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Modelstudy on dynamics of open fire in underground coal mines under varied air flow

A small scale model representing mine gallery has been designed, constructed and installed at Central Mining Research Institute, Dhanbad, India. The basic purpose of the model gallery was to study the complex phenomenon of open fires in simulated underground mine condition.

The model is 19 m long having two segments. The first one is 10m long insulated rectangular segment having cross section of 45 cm × 57 cm. Insulation lining of fire bricks leaves space of 13 cm × 13 cm for air flow through the model. The second segment is 9m long, 30 cm diameter, circular section having a centrifugal exhaust fan installed at its end.

Two sets of experiments were carried out in the model at air velocities 1. 0 m/s and 1.5 m/s using coal blocks of 5 cm thickness lined in all four inner sides of the model. The coal lining was made for a length of 3 m starting from 1 m of the model entry. After establishing the desired air flow inside the model, fire was initiated artificially at the begining of the coal zone. Governing parameters such as gas concentration, temperature, pressure drop across fire zone, air velocity and dust concentration inside the model were continuously monitored for about 8 to 9 hours.

The paper highlights the salient features of the model, instrumentation system, experimental procedure, important observations, results of the experiment and correlation of findings with particular reference to gas concentration, temperature and fire size.

Introduction

Outbreak of fire in open gallery of a mine causes large scale damage to property and loss of precious lives. Majority of deaths arising during fire and explosion are not caused by burning or blast effect but by inhalation of toxic gases particularly carbon monoxide. The fire in open gallery or in working district distribute the resultant combustion products quickly and directly throughout the mine.

Fire fighting and rescue operations are dampened by serious problems like generation of toxic gases, heat, poor visibility and chances of fire damp explosion.

An open fire in the gallery causes sharp increase in temperature which resulted in expansion of air producing two distinct effects. First, the expansion takes place in both directions along an airway. The tendency of expansion against prevailing direction of air flow produces a reduction of air flow due to throttling effect. Secondly the decrease in density results in the heated mass becoming more buoyant and causes local effect as well as change in the magnitude of natural ventilation energy due to buoyancy effect.

Extensive research work has been done in small, intermediate and large scale models to understand the complex phenomenon of open fire in mines and its effect on mine ventilation [1-5]. Few experiments have also been conducted in actual mine condition to verify the findings of model study. Barabara experimental mine of Poland is one such example.

In India, no such facility was available to study and understand this complex phenomenon of open fire. To bridge this gap a small scale model was constructed and installed at Central Mining Research Institute, Dhanbad, India. Two sets of experiments at air velocities 1.0 m/s and 1.5m/s were conducted in this model using coal of Dobrana seam of Raniganj coalfields.

The paper highlights the important features of the model, instrumental set-up, experimental procedure, experimental findings and correlation between fire size, temperature and generation rate of combustion products (CO and CO_2) in the model gallery.

Design of the model

The 19 m long model consists of two parts. First part is made of four segments of 2.5 m each of rectangular cross section having total length of 10 m, called insulated duct and the second one is 9 m long circular section of 0.3m diameter, called uninsulated duct. The model is a prototype underground mine gallery.

The insulated duct having an internal cross section of 45 cm × 57 cm is 10 m long. The duct is made of 0.31 cm thick metal sheet with 2.5 m long removable roof cover. It is completely lined inside with fire bricks leaving a space of

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13cm × 13 cm at the centre for entry of air. The coal zone was 3 m long and prepared by a lining of 5 cm thick coal slabs along the insulated floor, roof and sides. The circular portion of the duct is of 0.3 m internal diameter and is made up of 0.31 cm thick steel sheet. The circular duct is connected to a centrifugal exhaust fan for discharge of flue gases to the atmosphere through a chimney. The duct is also provided with the six number of openings which can be regulated for entry of fresh air into the system for cooling the fan and dilution of the pollutant in the flue gases and adjustment of air flow rate through the duct at predetermined levels. For sealing and control of air through the duct two shutters, one each at either ends of the insulated duct have been provided. The entire duct is supported on angle iron stand so that it remains horizontal. A sectional view of the model has been shown in Fig.1.

Instrumentation

Details of the instruments used in the model qallery have been shown in the Table I

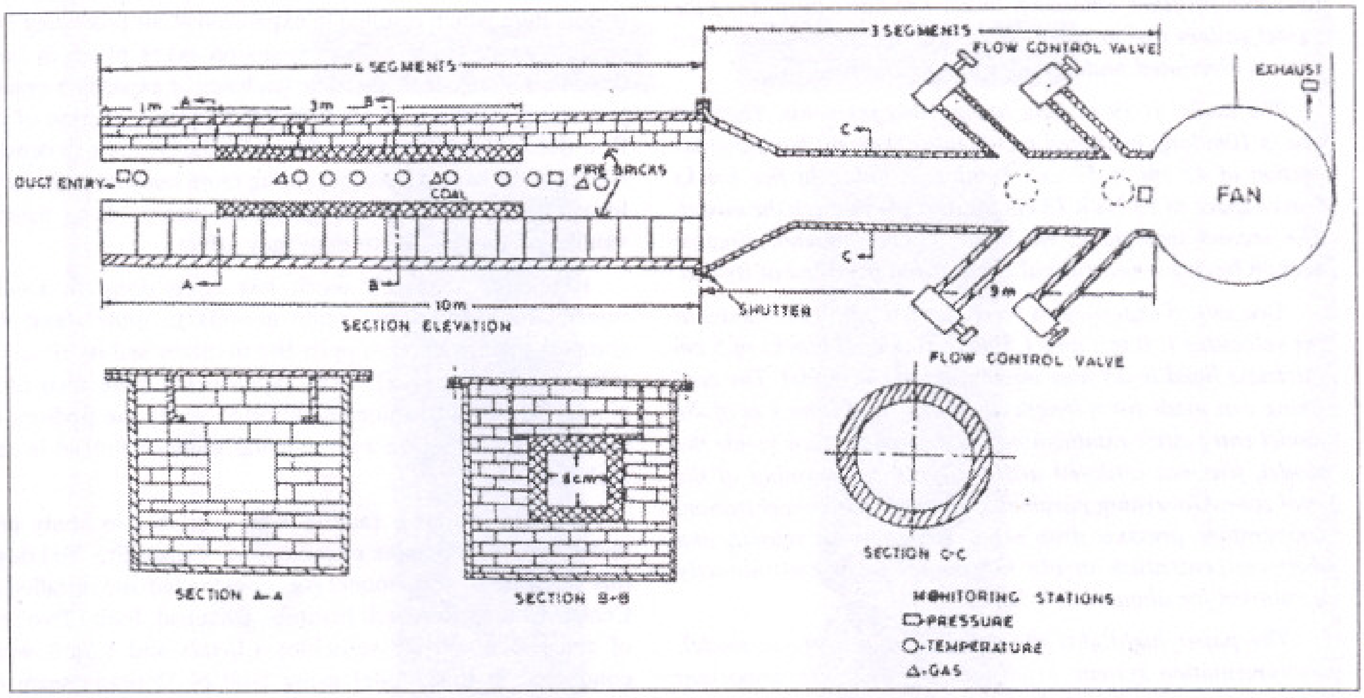

Fig.1 The model

TABLE I DETAILS OF INSTRUMENTATION

Instrument type	Function	Locations*
• Digital temperature recorder with Cromel-Almel thermocouple, range - 0-1200°C and mercury thermometer of - 250°C	Monitoring the temperature of air inside duct.. Coal and brick lining temperature were also recorded	0.3, 1.5, 2.05, 2.5, 3.05, 3.40, 3.99, 5.15, 7.11, and 8.52 m from duct entry
• Betz manometer having accuracy of 0.1 mmwg and Incline manometer .05 mmwg accuracy	Monitorina of pressure drop	Across the fire zone and the fan
• Pitot tube and incline manometer	To measure the velocity of air flowing through the duct	At the entrv of the duct
• Suction pump of 20 litre/min capacity	To draw the gas samples from inside the duct	At 1.5, 3.4 and 7.1 m from duct entry.
• Multi-gas analyser, Haldane and Graham Lawrence gas analvser	Analysis of gas samples collected from inside the duct	The instruments were kept in laboratory for analysis purpose
• Standard stack sampling system with thimble type filter paper	To mnnitnr the SPM	About 3 m downstream from the end of rectangular duct

* Locations of the sensors are also shown in Fig.1.

Experimental procedure

Coal slabs of 5cm thickness was prepared from a big coal block (1m × 1m × 0.8m) of Dobrana seam of Raniganj coalfields. The slabs were lined on all four inner sides of rectangular duct up to 3 m which was started from 1 m from the duct entry. A set-up was fitted at the entry of the duct to continuously monitor the air flow through it. Monitoring arrangements were fitted along the duct. Air flow through the duct was established by starting the fan and air velocity was adjusted to a predetermined value by means of shutters provided at both the ends of the rectangular duct. Fire was initiated just at the starting point of coal lining by igniting a small pieces of coal of the same block through electric heating coil. Immediately after initiation of fire, monitoring of the following parameters commenced and continued till sealing of the duct.

- velocity of air at the entry of the duct
- pressure drop across fire zone and fan pressure
- air temperature in the model gallery at a distance of 0.3, 1.5, 2.06, 2.5, 3.05, 3.40, 3.99, 5.15, 7.11 and 8.52m from the duct entry. Temperature of coal and fire bricks were also monitored at 1.5 m from duct entry
- gas concentration at a distance of 1.5, 3.4 and 7.1 m from the duct entry
- dust concentration at a distance of about 3 m down stream of fire from the end of rectangular duct

Correlation between fire size, gas concentration and temperature (theoretical criteria)

The suppression of fire may often depend critically upon the fire size, gas concentrations and temperature. More or less all these parameters are interrelated hence calculation of fire size and its correlation with other parameters is very important to control/combat the fire. To evaluate all these parameters, two sets of experiments were conducted in a small scale model at two different values of air velocity and calculations were made on the basis of earlier established equations given by various researchers [1-5].

According to Litton et. al. (1987) the total heat release rate or the fire size, Q can be expressed as a function of the rates of the production of CO and CO_2 for given coal by the following relationship:

$$Q(kW) = (HC/KCO_2)\,G\,CO_2 + (HC - HCO/KCO)\,G\,CO \qquad [1]$$

Where,

Q = Total heat release rate

HC = Heat of complete combustion of coal = 31.1 KJ/g

KCO_2 = Stochiomatric of CO_2 = 2.86 g/g

HCO = Heat of combustion of CO = 10.1 KJ/g

KCO = Stochiomatric yield of CO = 1.82 g/g

GCO_2 & GCO = Generation rate of CO_2 and CO respectively in g/sec.

By substituting the above value the equation 1 can be written as

$$Q = 10.87\,GCO_2 + 11.53\,GCO \text{ kW} \qquad [2]$$

if generation rates of CO_2 and CO was measured the fire size can be calculated.

CALCULATION OF GENERATION RATE OF CO AND CO_2

According to Margret R. Egan (1987) the generation rates of carbon monoxide and carbon dioxide in the ventilation system measured in g/sec, are related to, the bulk average concentration of these gases down stream fire by expression:

$$G\,CO_2 = V^* A^* d\,CO_2 {}^* CO_2 \text{ g/sec} \qquad [3]$$

$$\text{and } GCO = V^* A^* dCO^* CO \text{ g/sec} \qquad [4]$$

V = Air velocity m/sec

A = air way cross section sq.m

dCO_2 = density of carbon dioxide = 1.97×10^{-3} g per cu m per PPM

dCO = density of corbon monoxide = 1.25×10^{-3} g per cu.m per PPM

CO_2 and CO are the increase in the bulk average concentration of CO_2 and CO in PPM above their initial ambient levels measured on the immediate down stream of the fire. From the above expression it is evident that monitoring of CO_2 and CO can provide continuous information of the fire size or heat release rate.

CONVECTIVE HEAT

It is observed that the part of the total heat generated is lost due to conduction through the strata while rest of the total heat release flowing through air stream is known as convective component, Qc and can be expressed as:

$$Qc = d^*C^*V^*A^*\,\Delta T \qquad [5]$$

where,

d = density of the air at ambient temperature = 1.197×10^{-3} g/cu.m at T=293K

C = specific heat of air = 1.142×10^{-3} KJ/gK

ΔT = rise in temperature of the air due to fire = Tb - To

Where,

Tb = absolute temperature across the fire zone and

To = incoming cold gas temperature, °K

V = velocity of air, m/sec

A = cross section area of the duct in sq.m.

The heat release rate or fire size, rate of generation of CO_2 and CO and convective component of total heat release rate with the help of equations [2-5] at air velocity 1.0 and 1.5 m/s has been calculated and depicted in Tables II and III. It may be noted that the cross section of the gallery is 0.0064 sq.m. and incoming cold gas temperature was 30°C.

Results and discussion

Two sets of experiments were conducted at air velocity 1.0 and 1.5 m/sec. The monitoring of desired parameters as mentioned earlier was carried out for about 8 hours during the burning of coal. Results have been depicted in Figs.2-9. The important findings of these results have been discussed in the following sub headings:

Temperature

Temperature profile along fire zone at air velocities 1.0 m/sec and 1.5m/sec have been indicated in Figs.2 and 3 respectively. It has been revealed from Fig.2 that after 30 minutes of burning of coal temperature measured inside the duct at a distance of 1.5m from the duct entry was 773°C and attains a maximum value of 790°C after two hours of burning of coal and it decreases with time up to 600°C before sealing the duct. Further the initial temperature downstream of the fire (at a distance of 3.4m from the duct entry) was low but it increases gradually with time and attains a value of 875°C. It is evident from Fig.3 that after 30 minutes of

Table II Relation between generation rate of gases, fire size and temperature at air velocity 1.5 m/Sec. at a distance of 1.5 m from the duct entry

Time after initiation of fire in(min)	Temp °C	Generation rate of CO_2 (g/sec)	Generation rate of CO (g/sec)	Calculated value of total heat release rate (kW)	Calculated value of convective heat (kW)	Convective heat in (per cent)
60	735	0. 842	0. 267	12. .23	6.16	50.36
90	732	1. 26	0. 038	14.13	6.14	43.45
120	790	1. 026	0. 018	11.36	6.64	58.45
170	737	1. 580	0. 034	17.56	6.18	35.19
320	684	1. 042	0. 0017	11.52	5.72	49.65
400	680	0. 675	0. 019	7.55	5.68	75.23
450	680	1.640	0. 021	18.06	5.68	31.45
490	600	1.590	0.025	17.57	4.98	28.34

Average total heat generation rate during the experiment = 13.74kW
Average convective heat during the experiment = 46.51 ner cent
Total heat released during experiment (eight hours of burning of coal) = 395712 K Jule

Table III Relation between generation rate of gases, fire size and temperature at air velocity 1.5 m/Sec. at a distance of 1.5 m from the duct entry

Time after initiation of fire in(min)	Temp °C	Generation rate of CO_2 (g/sec)	Generation rate of CO (g/sec)	Calculated value of total heat release rate (kW)	Calculated value of convective heat (kW)	Convective heat in (per cent)
30	876	0.019	-	-	-	-
90	940	2.58	0.279	31.26	11.94	38.19
130	1060	2.42	0.496	32.02	13.51	42.19
160	1058	1.121	0.286	15.48	13.49	87.14
200	1074	2.02	0.568	28.50	13.70	48.07
240	1095	3.34	-	36.30	13.97	38.48
270	1095	2.78	0.272	33.35	13.97	41.88
340	1060	1.47	0.059	16.66	13.51	81.09

Average total heat generation rate during the experiment = 27.65 kW
Average convective heat during the experiment = 53.86 per cent
Total heat released during experiment (5-6 hours of burning of coal) = 563396 K Jule

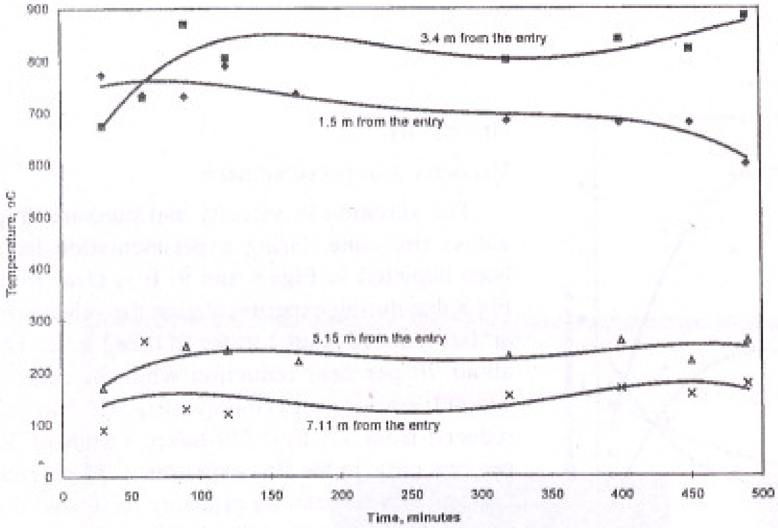

Fig.2 Air temperature inside duct at 1m/sec. velocity

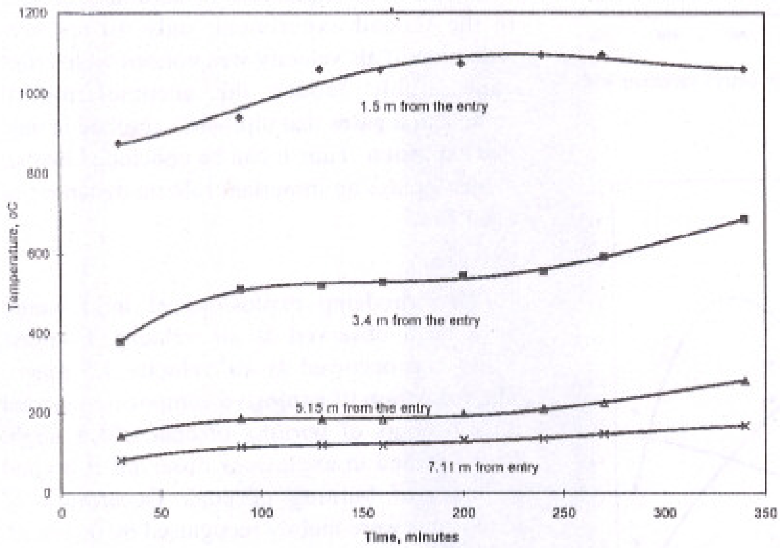

Fig.3 Air temperature inside duct at 1.5m/sec. velocity

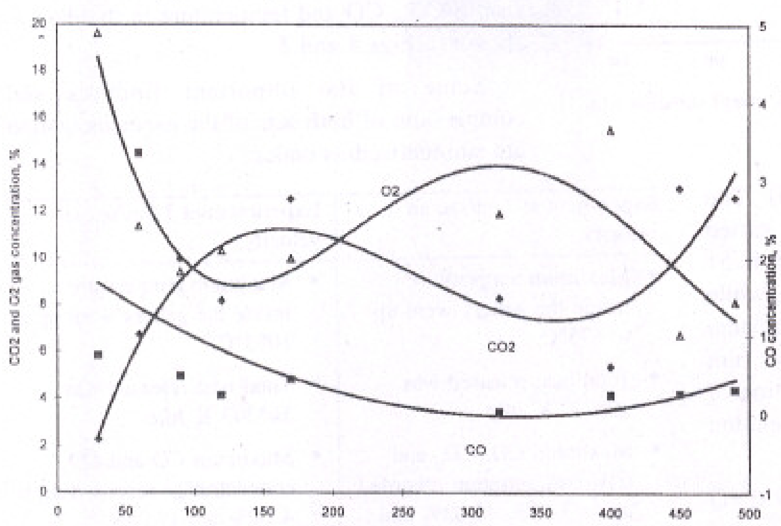

Fig.4 Gas concentration (mesured at 1.5m from the entry) variation with time at 1m/sec. air velocity

burnining of coal the temperature inside the duct at a distance of 1.5m from the duct entry was 876°C and gradually increases with time and reaches a maximum value of 1095°C after 4 hours of burning of coal. Subsequently the temperature followed the decreasing trend with time. It may be noted that lower value of temperature was recorded downstream of the fire (at 3.4 m from the duct entry) in comparison to the temperature measured at a distance of 1.5m from the duct entry during experimentation.

Gas composition

Concentration of gases measured at a distance of 1.5 m and 3.4 m from the duct entry at air velocities 1 m/sec. and 1.5 m/sec. have been depicted in Figs.4-7. There is considerable scattering in gas compositions and it has been observed that when CO and CO_2 concentration starts increasing the O_2 concentration follows the opposite trend. From critical analysis of the results as revealed in Fig.4 that after 1.5 hours of burning of coal O_2 concentration goes down to 9% while at the same time CO_2 and CO concentration increases to about 9 and 1.5 per cent respectively. While measuring the gas concentration at a distance of 3.4 m from the duct entry (Fig.5) it has been observed that the maximum CO_2 and CO concentration goes up to 11.73 per cent and 1.75 per cent respectively. The maximum CO_2, CO and CH_4 concentration during experimentation goes up to 13.03, 3.34 and 5.11 per cent respectively at 1 m/sec. air velocity. Further from Figs.4 and 5 it is evident that after 7.5 hours of burning of coal there is sharp increase in CO, CO_2 concentration and decrease in O_2 concentration. This is an indicative of flaming combustion stage of fire. When the experiment conducted at 1.5 m/s air velocity (Fig.6) the gas concentration follows the same trend as earlier but the maximum concentration of CO_2 and CO measured up to 17.65 per cent and 4.74 per cent respectively at a distance of 1.5 m from the duct entry. Further the maximum concentration of CO and CO_2 downstream of the fire i.e. at a distance of 3.4 m from the duct entry recorded are 1.08 and 6.25 per cent respectively.

Heat release

At 1 m/sec air velocity the maximum heat release rate at a distance of 1.5 m inside the duct was about 18.06 kW after 7-8 hours of burning of coal (Table II). In case of 1.5 m/sec air velocity the maximum heat release rate was about 36.30 kW after about 4-5 hours of burning

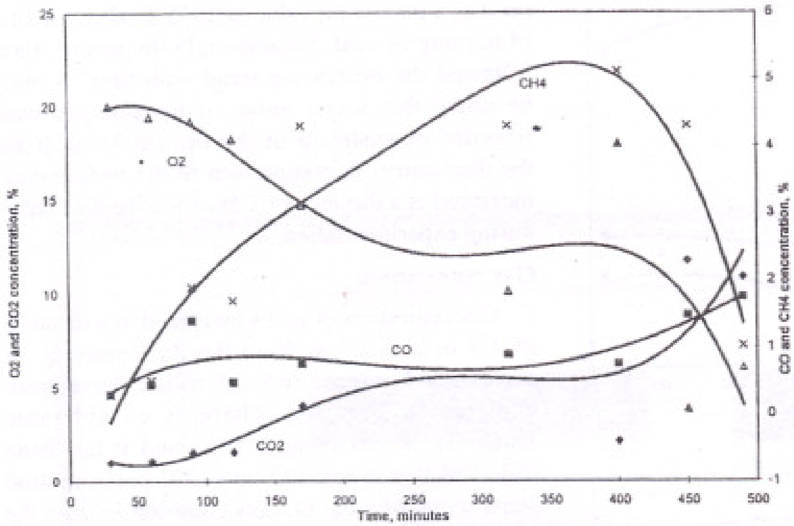

Fig.5 Gas concentration (mesured at a distance of 3.4m from the entry) variation with time at 1m/sec. air velocity

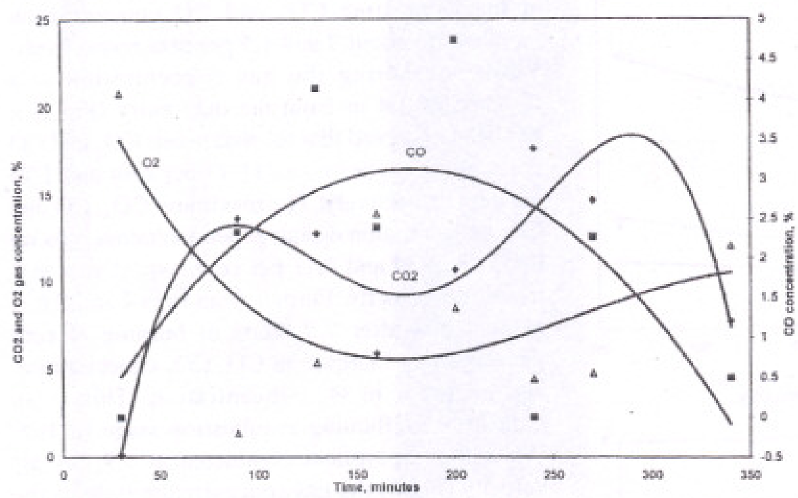

Fig.6 Gas concentration (mesured at a distance of 1.5m from the entry) variation with time at 1.5m/sec. air velocity

of coal measured at the same distance (Table III). The convective component of the total heat released varied between 28 and 75 per cent with an average value of 46.51 in case of experiment conducted at 1 m/s air velocity, while in case of 1.5 m/sec air velocity the convective component of total heat release rate varied between 38 and 87 per cent with an average value of 53. 86 per cent. The variation of convective component in both the cases conform the relation given by

Litton, (1987) which states that Qc = 0.5Q to 0.9Q depending upon the fire size where Qc and Q are convective heat and total heat release respectively. The total heat released during experimentation (eight hours) at 1m/s air velocity was 3,95712 K Jule while at air velocity 1.5 m/sec it was 5,63396 K Jule only after 5-6 hours of burning of coal. It seems from the results that generation of heat increases with increase in air velocity.

Velocity and pressure drop

The variation in velocity and pressure drop across fire zone during experimentation have been depicted in Figs.8 and 9. It is clear from Fig.8 that during experimentation the velocity of air has reduced from 1 m/sec to 0.282 m/sec i.e. about 70 per cent reduction while in case of second set of experiment (Fig.9) velocity reduced from 1.5 to 0.779 m/sec i.e. about 40 per cent only. In the first experiment, 70 per cent reduction in air velocity probably facilitated the accumulation of combustion gases which resulted in two explosions of mild nature while in the second experiment, only 40 per cent reduction in air velocity was noticed which may considerably reduce the accumulation of combustion gases that ultimately resulted in only one explosion. Thus it can be concluded that air velocity plays an important role on dynamics of open fire.

Explosion

Two firedamp explosions of mild nature have been observed at air velocity 1 m/sec. while one occurred at air velocity 1.5 m/sec. The formation of explosive composition started after 6 hours of burning of coal which might have resulted in explosions observed at around 8 hours of burning of coal. Occurrence of explosions were mainly recognised by its sound. However, it was also corroborated by sudden rise in CO_2, CO and temperature in the duct as shown in Figs.4 and 5.

Some of the important findings and comparision of both sets of the experimentation are summarised as under:

Experiment at 1 m/sec air velocity	Experiment at 1.5m/sec air velocity
• Maximum temperature inside the gallery went up to 875°C.	• Maximum temperature inside the gallery went up to 1095°C
• Total heat released was 395712 K Jule	• Total heat released was 563393 K Jule
• Maximum CO, CO_2 and CH_4 concentration recorded up to 3.34%, 13.03% and 5.10% respectively	• Maximum CO and CO_2 concentration recorded up to 4.74% and 17.05% respectively
• 70% reduction in air velocity recorded	• 40% reduction in air velocity recorded
• Two fire damp explosion of mild nature	• One fire damp explosion of mild nature

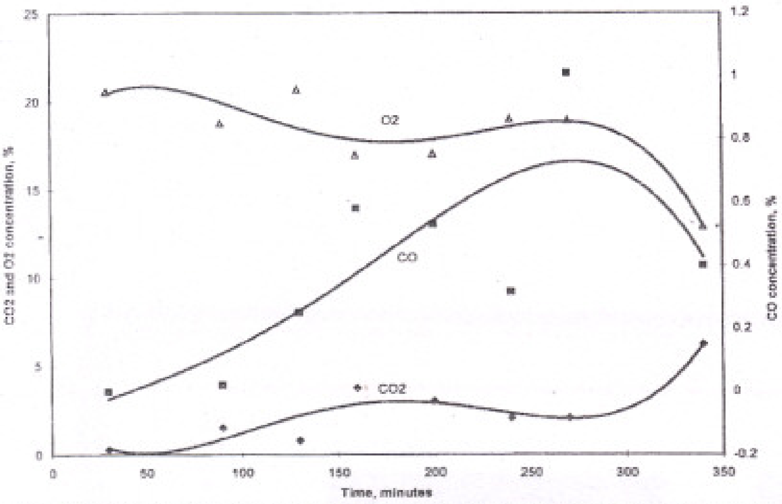

Fig.7 Gas concentration (mesured at a distance of 3.4m from the entry) variation with time at 1.5m/sec. air velocity

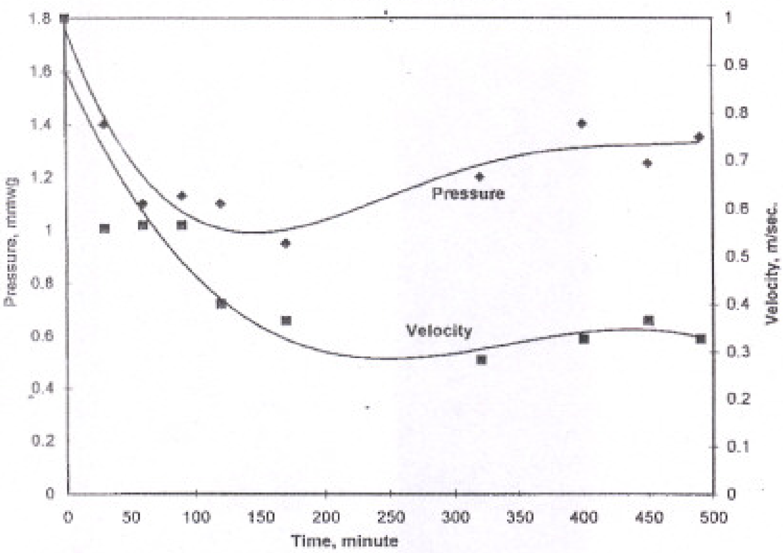

Fig.8 Variation in air velocity and pressure with time at 1m/sec. air velocity

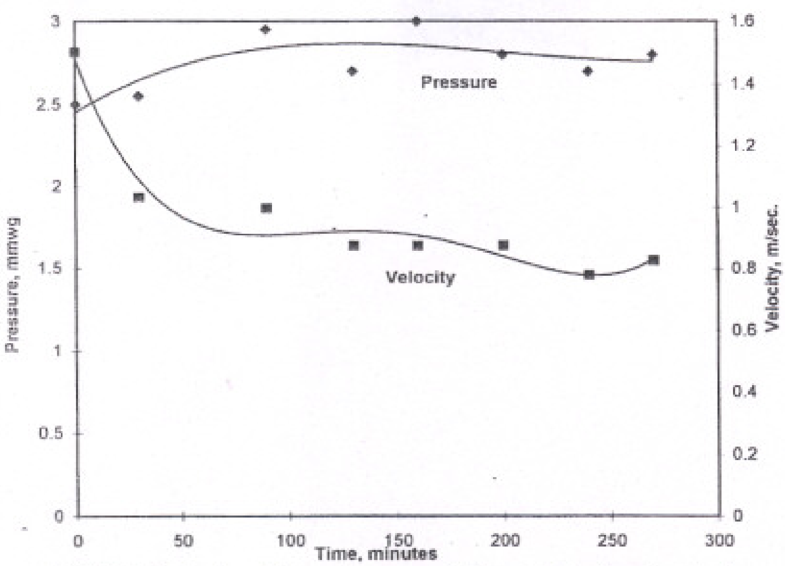

Fig.9 Variation in air velocity and pressure with time at 1.5 m/sec. air velocity

Conclusion

Following conclusions may be drawn from the results of two sets of experiments.

- Generation of CO, CO_2 and heat release rate are inter-related and directly proportional to temperature and air velocity which can give valuable information regarding status of fire and its dynamic behaviour.
- Explosion can occur in open fire condition and it has some relation with air velocity.
- Throttling effect of fire on mine ventilation is expected to decrease with increase in air velocity.
- Rate of generation of toxic/combustible gases is likely to increase with increase in air velocity.
- Heat release rate and temperature may increase with increase in air velocity.

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