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Experimental study on combustible gas explosion induced by inert gas injection in fire zone sealing of mine

Wang Haiyan Zhang Jiuling and Zhou Xinquan

Faculty of Resources and Safety Engineering, China University of Mining & Technology (Beijing) Beijing, China

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ABSTRACT

In order to acquire migration and interaction laws of smoke with inert gas in the process of inert gas injection in fire zone sealing of mine, two full-scale experiments on inert gas injection in fire zone were been conducted in the ambulance brigade of Hegang branch of Heilongjiang Longmay Mining Holding Group. The experiments continuously detected temperature, gas concentration, velocity, etc. in the experimental tunnel with beam tube detection, bladder detection, and thermal infrared analysis. The results indicate that the stratified distribution of combustible gas in the fire zone sealing of mine is obvious. The lower the gas concentration is, the more obvious the gas stratification is. Injected turbulence inert gas "disturbs" the laminar flow condition of combustible gas in the closed zone, thus weakening the stratification of combustible gas. In addition, the dilution effect of nitrogen injection on combustible gas layer is related to distance of the combustible gas layer from nitrogen injection port. Inert gas injected to the fire zone sealing will promote combustible gas layer in the fire zone sealing to migrate towards air intake side like gas piston. Thus, the combustible gas layer flows to fire source owing to piston action of inert gas injection. It is the reason of explosion at the initial stage of inert gas injection. The dilution effect of inert gas injection on middle and lower part of combustible gas layer is better than that of the upper part. Explosion hazard exists at initial period of inert gas injection.

Keywords: mine, fire zone sealing, inert gas, explosion, combustible gas

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INTRODUCTION

Sealing the fire zone is one of frequently-adopted effective measures to control fire when the coal mine catches fire and the fire behavior cannot be effectively controlled in a short time. Main coal-producing countries abroad applied inert gas injection technology to fire prevention and extinguishing in underground mines from the 1960s. After constant development and perfecting, fire prevention and extinguishing technology of inert gas injection has become an important measure of all countries to restrain spontaneous fire, handle large fire and prevent and control gas explosion in the fire zone under coal mine. The inert gas technology was widely applied in coal mines of developed countries such as Germany, France, British, etc. in the 1970s[1]. At the beginning of the 1980s, some coal mines coal beds of which are apt to catch fire spontaneously began to adopt prevention and extinguishing technology of inert gas injection and achieved certain effects in China. Chen Jiufu[2] studied comprehensive treatment method of nitrogen injection in fire zone sealing of highly gassy protruding mine. Shi Guoqing[3] analyzed characteristics and difficulties of fire zone sealing treatment in steeply inclined work face of highly gassy mine with thicker seam, and denied the feasibility of conventional fire prevention and extinguishing means, such as grouting, used in this kind of fire zone. Adamus A.[4] analyzed equipment and application effect of nitrogen used in preventing and extinguishing coal mine fire in British, Germany, France, former Soviet Union, Bulgaria, India, Poland, Czech Republic, etc. Zhou Fubao[5] had succeeded in making fire zone under super-huge coal mine inert with nitrogen-contained three-phase foam. Bulgakov Y. F. [6] made the fire zone inert with high-concentration nitrogen (up to 99%) and a few oxygen mixed gas according to double flow theory on methane and air. Zhou Chunshan [7] put forward mechanism, characteristics, preparation method and construction technology of injecting CO_2 to extinguish fire based on the spontaneous fire in gob.

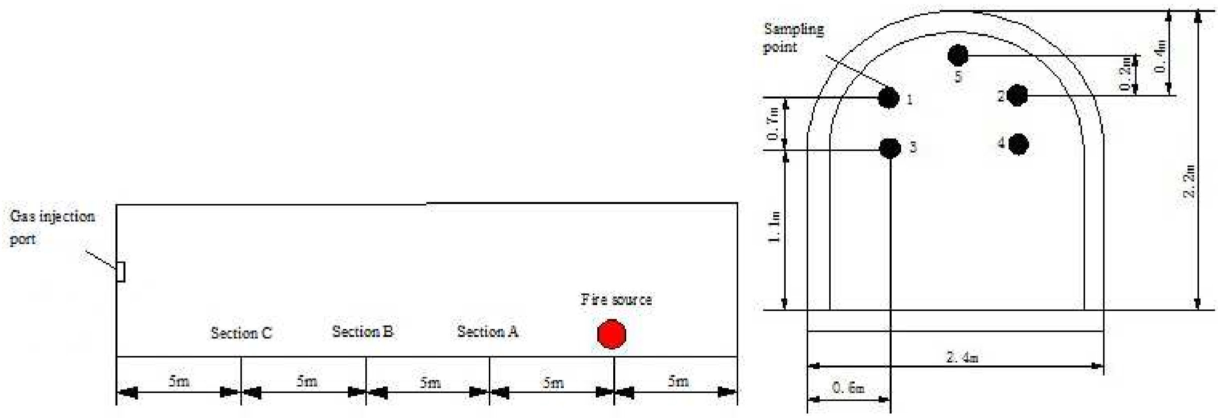
Many countries including China have extinguished hundreds of fire under the coal mine with inert gas generator during several decades. There are many successful cases in restricting gas explosion in the fire zone of the mine. However, there are many cases where inert gas injection induces gas explosion. Why does the inert gas injection safety measure aiming to restricting gas explosion in the fire zone induce gas explosion? It is a weak link of relevant study.

Most studies on explosion suppression technology of inert gas lay particular stress on studying and improvement of inert gas generator. There are a few studies on explosion suppression mechanism of inert gas and interaction between inert gas and explosive gas in the fire zone. Existing studies mainly focus on making preliminary analysis with numerical simulation technology and jet theory [8]-[10]. Corresponding experimental study on mine gas and inert gas in the fire zone is short. Experience is the main factor in practical application of fire extinguishing of gas mine. But the basic theoretical and technical guidance is insufficient. What's worse, explosion occurs at the course of inert gas injection. In November 18th, 2004, a special major gas explosion accident occurred in Chenjiashan coal mine of Tongchuan Mining Bureau in Shaanxi province. In the accident, rescue measures of inert gas injection in fire zone sealing were adopted. Four explosions occurred after 60m^3 inert gas (about ten minutes) was injected. Namely, secondary gas explosion occurred. Although there was no casualty in the process of disaster relief, the life safety of undergound relief workers was seriously threatened.

To further study the impact of inert gas injection on migration law of gas in the fire zone sealing, the author has conducted full size experiment on inert gas injection in the fire zone sealing in the exercise mine of the ambulance brigade of Hegang branch of Heilongjiang Longmay Mining Holding Group. The experiment tests the formation and migration law of combustible gas layer in the closed fire zone and the impact of inert gas injection on combustible gas layer migration in the closed zone. It will provide technical support and thoritical evidence for analyzing possibility of secondary explosion induced by relief measures such as inert gas injection.

FULL-SCALE EXPERIMENTAL SYSTEM ON INERT GAS INJECTION IN THE FIRE ZONE SEALING

The experimental tunnel is shown in Fig.1. The closed tunnel is 25m long, 2.2m high and 2.4m wide. The cross section is arched and the sectional area is 4.5m^2. The volume of experimental tunnel is 112.5m^3 .



(a) Longitudinal section **(b) Transverse section**

Fig. 1 Schematic diagram of experimental tunnel and layout of gas sampling points

The inert gas uses liquid nitrogen. Ground liquid nitrogen enters the fire zone from middle and upper reserved inert gas injection port at return air sealing side through the special pipeline after it flows from gas tank and is gasified by the gasifier. The inert gas injection port is 1.6m from the ground and the diameter of inert gas injection port is 5cm.

Fig. 2 Inert gas injection system and bulkheads

Boards are used for sealing the fire zone and the air doors are reserved so that personnel can access from here. Air regulator is reserved on the bulkhead so that air quantity can be changed. The inert gas injection port is reserved at middle and upper part of bulkhead on the side of return-air. The bulkheads are shown in Fig. 2.

Sampling section of gas sample and layout of sampling point are that the first sampling section shall be set up 5m from the fire source along the length of tunnel. Intervals of all sampling sections are 5m. There are 3 sampling sections in total (section A, section B and section C). Along the height of tunnel, two sampling point lines, which with two point each line, are set up at 1.1m and 1.8m away from the tunnel bottom. The sampling point is 0.6m from the wall along the width of the tunnel. The fifth point is set up on the central axis of tunnel 2m from the ground. Thus, five sampling points are on each sampling section and shall be numbered one by one shown as in Fig. 1b. The sampling instrument adopts bladder. Two workers take gas samples at each section for sampling gas, measuring temperature and recording airflow direction. Gas samples will be sent to the laboratory immediately after sampling. Chromatographic analysis instrument is used to analyze oxygen concentration, nitrogen concentration, carbon monoxide, concentration of carbon dioxide, etc.

FULL-SCALE INERT GAS INJECTION EXPERIMENT METHOD IN THE FIRE ZONE SEALING

Fire source: The fire source is set at 5m from the bulkhead on the side of intake air of experimental tunnel (shown as Fig. 1). To guarantee personnel security, the fuel of fire source adopts bulk coal or wood. The temperature in the tunnel is controlled within 40℃.

Preparation: Technicians reach the experimental mine based design. First, furnish a set of South Africa communication system for disaster area and start mobile gas analysis workstation. Second, furnish three routes of beam tube and move the command vehicle in the camping base. And then, furnish inert gas injection pipeline and a video line. At last, monitor the fire zone, prepare ignition material and complete labeling of sampling point.

Ignition test: After preparing well, technicians carry equipments (including 20 bladders for each group, a set of gas sampling tool, a portable monoxide block, a potable oxygen block, a portable gas block, a thermometer, a recorder folder and a recorder book, a micro-speed wind meter, a medium-speed wind meter, 30 micro-air hoses, a stopwatch and a set of infrared thermal imager) to enter the experimental tunnel to conduct ignition test.

Fig. 3 Preparation of experimenters

Experiment process: Two inert gas injection experiments have been conducted. The inert gas injection speed is low at the first time and high at the second time. Each experiment starts beam tube gas sampling system to conduct continuous monitoring and laboratory test for the experiment area. After the fire source is ignited, experimenters enter the experiment area and carry out sampling, survey in the fire zone. At the same time, sampling and analytical test of the first group of beam tube are conducted. Inert gas is injected after the first group of gas sampling in the fire zone. Afterwards, the second group of sampling is conducted and beam tube is monitored. The nitrogen injection system is closed after two groups of samplings. Afterwards, the air doors at both sides are opened to exhaust nitrogen accumulated in the experimental tunnel. The air door on the side of intake air shall be opened gradually to measure wind speed. The monitoring of beam tube shall be maintained until the experiment ends. Statistical table for nitrogen injection flow is shown as follows.

Table 1- Record Table of Flow Data of Nitrogen Injection

The first nitrogen injection				The second nitrogen injection			
Nitrogen injection time		Flowmeter display		Inert gas injection time		Flowmeter display	
Beginning time	12:19:00	Beginning	166	Beginning time	13:38:00	Beginning time	243
Ending time	12:36:00	Ending	239	Ending time	14:01:00	Ending time	373
Injection time	17 min	Injection quantity (m^3)	73	Injection time	23 min	Injection quantity (m^3)	130
Average speed		$257.6m^3/h$		Average speed		$339.1m^3/h$	

RESULTS AND DISCUSSION

Change law of gas composition

Each section takes gas with bladder simultaneously in the process of experiment. The process repeats four times and every sampling time does not exceed 1 minute. Composition and concentration of gas sample are tested immediately after the sample is taken. The following is analysis of test result of bladder gas sample.

(1) H_2 concentration

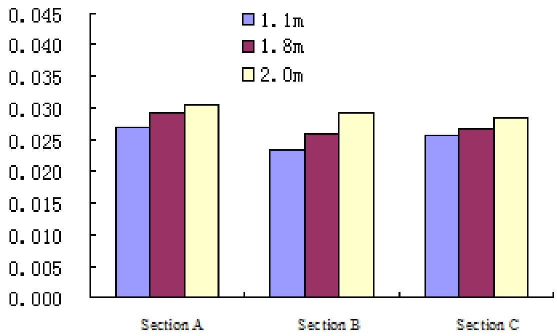


Fig. 4 H_2 concentration at different heights before the first nitrogen injection (at 12:18)

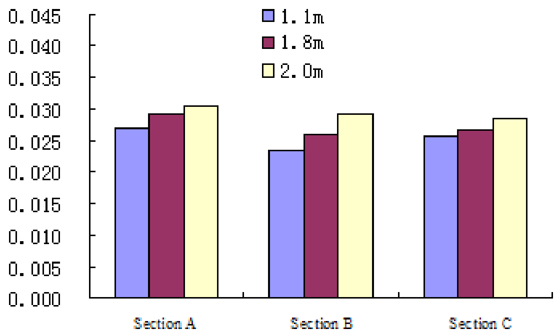


Fig. 5 H_2 concentration at different heights after the first nitrogen injection (at 12:36)

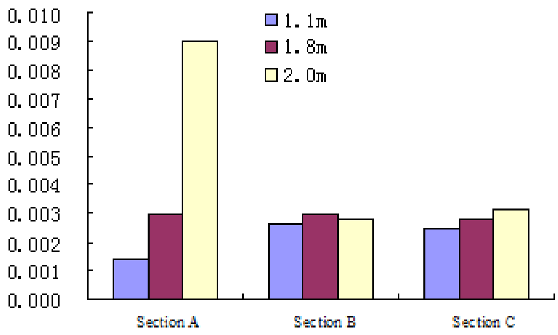


Fig. 6 H_2 concentration at different heights before the second nitrogen injection (at 13:37)

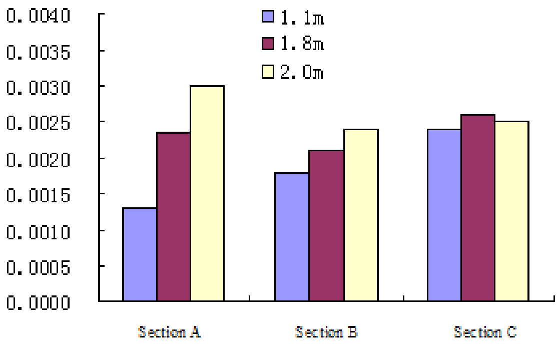


Fig. 7 H_2 concentration at different heights after the second nitrogen injection (at 14:01)

Shown as in Fig. 1, there are two sampling points at 1.1m and 1.8m respectively at each section, namely, point No. 3 and point No. 4 are at 1.1m height and point No. 1 and point No. 2 are at 1.8m height. There is one sampling point (No. 5) at 2m height. As concentration of H_2 at the same height is not drastically differentiated, H_2 concentration at each section adopts mean value at 1.1m and 1.8m. The mean values at 1.1m and 1.8m will be compared with the mean value at 2.0m. The H_2 concentration comparison diagrams at different heights in the experimental tunnel before and after two nitrogen injections are shown in Fig. 4 to Fig.7. The vertical ordinate represents H_2 mean volume fraction.

It shows that H_2 concentration is stratified in Fig.4 to Fig.7. Fig.5 and Fig.7 also shows that the difference of H_2 concentration in section C is small after nitrogen injection. At the same time, H_2 concentration is stratified in section A and section B. This shows that the dilution mixing effect of nitrogen injection to smoke on section C is bigger than that on section A and section B. The impact of the second nitrogen injection is bigger than the first nitrogen injection. It is mainly caused by enlargement of nitrogen injection velocity.

Above results show that the combustible gas in the closed zone of mine is stratified and the circumstance may continue after nitrogen injection. However, the nitrogen injection with turbulent condition disturbs flow condition of combustible gas layer and weakens stratification of combustible gas. Thus, the stratification after nitrogen injection is weaker than that before nitrogen injection. The dilution effect of nitrogen injection on combustible gas layer is related to distance of the combustible gas layer from nitrogen injection port. The nearer it is, the better the effect is; enlargement of nitrogen injection velocity can enhance the dilution effect on combustible gas.

(2) O_2 concentration
Fig.8 to Fig.13 are comparison diagrams of O_2 concentration in sections A, B and C before and after two nitrogen injections. The horizontal coordinate is sampling point and the vertical ordinate is O_2 volume fraction.

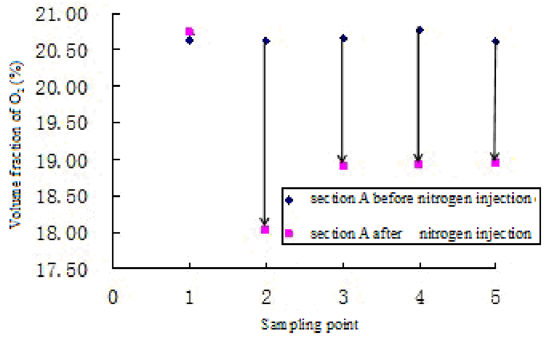


Fig. 8 O_2 concentration comparison of section A before and after the first nitrogen injection

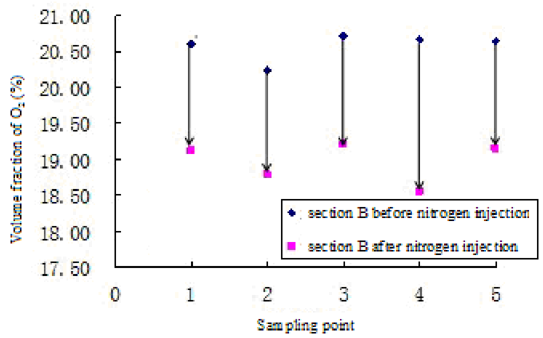


Fig. 9 O_2 concentration comparison of section B before and after the first nitrogen injection

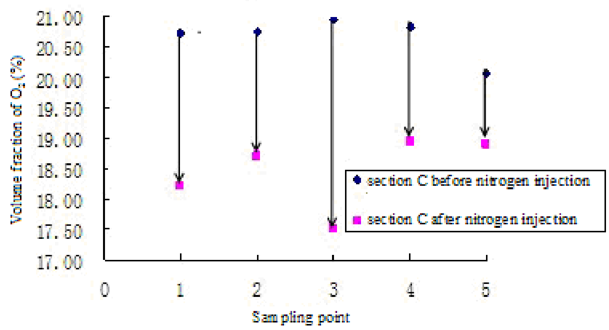


Fig. 10 O_2 concentration comparison of section C before and after the first nitrogen injection

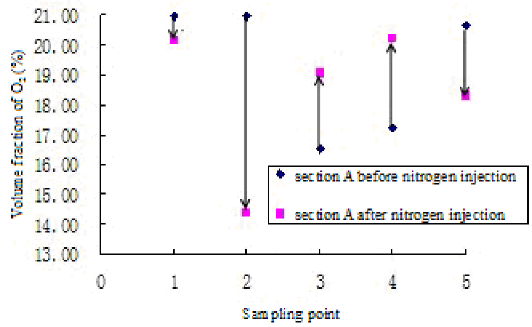


Fig. 11 O_2 concentration comparison of section A before and after the second nitrogen injection

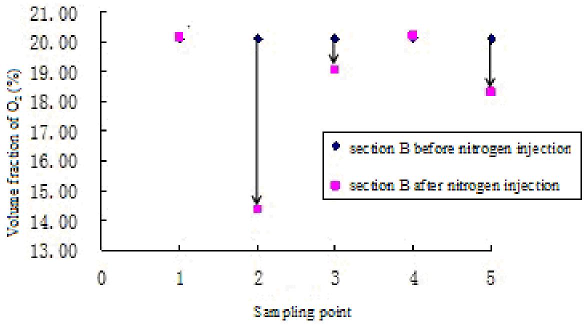


Fig. 12 O_2 concentration comparison of section B before and after the second nitrogen injection

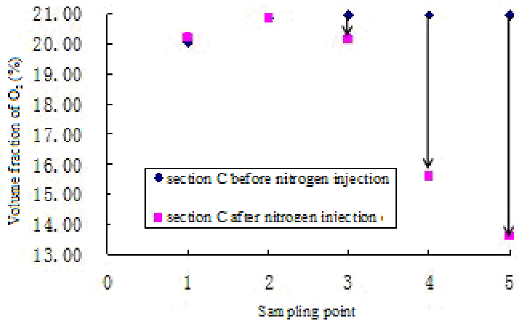


Fig. 13 O2 concentration comparison of section C before and after the second nitrogen injection

It is observed from above diagrams that O_2 concentration of three sections declines differently after nitrogen injection. It shows that inert gas injection has dilution effect on oxygen concentration. Fig.8 to Fig.10 are O_2 concentration change before and after the first nitrogen injection. The change of section C near the nitrogen injection port is the most obvious and the change degree of section A is bigger than that of section B. It is mainly because that section A is the nearest to the fire source and burning of fire source consumes oxygen in the process of nitrogen injection.

Fig.11 to Fig.13 show that the oxygen concentration change of section C near the nitrogen port is the most obvious at the second nitrogen injection. The concentration falls to below 14%. Overall change of section B is the smallest. Only a sampling point changes greatly. Change of section A is the smallest. Two sampling points of O_2 concentration before and after nitrogen injection are higher than that before nitrogen injection. The comparison of three diagrams shows that the dilution effect of nitrogen injection on oxygen of different distances is different.

(3) CO concentration

The comparison diagrams of CO concentration of three sections before and after two nitrogen injections are shown in Fig.14 to Fig.19. The diagrams are obtained after analysis of bladder gas. The horizontal ordinate is mark of sampling point and the vertical ordinate is CO concentration.

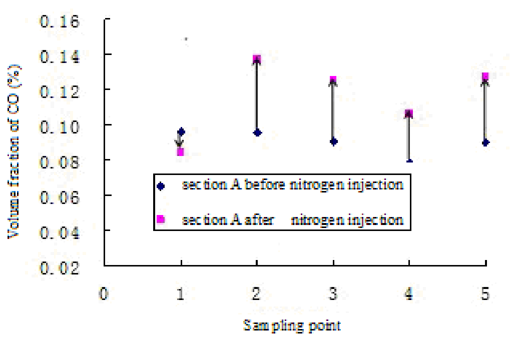


Fig. 14 CO concentration comparison of section A before and after the first nitrogen injection

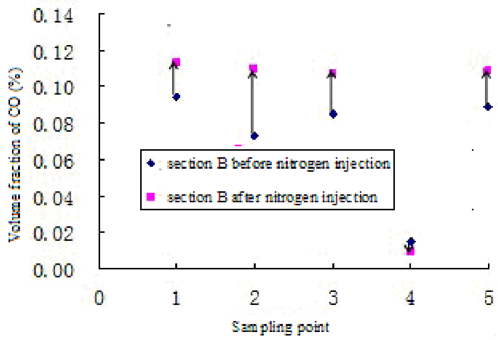


Fig. 15 CO concentration comparison of section B before and after the first nitrogen injection

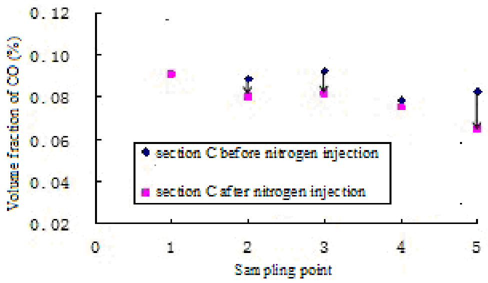


Fig. 16 CO concentration comparison of section C before and after the first nitrogen injection

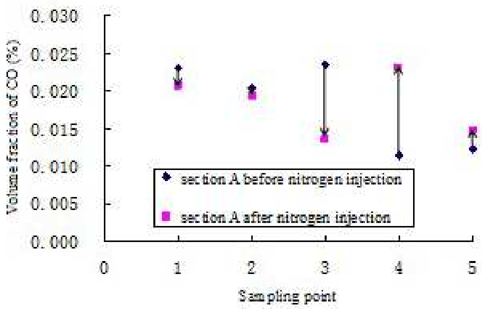


Fig. 17 CO concentration comparison of section A before and after the second nitrogen injection

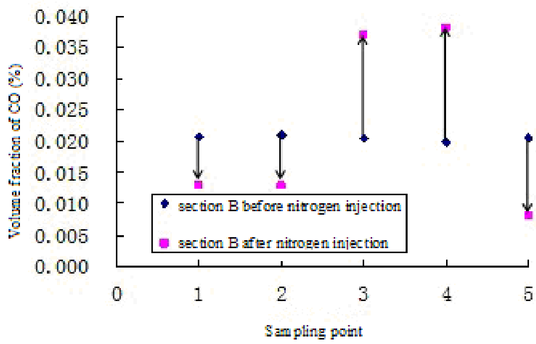


Fig. 18 CO concentration comparison of section B before and after the second nitrogen injection

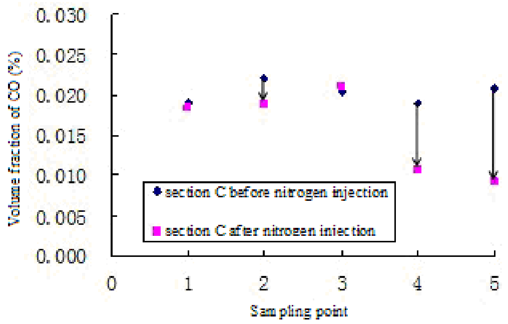


Fig. 19 CO concentration comparison of section C before and after the second nitrogen injection

It is observed in Fig.14 to Fig.16 that CO concentration of section near the nitrogen injection port declines entirely after the first nitrogen injection. It indicates that nitrogen injection has dilution effect on section C. Section B rises entirely. However, the rising degree of CO concentration of section A after nitrogen injection is larger than section B, showing that nitrogen injection drives CO on section C to migrate towards sections B and A.

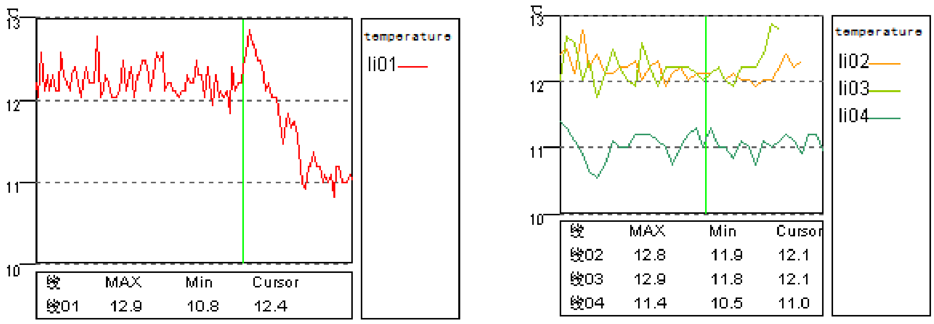
The CO concentration changes of three sections before and after the second nitrogen injection are shown in Fig.17 to Fig.19. CO concentration of section C declines after nitrogen injection and CO concentration of all sampling points in sections A and B has different changes. Two sampling points rise after nitrogen injection. It shows that dilution effect of CO is different in three sections. The dilution effect of enhancing nitrogen injection velocity on smoke is very obvious. The figures above also show that CO concentration of three sections is uniform entirely before nitrogen injection.

Above results show that combustible gas is evenly distributed in the closed zone longitudinally before nitrogen injection. The inert gas will promote combustible gas to migrate towards fire source after inert gas injection, causing smoke concentration in the tunnel ahead to rise and O_2 concentration to decline. The promoting effect is influenced by injection velocity. It proves that inert gas injection has the effects of the front-end piston on combustible gas and back-end mixing dilution on combustible gas.

Infrared imaging

Experimenters take photos in the experimental tunnel with infrared imager in the process of experiment.

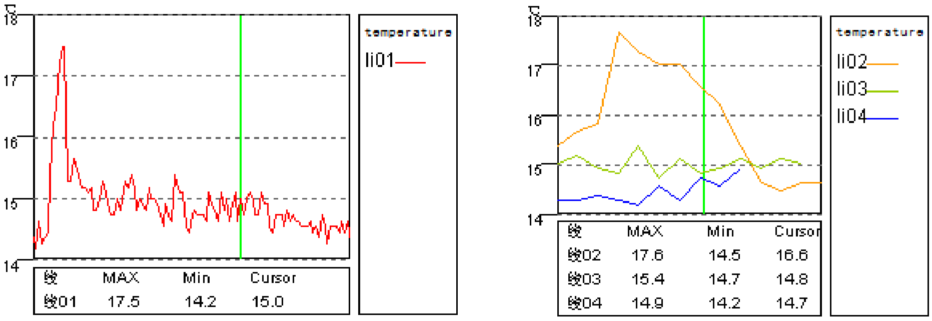
Fig. 20 to Fig.22 are infrared imageries shot on sections C, B and A in the process of the first nitrogen injection.



(a) Temperature Variation in Vertical Direction (b) Temperature Variation in Horizontal Direction

Fig. 20 Thermal imagery and analysis of section C

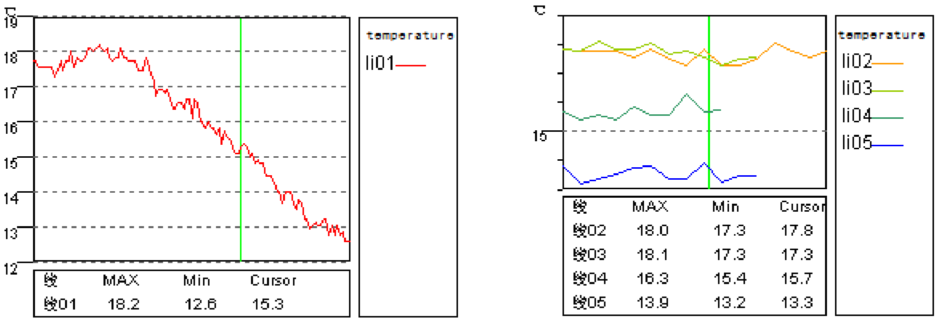
Fig. 20 is infrared imagery analysis of section C. It shows that inert gas injection makes temperature of smoke layer around section C fall. The average temperature of mixed gas of nitrogen and smoke is about 12℃ in vertical direction and the temperature difference is small. It indicates that gas stratification is not obvious and the mixing dilution effect of inert gas injection on section C is obvious.



(a) Temperature Variation in Vertical Direction (b) Temperature Variation in Horizontal Direction

Fig. 21 Thermal imagery and analysis of section B

Fig. 21 is infrared thermal imaging of section B. It can be seen that inert gas injection makes temperature of smoke layer around section B fall. The comparative analysis with Fig. 20 shows that the average temperature of mixed gas of nitrogen and smoke in vertical direction is higher than temperature of mixed gas in section C, which is about 15℃. In addition, temperature difference exits to certain degree.



(a) Temperature Variation in Vertical Direction (b) Temperature Variation in Horizontal Direction

Fig. 22 Thermal imagery and analysis of section A

Fig. 22 is that experiments are taking samples in section A. The infrared imagery shows that the impact of inert gas on section A is small. Comparing with Fig. 20 and Fig. 21, it shows that the average temperature of mixed gas of nitrogen and smoke in vertical direction is higher than temperature of mixed gas in section B and C, which is about 16℃. Big temperature difference exists and gas stratification is obvious.

By comparing Fig.20 to Fig.22, it also shows that the farther it is from the inert gas injection port is, the bigger the average temperature is in vertical direction in cross section. The temperature in the entire cross section in sections C and B tends to balance. Temperature in section A is stratified. It indicates that inert gas injected at this time mixes smoke layer in sections C and B uniformly. At the same time, the impact on smoke layer in section A is small.

Above results show that inert gas injection has dilution effect on gas layer which is near the inert gas injection port. The inert gas constantly consumes its own energy in the process of migration owing to impact of viscous resistance. It reaches balance with smoke layer after flowing certain distance, thus propelling the smoke layer to migrate towards fire source.

THE PRACTICE SIGNIFICANCE OF THE EXPERIMENT ON GUIDING INERT GAS INJECTION IN THE FIRE ZONE SEALING

(1) Mine fire can not only generate well-known gas, such as CO, CO_2, CH_4, but also generate H_2, C_2H_4 and C_2H_6. In addition, H_2 concentration is bigger than that of C_2H_4 and C_2H_6. Concentration of gas generated in the fire increases with augment of fire intensity.

(2) Based on the gas distribution in horizontal cross section of the tunnel, it can be seen that stratified distribution of combustible gas existed in fire zone sealing obviously. The lower the gas density is, the more obvious the gas stratification is. The reason is that the mine atmospheric temperature difference in horizontal cross section generates the gas density difference, and then induces the gas concentration difference.

(3) The turbulence inert gas injected into the fire zone sealing "disturbs" the laminar flow condition of combustible gas layer, thereby weakening the stratification function of combustible gas. In addition, the dilution effect of nitrogen injection on combustible gas layer is related to distance of the combustible gas layer from nitrogen injection

port. The nearer it is, the better the effect is.

(4) The combustible gas is distributed uniformly and longitudinally in the tunnel. Inert gas injected to the fire zone sealing is like injecting gas piston. It will promote combustible gas layer in the closed zone to migrate towards air intake side. Thus, the combustible gas flows to fire source owing to the piston effect of inert gas injection. It is the reason of explosion at the initial stage of inert gas injection in fire zone sealing.

(5) The dilution effect of inert gas injection on middle and lower part of combustible gas layer is better than that of the upper part; the effect is related to injection speed. The bigger the injection speed is, the more obvious the dilution inerting effect is.

(6) In light of above experimental analysis and example verification of disaster relief, explosion hazard exists at initial period of inert gas injection in fire zone sealing. Hence, implementation sequence of disaster relief measures shall be determined reasonably. People shall be evacuated immediately at the time of inert gas injection. After the inert gas injected mixes with explosive gas fully in the fire zone and the explosion hazard period passes, work can be carried out near the fire zone.

CONCLUSION

The experimental scheme for combustible gas explosion induced by inert gas injection in fire zone sealing of mine was designed and two inert gas injection experiments in experimental tunnel were conducted. The temperature, gas concentration, velocity, and so on, in experiments were tested and analyzed. The change characters of combustible gas layer and inert gas layer during injecting inert gas in the fire zone sealing were put forward. The researches provide theoretical basis and practice instruction to security Implementation of inert gas injection in the fire zone sealing of mine.

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