IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 36, No. 2, June, 2018, pp. 657-662
Journal homepage: http://iieta.org/Journals/IJHT

Application of liquid CO_2 conveying technology for fire control in goaf

Kai Wang[1,2*], Xiaowei Zhai[1,2], Jun Deng[1,2], Xiangrong Liu[3], Yanni Zhang[1,2]

[1] School of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China
[2] Shaanxi Key Laboratory of Prevention and Control of Coal Fire, Xi'an 710054, China
[3] School of Chemistry and Chemical Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

Corresponding Author Email: wangk912@xust.edu.cn

https://doi.org/10.18280/ijht.360230

Received: 13 September 2017
Accepted: 27 February 2018

Keywords:
liquid CO_2, transport system, coal spontaneous combustion, fire control, long-distance pipe, large vertical depth

ABSTRACT

This paper aims to design a desirable method to inject liquid CO_2 directly to the deep underground via long-distance pipe. To this end, a liquid CO_2 transport technology was put forward and applied to cool down the fire area in an underground coal mine. To ensure the liquid phase of CO_2, the pipe pressure was controlled by adjusting the flows at the inlet and outlet of the storage tank, and the pressure, flow and temperature parameters were monitored at several key positions. Through the theoretical analysis and case study, the proposed liquid CO_2 transport system was proved as feasible under the control of pipe pressure. The results show that the pressure of 2.2MPa is applicable for liquid CO_2 transport system, and the pressure change in the pipe hinges on the pressure at liquid CO_2 tank, vertical depth and pipe length. By this system, the temperature of liquid CO_2 could be controlled as low as -15^{o}C. The research findings provide valuable insights on the application of liquid CO_2 in fire control in underground coal mines

1. INTRODUCTION

Coal is a major energy source and a cornerstone of chemical industry. As a pyrophoric substance, coal may combust spontaneously during mining and utilization, leading to resource waste, environment pollution, and even personal casualty. Over the years, much research has been done on the spontaneous combustion coal fire [1-2].

The key to coal fire prevention and control lies in cooling and oxygen isolation [3-4]. Following this train of thought, inert gas injection, gel grouting and three-phase foam spraying have been proposed by Chinese scholars in recent years. Pan [5] studied the multiple fire extinguishing technology in the closed area and optimized the injection location and quantity for coal fire prevention and control. With a temperature control system, Yang [6] compared the inhibition effect of several materials on spontaneous combustion of coal, discovered that polymer gel is more effective than materials like coal ash gel and mud gel, and successfully controlled a coal fire with polymer gel. Qin [7] developed an injection technology of three-phase foam containing mud, nitrogen and water, and proved that the foam can cover, asphyxiate and cool down the combustibles. Ren [8] developed a foam–gel technique to overcome the shortcomings of existing technologies and improve the efficiency of mine fire control. Hao [9] investigated the preventive effect of iron-based deoxidizing inhibitors on spontaneous combustion of coal.

Among the above methods, the injection of liquid N_2 and CO_2 has the best performance in cooling down the fire area. For instance, Shi [10] succeeded in preventing coal fire in Yangchangwan Coalmine with liquid N_2, and lowered the heat stress with the material. Chen [11] used liquid CO_2 in coal mine to increase permeability of coal seams. Compared with liquid N_2, liquid CO_2 is known for its low cost and high adsorption capacity [12-13]. In particular, liquid CO_2 is extremely efficient in cooling thanks to its high vaporization heat. Moreover, the use of liquid CO_2 can reduce the carbon emission to the air, as evidenced by the previous research on CO_2 capture and storage [14-15].

Nevertheless, the liquid CO_2 injection technology is still underdeveloped, owing to the harsh storage requirements and the difficulties in the transport process. For one thing, the liquid CO_2 must be stored at low temperature and high pressure; for another, it is easy for the liquid CO_2 to vaporize and freeze during transport, and thus block the transmission pipe [16-17]. At present, the liquid CO_2 is often placed in small capacity (2t) tanks and injected to the fire area via underground drilling. By this method, the liquid CO_2 tanks must be transported to the underground, which is chaotic and inefficient. What is worse, the liquid CO_2 could vaporize on the ground before it is transported to the fire area via the long distance pipe. Thus, this method cannot fully display the cooling performance or efficiency of liquid CO_2. There is few report on the transport technology of liquid CO_2 in underground coal mine.

Considering the phase change features of liquid CO_2, this paper puts forward a method to inject liquid CO_2 directly to the deep underground via long-distance pipe. Then, the proposed method was applied to put out the coal fire in Qingshuiying Coalmine. The results demonstrate the high efficiency of our method in inhibiting coal fires.

2. MATERIALS

2.1 Liquid CO_2

Like N_2, the asphyxiating gas of CO_2 is a popular option for fire control and prevention in coal mining and other industries. Table 1 lists the basic fire control parameters of N_2, CO_2 and the air at standard conditions If CO_2 gas is mixed with the air, it will concentrate at the bottom layer because of its relatively high molecular weight and density, making it harder to be taken away by wind. Thus, CO_2 has an advantage in inerting at the bottom of the goaf. Besides, liquid CO_2 outperforms liquid N_2 in cooling, thanks to its high vaporization heat. Under 15°C and 1 atmosphere, the liquid CO_2 could expand to 640 times volume of gas through gasification. In terms of adsorption, it has been proved that CO_2 is more likely to be adsorbed by coal than CH_4 and N_2 [18]. To sum up, liquid CO_2 has an edge over liquid N_2 in inerting, cooling and absorbability. If injected to the fire area in underground coal mine, the liquid CO_2 below 0°C can absorb a massive amount of heat from the fire area, inert and suppress explosion, and speed up the outfire operation.

Table 1. Fire control parameters of N_2, CO_2 and the air

Name	Molecular weight	Density (ρ/kg·m^{-3})	Vaporization heat (kJ·kg^{-1})	Boiling point (°C)
CO_2	44	1.97	235	-78.5
N_2	28	1.25	196.9	-196.5

2.2 Phase change features

Despite its excellence in fire control, liquid CO_2 poses many challenges to storage and long-distance transport. Figure 1 illustrates the phase change of CO_2 under different temperatures and pressures.

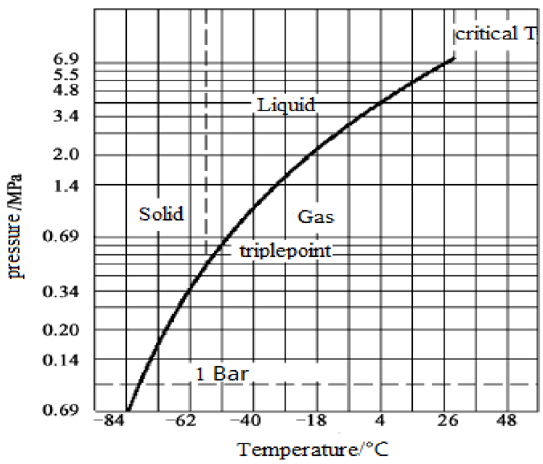

Figure 1. Three-phase diagram of CO_2

As shown in Figure 1, gaseous, liquid and solid CO_2 can coexist at -56.6°C and 0.52MPa. From the phase change of CO_2, it is clear that the liquid CO_2 is difficult to transport in pipe: when a part of liquid CO_2 vaporizes, a lot of heat is absorbed from the environment; then, the remaining liquid CO_2 can solidify easily in the cool environment, forming plugs in the pipe. The problem is especially severe in an open pipe system. Liquid CO_2 is more likely to vaporize in this type of pipe, because the pipe pressure is close to the ambient pressure.

In coal mines, pressure is more effortless to control than temperature. Thus, pressure can be regarded as the key controlling parameter in the storage and transport of liquid CO_2 in pipe. Here, the pressure at sub-zero temperatures is adjusted by controlling the inlet and outlet flows of the pipe, such that the CO_2 being transported is kept in the liquid phase.

3. METHODOLOGY

3.1 Liquid CO_2 transport system

Figure 2 presents the proposed liquid CO_2 transport system. The system mainly contains a liquid CO_2 storage system, a pressure control system, a monitoring system, an air-leakage test and pipe purging system and a transport pipe.

The liquid CO_2 is stored in a storage tank whose capacity is at least 20-ton and rated pressure is 2.2Mpa at usual. A vaporizer is connected to the tank to generate the CO_2 gas for air-leakage test and pipe purging. The pipe pressure is controlled by two types of flow control valves: governor valve and safety valve. The former regulates the flow of liquid CO_2, which the latter, installed on the surface, prevents overrun under high pressure and ensures the system safety. The monitoring system consists of pressure transducers, temperature sensors and flowmeters. High-level pressure transducers were selected to monitor the pipe pressure. The transducers can work at sub-zero temperature. The temperature sensors, with a range of -50~200 °C, is responsible for monitoring the pipe pressure. Target flowmeters record the flow of liquid CO_2, and can resist a temperature as low as -196 °C. All transducers, sensors and flowmeters can withstand the pressure up to 6MPa. The transport pipe is a seamless steel tube which can work under high pressure and fulfil the safety requirements.

3.2 Procedure

The procedure below must be implemented strictly to maintain a high pipe pressure with the valves. The procedure of liquid CO_2 transport and injection is depicted in Figure 3.

(1) Material preparation and installation

First, several pipe segments were prepared and placed along the underground roadway. Then, the segments were connected with welding flanges. Governor valves were installed at the inlet and outlet of the liquid CO_2 storage tank, and at the corner joint and discharge side. Then, the flowmeters, pressure transducers and temperature sensors were connected at the position of valves, for monitoring flow, pressure and temperature of liquid CO_2 the pipe.

(2) Air-leakage test

Before injecting liquid CO_2, the airtightness of the pipe was tested by gaseous CO_2 at 2.2MPa. During the test, all governor valves were opened, except those controlling the liquid CO_2 and that at the discharge side. The pipe segment found with air leakage was replaced, and the monitoring valves were disabled. Then, the preparation and installation were restarted. This test is critical to the safety of liquid CO_2 injection.

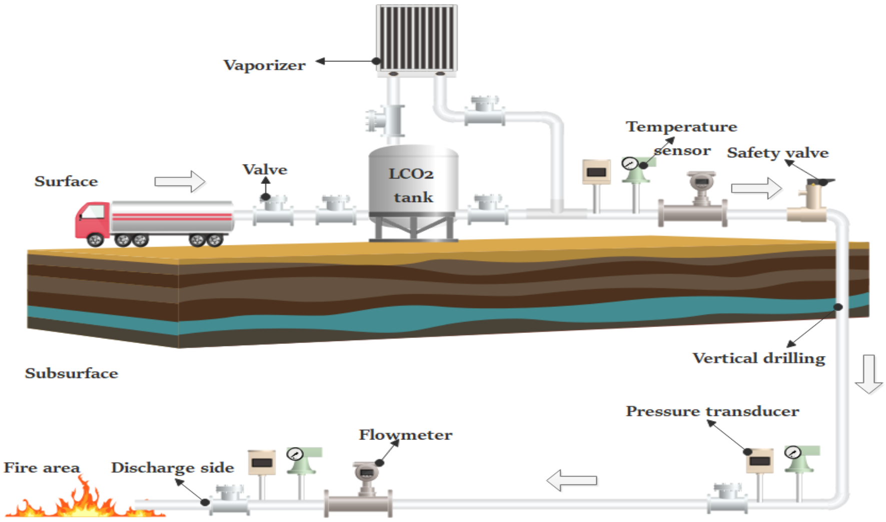

Figure 2. Liquid CO_2 transport system

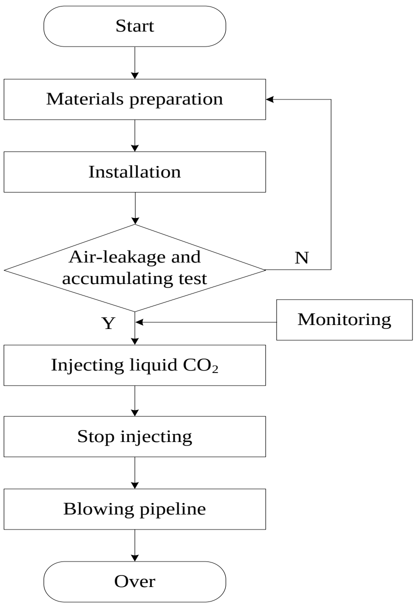

Figure 3. Liquid CO_2 transport and injection procedure

(3) Pressurization and maintaining

After the air-leakage test, the pipe was filled with gaseous CO_2 at 2.2MPa. All the valves were closed, and the liquid CO_2 was filled into the pipe on the ground. The underground valves were opened one by one when the pipe temperature and pressure met the requirements of liquid CO_2 phase state. Thus, the liquid CO_2 flowed down the pipe stage by stage. Next, the valve at the discharge side was opened slowly to inject the liquid CO_2 into the fire area, while the temperature and pressure were under monitoring. The flow was adjusted by the valves, so that the pipe pressure could keep the CO_2 in liquid phase.

(4) Pipe purging

After the injection, the control valve of the liquid CO_2 tank was closed and the gaseous CO_2 valve was opened. Then, the pipe was swept by the gaseous CO_2. The purging ensures the unclogged state of the pipe and the presence of gaseous CO_2 in the pipe and fire area. All valves were closed after the purging.

4. CASE STUDY

4.1 Overview of fire area

Located in Ningxia, China, Qingshuiying Coalmine was mined by fully-mechanized caving method. With a mean thickness of 9.3m, the coal seam is rich in non-caking coal, which is highly pyrophoric. Experiments show that the coal can combust spontaneously after being exposed to the air for less than 20 days. In our research, the 500m-deep, 1,008m-long and 245m-wide II020210 working face (Figure 4) is taken as the object. The cutting height and mining ratio of the face are 3.2m and 1:1.9, respectively, indicating that lots of coal are left in the goaf. This adds to the risk of spontaneous combustion of coal. Previously, the face had been extended to the long wall, leaving a transport roadway in the middle.

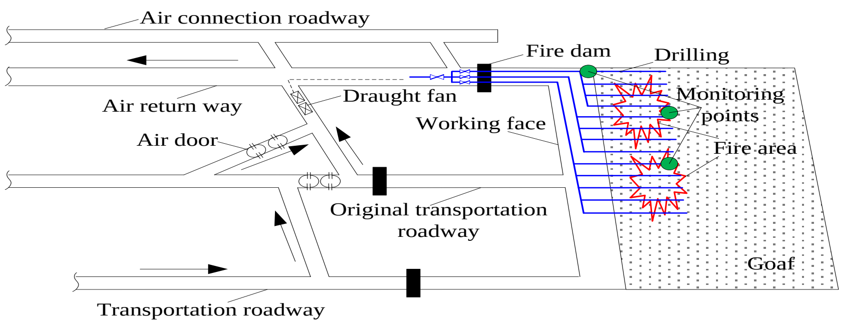

Figure 4. Overall condition of II020210 working face

Near the end of mining, the coal in the goaf was oxidized by air due to the slow mining speed. As a result, a high concentration of CO gas (up to 0.3%) accumulated in II020210 face. At this condition, the intake and return airflow roadways were closed by fire dams. Before closing the work face, the goaf was drilled for fire control and monitoring. The monitoring points was located at upper corner, and 60m rear 114# and 119# supports, which were shown in figure 4. Because the fire area was unknown, the water jetting, foam spraying and gel grouting all failed to put out the fire. The fire reburned after the fire area was opened several times, accompanied with the appearance of C_2H_6 and C_2H_4 gases. This means the temperature in the goaf reached the decomposition temperature (>100°C).

In this case, liquid CO_2 injection is a good way to lower the temperature of fire area and the O_2 concentration in the goaf. Considering the limited capacity of the liquid CO_2 tank, the author explored the method and technology of liquid CO_2 transport into deep underground across a long distance.

4.2 System layout

The liquid CO_2 injection plan was put forward after a few failed attempts. A shorter path of liquid CO_2 pipe was achieved through vertical drilling to avoid pressure drop over long distance. The bottom of the vertical drilling was at a chamber. The location of chamber and the path of the pipe are shown in figure 5. The photos of the noted location is displayed in Figure 6.

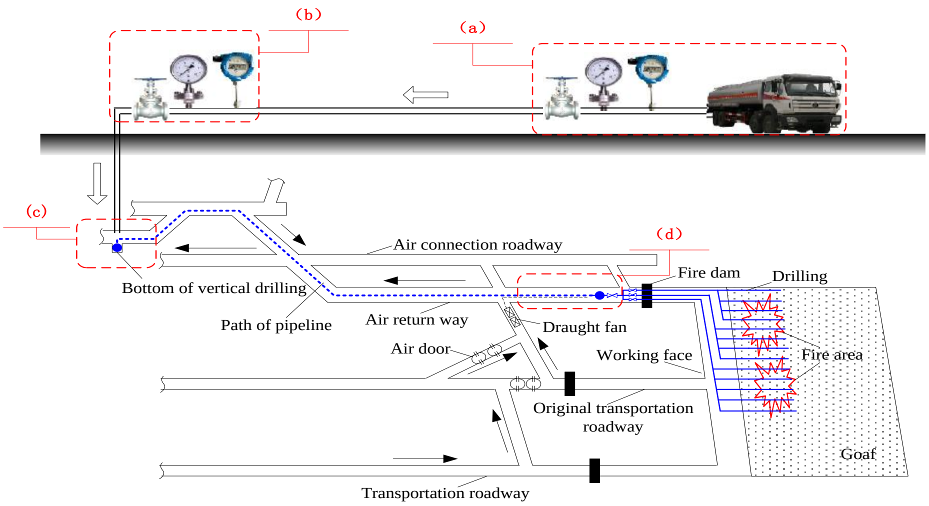

Figure 5. Chamber location and pipe path

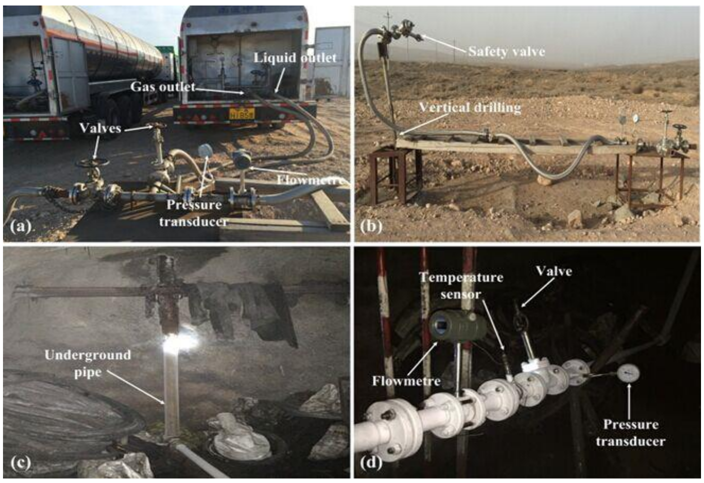

Figure 6. Photos of liquid CO_2 transport system

5. RESULTS AND DISCUSSION

Before injection, the plan was tested for three hours. The flow, pressure and temperature at the tank outlet, chamber and discharge side were monitored after the air-leakage test.

5.1 Pressure analysis

Figure 7 record the pressure changes at the monitoring points. In the pressure-holding phase, the valves of the pipe were opened step by step. At the beginning of the test, the pressure at the chamber and discharge side fluctuated due to the heat exchange between liquid CO_2 and outside pipe. After a period, the pressure at all points tended to be stable in the pipe. The pressure at the tank outlet was 1.5~2.0MPa, slightly below that in the tank. With the increase of the pipe length, the pressure dropped because of the on-way resistance. By contrast, the pressure remained high (3.0~4.0MPa) at the chamber, owing to altitude difference, joint, and square elbow. At the discharge side, the pressure fell in the range of 1.6~2.0MPa. At the time of 40min, due to the blocking of drilling, the pressure was increasing. When changing to another drilling, the pressure at the discharge side reduced and was stable. In addition, the total amount of CO_2 and the pressure in the tank generally decreased with the release of the pressure in the tank. To ensure the safety of the underground pipe at a big vertical depth, the pressure of the tank on the surface should be kept stable with a supercharger or tank replacement. Note that the vertical depth must be within the safety range, and the pressure at the joint and elbow must be monitored during the installation of the supercharger or replacement of tank.

5.2 Flow analysis

The flows of gaseous and liquid CO_2 in the pipe were captured by the flowmeters at the three monitoring points (Figure 8). Because of the pressure distribution, the CO_2 at the chamber was mostly in liquid phase. Thus, the liquid CO_2 flow at the chamber was smaller than mixed flow of gas and liquid CO_2 at other positions in the pipe, including tank outlet and discharge side. Before injecting liquid CO_2, the CO_2 existed in the form of gaseous phase, and the flows were similar across the pipe. When the tank outlet pressure was 1.5~2.0MPa, the CO_2 being injected into fire area could reach the mixed flow of 45~50m^3/h, parts of which were in gaseous phase.

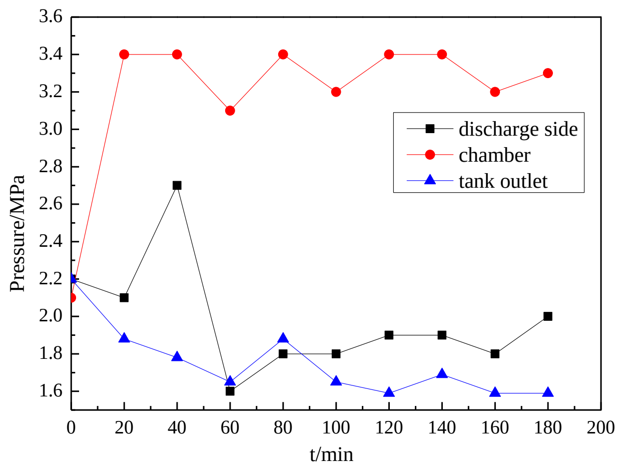

Figure 7. Pressure changes at the monitoring points

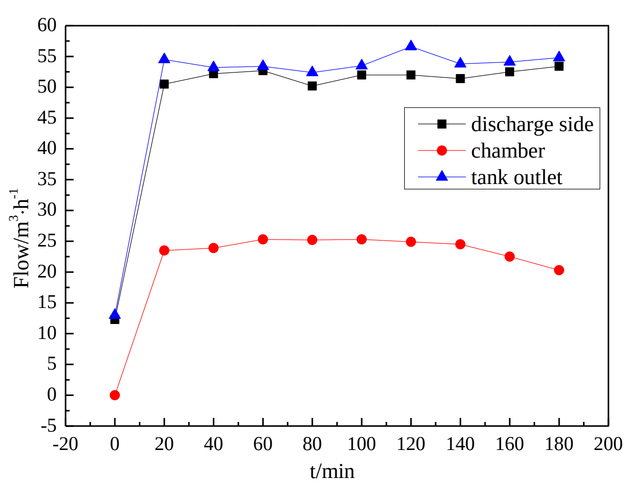

Figure 8. Flow changes at the monitoring points

5.3 Temperature analysis

In the early phase, the temperature at the discharge side exhibited a declining trend due to the delay of liquid CO_2 transport in the pipe. When the pipe was filled with gaseous and liquid CO_2, the pipe temperature plunged rapidly to the sub-zero level. The temperature at ground pipe fell in the range of -30~-20°C, and the temperature at discharge side was about -15 °C, which could improve the cooling efficiency in the fire area. Since the CO_2 temperature increased under high pressure, the temperature at the chamber was stable at -15~-10 °C.

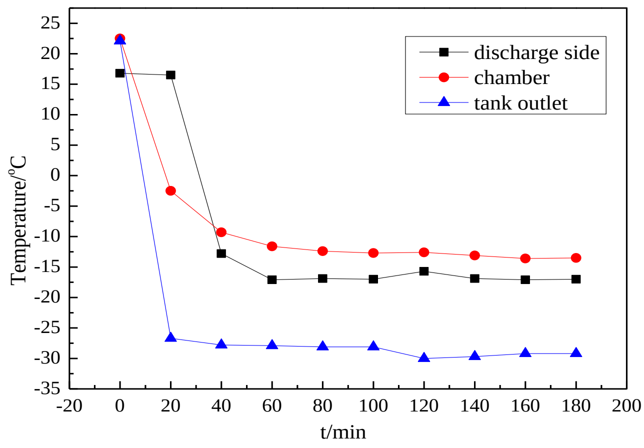

Figure 9. Temperature changes at the monitoring points

5.4 Fire control effect

The proposed liquid CO_2 injection technology was proved as feasible by the change laws of the pressure, temperature and flow in the test, and the tank pressure of 2.2MPa was demonstrated as applicable. After the test, the liquid CO_2 transport system was applied to cool the fire area. Over 6 days, about 500-ton liquid CO_2 was injected to the goaf. The temperature in fire area dropped rapidly to 18°C, way below that in normal mining, while the O_2 concentration fell to 3%. The concentration of the index gas CO decreased quickly. Before The variation in CO concentration at the upper corner and the observation well near 114# and 129# supports are given in Figure 10. The observation well was The CO changes reveal an outstanding effect of the proposed liquid CO_2 transport system.

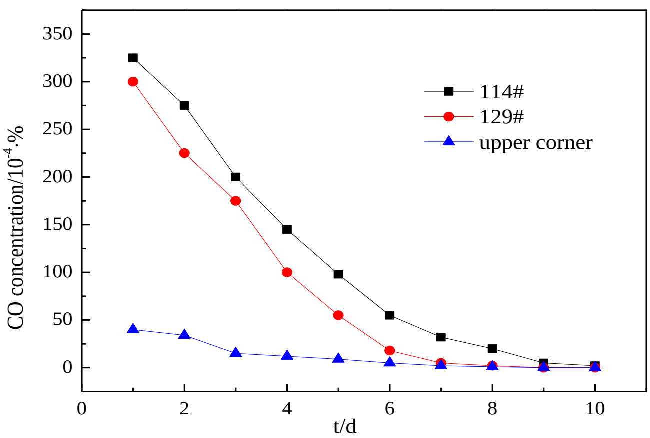

Figure 10. CO changes at different monitoring points

6. CONCLUSIONS

Through the theoretical analysis and case study, the proposed liquid CO_2 transport system was proved as feasible under the control of pipe pressure. The results show that the pressure of 2.2MPa is applicable for liquid CO_2 transport system. By this system, the temperature of liquid CO_2 could be controlled as low as -15ºC. Besides, the pressure at liquid CO_2 tank, vertical depth and pipe length directly bear on the pressure change in the pipe. The research findings provide valuable insights on the application of liquid CO_2 in fire control in underground coal mines.

ACKNOWLEDGMENT

This paper was supported by the China Postdoctoral Science Foundation (No. 2016M592819), the National Natural Science Foundation of China (No. 51704226), Natural Science Basic Research Plan in Shaanxi Province of China (No. 2017JQ5047), Scientific Research Program Funded by Shaanxi Provincial Education Department (No. 17JK0500), the Key technology projects for the prevention and control of major accidents in production safety (2016GJ-A3-010).

REFERENCES

[1] Wang K, Deng J, Zhang Y, Wang C. (2018). Kinetics and mechanisms of coal oxidation mass gain phenomenon by TG–FTIR and in situ IR analysis. Journal of Thermal Analysis and Calorimetry 132: 591-598. https://doi.org/10.1007/s10973-017-6916-x

[2] Wang G, Wang Y, Sun L, Song X, Liu Q, Xu H, Du W. (2018). Study on the low-temperature oxidation law in the co-mining face of coal and oil shale in a goaf—a case study in the liangjia coal mine, China. Energies 11(1): 174. https://doi.org/10.3390/en11010174

[3] Deng J, Xiao Y, Li Q, Lu J, Wen H. (2015). Experimental studies of spontaneous combustion and anaerobic cooling of coal. Fuel 157: 261-269. https://doi.org/10.1016/j.fuel.2015.04.063

[4] Deng J, Wang K, Zhang Y, Yang H. (2014). Study on the kinetics and reactivity at the ignition temperature of Jurassic coal in North Shaanxi. Journal of Thermal Analysis and Calorimetry 118: 417–423. https://doi.org/10.1007/s10973-014-3974-1

[5] Pan R, Fu D, Xiao Z, Chen L. (2018). The inducement of coal spontaneous combustion disaster and control technology in a wide range of coal mine closed area. Environmental Earth Sciences 77(10): 375. https://doi.org/10.1007/s12665-018-7540-1

[6] Yang Y, Tsai YT. (2018). Inhibition ability of ionic liquid [Bmim][NO_3], [Bmim][BF_4], and [Emim][BF_4] on spontaneous coal combustion. Journal of Thermal Analysis and Calorimetry 132: 1943-1951. https://doi.org/10.1007/s10973-018-7008-2

[7] Qin B, Wang D, Chen J, Liang X. (2005). Experimental investigation of high-performance three-phase foam for mine fire control. Journal of China University of Mining & Technology 34(1): 11-15.

[8] Ren W, Guo Q, Wang Z. (2016). Application of foam–gel technology for suppressing coal spontaneous combustion in coal mines. Nature Hazards 84: 1207-1218. https://doi.org/10.1007/s11069-016-2499-2

[9] Hao C, Chen Y, Wang J., Deng C., Xu G., Dai F., Si R., Wang H., Wang H. (2018). Study on the effect of iron-based deoxidizing inhibitors for coal spontaneous combustion prevention. Energies 11(4): 789. https://doi.org/10.3390/en11040789

[10] Shi B, Ma L, Dong W, Zhou F. (2015). Application of a novel liquid nitrogen control technique for heat stress and fire prevention in underground mines. Journal of Occupational & Environmental Hygiene 12(8): 168-177. https://doi.org/10.1080/15459624.2015.1019074

[11] Chen H, Wang Z, Chen X, Chen X, Wang L. (2017). Increasing permeability of coal seams using the phase energy of liquid carbon dioxide. Journal of CO_2 Utilization 19: 112-119. https://doi.org/10.1016/j.jcou.2017.03.010

[12] Ranathunga AS, Perera MSA, Ranjith PG, Wei CH. (2017). An experimental investigation of applicability of CO_2, enhanced coal bed methane recovery to low rank coal. Fuel 189: 391-399. https://doi.org/10.1016/j.fuel.2016.10.116

[13] Kiyama T, Nishimoto S, Fujioka M, Xue Z, Ishijima Y, Pan Z, Connell L. (2011). Coal swelling strain and permeability change with injecting liquid/supercritical CO_2 and N_2 at stress-constrained conditions. International Journal of Coal Geology 85(1): 56-64. https://doi.org/10.1016/j.coal.2010.09.010

[14] Lei M, Sun C, Wang C. (2018). Techno-economic analysis of a 600 MW oxy-enrich pulverized coal-fired boiler. Energies 11(4): 768. https://doi.org/10.3390/en11040768

[15] Peter V, Daniel V, Samuel H. (2015). Integrated assessment of Carbon Capture and Storage (CCS) in South Africa’s power sector. Energies 8(12): 14380-14406. https://doi.org/10.3390/en81212432

[16] VikramV. (2017). Saturation time dependency of liquid and supercritical CO_2 permeability of bituminous coals: Implications for carbon storage. Fuel 192(3): 201-207. https://doi.org/10.1016/j.fuel.2016.12.017

[17] VikramV. (2017). In-situ disposal of CO_2: Liquid and supercritical CO_2 permeability in coal at multiple down-hole stress conditions. Journal of CO_2 Utilization 17: 235-242. https://doi.org/10.1016/j.jcou.2016.12.011

[18] Song Y, Jiang B, Li J. (2017). Simulations and experimental investigations of the competitive adsorption of CH_4 and CO_2 on low-rank coal vitrinite. Journal of Molecular Modeling 23(10): 280. https://doi.org/10.1007/s00894-017-3442-5

NOMENCLATURE

F	flow, $m^3 \cdot h^{-1}$
P	pressure, Pa
T	temperature, ºC
t	time

Greek symbols

ρ	density, $kg \cdot m^{-3}$