{2L_2}(1 - S_s/S_b) \quad (2)$$

where  $S_b$  and  $S_s$  are large and small sections of the roadway, respectively.

Based on the idea of calculus, the section gradual reduction roadway can be divided into a number of units with infinitely small length and almost equal inlet and outlet sections, there are obviously  $S_1 > S_2 > \dots > S_{10} > S_{11} > \dots > S_{n-1} > S_n$  in the fluid dynamics model of the section gradual reduction roadway.

Assuming that the section gradual reduction roadway has a fixed contraction angle  $\mu$ , then

$$\left. \begin{aligned} S_1/S_2 = \mu \dots S_3/S_4 = \mu \dots S_{n-1}/S_n = \mu \\ S_1 = \mu S_2 \dots S_3 = \mu S_4 \dots S_{n-1} = \mu S_n \\ S_2 = S_1/\mu \dots S_{n-1} = S_1/\mu^{n-2} \dots S_n = S_1/\mu^{n-1} \end{aligned} \right\} \quad (3)$$

Since the calculation formula of the local ventilation resistance  $h$  is [3]:

$$h = \frac{1}{2} \rho v^2 \varepsilon \quad (4)$$

where  $\rho$  is the density of airflow,  $\text{kg/m}^3$ .  $v$  is the velocity of airflow,  $\text{m/s}$ .  $\varepsilon$  is the local ventilation resistance coefficient.

Substitute Eqs. (3) and (2) into (4), then

$$\left\{ \begin{aligned} h &= \frac{1}{2} \rho Q_i^2 \frac{1}{2L_2} \left(1 - \frac{1}{\mu}\right) \left(\frac{1}{S_1^2} + \frac{1}{S_2^2} + \dots + \frac{1}{S_n^2}\right) \\ &= \frac{1}{2} \rho v^2 S_i^2 \frac{1}{2L_2} \left(1 - \frac{1}{\mu}\right) \left(\frac{1}{S_1^2} + \frac{\mu^2}{S_1^2} + \frac{\mu^4}{S_1^2} + \dots + \frac{\mu^{2n-2}}{S_1^2}\right) \\ &= \frac{1}{2} \rho v^2 \frac{\mu^{2n} - 1}{2L_2(\mu + \mu^2)} \end{aligned} \right. \quad (5)$$

Thus, we can get the corrected local ventilation resistance coefficient  $\varepsilon'$  of the section gradual reduction roadway.

$$\varepsilon' = \frac{\mu^{2n} - 1}{2L_2(\mu + \mu^2)} \quad (6)$$

where  $n$  is the number of units of dividing the transition section of the section gradual reduction roadway.  $S_i$  equals  $S_1$ . The influence of roadway roughness is not taken into account.

### 3.2.2 Formula derivation of local ventilation resistance of the section gradual reduction roadway

The section gradual reduction roadway can be divided into several infinitely units. According to the law of conservation of fluid mass, the air volume of the inflow is positive, and that of the outflow is negative. The mass of the inflow and outflow at unit time is equal to zero without considering the

influence of other factors. Then

$$\sum_n (\rho_{ni} q_{ni} + \rho_{no} q_{no}) = 0 \quad (7)$$

where  $n=1, 2, 3, \dots$ .  $\rho_{ni}$  and  $\rho_{no}$  are the density of air flowing in and out on the  $n$ th unit,  $\text{kg/m}^3$ .  $q_{ni}$  and  $q_{no}$  are the inflow and outflow air volumes on the  $n$ th unit,  $\text{m}^3/\text{s}$ .

If the density change in the unit can be ignored, Eq. (7) can be simplified as:

$$\sum_n (q_{ni} + q_{no}) = 0 \quad (8)$$

The continuity equation of fluid flow is as follows:

$$\left. \begin{aligned} Q_n &= S_n v_n \\ v_n &= Q_n / S_n \end{aligned} \right\} \quad (9)$$

where  $Q_n$  is the total air volume entering the  $n$ th unit,  $\text{m}^3/\text{s}$ .  $S_n$  is the sectional area of the  $n$ th unit in the transition zone of the section gradual reduction roadway,  $\text{m}^2$ .  $v_n$  is the airflow velocity through the section of the  $n$ th unit,  $\text{m/s}$ .

Assuming that the total air volume in and out of the roadway is not affected by other external factors, that is,  $Q$  is a constant value, the section area  $S$  in the transition zone of the section gradual reduction roadway can be expressed in the form of calculus.

By substituting Eqs. (9) into (5), the local ventilation resistance formula for the section gradual reduction roadway can be described as follows:

$$\left\{ \begin{aligned} h &= \frac{1}{2} \rho \frac{Q_i^2}{S_n^2} \frac{\mu^{2n} - 1}{2\mu + 2\mu^2} \\ &= \frac{1}{2} \rho Q_i^2 \frac{\mu^{2n} - 1}{2L_2(\mu + \mu^2)} \int_{S_o}^{S_i} \frac{1}{S_n^2} ds \end{aligned} \right. \quad (10)$$

### 3.2.3 Eddy current effect analysis of the section changing roadway

The airflow in the roadway is mostly turbulent flow, when the turbulent flow through a suddenly changed section, due to the action of inertial force, the main airflow will be separated from the roadway wall, that is, the eddy current zone is formed between the main airflow and the wall surface of the roadway [3], as shown in Fig 2.

The eddy current in different locations of roadway is greatly affected by the roughness of wall surface and the unevenness of shotcreting support of the roadway. The large scale eddies generated are relatively close to the center of the roadway, which can be continuously carried away by the main airflow, but new eddies are formed by the added airflow later. The size and position of the eddy current zone may differ from the previous, this is a back-and-forth process, the alternating rebirth of old and new eddy currents will increase the loss of energy.

Fig. 3 shows two roadways with exactly the same cross-section area of the inlet and outlet, where  $a_2 = 2a_1$  and  $L_b = 0.48L_a$ . When the shrinkage angle increases by 2 times, the length of the section gradual reduction roadway decreases to 0.48 times of the original one, we found that there is an obvious eddy current phenomena in Fig. 3(b).

Based on the modified formula of the local ventilation resistance coefficient for the section gradual reduction roadway, the coupling relationship between the transition section length and the shrinkage angle should be paid full attention to minimize the eddy current losses or eliminate eddy current phenomena in the design of roadway.

In the increasing speed and decompression zone, the fluid particle is subjected to a positive pressure difference consistent with the flow direction, and the flow velocity is only increased not decreased. There is no eddy current in the section gradual reduction roadway under this condition. If the shrinkage angle is large, the eddy current zone will appear immediately after the gradual reduction of the section, but the influence range of the vortex zone can be smaller than that of the section sudden reduction roadway.

Under the premise that the shrinkage ratio of the roadway section is constant, the influence range of the eddy current zone is directly related to the size of the shrinkage angle. This study mainly focused on the local ventilation resistance of the roadway based on the flow dynamics model without eddy current phenomenon.

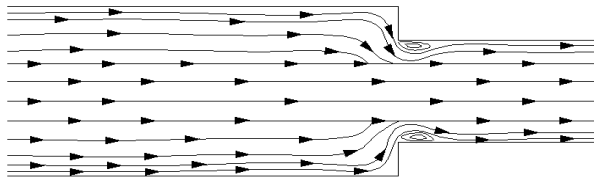


Fig. 2. Airflow through the section sudden reduction roadway

Table 1. Airflow parameters at inlet of large section roadway

Static pressure $P_b$ (Pa)	Air humidity	Partial pressure of saturated water vapor $P_{sb}$ (Pa)	Air temperature $t_b$ (°C)	Effective roadway area $S_b$ (m <sup>2</sup> )	Air density $\rho_b$ (kg/m <sup>3</sup> )
101324.70	0.70	1704	15	5	1.2197

Table 2. Airflow parameters at outlet of small section roadway

Static pressure $P_s$ (Pa)	Air humidity	Partial pressure of saturated water vapor $P_{ss}$ (Pa)	Air temperature $t_s$ (°C)	Effective roadway area $S$ (m <sup>2</sup> )	Air density $\rho_s$ (kg/m <sup>3</sup> )
101375.00	0.70	1704	15	3	1.2203

The density calculation formula of wet air can be obtained from the gas state equation and Dalton's law of partial pressure:

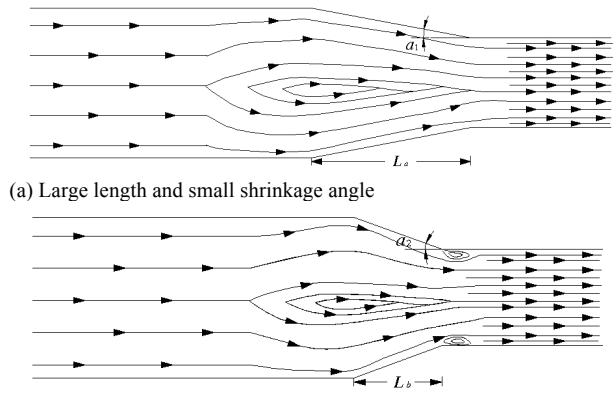
$$\rho = 0.003484 \frac{P}{273.15+t} \left(1 - \frac{0.378\phi P_s}{P}\right) \quad (11)$$

where  $P_s$  is the partial pressure of saturated water vapor at a certain temperature, Pa.  $\phi$  is the air humidity at the measuring point.  $P$  is the static pressure value at the measuring point, Pa.

$$\rho_m = \frac{P_s - P_b}{(n-1) \times \left(\frac{P_s}{\rho_s} - \frac{P_b}{\rho_b}\right)} \quad (12)$$

where  $\rho_m$  is the average density of airflow between large and small sections, kg/m<sup>3</sup>.  $n$  is the polytropic process index calculated by  $\frac{\ln P_s - \ln P_b}{\ln \rho_s - \ln \rho_b}$ .

The expression of local air resistance calculation is [3]:



(a) Large length and small shrinkage angle

(b) Small length and large shrinkage angle

Fig. 3. Airflow in the section gradual reduction roadway at different shrinkage angles

#### 4. Formula verification with measured data

The rationality of the formula for solving the local ventilation resistance coefficient of the section gradual reduction roadway directly determines and influences the accuracy and reliability of the calculation results. Taking on a mine roadway as the background, the relevant physical parameters in the roadway before and after the section change were measured at the same elevation, as listed in Tables 1 and 2.

$$R = \xi \rho_m / 2S_s^2 \quad (13)$$

To solve the local ventilation resistance coefficient, local ventilation resistance and local air resistance of the section sudden reduction roadway, the relevant data listed in Tables 1 and 2 are substituted into Eqs. (11) and (12), then  $\rho_m = 1.2199$  kg/m<sup>3</sup>.

The local ventilation resistance can be obtained by combining Eqs. (1), (4) and (13), then  $\xi = 0.60$ ,  $h = 3.05$  J/m<sup>3</sup>,  $R = 0.010844$  kg/m<sup>7</sup>.

Based on the established model of the section gradual reduction roadway, the local ventilation resistance coefficient, local ventilation resistance and local air resistance of the section gradual reduction roadway are solved. Assuming that the shrinkage angle of the section gradual reduction roadway is  $\alpha = 10^\circ$ , the cross-section area of the inlet and outlet of the airflow being determined, and the length of the section gradual reduction roadway is 5.76 m. Supposed that  $S_{n-1}/S_n = \mu = 1.1$ ,  $S_b = S_1$ ,  $S_s = S_n$ ,

substituting these parameters into Eqs. (3), then  $n=7$  can be obtained. Combining with Eqs. (6), (9), (10), and (13), the local ventilation resistance of the section gradual reduction roadway are obtained as follows:  $\xi' = 0.105$ ,  $h' = 1.92J/m^3$ ,  $R' = 0.007116 \text{ kg/m}^7$ .

As seen from Table 3 and Fig. 4, it can be obtained  $\xi_r = 5.71\xi'$ ,  $h = 1.59h'$ ,  $R = 1.52R'$ .

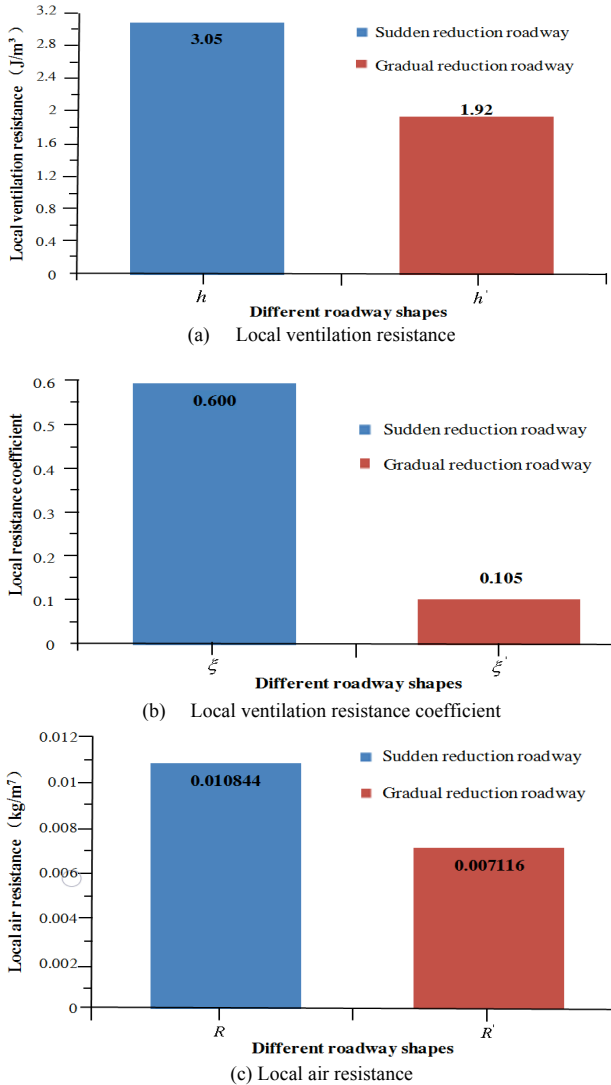


Fig. 4. Comparison of local ventilation resistance of two roadways

Table 3. Dimensionless comparison table of three parameters

Name	Section gradual reduction roadway		Section sudden reduction roadway	
	$\xi$	0.60	$\xi'$	0.105
Local ventilation resistance coefficient	$h$	3.05	$h'$	1.92
Local ventilation resistance ( $J/m^3$ )	$R$	0.010844	$R'$	0.007116
Local air resistance ( $kg/m^7$ )				

When the section sudden reduction roadway is optimized to the section gradual reduction roadway, the local ventilation resistance coefficient, local ventilation resistance and local air resistance can be significantly decreased. For the practical engineering, if each section sudden reduction roadway can be optimized to section gradual reduction roadway, the ventilation resistance of the whole mine will be significantly reduced, which can produce greater economic benefits.

### 5. Conclusions

The section gradual reduction roadway is a transition form connecting with different cross-section roadways, which has an important influence on the local ventilation resistance of mine. Based on the local ventilation resistance analysis of the section gradual reduction roadway and section sudden reduction roadway, the main conclusions are as follows:

(1) The fluid dynamics models are established for the section sudden reduction roadway and section gradual reduction roadway, the causes of eddy current in these roadways are analyzed, and found that the larger shrinkage angle of the section gradual reduction roadway, the eddy current phenomenon will be more obvious.

(2) Based on the idea of calculus, the parameter variables of each cross-section area are expressed. By solving the local resistance coefficient, the local ventilation resistance formula of the section gradual reduction roadway is deduced.

(3) The local ventilation resistance formula is verified by the measured data, and the local ventilation resistance coefficient, local ventilation resistance and local air resistance of the section sudden reduction roadway are 5.71, 1.59, and 1.52 times of that in the section gradual reduction roadway.

The transition section form of the roadway directly affects the trajectory of the wind flow, and the magnitude of the local ventilation resistance determines the total ventilation resistance of the mine. Considering the influence of the shrinkage angle and the roughness of the roadway support on the local ventilation resistance, it is the research direction to consider the mutual coupling of various factors in the future.

### Acknowledgements

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