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APPLIED RESEARCH OF U-SHAPE VENTILATION NETWORK IN UNDERGROUND MINE

BADANIA STOSOWANE SIECI WENTYLACYJNEJ W KSZTALCIE „U” W KOPALNI PODZIEMNEJ

For the purpose of fully and systematically observe, research and optimize the U-sharp ventilation system in Vilafruns mine, a simulation model based on the principles of geometric, kinematic and dynamic similarity is established in the simulation laboratory. By simulating a U-shape ventilation network, the air volume distribution and wind velocity in different sections of the model were measured and compared with practical data obtained in Vilafruns mine. Results show that the lowest wind velocity in the model is higher than 0.42 m/s, thus it is in a turbulent flow state, which satisfies the kinematical and dynamic similarity principles. The characteristic of air volume distribution and wind velocity in Vilafruns mine are basically simulated by the experimental model through the obtained data and figures, which reflects the establishment of the model is correct and successful, and the experimental data is accurate and reliable. Moreover, this model provides useful references for the selection of mine ventilation types and for the optimization of the existing ventilation network.

Keywords: simulation experiment, mine ventilation, wind velocity, dynamic similarity

W celu prowadzenia pełnej i systematycznej obserwacji, badań oraz optymalizacji sieci wentylacyjnej w kopalni Vilafruns, opracowano model do symulacji laboratoryjnych w oparciu o zasady podobieństwa geometrycznego, kinematycznego oraz dynamicznego. W ramach symulacji działania sieci wentylacyjnej w kształcie litery U, dokonano pomiarów rozkładu objętości powietrza oraz prędkości ruchu powietrza w różnych sekcjach modelu. Dane te porównano następnie z danymi rzeczywistymi uzyskanymi w kopalni Vilafruns. Wyniki pokazują, że najniższa prędkość przepływu powietrza w modelu przewyższa 0.42 m/s, mamy więc do czynienia z przepływem turbulentnym, w ten sposób spełnione są warunki podobieństwa kinematycznego i dynamicznego. Charakterystyka rozkładu objętości powietrza i prędkości przepływu w kopalni Vilafruns zasadniczo otrzymana została na podstawie modelu eksperymentalnego z wyko-

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rzystaniem uzyskanych wyników. Oznacza to, że zasadniczo model jest poprawny i skuteczny a dane eksperymentalne są dokładne i wiarygodne. Ponadto, model dostarcza nam cennych danych wyjściowych niezbędnych przy wyborze systemu wentylacji, a także przy optymalizacji istniejącej sieci wentylacyjnej.

Słowa kluczowe: eksperyment symulacyjny, wentylacja kopalni, prędkość przepływu, podobieństwo dynamiczne

1. Introduction

Working areas in underground mines have become far and deeper from several inlets and exhaust shafts while mining activities are performed (Widodo et al., 2008). Ventilation in any mine features permanently varying air flows under the influence of governor devices or engineering procedures (Yu et al., 2011), and it provides a flow of air to the underground workings of a mine of sufficient volume to dilute and remove noxious gases (typically NO_x , SO_2 , methane, CO_2 and CO) (De la Vergne, 2003). A reasonable ventilation network exerts a long-term effect on mine safety and economic benefits (Gao, 2011). The analysis and measurements of ventilation network present a crucial element of investigation of the course of ventilation processes in mines (Dziurzynski & Kruczkowski, 2011). As a matter of fact, it is quite difficult to fully observe mine ventilation systems and predict process behavior under different conditions and constraints in fieldwork (Gauti et al., 2012). Many scholars use the method of numerical simulation to simulate mine ventilation network, but it has limitations (Shen & Wang, 2011). Therefore, the phase of the ventilation network planning itself may be assisted by the experimental verification of models at laboratory site (Mierzwiński S & Popiołek, 1980). For the purpose of systematically researching the ventilation system of Vilafruns mine, a model based on simulation principles is established. The experiments based on a U-shape ventilation network are carried out in the laboratory. This model can be used to investigate and simulate the relative parameters of real ventilation system as the knowledge of flow parameters is of particular importance with respect to the control of air conditions in mines (Socha & Ligeza, 2010).

2. Theoretical basis of the simulation experiment

Simulation is the imitation of the operation of a real-world process or system over time (Banks et al., 2001). It can be used when the real system cannot be engaged, because it may not be accessible, or it may be dangerous or unacceptable to engage, or it is being designed but not yet built, or it may simply not exist (Sokolowski & Banks, 2009). Simulation can also be utilized for the ventilation system design and optimization in the area of mining industry (Farzanegan & Vahidipour, 2009). The purposes of simulation experiment are multiple (Klein, 2000). For example, mine ventilation resistance surveys can be simulated by the model in the laboratory (Inoue et al., 2011). Besides, the layout and type of the real mine ventilation system, the basic principles of air distribution and the control method of ventilation network can be intuitively understood when the experiment is performed.

2.1. Flow similarity theory

One essential factor of flow similarity among two fluids is that their flow condition satisfies geometric similarity, kinematics similarity and dynamic similarity (Jones, 1969).

Geometric similarity is also called space similarity, and it can be defined as two geometrical objects that have the same shape, or one which has the same shape than the mirror image of the other (Kundu & Cohen, 2008). Therefore, the coefficient of the length ratio is as follows:

$$w_l = \frac{l_m}{l_p}$$

its circumference ratio, area ratio and volume ratio are:

$$w_U = \frac{U_m}{U_p} = w_l$$

$$w_A = \frac{A_m}{A_p} = w_l^2$$

$$w_V = \frac{V_m}{V_p} = w_l^3$$

its corresponding relationship between angles is:

$$\alpha_m = \alpha_p$$

where, m is the model, and p is the prototype.

Kinematics similarity requires that the length and time scales are similar between model and prototype. Obviously, kinematics similarity includes geometrical similarity (Kundu & Cohen, 2008). The speed ratio is:

$$w_v = \frac{v_m}{v_p} = C$$

then

$$v_m = \frac{l_m}{t_m} \quad \text{and} \quad v_p = \frac{l_p}{t_p}$$

then,

$$w_v = \frac{l_m/t_m}{l_p/t_p} = \frac{w_l}{w_t}$$

its time ratio and acceleration ratio are:

$$w_t = \frac{t_m}{t_p}$$

$$w_a = \frac{a_m}{a_p} = \frac{v_m/t_m}{v_p/t_p} = \frac{w_v}{w_t} = \frac{w_l}{w_t^2}$$

Dynamic similarity exists between geometrically and kinematically similar systems, and it requires that the ratios of all forces acting on corresponding fluid particles and boundary surfaces in the model and prototype are constant (Konduri et al., 1997). Its force ratio is:

$$w_F = \frac{F_m}{F_p} = C$$

it can also be showed as:

$$w_F = w_m w_a = (w_p w_l^3) (w_l w_t^{-2}) = w_p w_l^2 w_v^2$$

For different flow movements, fluid particles could be influenced by different effects, e.g. gravity force (F_g), viscous force (T_v), pressure force (P) and inertia force (F_i), but the proportional relationship of the corresponding points in both real fluid and model fluid remain unchanged under the same pressure (Kundu & Cohen, 2008), and it can be showed as:

$$W_{pg} / W_{mg} = T_{pv} / T_{mv} = P_p / P_m = W_{pi} / P_{mi} = C_f$$

2.2. Flow similarity standard

Some of the basic similarity criteria can be used to explain the principle of the simulation experiments, including Strouhal similarity criterion ($S_r = l/v_t$), which means the ratio between time-varying inertia force and space-varying inertia force (Peters et al., 1993); Froude similarity criterion ($F_r = v^2/g_l$), which means the ratio between inertia force and gravity force (Znamenskaya, 1981); Euler similarity criterion ($E_u = p/\rho v^2$), which means the ratio between pressure force and inertia force (Znamenskaya, 1981); Reynolds similarity criterion ($Re = v_l/\nu = \rho v_l/\mu$), which means the ratio between inertia force and viscous force (Znamenskaya, 1981); Mach similarity criterion ($M_a = v/c$), which means the ratio between elastic force and inertia force (Peters et al., 1993).

Fluid motion differential equation are frequently used to describe the relation between fluid motion and stress; model flow and prototype flow, both incompressible, achieve flow similarity on the condition that they satisfy the motion differential equation, which are shown as follows (Kundu & Cohen, 2008):

$$\frac{\partial v_{xm}}{\partial t_m} + v_{xm} \frac{\partial v_{xm}}{\partial x_m} + v_{ym} \frac{\partial v_{xm}}{\partial y_m} + v_{zm} \frac{\partial v_{xm}}{\partial z_m} = f_{xm} - \frac{1}{\rho} \frac{\partial p_m}{\partial x_m} + v_m \Delta v_{xm} \tag{1}$$

$$\frac{\partial v_{xp}}{\partial t_p} + v_{xp} \frac{\partial v_{xp}}{\partial x_p} + v_{yp} \frac{\partial v_{xp}}{\partial y_p} + v_{zp} \frac{\partial v_{xp}}{\partial z_p} = f_{xp} - \frac{1}{\rho} \frac{\partial p_p}{\partial x_p} + v_p \Delta v_{xp} \tag{2}$$

Let equation (1) into (2). Equation (3) can be obtained

$$\frac{w_v}{w_t} = \frac{w_v^2}{w_l} = w_g = \frac{w_p}{w_\rho w_l} = \frac{w_v w_v}{w_l^2} \tag{3}$$

Formula (3) indicates Time-varying inertia force, Space-varying inertia force, Mass force, Pressure and Friction force respectively. It also shows the force polygon of model flow is similar to prototype flow.

Divide Formula (3) by space-varying inertia force, then,

$$\frac{w_l}{w_l w_v} = 1 = \frac{w_l w_g}{w_v^2} = \frac{w_p}{w_\rho w_v^2} = \frac{w_v}{w_l w_v} \quad (4)$$

Formula (4) indicates a certain constraint exists among different ratios when dynamic similarity of model and prototype flow is achieved, and similar standards can be obtained by further analysis. That is: dynamic similarity can be described by similarity criterion. In fact, model and prototype flow cannot become equal flow and fully dynamic similarity (Nicholas et al., 2001); therefore, the main dynamic similarity is a key point of the simulation experiments, which means if the Reynolds of two different flow types are similar, ($Re_m = Re_p$), they have dynamic similarity.

3. The establishment of the simulation model

3.1. Roadway geometric and dynamic similarity

The size of the whole ventilation system model is based on the roadway size of Vilafruns mine. Considering the simplicity of establishment of the model, the area of the model roadway in the ventilation system is based on the average area of prototype roadway area (32 m²). When its length ratio w_l is $50\sqrt{2}$, and the area ratio w_s is 5000, the main geometry size relation between the prototype and the model is as follows:

TABLE 1

Comparison of the roadway areas between prototype and model

Item	Mine Section (m ²)	Model Section (m ²)
Section	32	0.0064
Intake airway	32	0.0064
Return airway	32	0.0064

Reynolds similarity criterion and Euler similarity criterion should be satisfied as much as possible because these simulation experiments mainly focus on viscous force, pressure and inertia force. When Reynolds number of the model is in the resistance square area, it can be considered that Reynolds similarity criterion of the model and prototype are equal. This phenomenon is called the automatic mode, which means that if the model and the prototype satisfy geometric similarity, their dynamic and kinematics similarity can be automatically ensured (Kundu & Cohen, 2008).

The critical velocity of the model in the turbulent state is as follows:

- ① The second critical value of Reynolds number in the general experience model is:
 $1.0 \times 10^4 \sim 1.5 \times 10^5$, here when $Re = 1.0 \times 10^4$ (Wang et al., 2009),

$$V = \frac{ReU\nu}{4S}$$

where:

- V — the average velocity in the roadway, m/s;
- ν — dynamic viscosity coefficient of the fluid, related to fluid temperature and pressure, for the ventilation in mine, it usually takes $14.4 \times 10^{-6} \text{ m}^2/\text{s}$;
- U — perimeter of the roadway, the length and the width are both 0.08 m;
- S — area of roadway, m^2 .

$$V = \frac{10000 \times 2 \times (0.08 + 0.08) \times 14.4 \times 10^{-6}}{4 \times 0.08 \times 0.08} = 1.8 \text{ m/s}$$

② For simplicity, Reynolds number (Re) is usually considered as a criterion of flow state in the tunnel in the practical engineering calculation, namely:

When $\text{Re} \leq 2300$, it means the flow is in laminar state, and when $\text{Re} > 2300$, it means the flow is in turbulent state.

$$V = \frac{2300 \times 2 \times (0.08 + 0.08) \times 14.4 \times 10^{-6}}{4 \times 0.08 \times 0.08} = 0.414 \text{ m/s}$$

According to the results of ① and ②, it can be concluded that the minimum wind velocity for meeting turbulent state in the simulation model of ventilation network must be higher than 0.414 m/s. Fortunately, the minimum velocity measured in the model reached 0.42 m/s, which means its Re is in the resistance square area. Therefore, its linear scale w_l is $50\sqrt{2}$, density scale $w_\rho = 1$ and the speed scale $w_v = 1$ can be decided.

3.2. Experiment devices

The experiment model consists of five parts including model body (roadway, working face and gob), fan and affiliated device, gas drainage system, testing system and collection system, respectively. The physical model is shown in Fig. 1. The spherical valve is used to control the



Fig. 1. Model body of simulation ventilation network

ventilation door, which can realize the transformation among different ventilation systems and the adjustment of the air volume.

Through the measurement and calculation, the total air resistance of the ventilation model is approximately 3300 Pa, and the power is 9 KW. Therefore, a centrifugal fan is chosen as the main fan of the model. Its affiliated devices including explosion-proof door, inverted ventilation device, fans, piping shock absorber and diffuser, and its physical model as shown in Fig. 2 below.



Fig. 2. Fan of simulation model

4. Results of Vilafruns mine and the simulation model

4.1. Overview of Vilafruns Mine

The potassium deposit in the Catalan basin is currently being exploited by Iberpotash. Iberpostash is the largest mining company in Catalunya, and the only producer and supplier of potash fertilizers for agriculture and industry uses. The company is located in the comarca of Bages, a county in the center of Catalunya, in the municipalities of Balsareny, Sallent(Vilafruns) and Suria(Cabanasses). Iberpotash produces over one million tons of red potash for fertilizers and it represents one of Europe's most important potash resources, conveniently located near the major potash consumption areas of the European Union.

4.2. Results of airflow distribution measurements

In this simulation experiment, ventilation data from Vilafruns Mine are used as main reference. First, 14 measuring points in the major intake and return airway are chosen, making it a complete ventilation network, as is shown in Fig. 3. Due to the significant impacts of season and weather factors on ventilation, data collection in Vilafruns Mine is made twice both in summer and winter respectively. In the process of air quantity measurement, average value is adopted from multiple measurements. The specific results are shown in Table 2 and Table 3.

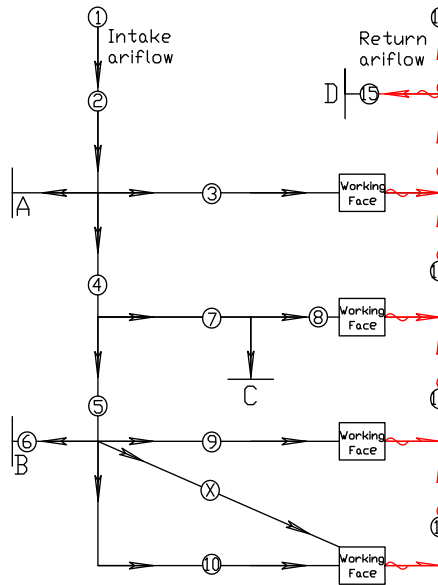


Fig. 3. Simplified ventilation system in Vilafruns Mine

TABLE 2

Results of distribution measurements of air quantity in Vilafruns Mine, July 2011, Summer

Points	Air velocity (m/s)	Section (m ²)	Flow rate (m ³ /s)	Dry T. (°C)	Hum. T. (°C)	Equal.T. (°C)
1	3.84	39.84	153.00	25	20	19.8
2	4.45	34.34	153.05	29	22	21.7
3	0.71	31.34	22.24	30	23	22.8
4	3.94	33.04	130.05	31	22	22.2
5	3.85	27.56	105.98	31	23	23.1
6	0.41	32.80	13.57	31	23	23.1
7	0.67	27.36	18.26	30	22	22.3
8	0.45	23.86	10.76	32	23	23.2
9	0.41	30.54	12.67	34	24	24.3
10	1.09	31.29	34.20	32	23	23.3
11	3.41	27.36	93.34	39	28	28.6
12	4.60	26.98	124.16	38	27	27.4
13	5.35	24.64	132.06	36	27	27.2
14	4.25	35.06	149.31	35	26	26.1
15	0.19	20.98	3.98	36	27	27.4

TABLE 3

Results of distribution of air quantity in Vilaforns Mine, January 2012, Winter

Points	Air velocity (m/s)	Section (m ²)	Flow rate (m ³ /s)	Dry T. (°C)	Hum. T. (°C)	Equival.T.(°C)
1	4.41	39.84	175.98	5	10	9.5
2	5.15	34.34	177.04	16	10	10.6
3	0.89	31.34	27.75	22	12	13.0
4	4.60	33.04	151.65	-	-	0.0
5	4.79	27.56	132.21	25	13	14.2
6	0.51	32.80	16.98	26	14	15.2
7	0.69	27.36	18.86	25	13	14.2
8	0.62	23.86	14.78	35	17	18.8
9	0.49	30.54	15.23	31	16	17.5
10	1.93	31.29	60.47	29	15	16.4
11	3.76	27.36	102.76	39	24	25.5
12	6.21	26.98	167.55	38	22	23.6
13	6.82	24.64	168.06	37	22	23.5
14	4.90	35.06	172.02	35	20	21.5
15	0.29	20.98	6.13	35	20	21.5

4.3. Results of the simulation experiment

In this case, the air is used as flow medium, and the airflow is regarded as the steady flow. According to the similarity theory, geometric similarity, kinematic similarity and dynamic similarity should be achieved when similarity relations are established between the prototype and the model. In the simulation experiment, the wind velocity measurement is used as reference;

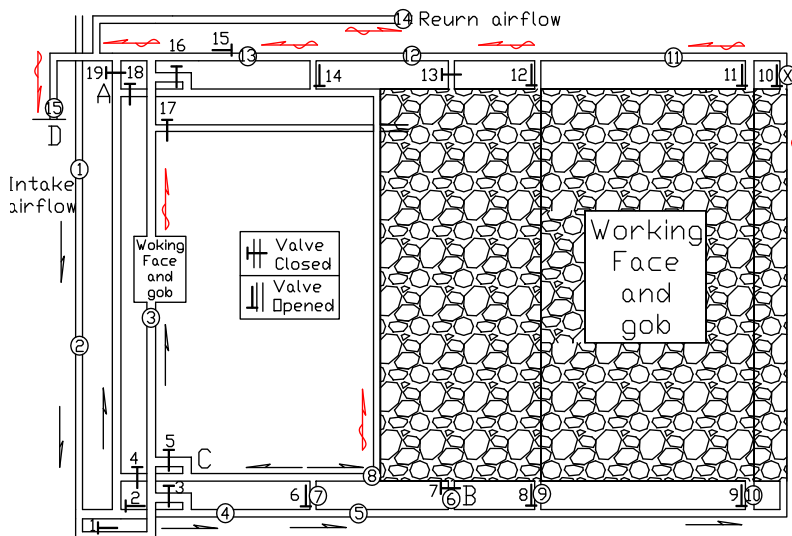


Fig. 4. Model ventilation system and its valve control

different valves in the simulation model are opened and closed, thus it makes the ventilation system as much similar as that in Vilaforns Mine. The chart of the simulated ventilation system of the adjusted valve is shown below. Similarly, wind velocity measurements in the laboratory are conducted twice, both in summer and winter respectively, and average value is adopted from multi-measurements. The specific results are shown in Table 4 and Table 5.

TABLE 4

Results of wind velocity and quantity in simulation experiment, Summer, June 2011

Points	Section (m ²)	T (°C)	Velocity (m/s)	Flow (m ³ /s)
1	0.0064	25	2.62	0.0168
2	0.0064	25	2.60	0.0167
3	0.0064	25	0.43	0.0028
4	0.0064	25	2.21	0.0141
5	0.0064	25	1.80	0.0115
6	0.0064	25	0.47	0.0030
7	0.0064	25	0.44	0.0028
8	0.0064	25	0.44	0.0028
9	0.0064	25	0.42	0.0027
10	0.0064	25	0.71	0.0045
11	0.0064	25	1.40	0.0090
12	0.0064	25	1.48	0.0095
13	0.0064	25	1.86	0.0119
14	0.0064	25	2.30	0.0147
15	0.0064	25	0.42	0.0027

TABLE 5

Results of wind velocity and quantity in simulation experiment, Winter, January 2012

Points	Section (m ²)	T (°C)	Velocity (m/s)	Flow (m ³ /s)
1	0.0064	15	2.95	0.0189
2	0.0064	15	2.97	0.0190
3	0.0064	15	0.52	0.0033
4	0.0064	15	2.49	0.0160
5	0.0064	15	2.26	0.0145
6	0.0064	15	0.56	0.0036
7	0.0064	15	0.46	0.0030
8	0.0064	15	0.45	0.0029
9	0.0064	15	0.42	0.0027
10	0.0064	15	1.00	0.0064
11	0.0064	15	1.39	0.0089
12	0.0064	15	1.91	0.0123
13	0.0064	15	2.42	0.0155
14	0.0064	15	2.73	0.0175
15	0.0064	15	0.42	0.0027

5. Comparison between measurements and experiments

5.1. Comparison of the air quantity

Fig. 5 and Fig. 6 show the results of air volume measurements in Vilafruns Mine and the simulation experiment model at different ventilation points in both summer and winter.

It can be deduced from the Fig. 5 that the air volume in the main roadway of intake and return is larger than that in the other sections of the tunnel, being the maximum air flow volume $175 \text{ m}^3/\text{s}$, and the minimum flow volume less than $10 \text{ m}^3/\text{s}$. Besides, the air volume in winter is higher than that in summer at the same ventilation point.

Fig. 6 is the result of air volume measurements of the simulation experiment model. It indicates the air volume in main roadway of intake and return is higher than that in other sections, and the air volume in winter is higher than that in summer at the same ventilation points.

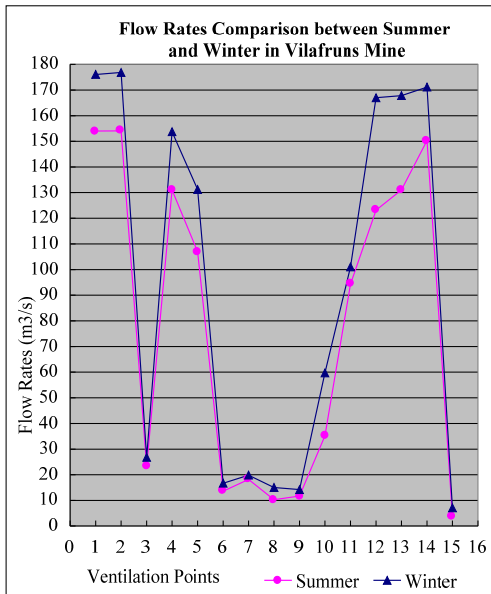


Fig. 5. Distribution diagram of air quantity in Vilafruns Mine

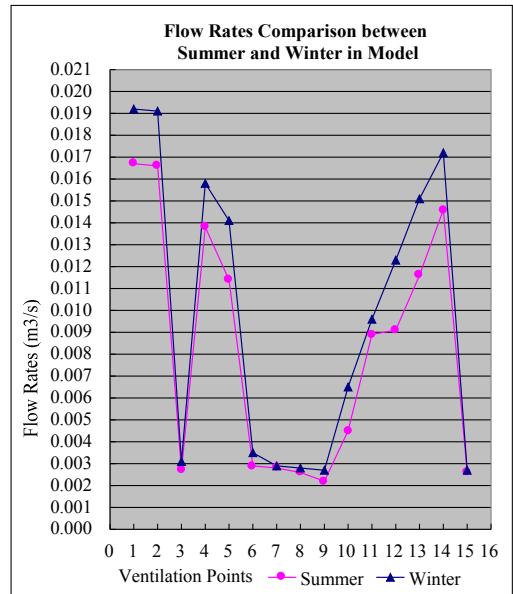


Fig. 6. Distribution diagram of air quantity in simulation experiment

It can be seen by comparing Fig. 5 and Fig. 6 that the distribution of air volume in the experiment is essentially the same as the one of the mine. The air volume in the main roadway of intake and return is higher than that in other sections, and the air volume in winter is higher than that in summer at the same ventilation points in both Vilafruns mine and the experiment model as natural wind pressure in winter exerts a positive influence on ventilation network.

5.2. Wind velocity pattern in Vilaforns Mine

Fig. 7 and Fig. 8 are the results of the wind velocity measurements in Vilaforns mine and the simulation experiment model at different ventilation points in both summer and winter.

It can be seen from Fig. 7 that in spite of the similarity in air volume between the main road of intake and return, the wind velocity in return airway is higher than that in intake airway. This is because the drift sections of intake airway are larger than that of return airway. Besides, the wind velocity in winter is higher than that in summer due to the effect of natural ventilation.

It can be observed from Fig. 8 that the wind velocity in winter is higher than that in summer, the minimum wind velocity is 0.42 m/s, it indicates the airflow in the experiment is in turbulent state, and kinematic and dynamic similarity are achieved. However, under the circumstance where air volume is identical, the wind velocity in the intake airway is higher than that in the return airway. There are two reasons for this: First, the drift sectional areas are the same in every tunnel of the model (0.0064 m²); second, the fact that many of the drift sections in the simulation model are right-angled and that results into excessive frictional restriction in the tunnels.

The comparison of Fig. 7 and Fig. 8 indicates that the wind velocity in the simulation model is able to basically reflect the wind velocity pattern in Vilaforns mine, and it also simulates the same situation that the air volume and velocity in winter are higher than that in summer respectively.

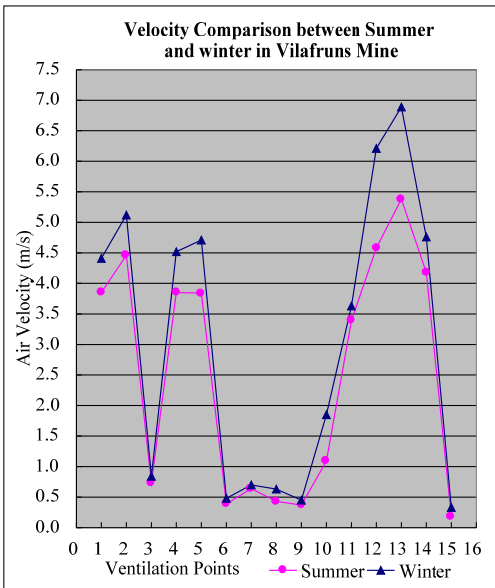


Fig. 7. Air velocity pattern in Vilaforns Mine

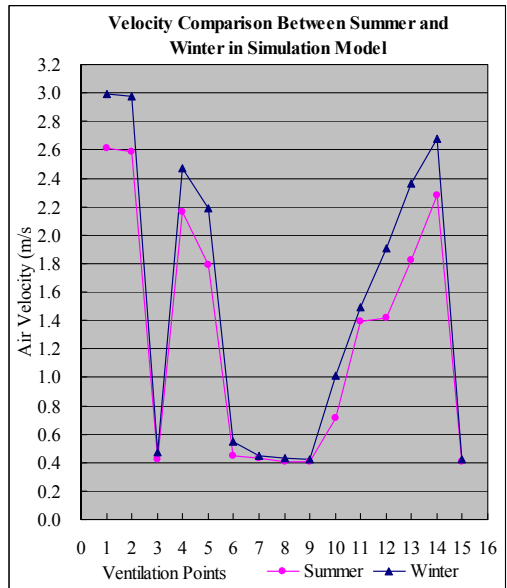


Fig. 8. Wind velocity pattern of the simulation experiment

If a statistical analysis is performed, the following conclusion can be obtained that the U of Mann-Whitney test has a p-value of 0.1645 and 0.0851 for the test between real velocity and velocity of model in summer. Since the p-value is not lower than the chosen confidence level of

0.05, it can be considered that there is insufficient evidence to reject the null hypothesis. Therefore, the comparisons indicate with a confidence level of 0.05 that a difference between wind velocities in summer and winter versus the velocities of the model does not exist.

6. Conclusion

It is extremely difficult to conduct on-site comprehensive observation and research on mine ventilation systems due to the effects of objective factors such as the restriction of the production condition. Therefore, the following experiments are performed.

First, based on the actual situation in Vilafruns Mine, a simulation experiment of ventilation system is established in the laboratory. Second, a simulation experiment of airflow pattern in U-shape ventilation system is conducted. Third, comparisons of experimental data and observational data are performed. The results indicate that the air volume and wind velocity in both types of data are higher in winter than that in summer. Besides, the air volume in the main roadway of intake and return is larger than that in the other sections of the tunnel, which is in accordance with the distribution of the actual situation in Vilafruns. Last but not least, with the minimum wind velocity being 0.42 m/s, the airflow in the model is in turbulent state, and kinematic similarity and dynamic similarity are achieved. However, due to the excessive local resistance caused by the same drift sectional area in the tunnels and a number of right-angled drift sections, the air volume and velocity in the intake airway in the model are relatively higher than that in the return airway.

Overall, the characteristics of the air volume distribution and wind velocity in Vilafruns mine are basically simulated by the simulation model in the laboratory. The results show that the rules of the air volume distribution and the characteristics of wind velocity are essentially the same as the actual situation in Vilafruns mine. Therefore, it can be concluded that the establishment of the model is successful, and the experimental data is relatively accurate. The experiments provide benefits for Vilafruns mine because the simulation model can be first adjusted before adjusting the real ventilation network. Then the decision of whether or not to apply it to the real ventilation system in Vilafruns mine can be made based on the experimental results of the model. It can also provide experimental evidence on the selection of the ventilation system in on-site production and the optimization of the existing ventilation systems in mines.

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References

- Banks J., Carson J., Nelson B., Nicol D., 2001. *Discrete-Event System Simulation*. Prentice Hall, p. 3.
- De la Vergne J., 2003. *Hard Rock Miner's Handbook*. Tempe/North Bay: McIntosh Engineering, p. 157.
- Dziurzynski W., Kruczkowski J., 2011. *Variability of the volumetric air flow rate in a mine fan channel for various damper positions*. Arch. Min. Sci., Vol. 56, No 4, p. 641-650.
- Farzanegan A., Vahidipour S.M., 2009. *Optimization of comminution circuit simulations based on genetic algorithms search method*. Minerals Engineering, Vol. 22, Iss. 7-8, p. 719-726.
- Gao Wei, 2011. *Optimization of Mine Ventilation System Based on Bionics Algorithm*. Procedia Engineering, Vol. 26, p. 1614-1619.
- Gauti A., Erik H., Magnus E., 2012. *Modelling and dynamic simulation of gradual performance deterioration of a crushing circuit – Including time dependence and wear*. Minerals Engineering, Vol. 33, p. 13-19.
- Inoue M., Yang, Wen-yu, 2011. *Airflow adjustment and minimization of the air power of ventilation network*. Journal of Coal Science and Engineering (China), Vol. 17, Iss. 3, p. 237-242.
- Jones R.T., 1969. *Blood Flow*. Annual Review of Fluid Mechanics.
- Klein U., 2000. *Simulation-based distributed systems: serving multiple purposes through composition of components*. Safety Science, Vol. 35, Iss. 1-3, p. 29-39.
- Konduri I.M., McPherson M.J., Topuz E., 1997. *Experimental and numerical modeling of jet fans for auxiliary ventilation in mines*. Proceedings of the 6th International Mine Ventilation Congress, Pittsburgh, US, p. 505-510.
- Kundu P.K., Cohen I.M., 2008. *Fluid Mechanics* (4th revised ed.). Academic Press.
- Mierzwiński S., Popiołek Z., 1980. *Anemometria i jej zastosowanie w badaniach modelowych procesów odpylania i wentylacji*. Zakład Narodowy im. Ossolińskich, PAN, Oddział w Katowicach.
- Nicholas P.W., Carlos V.A., Sean J.B., Colin R.T., 2001. *Distorted Froude-scaled flume analysis of large woody debris*. Earth Surface Processes and Landforms, Vol. 26, Iss. 12, p. 1265-1283.
- Shen Yun, Wang Hai-ning, 2011. *Study and Application on Simulation and Optimization System for the Mine Ventilation Network*. Procedia Engineering, Vol. 26, p. 236-242.
- Socha K., Ligeza P., 2010. *Method of measurement of velocity vector fields of unsteady reverse flows in ventilation systems*. Arch. Min. Sci., Vol. 55, No 1, p. 41-48.
- Sokolowski, J.A., Banks C.M., 2009. *Principles of Modeling and Simulation*. Hoboken, NJ: Wiley. p. 6.
- Peters M.C.A.M., Hirschberg A., Reijnen A.J., Wijnands A.P.J., 1993. *Damping and reflection coefficient measurements for an open pipe at low Mach and low Helmholtz numbers*. Journal of Fluid Mechanics, Vol. 256, p. 499-534.
- Wang Min, Jin Long-zhe, Ou Sheng-nan, Li Zhi-jun, 2009. *Study on low-concentration methane disposal at upper corner based on PSA*. Journal of Safety Science and Technology, Vol. 4, p. 120-124.
- Widodo N.P., Sasaki K., Gautama R.S., Risono, 2008. *Mine ventilation measurements with tracer gas method and evaluations of turbulent diffusion coefficient*. International Journal of Mining, Reclamation and Environment, Vol. 22, Iss. 1, p. 60-69.
- Yu V.K., Levin L.Y., Zaitsev A.V., 2011. *Calculation Method for the Unsteady Air Supply in Mine Ventilation Networks*. Journal of Mining Science, Vol. 47, No 5, p. 651-659
- Znamenskaya N.S., 1981. *Conditions of similarity of flows based on simultaneous consideration of criteria including homochronous, Froude, Euler, and Reynolds numbers*. Hydrotechnical Construction, Vol. 15, Iss. 1, p. 30-34.

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