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Study on control of disastrous open fires in underground coalmines

R P Singh* and S K Ray

Central Mining Research Institute, Barwa Road, Dhanbad 826 001

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Outbreak of open fires in coalmines is one of the major causes of disaster. To understand the complex phenomenon of open fires and to work out suitable fire suppression techniques, a mine fire model gallery is designed and constructed at Central Mining Research Institute, Dhanbad. The gallery is equipped with state-of-the-art instrumentation system to monitor the important fire parameters. Three fire suppression techniques — liquid nitrogen, high-pressure high stability (HPHS) nitrogen foam, and water mist, were tried in three sets of experiments. It was observed that either HPHS nitrogen foam or water mist can be used to control the open fires. Despite control of open fires the water mist has other advantages, which can prevent the open fire to become disastrous.

Keywords: Disaster, Open fires, Model gallery, Liquid nitrogen, HPHS nitrogen foam, Water mist, Coalmines

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Introduction

In underground coalmines, generally disaster takes place due to fire, explosion, inundation, and roof fall. During 1901-2001, 53 disasters had taken place in Indian coalmines. During 1948-73, fire and explosion contributed about 76 per cent of the total fatalities, while after coalmines nationalisation during 1974-2001, its share reduced to 18 per cent[1]. During 1974-2001, five major disasters occurred due to fire and explosion in Indian coalmines (Table 1). The disaster in New Kenda colliery was a horrible example, where 55 persons lost their lives due to open fire in the main intake gallery of the mine. Open fires are generally caused due to electrical fault, mechanical friction, blasting, welding, explosions, and illicit distillation of liquor. Outbreak of such fires in an open gallery of a mine generates huge quantity of toxic gases and smokes, which spread quickly and directly throughout the mine and creates difficulties in rescue and recovery operations. The majority of deaths caused due to open fires are not by burning or blast effect but by inhalation of toxic gases particularly carbon monoxide[2].

Till recent past, no facility was available in India to perform systematic in-depth study to understand the complex dynamic phenomenon of open fires, while in other parts of the world lot of research has been carried out[3-6]. A mine fire model gallery has been designed and constructed in CMRI premises, Dhanbad. Three sets of experiments have been conducted maintaining three different air velocities viz., 1, 1.5, and 2 m/s. Three different fire suppression techniques viz., liquid nitrogen (LN_2), high-pressure high stability (HPHS) nitrogen foam, and water mist have been deployed to control open fires in the gallery. These techniques have been tried to control underground coalmine fires in different countries[6-8].

Table 1 — Major disaster due to fire and explosion in coal mines

Date of accident	Name of mines	Number of fatalities	Cause of accident
04.10.1976	Sudamdih shaft mine	43	Explosion (firedamp)
22.01.1979	Baragolai colliery	16	Explosion (firedamp)
24.06.1981	Jagannath colliery	10	Fire (open cast fire)
25.01.1994	New Kenda colliery	55	Fire (open fire)
03.03.1997	New Moghla	10	Explosion (firedamp)

*Author for correspondence
E-mail: rpsingh_cmri@yahoo.com

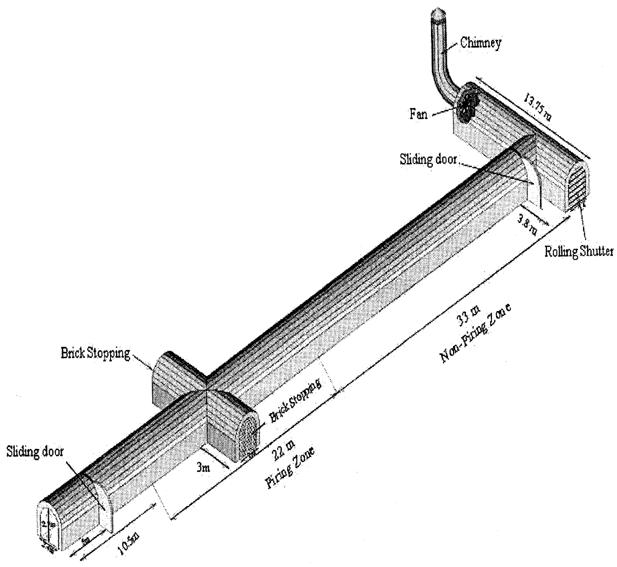


Fig. 1 — Isometric view of mine fire model gallery

The study deals with important design features of the gallery, its instrumentation system, experimental procedure, and results of fire suppression techniques adopted to control open fires in the mine fire model gallery.

Design Features of the Gallery

CMRI mine fire model gallery is 65.5m long arched sections with a base of 2.4 m and crown height of 2.7 m (Fig. 1). Gallery is slightly inclined, dipping 1 in 20 west to east direction. Cross section of gallery is 5.86 m^2. It is basically divided in two zones, non-firing and firing. First 10.5m long segment of the gallery is known as non-firing zone, the middle 22m long is firing zone and the last 33m long segment is again a non-firing zone. One 3m long cross-cut gallery with two stoppings has been provided in the centre of the firing zone and a second cross-cut gallery of same cross section but 13.75m length has been provided at the dip end of the gallery. The cross-cut gallery is also a non-firing zone. An exhaust fan having a capacity to deal with 25 m^3/s of air quantity at 50 mmwg pressure has been installed at the end of second cross-cut gallery. To avoid air pollution in the surroundings due to burning of coal in the gallery, a chimney (10m high, 1m diam, made of 6mm thick steel plate) has been provided with the fan. Two sliding doors, one at 5m from the gallery entry and another at the end of the gallery, have been provided for sealing of the firing zone, whenever needed. One rolling shutter has been fitted at the end of the second cross-cut gallery opposite to the fan for regulation of airflow in the gallery and dilution of the incoming toxic gases and cooling of hot air from the firing zone. A monitoring room for installation of instruments, data logger, computer, printer, plotter, etc., adjacent to the gallery has been constructed.

Instrumentation System

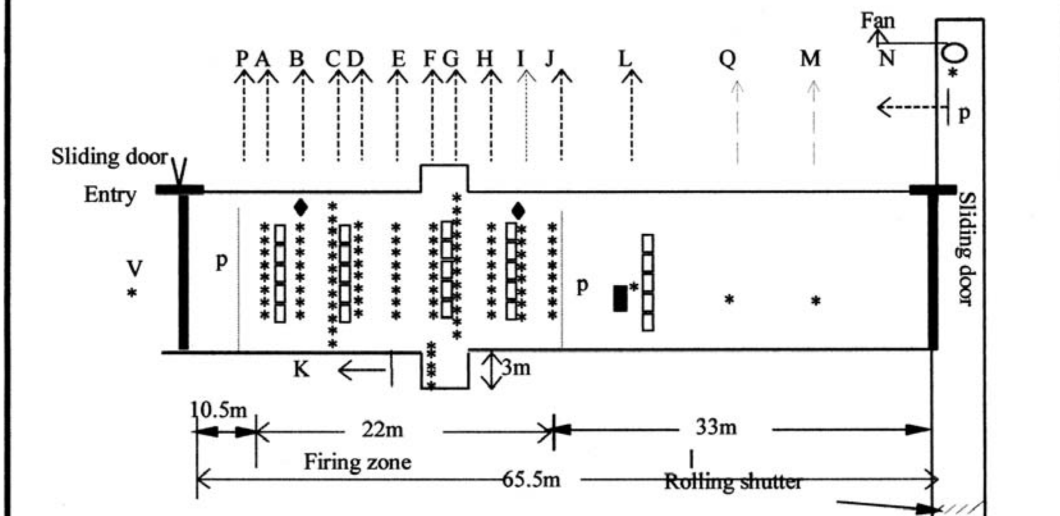
The mine fire model gallery is equipped with state-of-the-art computer aided on line telemonitoring system. The instrumentation system was designed with care in view of the stringent requirements of the experiment. To have an in-depth understanding of dynamics of open fire in a mine gallery, it was necessary to record every bit of changes that would take place in the gallery in regard to temperature of air, coal slabs and gallery walls, gas concentration, and other parameters. The system consists of 130 sensors with data logger, computer, computer peripheral, etc., for continuous monitoring of various fire parameters like, gas concentration, air velocity, pressure across fire zone and fan pressure, temperature, heat flux, dust, and particulate matter concentration inside the gallery. For better understanding, the entire monitoring system may be explained in two stages: (i) Instrumentation in the gallery; and (ii) Data acquisition system for collection, analysis and storage of data.

Instrumentation in the Gallery for Data Generation

The computer aided on line telemonitoring system comprises 130 sensors installed in the gallery as well as in the monitoring room (Fig. 2). The sensors installed at the gallery site are 98 temperature sensors, three pressure sensors, one air velocity sensor, two heat flux sensors, and one dust/particulate sensor. While 25 gas sensors/analysers are mounted on a panel in the monitoring room for continuous monitoring of CO, CO_2, CH_4, O_2 and H_2 gases. Gas samples from inside the gallery will be continuously drawn out by suction pump. The gases so drawn would pass through a stack of gas analysers after being cooled and filtered. Altogether, five gas sampling systems are provided at five gas monitoring stations.

Data Acquisition System for Collection, Storage and Analysis of Data

Data acquisition system consists of signal processor and transmitter, data logger, computer



Locatio	Entry	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Distanc from openin (m)	4.8	12.7	14.9	17.1	19.3	21.5	23.7	25.9	28.1	30.3	32.5	Side gallery	42.5	52.5	62.5	Near fan	10.2	48.5

Type of Sensor	Temperature	Gas	Velocity	Pressure	Heat flux	Smoke density meter	Total
Symbol	*	□	V	P	♦	▮	
no. of sensors	98	25	01	03	02	01	130

Fig. 2 — Details of various monitoring stations and sensors locations along the gallery length

peripheral, printer, plotter and software for on line transmission and analysis of data obtained during experimentation (Fig. 3). About 130 sensors installed in the mine fire model gallery and signal from all sensors are transmitted to the data logger and then to a computer. To meet these requirements, two data logger of 98 and 48 channels, model 8030-MI is provided. SCADA software on Window-98 operating system for analysis, graphical presentation and fault detection is incorporated in the computer.

Experimental Procedure

Coal slabs (8-10 cm thick), prepared from freshly exposed coal samples collected from Dobrana seam of New Kenda colliery, ECL, were carefully fixed to the inner wall, roof and floor of 22m long fire zone of the gallery. Fixing of coal slabs was effected with a mixture of air setting cement and a liquid binder. Utmost care was taken for no gaps between two slabs; any gap found was filled up by a mixture of loose coal and air setting cement.

The fixing materials were earlier tested in the laboratory for its thermo-decomposition property to ensure that it does not decompose at high temperature and does not release any toxic and combustion gases. Test results indicate that the material can withstand a temperature up to 1400 °C and does not liberate any toxic and other gases that could vitiate the proposed experiments.

Before starting the experiments, all sensors installed in the gallery and monitoring room were checked and calibrated. Fire was initiated in the beginning of the coal zone by burning of small amount of wood chips, newspaper, jute wool, etc.,

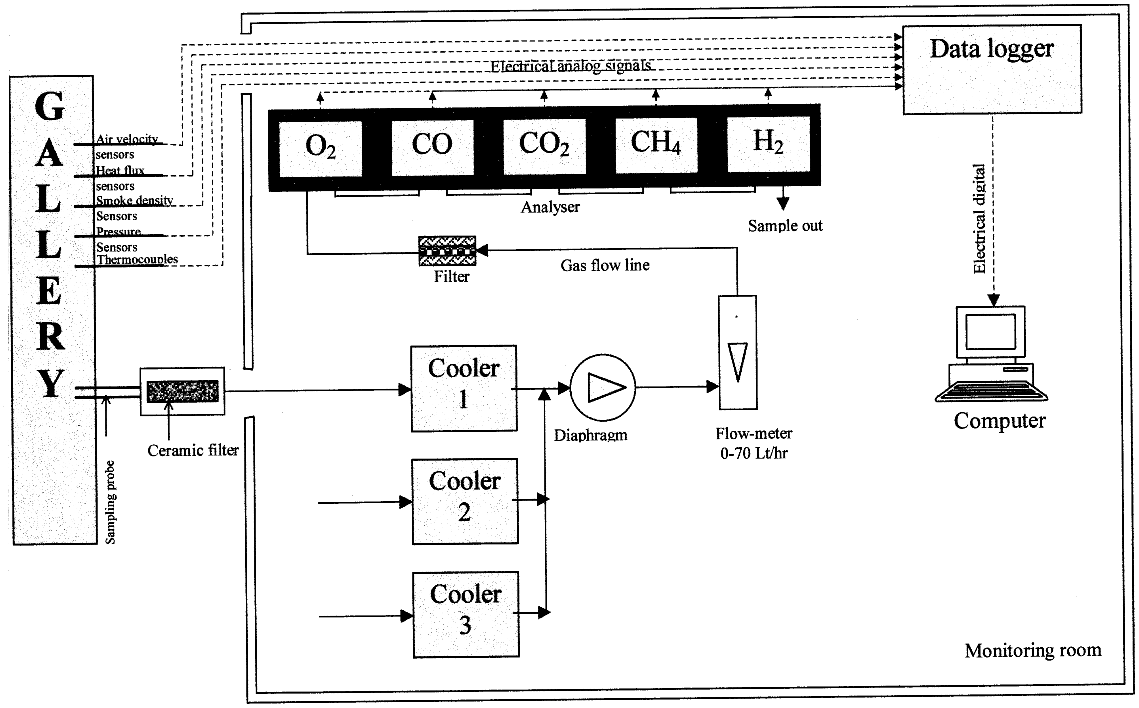


Fig. 3 — Sampling and Data Acquisition System

soaked in kerosene oil after establishing the desired air velocity through the gallery. For maintaining desired air velocity, opening of the shutter at second cross-cut was adjusted. For the 1st set of experiment, air velocity selected was 1 m/s, for the 2nd experiment it was 1.5 m/s while for the 3rd set it was 2 m/s. When coal in the roof, sides and floor caught fire at the initiation points, the entire instrumentation system was switched on so that all the desired fire parameters like, temperature, pressure, gas concentration, heat flux, air velocity and smoke density were continuously monitored. Data thus generated were recorded in the computer.

After monitoring of above parameters for 4-5 h in open fire condition, the effectiveness of fire suppression techniques viz., infusion of LN_2, infusion of HPHS nitrogen foam and water mist were tried separately in three sets of experiments in open and sealed conditions (Table 2).

Table 2 — Design parameters for experimentation

Parameters	1st set of experiments	2nd set of experiments	3rd set of experiments
Coal seam	Dobrana	Dobrana	Dobrana
Length of coal lining	22 m	22 m	22 m
Fire suppression technique in open fire condition	LN_2	HPHS N_2 foam	Water mist
Velocity of air	1 m/s	1.5 m/s	1.5 and 2 m/s
Infusion rate	500, 1000, 2000 L/h	200 m^3/h	33 L/min

Results and Discussion

After initiation of fire in the gallery, it gradually progressed towards downstream of the firing zone with time. When the intensity of fire was very high, heavy backlash with dark smoke with flame started coming out towards the entry of the gallery (Fig. 4). It was also observed that duration of backlash was about 5 min, recurring at an interval of 15-20 min. Gallery was divided into two distinct zones. Up to 1.4 m height from the floor of the gallery, airflow was normal, but in the rest upper portion of the gallery the airflow was reverse. This phenomenon is due to throttling or choking effect and thereafter backlash.

Dynamics of open fire was assessed by continuous monitoring of fire parameters for 4-5 h during each set of experiments. After that, different fire suppression techniques were employed in open fire condition. The effect of fire suppression techniques was assessed in terms of reduction in temperature and concentration of products of combustion (POC) gases.

Fig. 4 — Blazing fire with backlash

Liquid Nitrogen Infusion (LN_2)

In the first set of experiments, full-fledged fire was developed at around 12:15 h in the gallery. Infusion of liquid nitrogen was done from 17:00-21:30 h in open fire condition. Liquid nitrogen was injected in the beginning of the fire zone.

Injection of LN_2 has been carried out directly from the liquid nitrogen tankers with the help of a specially designed pressure attenuation system made of brass and connected to the tankers. The basic purpose of this attenuation system is to minimise the delivery pressure of LN_2, which is directly connected to the LN_2 tankers having a pressure of 6-7 bar. Delivery of LN_2 with minimum pressure was helpful in smooth flowing of LN_2 and gaseous nitrogen through the air stream in the model gallery and quantifying its effect along the fire zone.

Temperature

Before injection of LN_2 temperature in the gallery at locations A, B, C, D, F, G, H, I and J were 961, 830, 979, 901, 854, 952, 864, 987, and 609°C, respectively. After 2 h of injection of LN_2 @ 500 L/h the temperature at these locations decreased to 814, 756, 734, 762, 817, 791, 769, 839, and 620°C (Fig. 5). From the data, it is indicated that rate of reduction in temperature throughout the gallery was not uniform. It varied between 19-122°C/h, with an average rate of reduction in temperature of 66°C/h. The infusion rate

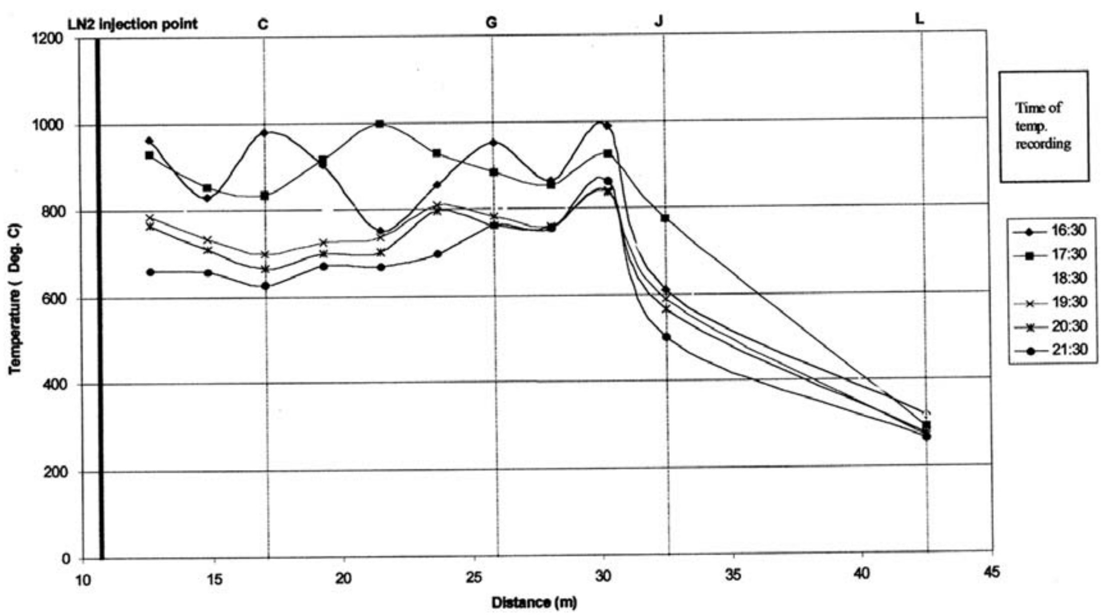


Fig. 5 — Effect of LN_2 infusion on temperature in open fire

increased to 1000 L/h and continued for about 1½ h. During this period, the rate of reduction in temperature along the gallery length varied in between 9-47°C/h, averaging 32°C/h. The rate of infusion had been further increased to 2000 L/h for 1 h, the rate of reduction in temperature varied between 3-105°C/h with an average value of 48°C/h. Thus, the rate of reduction in temperature was not proportional to the rate of infusion of LN_2.

Gas Concentration

After application of LN_2, the CO concentration at location C has been reduced from 2.70 to 0.098 per cent @ 0.809%/h and at location F it reduced from 3.62 to 0.098 per cent @ 0.755%/h, while at other locations it increased marginally (Table 3). On the other hand, CO_2 concentration increased @ 0.80, 1.60, 0.58, 0.56 and 0.29%/h at locations A, C, F, I and L, respectively.

Although there was reduction in temperature and CO concentration thereby indicating lowering of intensity of fire to some extent, but increase in CO_2 concentration at all locations indicates active stage of fire inside the gallery. Therefore, the infusion of LN_2 seems to be not very effective to control disastrous open fire.

HPHS Nitrogen Foam Infusion

In the second set of experiments, a full-fledged fire was developed at around 14:30 h. The infusion was carried out from 19:00 to 21:30 h @ of 200 m^3/h. In open fire condition, the infusion was done in the beginning of the fire zone.

Temperature

There was substantial reduction in temperature (251-662°C) along the gallery length in 2½ h (Fig. 6). The average value of this reduction in temperature was found to be 207°C/h or 3.44°C/min.

Table 3 — Effect of application of different fire suppression techniques on gas concentration

Locations	Percentage of gas concentration before and after infusion of LN_2									
	Before infusion					After infusion				
	CO	CO_2	O_2	CH_4	H_2	CO	CO_2	O_2	CH_4	H_2
A	0.019	2.00	17.60	0.00	0.00	0.098	5.43	9.00	0.00	0.00
C	2.70	1.49	2.09	0.00	0.00	0.098	8.00	6.15	0.00	2.017
F	3.63	4.49	11.33	0.26	0.00	0.098	7.19	15.36	0.00	0.00
I	0.00	3.96	17.34	0.00	0.00	0.098	6.64	16.28	0.00	0.00
L	0.00	1.13	19.89	0.00	0.00	0.20	2.50	18.58	0.00	0.00
Locations	Percentage of gas concentration before and after infusion of HPHS nitrogen foam									
	Before infusion					After infusion				
	CO	CO_2	O_2	CH_4	H_2	CO	CO_2	O_2	CH_4	H_2
A	0.098	1.82	18.59	0.05	0.02	0.098	1.86	18.99	0.00	0.00
C	0.040	5.46	15.71	0.00	0.00	0.289	1.86	19.79	0.00	0.00
F	0.722	15.13	2.66	0.54	0.235	0.397	3.08	18.09	0.00	0.00
I	1.02	11.54	9.58	0.80	3.74	0.20	1.71	19.55	0.00	0.23
L	0.60	6.43	13.88	0.00	0.00	0.20	0.40	20.80	0.00	0.17
Locations	Percentage of gas concentration before and after infusion of water mist									
	Before infusion					After infusion				
	CO	CO_2	O_2	CH_4	H_2	CO	CO_2	O_2	CH_4	H_2
A	0.06	0.25	19.89	0.097	0.049	0.00	0.227	19.19	0.097	0.01
C	0.00	3.30	15.30	0.00	0.00	0.00	0.65	20.20	0.00	0.20
F	0.00	8.70	4.40	0.00	0.00	0.098	1.60	19.30	0.00	0.059
I	1.90	7.79	3.77	0.00	2.60	0.098	1.70	14.46	0.00	0.17
L	1.88	10.89	2.39	0.00	1.40	0.268	2.20	19.49	0.00	0.00

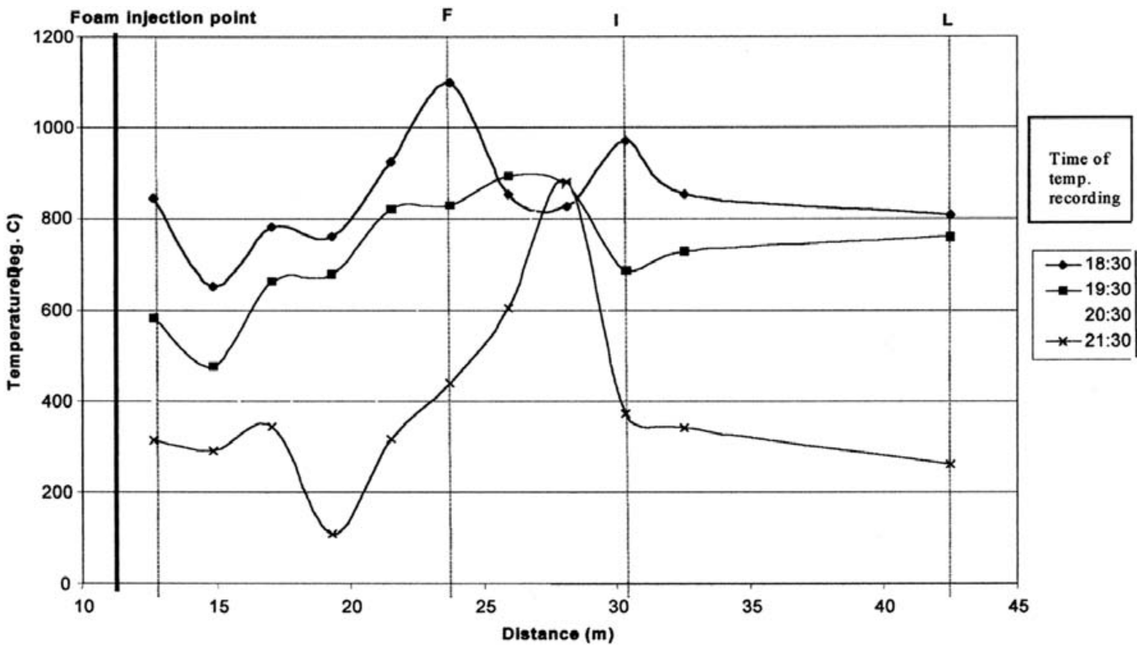


Fig. 6 — Effect of foam injection on temperature in open fire

Gas Concentration

After application of HPHS nitrogen foam, substantial reduction in CO and CO_2 concentration all along the gallery was noticed (Table 3). The gases like CH_4 and H_2 were found in negligible concentration. This indicates retardation in intensity of fire in the gallery. Hence, it shows that HPHS nitrogen foam is very effective in controlling underground open fire.

Water Mist Infusion

In the third set of experiments, a full-fledged fire was developed at around 12:00 h. Water mist was infused @ of 33 L/min at a distance of 5 m from the entry of the gallery. The infusion of water mist was started from 12:10 to 12:30 h and it was stopped from 12:30 to 16:30 h by switching off fan. Further the mist infusion restarted with switching on fan from 16:30 to 21:30 h.

Temperature

After only 20 min of infusion of water mist, the temperature along the axis of gallery was reduced between 0.5-10.7°C/min with an average value of 4.9°C/min. Therefore, the average rate of reduction in temperature becomes 294°C/h (Fig. 7).

To control open fire in mines, some experts opine that fan should be stopped, while others are against it. In view of the above the fan was switched off from 12:30 to 16:30 h. After switching off the fan for 4 h, temperature inside the gallery was reduced from 15 to 453°C in the fire zone with an average value of 41°C/h. The fan was switched on at 16:30 h keeping air velocity at 1.5 m/s. Again water mist infusion was started and it was continued for about 5 h. It has been observed that after mist infusion, the temperature has reduced substantially, i.e. between 141-618°C with an average value of 59°C/h.

Gas Concentration

After application of water mist the product of combustion gases like, CO, CO_2, CH_4 and H_2 have reduced substantially (Table 3). This substantial reduction in temperature and product of combustion gases is an indicative of suppression of fire in the gallery. Thus, water mist is also a very effective technique in controlling underground open fire. One of the great advantages of this technique is that after its application the Suspended Particulate Matter (SPM) concentration has drastically reduced and gone down to 19 mg/m^3, while in other two sets of experiments the SPM concentration has never gone below 200 mg/m^3. This substantial reduction in SPM concentration in the case of water mist infusion may enhance the visibility of the mine, which requires during fire fighting and rescue operations.

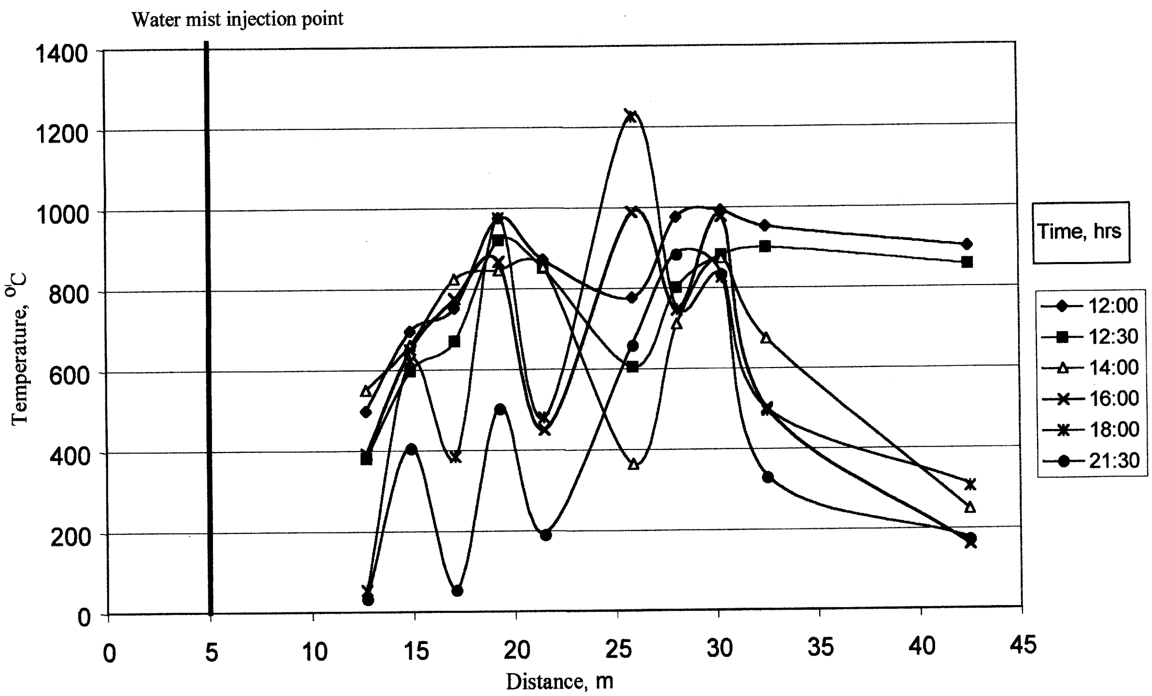


Fig. 7 — Effect of water mist on temperature in open fire

From the above discussion, it is shown that infusion of LN_2 is not very effective in controlling open fires, while the HPHS nitrogen foam could reduce temperature as well as gas concentration. Hence, this technique can be used to control open fires. During application of water mist it was noticed that the backlash with smoke and flames coming out from the gallery has been reduced drastically. Substantial reduction in gas concentration has also been observed. This reduction in gas concentration, SPM concentration and backlash prevented the fire to become disastrous. Therefore, water mist technique seems to have great potential to control devastating open fires.

Conclusions

The following facts emerged from the studies:

- LN_2 alone is not sufficient to control open fires. It can, however, reduce temperature to some extent.
- With the infusion of HPHS nitrogen foam on open fire, substantial reduction in temperature and gas concentration has been noticed. Therefore, foam appears to be a better technology for controlling open fires however, injection rate must be increased to control fire in actual mine condition.
- After infusion of water mist on the full-fledged open fire, the temperature and gas concentration along the axis of the gallery is reduced substantially.
- Among all these techniques, the water mist seems to be most suitable and cost-effective in controlling open fires. Apart from reducing the temperature and gas concentration (POC) along the axis of the gallery, with the infusion of water mist the backlash gradually diminished which was not possible by earlier two methods (LN_2 and HPHS nitrogen foam). Water mist has great potential to reduce SPM concentration, which is considered to be most dangerous for open fire.

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