

Article

Study of the Influence of Ventilation Pipeline Setting on Cooling Effects in High-Temperature Mines

Zhiyong Zhou, Yimeng Cui, Long Tian , Jianhong Chen *, Wei Pan *, Shan Yang and Pei Hu

School of Resources and Safety Engineering, Central South University, Changsha 410083, China; csuzzy@126.com (Z.Z.); sheilameng123@163.com (Y.C.); csultian@163.com (L.T.); yangshan@csu.edu.cn (S.Y.); pattiesu1994@163.com (P.H.)

* Correspondence: cjh@263.net (J.C.); panwei2012@csu.edu.cn (W.P.)

Received: 29 August 2019; Accepted: 22 October 2019; Published: 25 October 2019



Abstract: The high-temperature environment is a major factor that affects deep mining. Cooling has become a major expense, accounting for up to 25% of the total energy consumption of such mines. To address methods of cooling and the cooling cost, this paper studies the influence of the ventilation duct layout on the cooling effect. Six models were created in ICEM-CFD (3D modeling software), and the influence of cold airflow diffusion on the temperature of the mine environment was numerically simulated using ANSYS Fluent. Under the condition of the same ventilation volume, two models utilizing single pipe and double pipe scenarios were established, and six points were selected as the pipeline suspension position, forming six ventilation duct models. The cooling effect of each model was evaluated by analyzing the average temperature of the roadway section, the three-dimensional distribution of the roadway temperature and the velocity streamline of the whole roadway. The results show that the double-tube model has greater advantages than the single-tube model does, due to its superior local temperature, average temperature of the cross-section, range below 303 K, temperature uniformity and local wind speed. Among the models, model 4 (diameter of 0.5 m, 1.9 m away from the bottom of the roadway and 2.4 m away from the center of the circle) is the best pipeline layout scheme for comprehensive temperature values, roadway temperature uniformity and other factors. The average temperature is 299.3 K within 8 m from the mining face, which is 1.66 K lower than that of the single tube model. This configuration will increase the comfort of the mining environment and reduce cooling costs. These results can provide a reference for ventilation duct layouts of roadways in high temperature mines.

Keywords: mine ventilation; ventilation duct setting; mine cooling; numerical simulation

1. Introduction

Sustainable development is a lifelong challenge around the world. Considering relevant environmental factors, economic development, and sustainable development, energy demand should be controlled. Among consumers, the energy consumed by the industrial and mining sectors accounts for approximately 37% of the world's total consumption [1]. The progress in underground mining technology, the increasing demand for mineral products in the market, and the gradual depletion of shallow mineral resources had led to gradual deepening of mining. High temperature and high humidity environments are common in deep mines. The hot and humid environment leads to disorders related to heat balance in the human body, with problems associated with heat stroke and work efficiency becoming increasingly prominent. South Africa is at the forefront of mine cooling, and South African legislation stipulates that the mining environment temperature should not be higher than the wet bulb temperature of 300.5 K [2]. China's "Safety Regulations for Coal Mines" stipulates that the temperature of the working surface shall not exceed 299 K for the dry bulb temperature. When

the temperature of the mining surface is between 299 and 303 K, the working hours of mine workers must be reduced, and high temperature protection or treatment should be administered according to regulations. Mining operations must be stopped when the air temperature at the mining surface exceeds 303 K [3].

The earliest known record of mine thermal disaster management was the 19th Century Cornish tin mine that had a virgin rock temperature (VRT) of 318.6 K at a depth of 380 m, which used cold water for mine cooling [4]. In 1992, the first fatal heat stroke case was reported in South African mines. In subsequent years, some theoretical and practical work on mine thermal management was performed, specifically in mines with higher VRTs [5]. In 1919, the first equipment for mine cooling was installed in the Anglo American Morro Velho gold mine (Brazil). In the 1930s, a South African mine installed the first bulk air cooling system (BAC), which was introduced to underground mine cooling in the 1970s; the transfer of BAC to the ground could compensated for the loss of cooling capacity caused by the increasingly long distance between the pit and the mining face [4].

As mining depths have increased, (the current depth is over 3 km [6], which is called ultradeep mining), increases in VRT and air self-compression heat have made the mining environment very unfavorable, which has led to a significant increase in mining cost (in deep mines, the cost of air conditioning cooling systems accounts for approximately 1/4 of the total energy consumption of the mine [7,8]). Generally, air ventilation is insufficient to remove the heat generated by the deep surrounding rock, mining equipment and blasting (the outdoor temperature in summer in southern China can exceed 308 K). Thus, it is necessary to add deep cooling systems to ensure normal mining activities.

It has been found that the ventilation temperature is the biggest factor that affects mine temperature [6]. The mining depths and virgin rock temperatures of some mines are listed in Table 1. It is apparent that the virgin rock temperatures of different mines vary between 303–353 K. Therefore, it is necessary to cool the roadway to produce a comfortable mining environment and increase work efficiency. Due to the high energy consumption of the entire mine cooling system, it is necessary to properly design the roadway cooling system, which can ensure comfortable mining temperatures and reduce unnecessary energy consumption.

Table 1. Statistics for thermal disasters in some mines.

Coal Mine	Depth (m)	Virgin Rock Temperature (K)
Amandelbult (South Africa)	3300	328
Fengyu-Lead (Japan)	500	353
Pingmei No. 8 Mine (China)	650	315
Sanjianhe Mine (China)	1300	329
Fengchengjian Mine (China)	650	315
Zhang Shuanglou Mine (China)	1000	309
Yongchuan Mine (China)	800	303
Xinji Mine (China)	550	35.2

To date, several mature mathematical models have been established in the field of mine ventilation, including a one-dimensional heat transfer model, a one-dimensional network flow model, three-dimensional computational fluid dynamics (CFD) models focusing on ventilation airflow [9–11] as well as others [12–15]. Some workers have studied the optimal design of mine ventilation through CFD simulation [16]. Jongyung Park et al. [17] studied the air quality problems of closed mines used for storage by designing several unused pipeline parameters. Agus P. Sasmito et al. [6] created a three-dimensional model for underground mine thermal management. However, these studies lack a systematic, integral analysis of the design of air conditioning ventilation ducts for high temperature mines. In this paper, starting with two basic models of single tube and double tube ventilation and learning from previous research experience, six ventilation duct models (three types of single and

double tube models, respectively) were built. Under the premise of the same ventilation conditions, the quality of each ventilation model was evaluated by analyzing the tunnel temperature and distribution.

2. Geometric Model Setting

The simulation was based on a three-dimensional underground mining model created by Agus P. Sasmito et al. [6]. Figure 1 shows the basic parameters of the entire roadway (36 m long, 3.6 m wide and 2.9 m high) and the position of the air duct. The diameter parameters are listed in Table 2.

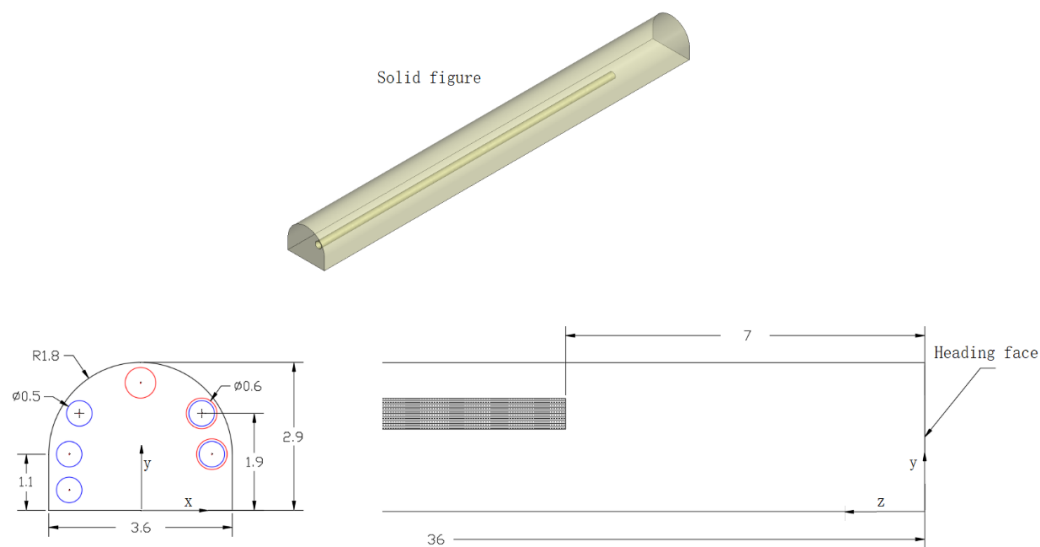


Figure 1. Roadway and ventilation duct parameters and arrangement.

Table 2. Pipe position and pipe diameter parameters of each model.

	Tube 1 Center Coordinates	Tube 2 Center Coordinates	Diameter
Model 1	(1.2, 1.9)		0.6
Model 2	(0, 2.5)		0.6
Model 3	(1.4, 1.1)		0.6
Model 4	(1.2, 1.9)	(−1.2, 1.9)	0.5
Model 5	(1.4, 1.1)	(−1.4, 1.1)	0.5
Model 6	(1.2, 1.9)	(−1.4, 0.4)	0.5

3. Calculation Model and Boundary Conditions

3.1. Software and Numerical Model

Both geometric model creation and meshing were performed in ICEM-CFD. (3D modeling software) To determine the appropriate grid size, three different quality grids (0.5×10^6 , 2.9×10^6 and 6×10^6) were tested. It was found that the accuracies of the 0.5×10^6 and 2.9×10^6 grids were more different, whereas the 2.9×10^6 and 6×10^6 grids had small differences, greatly reduced the computing time. Therefore, a mesh of approximately 2.9 million elements was sufficient for the numerical investigation purposes.

The numerical simulations were carried out in ANSYS Fluent. The turbulence model is a key part of the simulation of fluid flow behavior in the subsurface environment [18]. There are four turbulence models in Fluent: Spalart-allmaras, k-epsilon, k-omega and RSM (Reynolds stress model). Kurnia et al. verified four models via experiments, finding that the k-epsilon model fit well with their experimental data [19]. This model is widely used in the engineering field and was adopted in this study.

3.2. Mathematical Model

Along the roadway, turbulent mass, momentum and energy transport simultaneously occur. The heat dissipation of the surrounding rock and ventilation air necessary to cool-down the ambient temperature is considered. Conservation equations for mass, momentum and energy are expressed as:

$$\nabla \cdot \rho U = 0 \quad (1)$$

$$\nabla \cdot \rho U U = -\nabla p + \nabla \cdot \tau + \rho g \quad (2)$$

$$\nabla \cdot (\rho c_p U T) = \nabla \cdot \left(k_{eff} + \frac{c_p \mu_t}{Pr_t} \right) \nabla T \quad (3)$$

where ρ is the fluid density, U is the fluid velocity, p is the pressure, τ is the viscous stress tensor, g is the gravitational acceleration, c_p is the fluid specific heat, k_{eff} is the effective fluid thermal conductivity, T is the temperature and Pr_t is the turbulent Prandtl Special number.

Based on the equation for kinetic energy k , another equation for the turbulent energy dissipation rate ε was introduced and a k-epsilon two-equation model was formed, which is called the standard k-epsilon model, where ε represents the turbulent dissipation rate. The model is defined as:

$$\varepsilon = \frac{\mu}{\rho} \left(\frac{\partial u'_i}{\partial x_k} \right) \left(\frac{\partial u'_i}{\partial x_k} \right) \quad (4)$$

The turbulent viscosity μ_t can be expressed as a function of k and ε , as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

where C_μ is an empirical constant.

The k-epsilon model considers a two-equation model for solving the turbulent flow energy k and the dissipation rate ε , which is combined with turbulent viscosity. The model is:

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k + G_B - \rho \varepsilon \quad (6)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho U \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_B) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (7)$$

where G_k is the term for the turbulent energy k associated with the average velocity gradient, G_B is the term for the turbulent k caused by buoyancy, and terms $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_p , σ_k and σ_ε are constants with respective values of 1.44, 1.92, 0.09, 1.0 and 1.3.

3.3. Boundary Conditions

The boundary conditions and calculation model settings for this study are shown in Tables 3 and 4. Among them, the inlet wind speed was set to 12 m/s, which refers to the literature [6]; the wall temperature was set to 318 K, which came from the field observation worth the average.

Table 3. Boundary conditions.

Type or Parameter	Setting Type or Parameter
Ventilation duct outlet	Velocity-inlet
Ventilation duct speed (m/s)	12 (Models 1–3)/8.64 (Models 4–6)
Roadway exit	Outflow
Others wall	Wall
Ventilation temperature (K)	293
Roadway initial temperature (K)	305
Virgin rock temperature (K)	318

Table 4. Calculation model.

Type or Parameter	Setting Type or Parameter
Solver	Pressure-Based
Velocity	Absolute
Time	Steady
Viscous Model	Standard k-epsilon
Pressure/kPa	1.013
k	0.2087 (Models 1–3)/0.1229 (Models 4–6)
ϵ	0.3730 (Models 1–3)/0.2023 (Models 4–6)
Convergence tolerance	1×10^{-4}
Number of Iterations	3000

The ANSYS FLUENT numerical code was employed for all numerical predictions. The semi-implicit pressure-linked equation (SIMPLE) algorithm, the second-order upwind discretization method and the algebraic multigrid method (AGM) were used to solve the equation. On average, each simulation required approximately 2500–2800 iterations, with a convergence tolerance of 10^{-4} for all variables.

4. Numerical Simulation

4.1. Single Tube Model Section Average Temperature

The average temperature of the roadway section can directly reflect the temperature of the underground mine. To study this problem, the average temperature of the section of Models 1–3 was shown by a graph, and Figure 2 shows the change in the average temperature of the section. Obviously, as the distance from the mining face increased, the average temperature of the section increased almost linearly. The temperature of Model 3 was the lowest in the range of 0–2 m, but this was not obvious. At the maximum difference point (1 m away from the mining surface), there was only a difference of 0.52 K (Between model 3 and model 2). This had little impact on the miners' actual experience and was only a very short-lived advantage zone. In terms of cooling performance, the distances from the section below 30 K were 9.5 m for Model 1, 12.5 m for Model 2 and 10.5 m for Model 3.

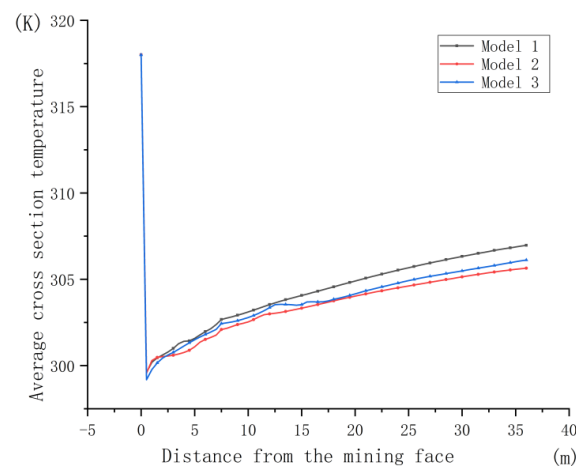


Figure 2. Models 1–3 section average temperature curve.

4.2. Single Tube Model Roadway Temperature Distribution

The temperature distribution of the entire roadway is one of the key factors that determine the comfort of the working environment.

For Model 1, Figure 3 shows the temperature distribution at $z = 2$ m was extremely uneven; a temperature band of 299.5 K was obliquely distributed in the roadway, while the temperature of the upper left and lower right areas was approximately 302.5 K. The temperature distribution shows a situation of “head hot foot cold” on the left side and “foot hot head cold” on the right side. After $z = 12$ m, the temperature distribution in the main belt was composed of two regions less than 1 K, but it was out of the miners’ main activity area and the average temperature increased. From the roadway profile of $x = 0$ m (Figure 4), it was apparent that the cooling air sprayed from the air duct formed a vortex after impacting the mining surface, the cooling range gradually diffused into the interior of the roadway, and the cooling performance degraded. Figure 5 shows the three-dimensional distribution of the roadway temperature: There was a short distance of low temperature space near the roadway face, and there was an obvious high temperature line between the ventilation pipe and the roadway wall.

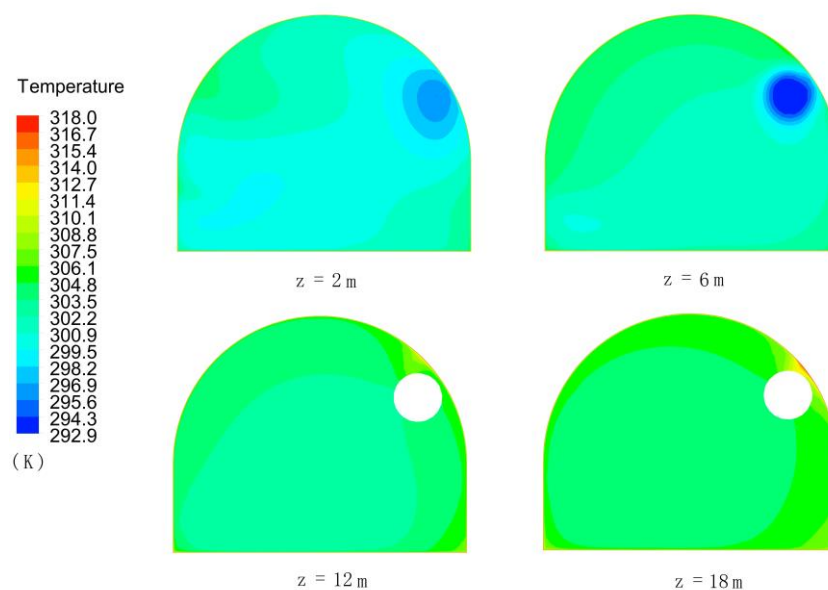


Figure 3. Model 1 section temperature distribution.

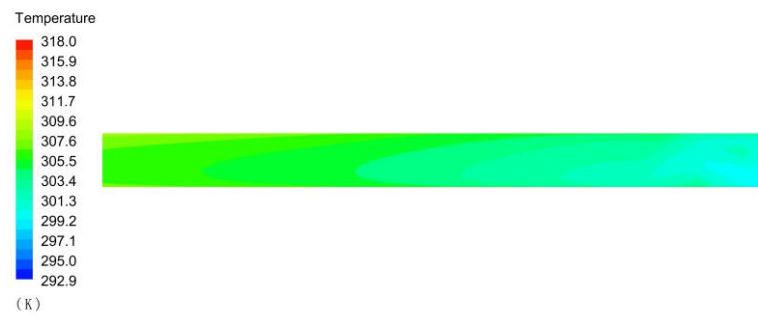


Figure 4. Model 1 side view ($x = 0$).

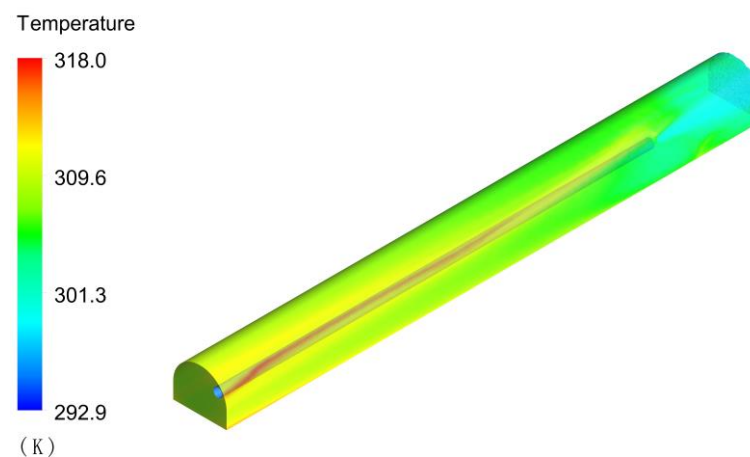


Figure 5. Three-dimensional distribution of Model 1 roadway temperature.

The Model 2 pipe was arranged at the top of the roadway. From $z = 2$ m and $z = 6$ m in Figure 6, it was apparent that the temperature was almost symmetrically distributed, and there was a problematic, uneven temperature distribution. It is shown in Figure 7 that there was a wide range of low temperature range near the section of $x = 0$ m. Combined with the three-dimensional distribution of roadway temperature (Figure 8), it was concluded that Model 2 had a better temperature zone only in the narrow area in the middle of the roadway.

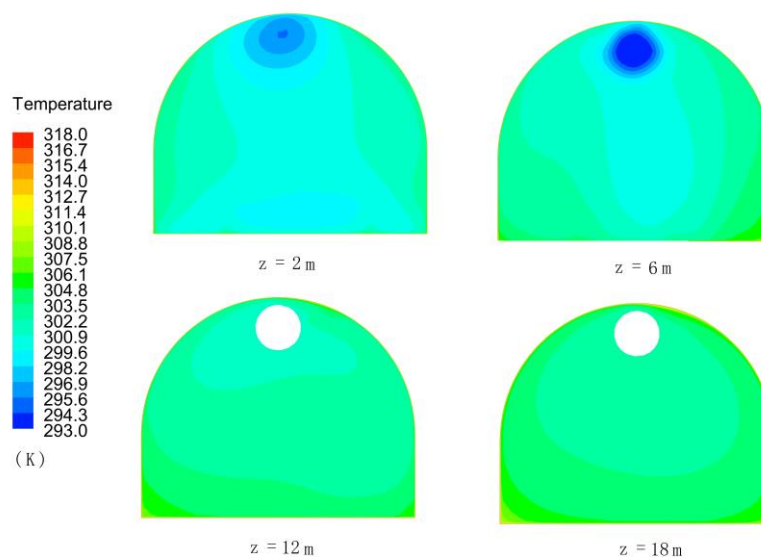


Figure 6. Model 2 section temperature distribution.

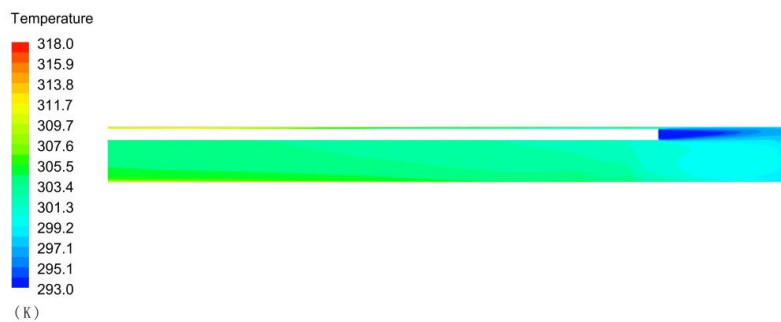


Figure 7. Model 2 side view ($x = 0$).

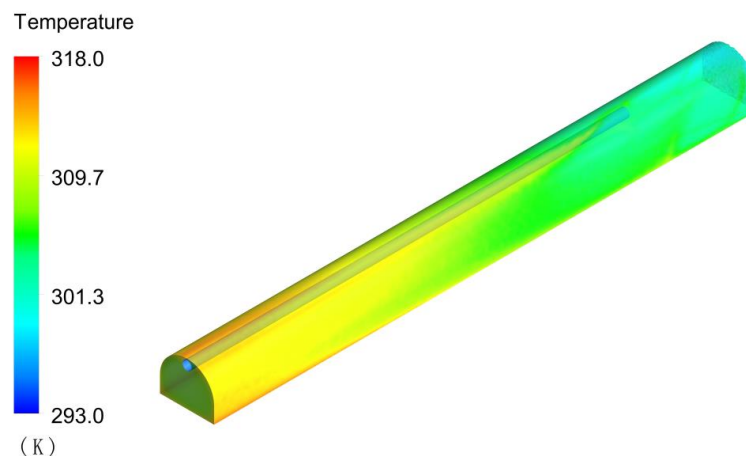


Figure 8. Three-dimensional distribution of Model 2 roadway temperature.

Model 3 was similar to the other two cases. It is apparent in Figure 9 that there was a large temperature difference and a non-uniform distribution. Figure 10 completely reflected this distribution. The large vortex formed by the cooling air jetted from the side pipe of the roadway impacted the excavation face and circulated in the lower part of the roadway, thus forming the temperature distribution state of the entire roadway.

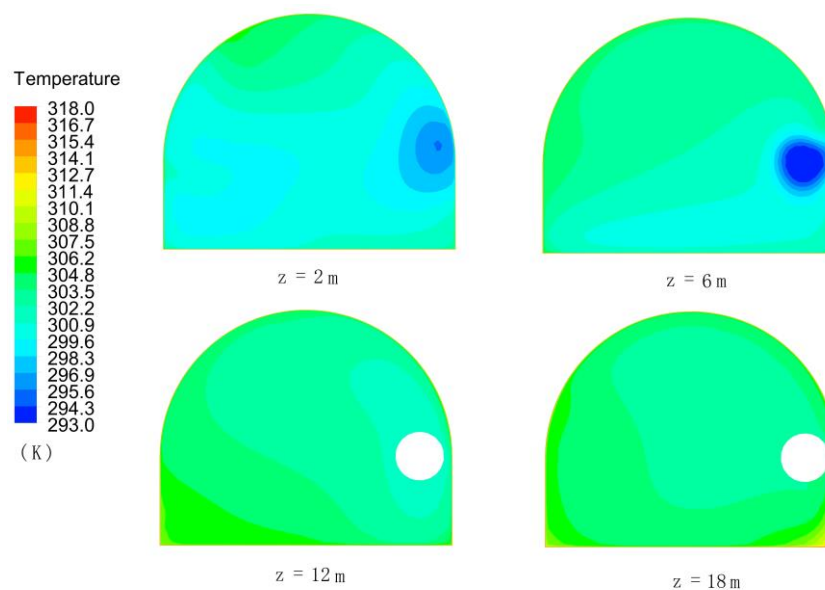


Figure 9. Model 3 section temperature distribution.

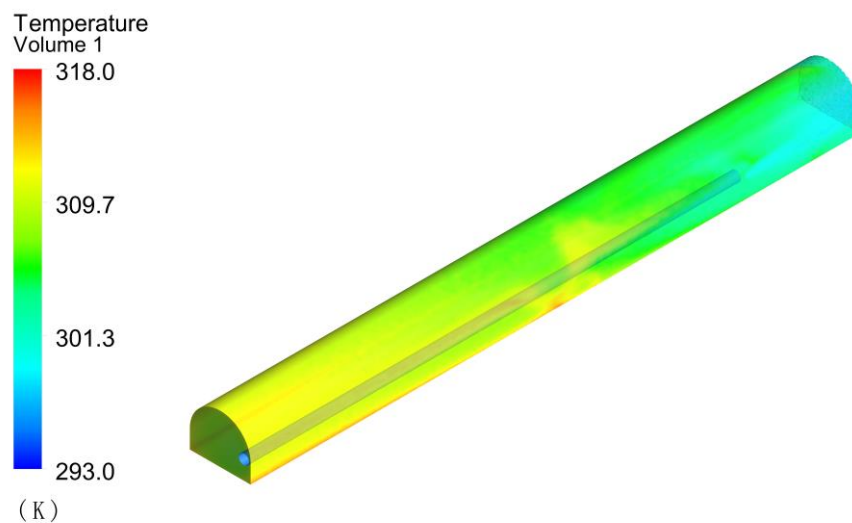


Figure 10. Three-dimensional distribution of Model 3 roadway temperature.

4.3. Single Tube Model Roadway Speed Streamline

Figure 11 shows the flow path of the single tube model over the entire tunnel. The cold air flowing at high speed from the vent pipe encounters the end wall, and the air flow revolved to form a single large-scale circulating flow and several small vortices. The flow path of the airflow explained the uneven temperature distribution of the above section well: Model 1 streamlines were densely distributed in the diagonal region, Model 2 streamlines were mainly distributed in the lane centerline and Model 3 streamlines were mainly distributed in the lower part of the roadway. It is worth noting that the flow line fluctuation range of Model 3 was longer, which also explains that the average temperature of the section shown in Figure 2 was in a fluctuation growth state before $z = 17$ m.

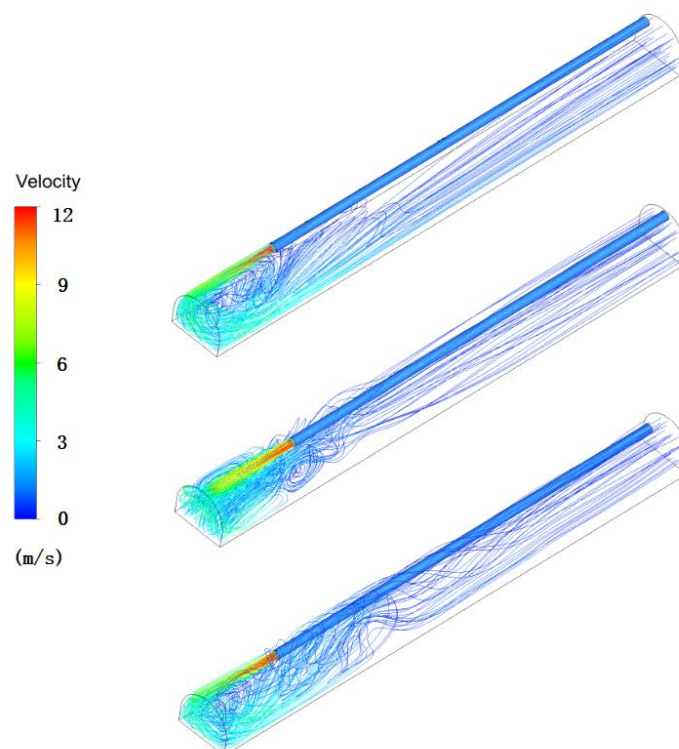


Figure 11. Speed streamline distribution of Models 1–3.

4.4. Double Tube Model Section Average Temperature

In the two-tube model, the pipe diameter was reduced while reducing the wind speed in order to maintain the same amount of cold air flow as in the single pipe model. It is clear from Figure 12 that the average cross-sectional temperatures of Models 4–6 increased almost linearly with increasing distance from the mining face. Obviously, the double-tube model had a lower average temperature of the section that was more pronounced in the first 8 m, which was the main activity area of the workers. The average cross-sectional temperatures of Models 4–6 between 0 and 8 m were 1.65 K, 0.98 K and 1.88 K lower than that of Model 2, respectively. From the performance comparison of cooling, the distances of the section of Models 4–6 below 303 K from the mining face were 23.84 m, 20.76 m and 20.5 m, which were much longer than that of the single pipe model. The average temperature curve shows that the double-tube model had a large advantage in cooling performance.

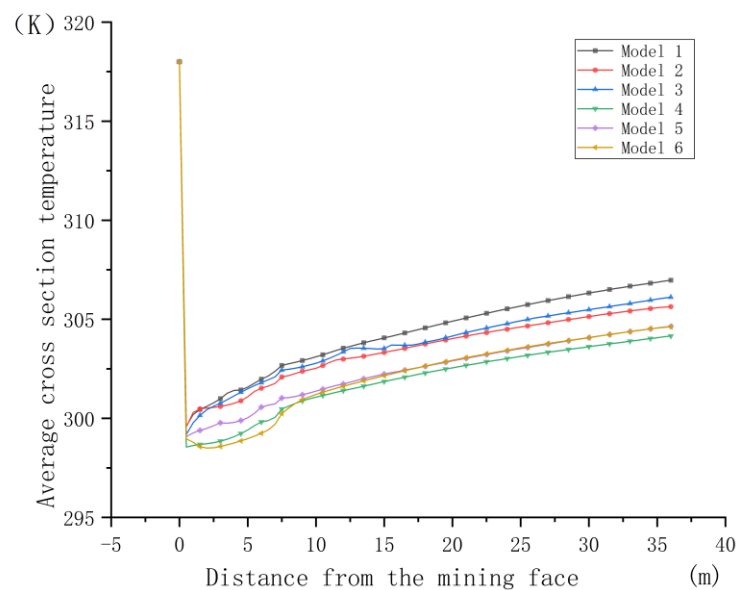


Figure 12. Models 4–6 section average temperature curve.

4.5. Double Tube Model Roadway Temperature Distribution

In the case of the same amount of cold air, the double tube model achieved a lower average cross-sectional temperature and a larger low temperature environment. The uniformity of the tunnel temperature while achieving a better cooling state is discussed below.

Figures 13–15 show the cross-sectional temperature of Model 4 ($z = 2$ m, $z = 6$ m, $z = 12$ m and $z = 18$ m), the side temperature profile of the roadway ($x = 0$ m) and the three-dimensional distribution of the tunnel temperature. At $z = 2$ m, it was clear that the roadway was mainly covered by the area of $T = 298.5$ K, and the temperature distribution was uniform. At $z = 6$ m, the main temperature of the section was 299.5 K, and the isothermal zone at the top of the roadway was insufficient at 1 K. Similar to the single-tube model at $z = 12$ m, at $z = 18$ m, the cooling airflow flowed through the remaining lanes after sufficient development. Figures 15 and 16 show the temperature distribution of the roadway more intuitively.

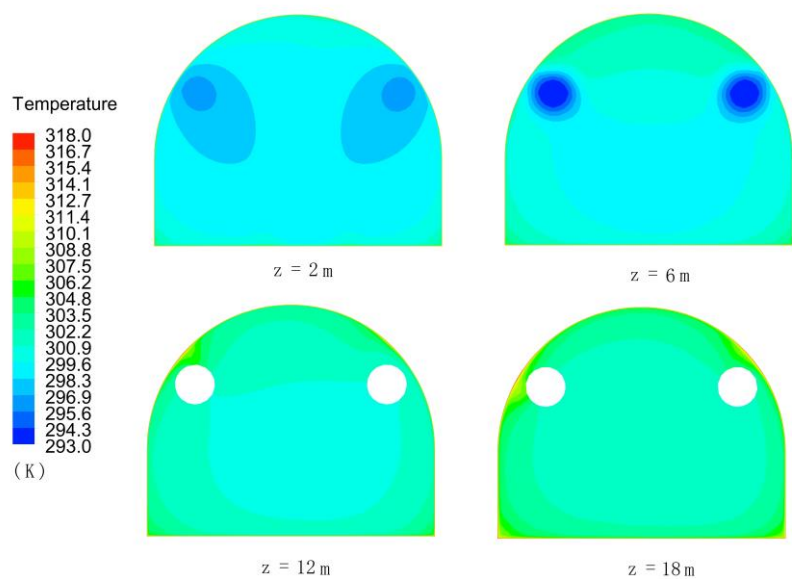


Figure 13. Model 4 section temperature distribution.



Figure 14. Model 4 roadway temperature side view ($x = 0$).

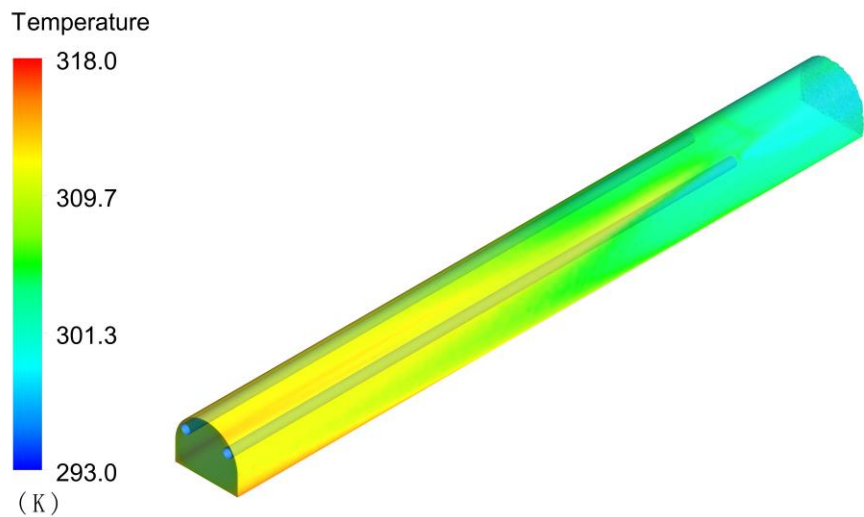


Figure 15. Three-dimensional distribution of Model 4 roadway temperature.

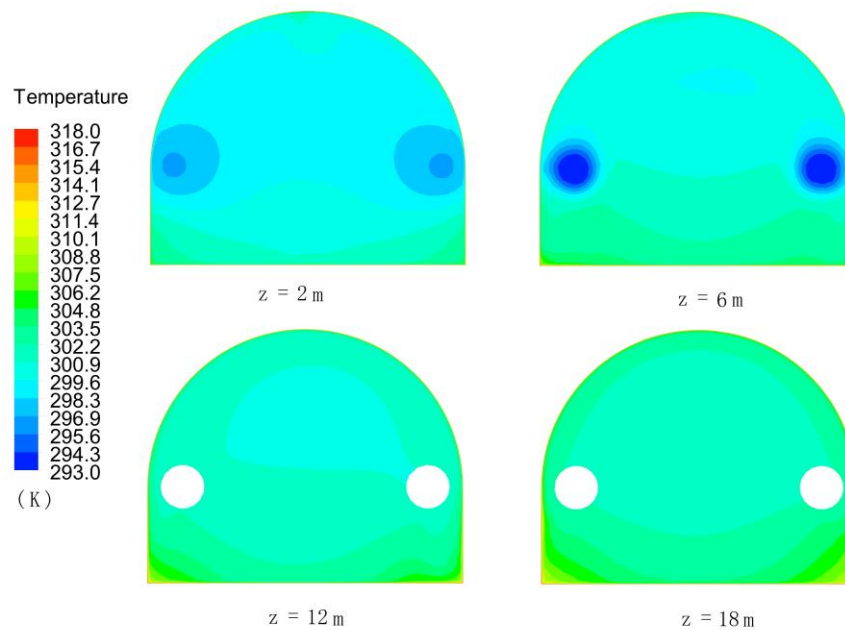


Figure 16. Model 5 section temperature distribution.

For Model 5, the overall situation was similar to that of Model 4, but the distribution of cross-sectional temperature was insufficient compared to Model 4; Figure 16 shows, the temperature uniformity was not good at $z = 2$ m or $z = 6$ m, for which the average temperature of the section increased by 0.77 K and 0.75 K. Figure 17 (the $x = 0$ m roadway side view) clearly shows a lower temperature at the top of the roadway, which explains why Figure 18 shows that Model 5 had the longest cooling distance.



Figure 17. Model 5 roadway temperature side view ($x = 0$).

Model 6 was the only asymmetric structural model in the double-tube model. As we can see clearly from Figure 19, that the temperature at the section of $z = 2$ m was approximately 298.5 K, and at $z = 6$ m, the section consisted of two isothermal surfaces of 298.5–299.7 K. The average cross-sectional temperatures of $z = 2$ m and $z = 6$ m were 0.22 K and 0.57 K lower than that of Model 4, which was the lowest of the three models and could be derived from Figure 11. However, after $z = 7.5$ m, the cross-sectional temperature of the roadway appeared as a multilevel isotherm, and the uniformity of roadway temperature distribution began to deteriorate. At $z = 12$ m and $z = 18$ m, the most obvious high temperature areas of several models appeared adjacent to the lower-left pipeline. This phenomenon could be found in Figure 20.

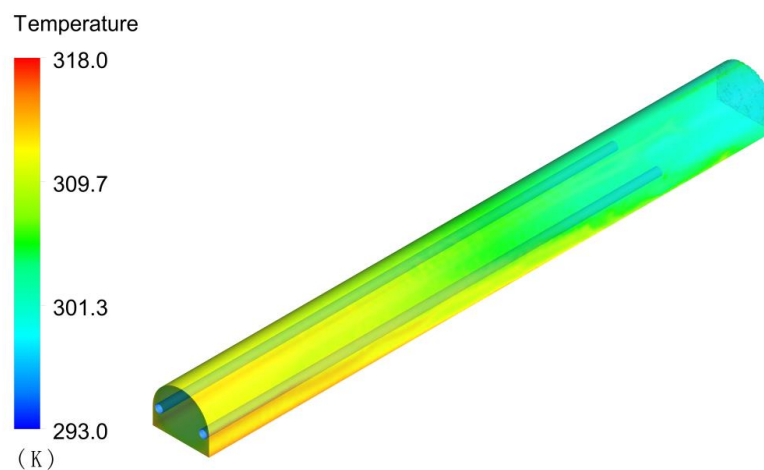


Figure 18. Three-dimensional distribution of Model 5 roadway temperature.

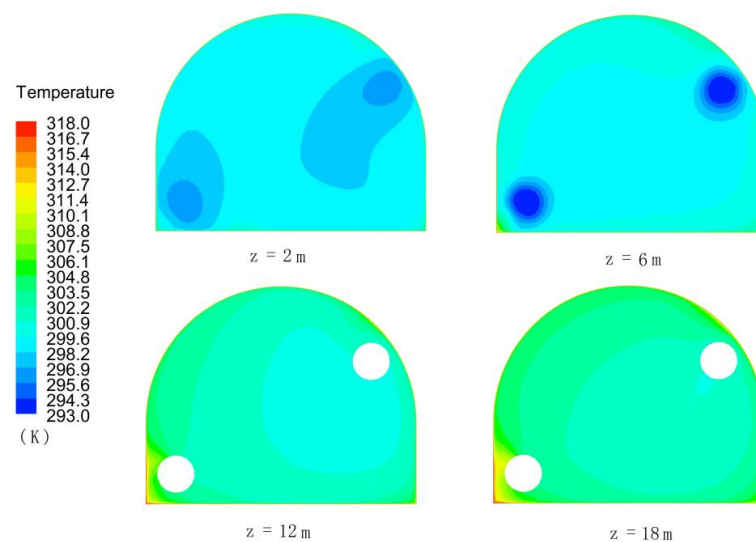


Figure 19. Model 6 section temperature distribution.

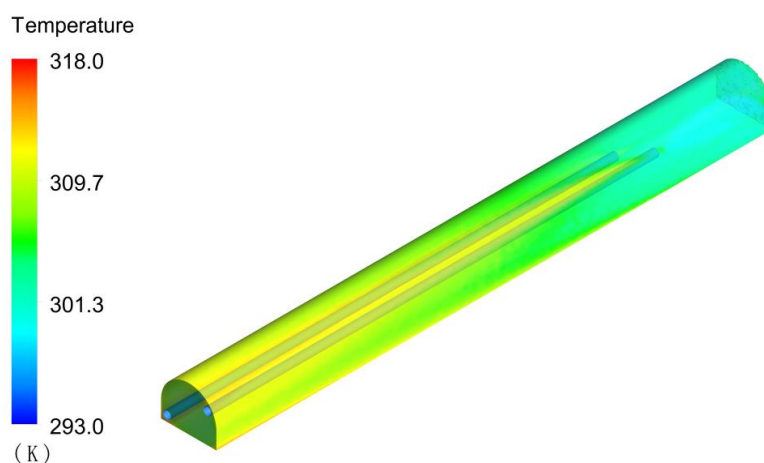


Figure 20. Three-dimensional distribution of Model 6 roadway temperature.

In summary, Model 4 shows the best roadway temperature distribution from the excavation face to the roadway exit, Model 6 shows the lowest temperature of the main work area (within 8 m from the face), and Model 5 shows no advantage in temperature distribution or values.

4.6. Double Tube Model Roadway Speed Streamline

Figure 21 shows the velocity streamlines for Models 4–6. From the streamline diagram, the cause of the above temperature distribution could be analyzed. The vortex of Model 4 was formed between the outlet and the tunneling surface, in which the cold air circulated from the top to the bottom and then flowed uniformly through the subsequent roadway. In Model 5, the front vortices were mainly formed in the upper part of the roadway, which explained why the cooling ventilation duct was lowered; however, the temperature in the lower part was high. For Model 6, the airflow vortex was shorter and more complicated. After the end of the vortex, the complex flow vortex produces multiple-level temperature streamlines, resulting in a complex temperature distribution in the subsequent roadway.

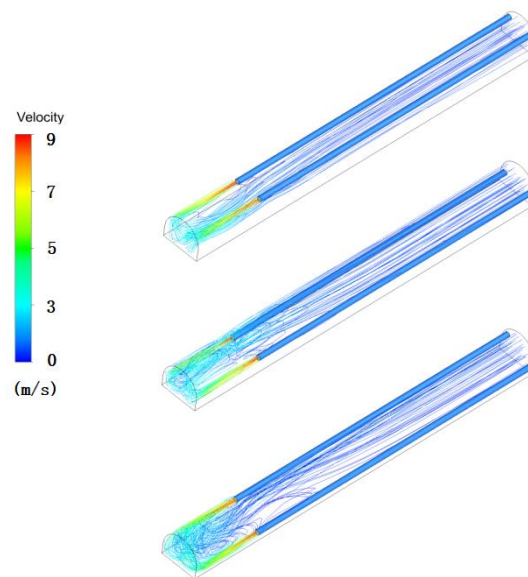


Figure 21. Models 4–6 speed streamline distribution.

5. Result Verification

Figure 22 shows the numerical simulation results of Model 4 and the field test results for the same conditions. It is apparent that the numerical simulation results were basically consistent with the experimental results. Due to the influence of field test selection points and other factors, the experimental results show small fluctuations, but they did not affect its accuracy. Therefore, the results of the numerical simulations had a reference value.

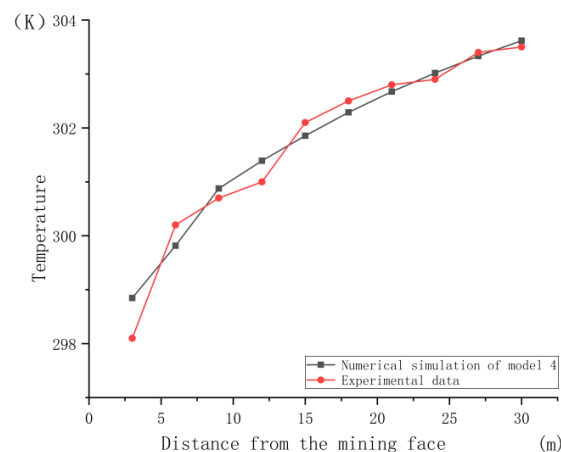


Figure 22. Comparison of experimental and numerical simulation results.

6. Conclusions

This paper investigated six roadway ventilation duct models and analyzed the cooling effects of each model, combined with numerical simulations, with a purpose of achieving a more comfortable mining temperature environment with lower energy consumption. The results of this study are summarized as follows:

- (1) The double-tube model (Models 4–6) was superior to the single-tube model (Models 1–3) in terms of temperature distribution and temperature values. The dual-tube ventilation models have the natural advantage of making it easier to mix cold air evenly with the air inside the tunnel. This results in a decrease in the average temperature near the face, and the optimum value of the double pipe model has a temperature difference of more than 2.5K than the worst case of the single pipe model.
- (2) Under the same ventilation volume for the single-pipe model and the two-pipe model, the wind speed at the outlet of the double-tube model was 8.64 m/s, which provides a natural advantage over the wind speed of the single-tube (which was 12 m/s). Dispersed ventilation will result in lower local wind speeds, making the mining environment more comfortable.
- (3) The double pipe model with a longer roadway area below 303 K of 21.7 m was better than the single pipe model with a roadway area of 10.8 m. Among them, the roadway temperature distribution of Model 4 (with a pipe diameter of 0.5 m, located 1.9 m away from the bottom of the roadway and 2.4 m away from the center of the circle) was the best, and the average temperature curve of the section increased stably and slowly with increased distance from the mining face. The average temperature 8 m in front of the roadway was 299.3 K, the minimum temperature of the section was 298.5 K and the maximum temperature was 300.6 K, which was only 2.1 K different.

Therefore, the simulation results show that Model 4 could obtain the best roadway cooling effect.

Author Contributions: Z.Z.: Writing—review & editing, Formal analysis. Y.C.: Data curation, Software. L.T.: Conceptualization, Project administration. J.C.: Supervision. W.P.: Investigation. S.Y.: Validation. P.H.: Resources.

Funding: This research was funded by [National Natural Science Foundation of China] grant number [51504286].

Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

1. Abdelaziz, E.A.; Saidur, R.; Mekhilef, S. A review on energy saving strategies in industrial sector. *Renew. Sustain. Energy Rev.* **2011**, *15*, 150–168. [\[CrossRef\]](#)
2. Vosloo, J.; Liebenberg, L.; Velleman, D. Case study: Energy savings for a deep-mine water reticulation system. *Appl. Energy* **2012**, *92*, 328–335. [\[CrossRef\]](#)
3. Li, R. Research on Thermal Disaster Prediction Model for Deep Mine Roadway. Master's Thesis, Xi'an University of Science and Technology, Xi'an, China, 2009. (In Chinese).
4. Gebler, W.F. A reviews of mine cooling practices through the ages. *J. Mine Ventil. Soc. S. Afr.* **1980**, *33*, 209–222.
5. Belle, B.; Biffi, M. Cooling pathways for deep Australian longwall coal mines of the future. *Int. J. Min. Sci. Technol.* **2018**, *28*, 865–875. [\[CrossRef\]](#)
6. Agus, P. Sasmito Computational evaluation of thermal management strategies in an underground mine. *Appl. Therm. Eng.* **2015**, *90*, 1144–1150.
7. Bornman, W. Improved Mine Cooling System Performance Through the Control of Auxiliary Systems. Master's Thesis, North-West University, Potchefstroom, South Africa, 2012.
8. Du Plessis, G.E.; Arndt, D.C.; Mathews, E.H. The development and integrated simulation of a variable water flow energy saving strategy for deep-mine cooling systems. *Sustain. Energy Technol. Assess.* **2015**, *10*, 71–78. [\[CrossRef\]](#)
9. Wala, A.M.; Vytlia, S.; Taylor, C.D.; Huang, G. Mine face ventilation: A comparison of CFD results against benchmark experiments for the CFD code validation. *Min. Eng.* **2007**, *59*, 49–55.

10. Parra, M.T.; Villafruela, J.M.; Castro, F.; Méndez, C. Numerical and experimental analysis of different ventilation systems in deep mines. *Build. Environ.* **2006**, *41*, 87–93. [[CrossRef](#)]
11. Hargreaves, D.M.; Lowndes, I.S. The computational modeling of the ventilation flows within a rapid development drivage. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2007**, *22*, 150–160. [[CrossRef](#)]
12. Zhou, Z.; Hu, P.; Qi, C.; Niu, T.; Li, M.; Tian, L. The Influence of Ventilation Arrangement on the Mechanism of Dust Distribution in Woxi Pithead. *Shock Vib.* **2018**, *2018*, 8928120. [[CrossRef](#)]
13. Torano, J.; Torno, S.; Menéndez, M.; Gent, M. Auxiliary ventilation in mining roadways driven with roadheaders: Validated CFD modelling of dust behaviour. *Tunn. Undergr. Space Technol.* **2011**, *26*, 201–210. [[CrossRef](#)]
14. Kurnia, J.C.; Sasmito, A.P.; Mujumdar, A.S. Dust dispersion and management in underground mining faces. *Int. J. Min. Sci. Technol.* **2014**, *24*, 39–44. [[CrossRef](#)]
15. Kurnia, J.C.; Sasmito, A.P.; Hassani, F.; Mujumdar, A.S. Introduction and evaluation of a novel hybrid brattice for improved dust control in underground mining faces: A computational study. *Int. J. Min. Sci. Technol.* **2015**, *25*, 537–543. [[CrossRef](#)]
16. Bartak, M.; Cermak, M.; Clarke, J.A.; Denev, J.; Drkal, F.; Lain, M.; Stankov, P. Experimental and numerical study of local mean age of air. In Proceedings of the Seventh International IBPSA Conference, Rio De Janeiro, Brazil, 13–15 August 2001; pp. 773–779.
17. Park, J.; Park, S.; Lee, D.K. CFD modeling of ventilation ducts for improvement of air quality in closed mines. *Geosyst. Eng.* **2016**, *19*, 1–11. [[CrossRef](#)]
18. Versteeg, H.K. *Malalasekera an Introduction to Computational Fluid Dynamics—The Finite Volume Method*; Longman Scientific and Technical: Belgrade, Serbia, 1995.
19. Kurnia, J.C.; Sasmito, A.P.; Mujumdar, A.S. CFD simulation of methane dispersion and innovative methane management in underground mining faces. *Appl. Math. Model.* **2014**, *38*, 3467–3484. [[CrossRef](#)]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).