

Proposed liquid CO₂ cycle refrigeration system for heat hazard control

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Abstract. Liquid CO₂ can absorb heat via phase change and generates cryogenic CO₂ which can effectively solve the problem of thermal damage in the deep coal mining process. The CO₂ cycle refrigeration device system is designed to effectively cool down the working surface of the mine in which CO₂ is cyclically utilized. COMSOL Multiphysics simulation software is used to characterize the CO₂ cycle refrigeration system in mine of the heat transfers process between CO₂ and the air flow in tunnel. The results show that the reduction of steady air flow temperature reach at 8 °C in the tunnel by CO₂ cycle refrigeration system before the air flow into work face. we analyzed the influence of main parameters on refrigeration system and gets the results:1) The refrigeration system get higher cooling efficiency of cryogenic CO₂ when the ventilation velocity of local fan is increased, and the temperature of outlet CO₂ and steady air flow in tunnel has increased; 2) Increasing the CO₂ flow, the refrigeration effect of the system is enhanced obviously, but CO₂ refrigeration capacity utilization ratio is reduced; 3) Increasing the length of helical tube would led to use CO₂ refrigerating capacity more efficiently; 4) The cooling effect of the cooling system can be improved obviously by lowering the the CO₂ cooling temperature.

1 Introduction

With the increases in the depths of mines, high-temperature mines have been more and more now [1]. A high-temperature environment directly affects mineworkers in work condition and work efficiency, and is easy to cause insecure behavior and lack of enthusiasm [2]. In addition, it will seriously endanger the health of workers that working in a high temperature environment for a long time [3]. Therefore the heat harmful problem of high temperature mine needs to be solved urgently.

Various cooling technologies have been used to prevent heat hazards and ensure safe and efficient mining. Based on the principle of vortex tube energy separation, Ma Li et al. studied the portable cooling technology and method in high temperature mine for individual cooling [4]. Chen W et al. proposed a split-type vapor compression refrigerator [5], using air as the refrigerant, pneumatic refrigerator was cooled down in a local freezer and it combined with cooling clothing to cool the workers in high temperature working environments. Deng bao developed an air-to-air conditioning system with compressors, condensers, evaporators, etc., to cool down the working face [6]. However, due to the small heat capacity of the air, the thermal damage of the working face was not effectively controlled. SUN Xikui et al. studied the influencing factors of radiation cooling technology of ice water cooling, and established a refrigeration system that can

produce 37.5t of ice and 62.7t cold water at 2 °C per hour [7]. Guo Pingye et al. has designed a refrigeration systems which used the cold water as the cold source, and established evaluation method for mine refrigeration system to optimizes the refrigeration system and improve the cooling effect of the working face [8,9].

However, this system needs a lot of cold water from the ground as refrigeration. Furthermore, there are impurities in the water, and the cooling system pipes form scales in the process of transporting water after a long run time, which increases the resistance of the water transportation and increase the system operation burden. The heat exchange efficiency is reduced because of the decrease in the heat conductivity of the pipes caused by the scale of water, which leads to a distinct reduction in the cooling effect of the refrigeration system.

Due to its low price, accessibility, large heat capacity and being environmental friendly, the use of CO₂ as a refrigerant has attracted widely attention in recent years [10]. Previous studies have focused on the transcritical cycle and the relationship between the storage environment of carbon dioxide and refrigeration capacity is conducted [11-14]. However, the processes of heat exchange between the CO₂ and air flow or thermal diffusion in mine are less reported. These are the critical processes for the refrigeration system which ultimately determine the cooling effect for the work face, refrigeration efficiency and working cost of the refrigeration system. In this paper, a model of mine CO₂ cycle cooling system is developed, and the parameters of

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the local fan air volume, CO₂ velocity, CO₂ helical tube length and CO₂ cooling temperature are investigated.

2 Cooling method of CO₂ cycle refrigeration in mine

The CO₂ cycle refrigeration system is designed to cool down the working face of a high temperature mine. The system includes compressor, gas cooler, throttle device, monitoring device, evaporator, pipeline, heat-exchanger and local fan. The low temperature CO₂ gas is performed as cold source and cyclically utilized. If the liquid CO₂ is cooled in the heat exchange system directly, it will easy to the tube jam in pipelines for the liquid CO₂ phase change produce dry ice. So the liquid CO₂ phase transition is carried out in a special evaporator. In the evaporator device, as the pressure reduce, the liquid CO₂ absorb heat by change of state and forms low temperature CO₂, then the low temperature CO₂ enters the helical tube. The helical tube is located in the local air duct and contact with the wind flow provided by the local fan in the tunnel, which makes the low temperature CO₂ exchange heat with the wind flow to form the cold air flow. The cold air flow is sent to the working face in the last by the duct to create comfortable working conditions for workers. Fig.1 shows a schematic of CO₂ cycle refrigeration system.

In the Fig. 2, after the heat exchange, the CO₂ gas returns to the ground through the pipeline and forms liquid CO₂ by compression system and gas cooler. Then the liquid CO₂ through the pipeline into vaporization system which are installed on the underground and vaporizes into low-temperature CO₂ gas. In order to ensure the safety of the system, a safety valve is installed

on the ground of the conveying pipe. When the CO₂ leaks occur in the pipe, the safety valve will be opened and the CO₂ in the pipeline will be released into the air on the ground. The CO₂ is circularly used in the CO₂ cycle refrigeration system for sustainable cooling the work face in mine, which greatly reduces the cost of materials required for refrigeration. At the same time, the CO₂ has more larger heat capacity than water and air resulting it has a better cooling effect at the same mass of water or air. The heat exchange between CO₂ and air is the key for the refrigeration system. To analyze the process of heat exchange between CO₂ and the air flow as well as the influence of main parameters on the cooling effect, a cooling model of CO₂ refrigeration in mine is established in this paper.

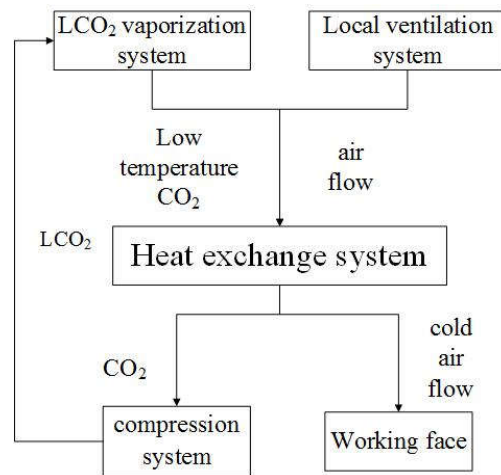


Fig. 1. Schematic of CO₂ cycle refrigeration system.

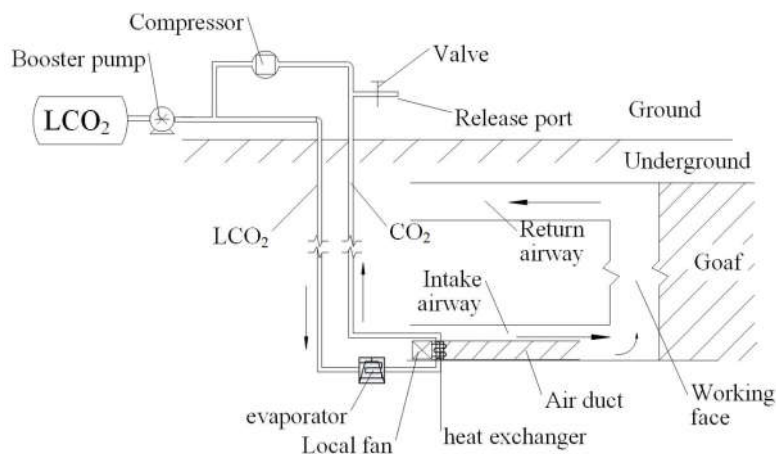


Fig. 2. The device of CO₂ cycle refrigeration system.

3 Modeling and simulation

3.1 Flow equation

Considering the balance of hydrostatic energy, kinetic energy and potential energy, one can be obtain the fluid flow equation which is used to describe the motion of a

fluid in a pipeline under the action of gravity, viscous resistance and pressure.

$$\begin{cases} -\nabla p - f_D \frac{\rho}{2d_h} u|u| + F = 0 \\ \nabla \cdot (A\rho u) = 0 \end{cases} \quad (1)$$

where p is the pressure, Pa; ρ is the density, kg/m³; A is the cross-sectional area, m²; u is the tangential fluid

velocity, m/s; d_h is the pipe diameter, m; and F is the volume force, N/m³.

In Eq.(1), f_D is the *Darcy* friction factor, which is related to the Reynolds number, pipe surface roughness and pipe diameter. It can be expressed as:

$$f_D = 8 \left[\left(\frac{8}{Re} \right)^{12} + (B+C)^{-1.5} \right]^{1/12} \quad (2)$$

where the B is defined as:

$$B = \left[-2.457 \ln \left(\left(\frac{7}{Re} \right)^{0.9} + 0.27 \left(\frac{e}{d} \right) \right) \right]^{16} \quad (3)$$

C is defined as:

$$C = \left(\frac{37530}{Re} \right)^{16} \quad (4)$$

where Re is the Reynolds number; e is the surface roughness; d is the pipe diameter, m.

3.2 Energy conservation equation

The energy equation of pipeline flow is used to describe the heat exchange and thermal diffusion between the fresh air flow and the CO₂ pipeline.

$$\rho A C_p u \cdot \nabla T = \nabla \cdot A k \nabla T + f_D \frac{\rho}{2d_h} |u|^3 + Q_{wall} \quad (5)$$

where C_p is the heat capacity at constant pressure, J/(kg·K); T is the temperature, K; and k is the thermal conductivities, W/(m·K). Q_{wall} is the a source of heat exchange between the wall and the surrounding wall, W/m; which can be can be expressed as:

$$Q_{wall} = hZ(T_{ext} - T) \quad (6)$$

where Z is the circumference of the CO₂ transportation pipeline, m; h is the overall coefficient of heat exchange, W/(m²·K); T_{ext} is the external temperature of the CO₂ conveying steel tube, K; and T is the temperature of CO₂, K.

3.3 Physical model and numerical simulated

Based on the Section 2.1 and 2.2, as a background of CO₂ cycle refrigeration system in a mine, a simulated model of heat-exchange system in tunnel was constructed at a ratio of 1:1, as depicted in Fig. 3. The physical model was a cuboid tunnel with width of 4 m, height of 4 m and length of 30 m. The tunnel of inlet wind speed is set to 1m/s, and the temperature set as 313.15 K. There is a duct with a radius of 0.6 m in the tunnel, which is supplied by a local fan with wind air of 5 m/s. A helical steel tubes for conveying low temperature CO₂ gas are installed inside the wind tubing for heat transfer between air flow and CO₂, which is 3.6 m long, radius of the outer ring with 0.4 m, radius of the inner ring with 0.05 m. The CO₂ flow of transmission pipeline inlet is set to 4 m/s and the inlet temperature is set to 233.15 k. The physical model of heat-exchange system in tunnel mesh illustration consisting of 10,000 elements. To achieve the coupled process, all the governing equations can be

implemented into and numerical solved by COMSOL multiphysics based on the finite element method, as determination of wind speed and temperature distribution under steady state, and the transient solver was properly selected.

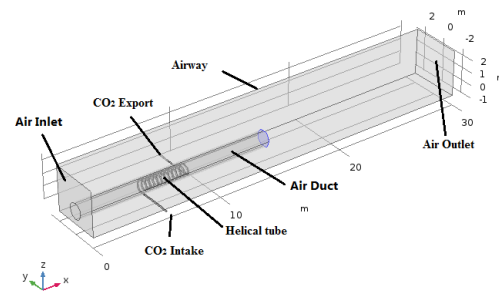


Fig. 3 The model of heat-exchange system in tunnel.

4 Simulated result

In the Fig. 4, we can see that a high speed wind flow is gradually mixed with the air flow after it comes out of the local wind duct, and the air speed is gradually distributed evenly in the tunnel. In the process of wind flow movement, the wind flow in the duct exchanges heat with the helical pipeline which used to carried CO₂, forming a large amount of cold air flow. Then, the high speed cold wind flow enters the tunnel gradually mixes with the fresh air flow and the wind flow tend to stable gradually, at the same time the temperature of wind flow decrease. Finally, the stable air flow temperatures in the tunnel are reduced obviously. We can see the temperature distribution in the tunnel in Fig. 5.

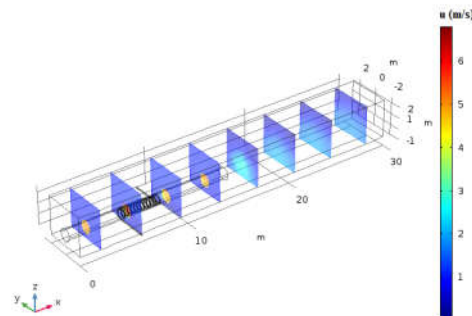


Fig. 4 Velocity distribution in the model.

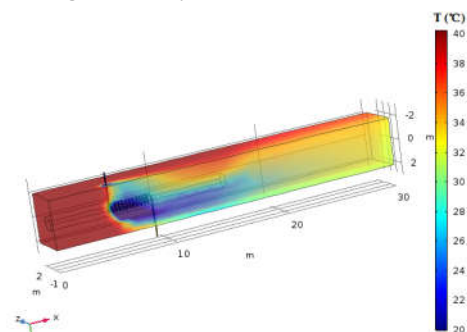


Fig. 5 Temperature distribution in the model.

The velocity and temperature distribution in the central axis of the duct, as shown in Fig. 6, has nonlinear change

characteristics. When the wind flow in the duct is in contact with the CO₂ conveying pipeline, the wind flow velocity increases due to the resistance of the pipe, and the heat exchange occurs between the air flow and the CO₂ pipeline cause of the wind flow temperature fast reduce. At that time the cold wind flow temperature is rapidly lower to 24 °C. When the wind flow in the duct enters the tunnel, the velocity of the cold air flow decreases and the temperature increases gradually and stably, because of cold air flow is mixed with the hot air flow gradually. The temperature of the air flow is stabilized at 32.54 °C in the tunnel.

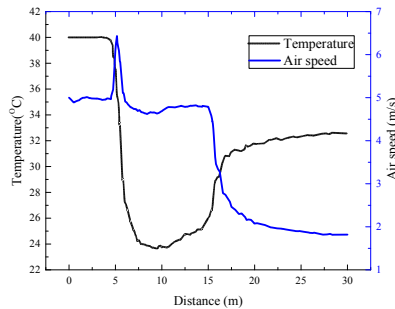


Fig. 6 Temperature and wind speed curve of the central axis of the duct.

5 Analysis of cooling effect

5.1 The effect of the ventilation speed

To analyse the effect of ventilation speed on CO₂ cycle refrigeration system, we set the flow velocity in the CO₂ pipeline is 4 m/s, and changed the wind speed in the duct of the model to obtain the refrigeration effect under different local fan air speed. When the wind speed is 2 m/s, the wind flow temperature is 18.73 °C in duct, and the final steady air flow temperature is 33 °C in the tunnel.

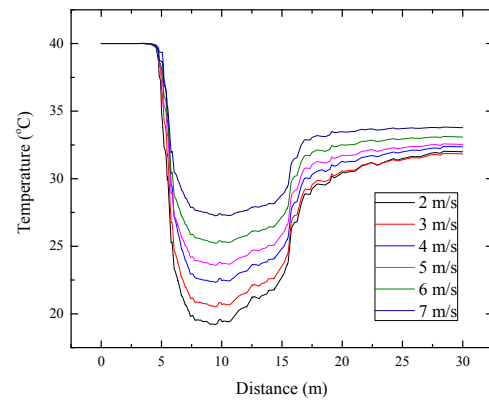
With the increase of ventilation speed, the average heat exchange capacity of per cubic flow decreases, so the outlet wind temperature in the duct increases obviously. However, due to the increase of the total cold air flow, the temperature of cold air flow dilution by the hot air in tunnel is weakened, and the steady air flow temperature in the tunnel change little compared to low ventilation speed.

In Fig. 7(b) shows that with the increase of ventilation speed, the heat exchange between CO₂ and air increase, and the temperature of CO₂ at the outlet pipeline increases. However, the temperature of steady air flow increases because of the increase of cold air volume, but the air flow temperature in the tunnel is very small after dilution.

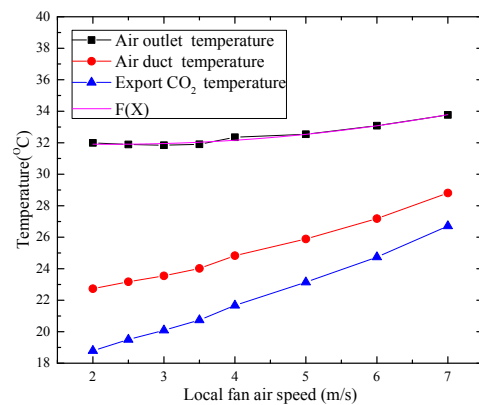
To obtain the functional relationship between the cooling effect in tunnel and the ventilation speed. The formula of steady air flow temperature and ventilation speed are fitted by using ORIGIN software. The expression of function relation between steady air flow temperature $T(u)$ and ventilation speed are obtained:

$T(u) = 32.326 - 0.375u + 0.0835$. The temperature of

steady air flow in the tunnel is proportional to the square of local fan air speed.



(a)



(b)

Fig. 7. The effect of ventilation speed u on the CO₂ cycle refrigeration system, where the subfigure (a) correspond to the ventilation speed of local fan at $u = 2, 3, 4, 5, 6$ and 7 m/s with the temperature curve of the central axis of the duct, respectively.

5.2 The effect of the CO₂ flow

Fig. 8 illustrates the effect of the CO₂ flow l on the CO₂ cycle refrigeration system. The local ventilation speed is set at 5 m/s, and the CO₂ velocity in the pipeline is set at 2, 3, 4, 5 and 6 m/s, respectively. It can be seen from Fig. 8(a) that with the increase of CO₂ velocity, the cooling capacity of the system increases, and the temperature of air flow decrease more obviously. When the CO₂ velocity is 6 m/s, the temperature of cold wind in the duct reaches to 20.39 °C, and the steady air flow temperature in the tunnel decreases to 30.39 °C.

Compared with the increase of ventilation speed, the temperature descends more obvious by increases CO₂ velocity. According to figure. 8(b), with the increase of CO₂ flow velocity, the CO₂ temperature in outlet pipeline decreases after heat transfer, so the cooling utilization ratio of CO₂ decreases, but the air flow temperature in tunnel drop more obvious. The formula of steady air flow temperature and CO₂ flow velocity are fitted by ORIGIN software. Then, the expressions of steady air flow temperature $T(l)$ and CO₂ current is: $T(l) = 42.11 - 3.469l + 0.267l^2$.

Therefore, when refrigeration effect of the system improved by increase of the CO₂ flow velocity, the length of heat transfer pipe or the air speed of ventilation should be increased in order to increase the cooling utilization ratio of cryogenic CO₂ and the cost be saved.

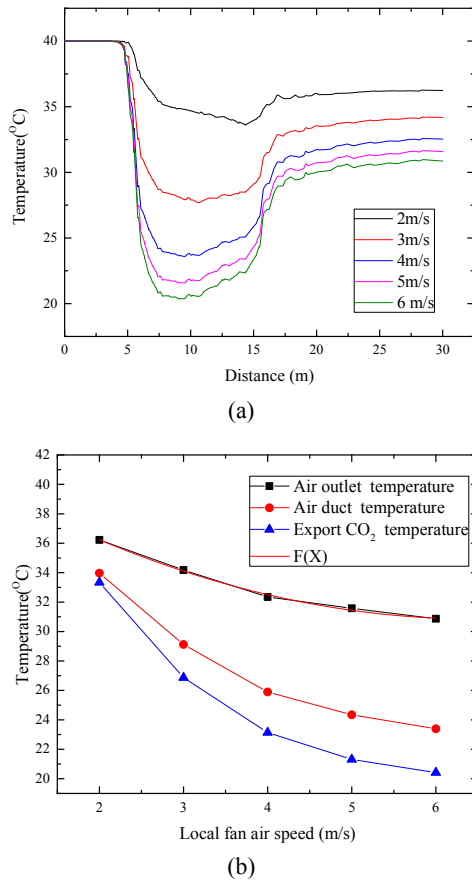


Fig. 8. The effect of CO₂ flow l on the CO₂ cycle refrigeration system, where the subfigure (a) correspond to the CO₂ velocity in pipeline at $l = 2, 3, 4, 5$ and 6 m/s with the temperature curve of the central axis of the duct, respectively.

5.3 The effect of the helical tube length

The helical pipes are used to heat exchange with wind flow directly and transport CO₂. It can be observed in the Fig. 9 that with the increase of the helical tube length, the heat exchange between CO₂ and air flow increase results in the increase of CO₂ temperature after heat exchange and more efficient use of CO₂ refrigerating capacity. When the length of helical tube was increased from 1.8 m to 4.2 m, the temperature of CO₂ in outlet pipeline increased from 22.01 to 23.25 °C due to the sufficiently heat exchange between CO₂ and air flow. Meanwhile the air flow temperature at outlet of tuyere from 27.76 °C reduced to 25.50 °C and air temperature in the laneway is also reduced by 1.34 °C degrees centigrade than that of the original.

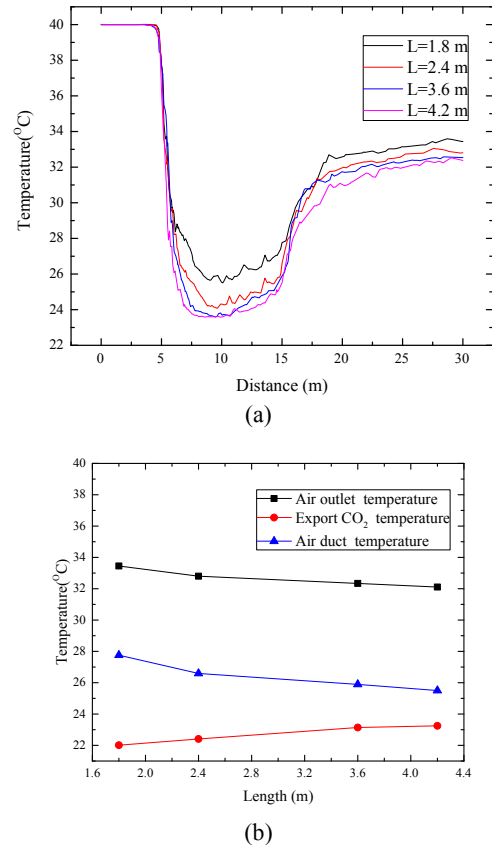


Fig. 9. The effect of CO₂ helical tube length on the CO₂ cycle refrigeration system, where the subfigure (a) correspond to the CO₂ helical tube length at $L = 1.8, 2.4, 3.6$ and 4.2 m with the temperature curve of the central axis of the duct, respectively.

5.4 The effect of CO₂ the cooling temperature

In the evaporator, the heat is absorbed by liquid CO₂ phase change which forms low temperature CO₂, and then the low temperature CO₂ enters the heat exchanger and exchange heat with the air flow to form the cold air flow. Before CO₂ entering the heat exchanger, The CO₂ temperature have an important impact on the CO₂ cycle refrigeration system. We can be seen from the Fig.10, as the CO₂ cooling temperature raise, the temperature of wind flow in duct, CO₂ in outlet pipeline and steady air in tunnel are all increased because of CO₂ refrigerating capacity decreases. When the CO₂ cooling temperature is -45 °C, the temperature of steady air flow in tunnel drop 8 °C after passing through the CO₂ refrigeration system. However, when CO₂ cooling temperature is at the -30 °C, the steady air flow temperature is only reduced 6.72 °C. Thus, the temperature of CO₂ formed by the phase transition of the liquid CO₂ in the evaporator is an important parameter affecting the refrigeration system. Before CO₂ enters the heat exchanger, the heat preservation measures should be taken on the CO₂ pipeline to prevent cooling loss to improve the cooling effect of the cooling system on the working surface in the mine.

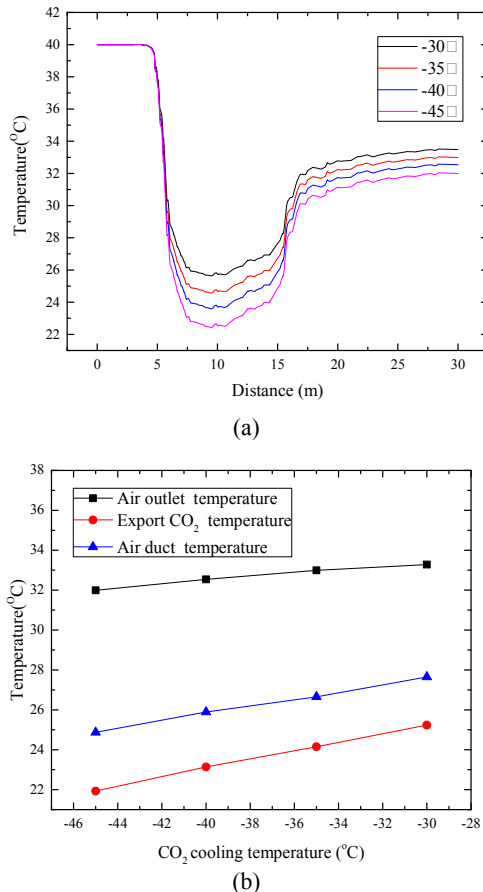


Fig. 10. The effect of CO₂ cooling temperature on the CO₂ cycle refrigeration system, where the subfigure (a) correspond to the CO₂ cooling temperature $T = -30, -35, -40$ and -45 °C with the temperature curve of the central axis of the duct, respectively.

6 Conclusion

In this work, a fully coupled steady model of compositional gas flow in tunnel and the non-equilibrium heat transfer between the CO₂ and the gas is developed to characterise the CO₂ cycle refrigeration system in mine of the heat transfer process between CO₂ and the air flow in the tunnel. Based on the results of this study, the following conclusions can be drawn:

- 1) The wind flow provided by the local fan is cooled by CO₂ heat exchange system and then the high speed wind flow is gradually mixed with the air flow form low temperature steady cold air flow in tunnel.
- 2) When the the CO₂ flow in pipeline is constant, the refrigeration efficiency would be improved with the increase of ventilation speed of local fan, and the temperature of steady air flow in tunnel and CO₂ in outlet pipeline also has increased.
- 3) Under the condition of wind speed of local fan is constant, the increase of CO₂ velocity is beneficial to enhance the refrigeration capacity of the system, but the

efficiency of CO₂ refrigeration will be reduce. Therefore, the length of the heat exchanger tube and air speed of the local fan should be increased when the CO₂ flow velocity is increased.

4) With the increase of the helical tube length, the heat exchange recovery between CO₂ and the air flow increase results in the temperature of CO₂ in outlet pipeline increases and the use of CO₂ refrigerating capacity more efficiently.

5) The temperature of cooling CO₂ have an important impact on the cycle refrigeration system. The air outlet temperature, export CO₂ temperature and air duct temperature would increased with the increase of the CO₂ cooling temperature. To improve the cooling effect of the cooling system on the working surface in the mine, the heat preservation measures should be taken on the CO₂ pipeline to prevent cooling capacity loss.

References

1. M.C. He, H.P. Xie, S.P. Peng, YD. Jiang. *J. Rock Mechanics & Engineering* **24**, 16, 2803-2813 (2005)
2. Z.G. Su, Z.A. Jiang, Z.Q. Sun. *J. Procedia Earth & Planetary Science* **1**, 1, 414-419 (2009)
3. A.G. Chen, A.J. Prof. *China Safety Science Journal* **645**, 889-892 (2004)
4. L. Ma, L.R. Zhang, B. Li, H. Wen, Z.P. Wang. *J. Coal Technology* **33**, 11, 278-281 (2014)
5. W. Chen, S. Liang, J. Liu. *Appl. Thermal Eng.* **105**, 425-435 (2016)
6. B. Deng, H. Zhang, Y.D. Song, Z. Jiang, Y. Shi. *J. Refrigeration and Air Conditioning*, **3**, 301-304 (2014)
7. X.K. Sun, X.H. Li, W.M. Cheng. *J. Mining & Safety Engineering*, **26**, 1, 105-109 (2009)
8. P.Y. Guo. *Int. J. Mining Science and Technology* **23**, 3, 453-456. (2013)
9. P.Y. Guo, Y. Wang, M. Duan, D. Pang, N. Li. *Int. J. Mining Science and Technology* **25**, 4, 649-654 (2015)
10. A. Pearson. *Int. J. Refrigeration* **28**, 8, 1140-1148. (2005)
11. L. Cecchinato, M. Chiarello, M. Corradi. *Applied Energy* **87**, 6, 2095-2101 (2010)
12. A. Subiantoro, K.T. Ooi. *Int. J. Refrigeration* **33**, 4, 675-685 (2010)
13. J. Sarkar. *Adv Res Mech Eng* **1**, 22-29 (2010)
14. Y. Cai, C. Zhu, Y. Jiang, H. Shi. *Energy Conversion & Management*. **89**, 92-98 (2015)