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A New Approach to Control a Serious Mine Fire with Using Liquid Nitrogen as Extinguishing Media

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Abstract. Subsurface fires are a common threat for coal mining, since spontaneous coal combustion can easily result in gas combustion and explosion. In this paper, aiming to solve problems of the low efficiency, the line clogging, and some other related field issues in liquid nitrogen perfusion, a fire extinguishing application by using immediate liquid nitrogen infusion was presented. The presented technique is efficient in absorbing heat, and consequently, displacing oxygen and combustible gases. Field tests justified the efficiency of the technique. Only 12 days were taken to unseal the coal mine, which provides a quick and efficient management of the fire zone. Furthermore, by using the presented technique, there was no waste left behind which may impede the subsequent production. The presented technique is of great benefit from the social, economic, and environmental aspects, which indicates its broad application in fire prevention for large-scale coal mines.

Keywords: Subsurface fire, Liquid nitrogen, Immediate infusion, Fire extinguishing, Inerting

1. Introduction

Despite the increasing attention to renewable energy sources, fossil energy, as as coal, will still play a major role in meeting the global demand for energy. However, subsurface fires widely threaten the industry of coal mining [1, 2], especially for coal mines with high volumes of gases. The consequent gas combustion and explosions are common results for these coal mines [3, 4], which brings severe consequences of human and property losses.

With respect to the control of the spontaneous coal seam combustion, confined to the current fire extinguishment technology, the location of the fire is difficult to identify. Further constraints are the shortage of water and soil in the field, therefore,

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fire-proof techniques as grouting, foam, or colloid injection were not able to function ideally, failing due to the limited coverage [1, 3, 5–8], stoping the extinguishment substance from reaching the fire location. The grouting material tends to inflow into the working face, which causes the pollution of working section in mine. With the rapid development of coal mine exploitation, a fully submerged fire extinguishing technique that can meet the needs of coal mine fire extinguishing in large-scale exploitation is needed. Gaseous nitrogen has been used to prevent and extinguish fire as an efficient inert gas. This technique is of advantages of quenching the fire zones, preventing gases from explosion, and is of wide-range diffusion. However, the technique has low specific heat, and inefficient heat transfer, therefore, the normal cooling effect make it necessary to supplement it with some other fire extinguishing measures to control fire. This extends the fire extinguishing period, leading to failure to meet the anticipated fire extinguishing period in the field.

By contrast, liquid N_2 is a potentially more efficient heat transfer medium. At their low temperature, cryogenic liquids absorb large quantities of heat. Changes in state from the liquid to the gas phase also absorb heat and produce an 800-fold increase in the volume of the cryogenic material. The expansion promotes isotropic distribution of the heat-absorbing gas that forces hot combustion gases out and also displaces oxygen [9–12]. The first case of liquid nitrogen adopted in fire extinguishing was in 1949, in the Doubrave coal mines of the Czech Republic, which successfully prevented the fire from spreading [13]. After that, this technique was used in Fernhilly and Fryston coal mines of Britain; Osterfeld, Schlagel, Eisen coal mines in Germany; Rozelay coal mine in France; and the Springfield coal mine in South Africa [14–18]. In the view of the current application of coal mine, liquid nitrogen for fire extinguishing technique is mainly used as the conventional vaporization nitrogen, the real function does not work [5]. However, injection of low-temperature gaseous nitrogen has a high flow rate and low damage to pipelines.

Generally, issues of immediate infusion technique of liquid N_2 are two folds: (1) material issues: a great amount of liquid nitrogen is needed, the transportation is not convenient and costly, the cost of this technique limits the wide application; (2) technical issues: immediate infusion of liquid nitrogen usually is associated with "air plug" (the balloons and bubbles in the pipeline which hinder the flow of low-temperature gas), which blocks pipeline for liquid nitrogen injecting. Another issue is that the pipeline tends to be damaged from freezing, which undermines the injecting efficiency of liquid nitrogen and the application resulting.

Based on the case study of the gas explosion and fire control in Rujigou coal mine, in this paper we present a technique of controlling a large-scale subsurface fire zone by using immediate liquid nitrogen infusion, which can manage the underground fire zone in a quick and efficient way.

2. Methodology and Theories

2.1. Materials

The Ningdong energy chemical industry base, located in Ningxia, is one of 13 large-scale coal production bases of more than 100 Mt, and one of eight national

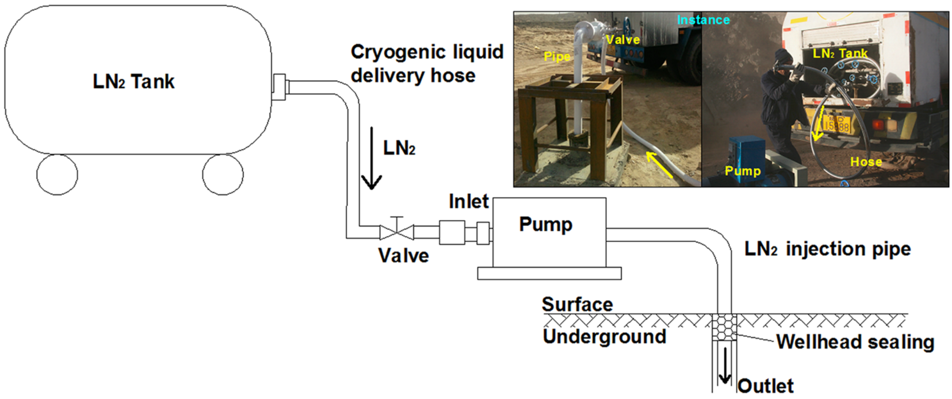

Figure 1. The fundamental of the fire extinguishing by liquid nitrogen injection.

coal chemical product bases. Relying on the Ningdong energy industry base, large amount of liquid nitrogen by-products can be obtained in the process of basic material for preparation of coal chemical industry-liquid oxygen. The production of liquid nitrogen in the local energy chemical industry base is 600 kt per year, with the purity above 99.99% and a cost of US$ 60/ton.

2.2. Equipment

Injecting liquid nitrogen through surface borehole, is an important way during the period of mine catastrophe. The immediate injecting liquid nitrogen fire extinguishing system on the surface includes a liquid nitrogen tank truck, roundtrip low-temperature gas pump, low-temperature liquid transporting soft pipe, and a nitrogen injecting pipe (Figure 1). The stainless steel seamless pipe was used for liquid transportation, preventing the pipeline from being cryogenic brittled and damaged. The function of roundtrip low-temperature pump is to inject the turbocharged liquid nitrogen into the pipelines immediately, effectively forcing the liquid nitrogen into the fire. The immediate injecting liquid nitrogen fire extinguishing system can be installed conveniently, and the continuous low-temperature liquid nitrogen is capable of absorbing heat in large quantities in fire zone. Additionally, amount flow of nitrogen vapor after the cryogenic liquid gasification can inert the fire zone which makes the extinguishing process more effective and efficient.

2.3. Extinguishment Mechanism

The extinction mechanism is said to be thermal, not chemical which can be understood qualitatively on the basis of the Damkthler criterion for extinction [19].

$$D = \begin{pmatrix} l/v \\ \text{or} \\ l^2/\alpha \end{pmatrix} c_F c_0 A e^{-E/RT} \quad (1)$$

where c_F is the fuel concentration ing/cm^3, c_0 is the oxygen concentration in g/cm^3, E is the activation energy of the reaction in cal/mol, R is the ideal gas constant in cal/mol K, l is the characteristic length, and v represents the characteristic velocity. The injected liquid nitrogen is believed to isolate the oxidizer and thereby reduce D by reducing the oxygen concentration c_0 in the gas. Cooling condensed fuel tends to reduce c_F as well as the flame temperature T in Eq. (1), thereby reducing D; blowing out the flame increases v, which has a strong influence on D.

2.4. Calculation for Extinguishment

For practical extinguishment calculations, rougher approximations must be employed. Based on the principles of the entire space completely filled with nitrogen, the weight of injected liquid nitrogen m_{inert} can be calculated by Eq. (2).

$$m_{\text{inert}} = \xi \cdot V/800 = f(\lambda, \phi, \varepsilon, \ldots) \cdot (V_1 + \alpha V_2)/800 \tag{2}$$

where ξ is the surplus coefficient (the value ranged from 2 to 4 according to the mining engineering experience), which related to the air leakage λ, loss of nitrogen injection ϕ, purity of the nitrogen ε et al., V is the needed inerting volume, including the volume of the roadway space V_1 and the mined-out areas αV_2 (α is the degree of goaf looseness), 800 is the coefficient of liquid nitrogen mass translated by the vaporized nitrogen volume.

3. Case Demonstration

3.1. Mine Fire Description

The Rujigou coal mine is located in the north of the Ningxia Hui Autonomous Region. The area of mine field is 11.4 km^2. Its production capacity is 1.5 Mt per year and seven mining coal seams are available. In the Rujigou coal mine, the 34 m-thick 2_2^1 seam is the primary mining seam. The absolute outflow of gas is 153.82 m^3/min, and the relative gas emission rate is 67.7 m^3/t. The first sub-layer of the 2_2 seam is selected as the fully mechanized coal face. The length of its working face is 642 m, the inclined length is 252 m, and the mining height is 3 m.

On 4 June 2011, an accident happened when the source of high temperature ignition of the upper abandoned mine goaf dropped at the working face along the crack (Figure 2), igniting the gas near the working face. The fire started from the working face's 76# hydraulic support, and then spread rapidly to other supports. The concentration of carbon monoxide in the upper corner of the working face rapidly peaked at 7218 ppm. The workers tried to employ several methods to put out the fire, including water infusion and grouting, but, when none worked, the working face was then sealed. However, after that, secondary explosions happened several times. Besides that, the grouting plastic pipelines of the ventilation roadway were almost ruined due to the wide range of fire zones, the roof fell in many places, and the pipelines of gas extraction were broke off and damaged in many places. With such a circumstance, the whole mine was forced to shut down.

(a) The grouting pipe was burned down (b) Cracks produced by the fire on the floor

(c) Roof falling of working face (d) The plastic net was almost ruined

Figure 2. Fire results in the loss of the equipments surrounding the working face.

Suspected fire locations were judged as fire zones of the upper coal seam, the rear of supporters (methane combustion location), the whole roadway and working face space, and other combustible materials ignited by burned gas. After the mine was closed, the entire underground working face can be considered as a fire zone. Hence, the volume of fire zone was calculated as $V = V_1 + \alpha V_2 = 4800 + 0.7 \times 546000 = 387000\ \text{m}^3$.

3.2. Liquid Nitrogen Injection

The drilled boreholes should be closest to the fire zones. Therefore, boreholes for injecting the liquid nitrogen separately as B-1#, B-3#, B-4#, B-5#, and 8# were set. The 8# and B-1# boreholes were used to extinguish the fire zone in the upper coal seam; B-4# and B-3# boreholes were used to inert the original fire source located in working face; through the B-5# borehole infusion of liquid nitrogen to the ventilation roadway, the whole roadway and face is inerted. The arrangement is shown on Figure 3, and the parameters of boreholes are shown in Table 1.

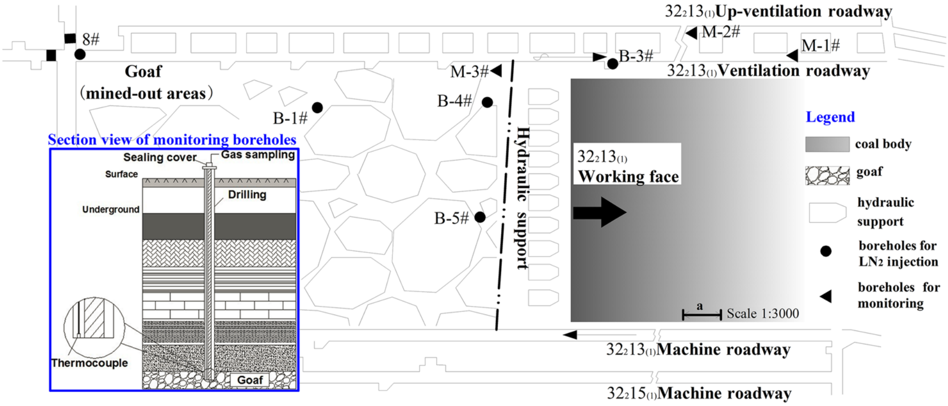

Figure 3. The drawing of liquid nitrogen infusion arrangement in surface boreholes.

Table 1
Construction Parameters of the Boreholes for Injecting the Liquid Nitrogen

Borehole number	Depth (m)	Size (diameter) (m)	Borehole location	Reason for borehole arrangement
8#	308	0.13	2_2^1 mine goaf	Quenching the suspected fire zone of the upper coal seam
B-1#	313	0.13	2_2^1 mine goaf	Quenching the suspected fire zone of the upper coal seam
B-4#	232	0.13	$2_2{}^1$ coal seam	Corresponding to the rear of 157#'s hydraulic supporter (ignition location)
B-3#	235	0.13	Roadway of $2_2{}^1$ coal seam	Injecting the liquid nitrogen in ventilation roadway in order to inert the whole roadway and working face space
B-5#	217	0.13	Roof of $2_2{}^1$ coal seam	Corresponding to the rear of 89#'s hydraulic supporter (ignition location)

By employing the fire extinguishing system, injecting the liquid nitrogen with large amount to the $32_213_{(1)}$ goaf, the location of the fire area and the above coal seam, the fire zone can be inerted completely.

3.3. Monitoring

At the same time, M-1# (located in the air-return roadway), M-2# (located in the up-ventilation roadway), M-1# (located in the upper corner in the workface) boreholes were used as the monitoring point for fire area (Figure 3). Based on the temperature and the gas content in boreholes, the state of fire movement and cooling effects of nitrogen can be monitored. The tested temperature was measured by thermocouple in the borehole bottom, and the content of gas was the one that extracted from hole by gasbag. U-type water column differential manometer for the changes of pressure difference in the sealing walls of each shafts, and the monitoring system for gas collection were also installed.

From the day that accident happened till 12 June, by using the liquid nitrogen immediate infusion system, approximately 1450 t ($\xi = 3$) liquid nitrogen was injected to working face according to Eq. (2). The fire was ultimately extinguished.

4. Results

CO and temperature are important indicators for fire extinguishment [20]. According to the temperatures and gas constitutions in boreholes, temperature and gas trend chart are drawn. As shown in Figure 4, concentrations of CO in the ventilation roadway, the up-ventilation roadway and the upper corner of goaf showed a sharp decrease. For example, the concentration of CO in the ventilation roadway descended from 1949 ppm on 4 June to 5 ppm on 9 June. During this period, as the temperature measurements in fire zone show, the temperature continued to decrease. This shows that liquid nitrogen has a prominent effect of extinguishment and explosion suppression. The high efficiency of the technique of fire extinguishing can then be demonstrated from temperature data.

Until 14 June, gas in mine closed region was at a stable condition, and O_2 concentrations in the closed region and the $32_213_{(1)}$ working face were steadily under 5%, and CO concentrations were consistently under the unsafe value (Table 2). Ethylene and acetylene concentrations were zero. The pressure differences between inner and outer of closed-in wellhead ranges from 30 Pa to 100 Pa. This indicates that keeping positive pressure in sealed regions can effectively prevent air leakage

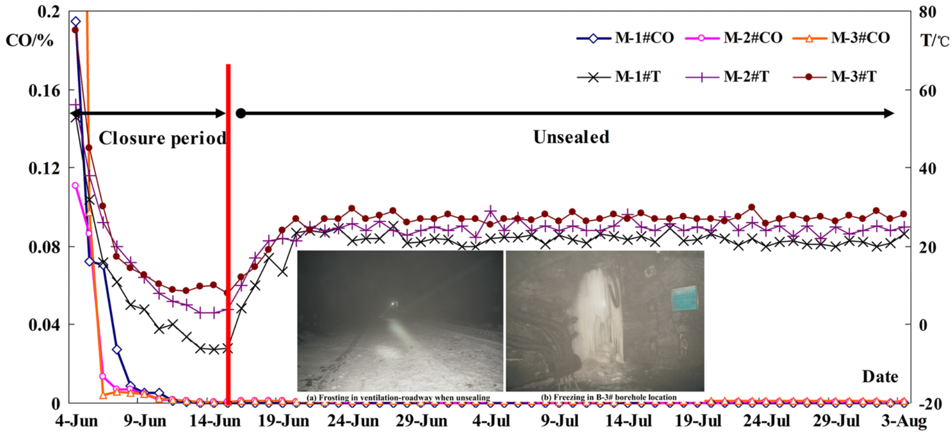

Figure 4. Changes of CO concentration and temperature in fire zone.

Table 2
Gas Sample Analysis of Monitoring Stations

Monitoring stations	N_2 (%)	O_2 (%)	CO (%)	CO_2 (%)	C_2H_6 (%)
M-1#	80.87	2.55	0.0003	0.73	0.0028
M-2#	81.42	2.37	0.0009	0.88	0.0003
M-3#	80.06	2.86	0.0005	0.73	0.0015
Main-belt shaft	81.84	1.85	0.0005	0.54	0.0025
Pedestrian shaft	80.56	3.15	0	0.35	0.0025
Inclined shaft	80.22	4.40	0	0.29	0.0070
Centre ventilation shaft	86.40	4.59	0	0.33	0.0006

and displace oxygen. According to the closed situation and fire area management, mine unsealing criteria were satisfied and the seal was broken on 16 June. With unsealing, the average temperature of mine return airway was as low as 5°C below zero, and many icicles formed in 3# borehole for seepage, and reignition did not happened.

5. Discussion

(1) The cooling and inerting effects of immediate liquid nitrogen infusion in unconfined space are superior to confined goaf, which is due to the fact that heat conductivity of air exceeds that of the coal and rock. Coal, rock mass, and other confined space will impact the injecting efficiency and the total quantity of liquid nitrogen.

(2) A total of 16t liquid nitrogen was effectively injected into the underground of coal mine within 1 h by the application of immediate liquid nitrogen injecting. After the liquid nitrogen was entirely evaporated, the gaseous nitrogen which is generated in 1 h equals a flow value of 1.28×10^4 m^3/h, which is 21.3 times as single general nitrogen-generating machine (600 m^3/h). After the injected liquid nitrogen is heated, the expansion promotes isotropic distribution of the heat-absorbing gas that forces hot combustion gases out and displaces oxygen. This is the reason why there was a slightly rise of CO concentration on 6 June and 7 June (Figure 4). With respect to the closed or semi-closed mined-out areas, the amount of mixed gas in the space increased after liquid nitrogen infusion, the pressure difference between inner and outer of the closed zone is reduced, cutting down air leakage into closed zone from outside, resulting in better fire prevention and extinguishing.

(3) Economy strategies of liquid nitrogen injection should be a large quantity first and small later. The initial (the former 6 days) nitrogen injection is 72.4% of the total nitrogen quantity, which makes the extinguishing process more efficient. After a smaller quantity of nitrogen injection was employed in order to achieve the purposes of the inerting fire area continuously.

(4) The technological system of liquid-nitrogen fire prevention and extinguishing plays a significant role in fire management project of complex large-scale coal mine. Rujigou coal mine was sealed on 23:00 h, 4 June, and was unsealed on

19:00 h, 16 June, which means that it only took 12 days to extinguish the fire and regain access to the working face. A similar scale coal fire management, which occurred in Baijiou colliery (24/Oct/2003), required 11 months [4] and a previous fire in the Rujigou coal mine (25/Nov/2010) required 76 days to unseal fire zones, with an additional 2 months to clean up because the sludge was submerged mid-to-lower place in the working face during slurry infusion. Fire extinguishing by liquid nitrogen infusion, which is an effective and environment friendly fire prevention and extinguishing medium, leaves no waste in the working face.

6. Conclusions

Liquid N_2, as kind of all-submerged fire prevention and extinguishing method, can rapidly extinguish fires, preventing gas explosion, minimizing extinguishment time, and resuming operation at the earliest time; and consequently providing a great economic benefit. But liquid N_2 is not effective enough in infusion; technical issues restrict the development and utilization of liquid N_2 fire prevention and extinguishing technology. This paper discussed the immediate injection of liquid N_2 for fire prevention and extinguishing, which accomplished high efficiency of infusion, and played a significant role in extra large fire management of Rujigou coal mine. The successful application of the technique implies its great potential of social, economic and environmental benefits, and broad applications for managing subsurface fires in large-scale coal mines.

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