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Optimization of ventilation system for prevention of spontaneous heating/fire during extraction of thick coal seam – a CFD approach

The developed thick coal seams locked on standing bord and pillar development with a low percentage of extraction has been an enduring problem for Indian geo-mining condition due to strata control issues, methods of mining, equipment selection, ventilation and spontaneous combustion. The occurrences of goaf fire and explosions due to rise in goaf ignition temperature causes substantial property losses and casualties all around the world. It is a threat to the underground coal mine safety. As such no guidelines or methodologies are available for solving the problems of spontaneous heating/fire rising due to depillaring of thick coal seams. The paper addresses, study related to prevention and control of spontaneous heating/ fire in depillaring panels of thick seam mining using laboratory experiments, calculating goaf ignition temperature and computational fluid dynamics (CFD) techniques. The objectives of CFD simulation study is to find out the minimum air quantity requirement for the panel to maintain safe workplace environment and optimize the number of intakes and returns of ventilation system for prevention of spontaneous heating in goaf areas. Field investigations have been carried in Khottadih colliery of Eastern Coalfields Limited (ECL), Sanctoria (West Bengal), India. Laboratory study and field investigation postulates that coal is more prone to spontaneous heating. The simulation study reveals that partial stowing with the incombustible material in the goaf area up to a height of 100 cm is beneficial to prevent spontaneous heating due to roof fall with an air quantity of 2100 m^3/min maintaining three intakes and two return airways.

Keywords: *Spontaneous heating, thick coal seam, goaf ignition temperature, computational fluid dynamics (CFD)*

Introduction

In India, thick coal seams (>4.8m, as per Coal Mine Regulation 2017) are developed by bord and pillar method with a very low percentage of extraction leading to a loss of the substantial amount of good quality coal in roof and pillars [1]. As per a recent estimate, the increased demand for coal in India for 2020 will be one billion tonnes[2]. Safe liquidation of the thick seam from underground coal mine would contribute a share to meet this demand. Extraction of thick coal seams has been a chronic problem for Indian geo-mining condition due to strata control issues, methods of mining, equipment selection, ventilation and spontaneous combustion. In addition, planning the size of a panel for depillaring is mainly based on the incubation period of the panel. For practical utility incubation period of a panel is mainly being estimated on the basis of history/observations taken in past panels or even neighbouring mines in India. It has been observed that the incubation period is influenced from case to case basis. In some cases, it has been reduced by more than half by sudden heating in goaf after the occurrence of main roof fall [3]. The goaf ignition temperature (GIT) produced due to roof fall is a threat to the underground coal mine safety [4]. The occurrences of goaf fire and explosions cause substantial property losses and casualties all around the world. The incidences of GIT have been reported all over the world with a maximum number of cases in China. A total of 26 goaf fire and explosion incidents were reported in India for last century. Effective control measures can be developed to limit the friction distance and friction speed associated with roof falls in the goaf. Therefore it is imperative to avoid the development of an incendive ignition source, which can be developed by keeping the methane-air admixture beyond the explosive range. These control measures include forced or induced roof caving, ventilating goaf areas for dissipation of heat and rapid goaf seal-off [5]. It reveals from other different literature that too little ventilation would not support aerial oxidation, and too high

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ventilation would not allow accumulation of heat [6]. The optimum ventilation level for a particular mine would depend on the heat transfer conditions [7, 8]. Hence high ambient temperature conditions caused due to geothermal gradient, presence of hot springs or fire in adjoining areas increases the risk of spontaneous heating. In this case direction and strength of air leakage path feeding to the fire depends on pressure difference and drought created by fire [9]. Diurnal change in barometric pressure can also further aggravate this. In addition the intrinsic parameters of coal with the help of external factors i.e. ventilation parameters, extraction sequences, seam thickness, adiabatic compression of the air under a fall of large aerial extent increases the propensity of coal to spontaneous heating and some cases initiate a gas or coal dust explosion in goaf [10].

In the present scenario, the method or guidelines are yet to be developed for solving the problems like strata management and control of fire during depillaring of the thick coal seam (5.34m). The paper describes study related to prevention and control of spontaneous heating/fire in depillaring panels of thick seam mining using laboratory experiments, calculating goaf ignition temperature and computational fluid dynamics (CFD) techniques. Field investigations have been carried out to address the above issues in Khottadih colliery, Eastern Coalfields Limited (ECL), Sanctoria, West Bengal, India.

TABLE 1: HISTORY OF DEPILLARING IN R-VI SEAM

Name of the panel/sub panel	Air quantity (m^3/min)	Whether fire occurred or not	Duration of the panel
B4A panel	1730	Yes	140 days
B4B panel	1780	Yes	110 days
B3B (lower portion)	1620	Yes	115 days
B3B (upper portion)	1690	Yes	46 days
B5A (upper portion)	1710	No fire	110 days
B5B (lower portion)	1850	No fire	104 days
B6	1500	Yes	129 days

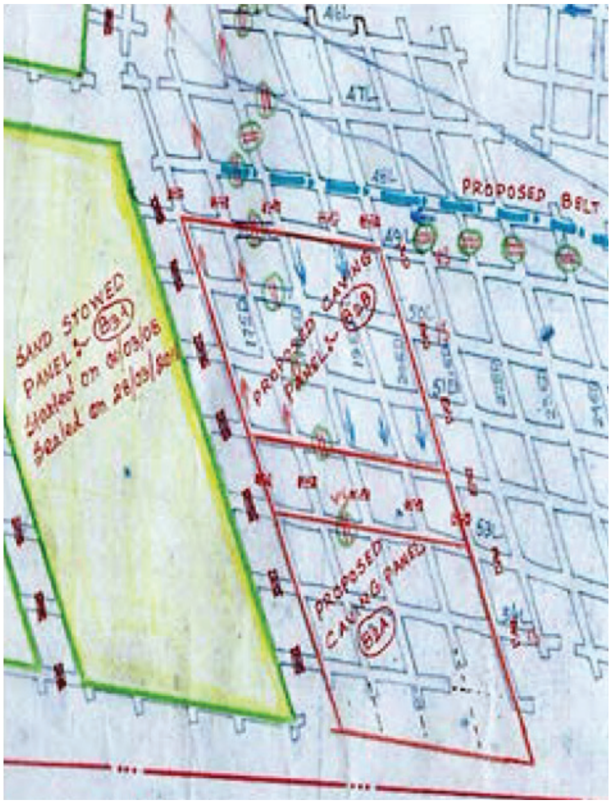


Fig.1 Mine plan of panel B2A of seam VI of Khottadih colliery, ECL

Experimental methods

DETAILS OF STUDY AREA

Khottadih colliery of ECL is situated about 102 km away from Kolkata having latitude 23.7264N and longitude 87.2397E. Its geological block is located in the north-eastern part of the Raniganj coalfields (RCF). RCF is extended to an area of 1530 km^2 spreading over 107 operating mines out of which 89 are underground mines and remaining 18 are opencast mines. Seven major coal seams, viz. R-VII, R-VIIA&B, R-VI, R-V, R-IV, R-III and R-II occur within this block. The R-VI seam (locally named as Bonbahal) of 5.4m thick has dipping 1 in 10 which is developed along the floor. The mine is suffering from the acute problem of spontaneous heating/fire in depillaring panel even with conservative planning of panel size. The occurrence of fire in the depillaring panel has been observed within 46 days to 140 days from the start of a panel or sometimes after one month of occurrence of main fall (Table 1). Mine management is not in a position to suitably design the panel size due to wide variation in incubation period in their earlier extracted panels. Panel B2A in RIV seam has been selected for studying in this research paper. The panel B2A in RVI seam has been extracted by depillaring with caving to study the spontaneous heating problems during depillaring operation. The panel containing 12 pillars located between 56L-20D and 56L-16D (Fig.1) has been developed by bord and pillar pattern along floor leaving 1.5 m coal in the roof. The thickness of RVI seam is 5.34m and the location of the subpanel is between 53L to 56L and 16D to 20D. Size of a single pillar is 30m*30m and height of extraction is 5.34m. Depth of the seam is 81-100m and its gradient is 1 in 10. Coal reserve is around 49000 tonne and it is degree II gassy mine.

LABORATORY STUDIES

Six coal samples were collected from the panel following channel sampling procedure and brought to the laboratory in sealed condition for analysis. The intrinsic parameters of coal, viz. onset temperature of differential scanning calorimeter, critical oxidation temperature, crossing point temperature and ignition point temperature have been determined using a standard set up, installed in the laboratory. The average value of moisture content, ash, volatile matter content and fixed carbon was found to be 5.71%, 15.05%, 32.31% and 46.91% respectively. The results indicate that the value of moisture content is slightly higher than the critical value i.e. 5-% which indicates that coal is susceptible towards spontaneous heating [11]. The average value of volatile matter (VM) content was found to be of the order of 32.31% which indicate that the coal contains high VM content that may facilitate the ignition process during roof fall. The onset temperature and critical oxidation temperature of coal were 64.4ºC and 65ºC respectively which indicate low oxidation temperature. The crossing point and ignition point temperatures of coal sample were found to be 116ºC and 163ºC respectively. The laboratory investigation results reveal that coal is highly prone to spontaneous heating/fire.

GOAF IGNITION TEMPERATURE STUDIES

Goaf ignition temperature (GIT) arises due to frictional heat from roof fall is a great threat to the underground coal mine safety. The falling slab of roof produces movement of air which causes wind blast due to air compression. Further, the slab creates frictional heat at the floor. When air is compressed beneath a falling mass in a bounded system (no leakage) then it is contained completely in the space under the falling materials (Fig.2) [4]. If there are no frictional effects, the net force exerted on the falling mass arises due to the combined effects of its weight and the pressure difference across it. Let us assume the compression process undergone by the air beneath the falling slab. The process is essentially adiabatic as there is very little time for heat transfer to occur between rock surfaces and the air during the compression which follows the law:

$$PV^k = constant = C \qquad \dots (1)$$

where, P = air pressure (Pa), V = volume of gas (m^3), k = the adiabatic index (1.4 for dry air), C' = constant.

However, $V = A \times zm^3$ ... (2)

where z = distance between the floor and the falling roof (m); A = plan area of the falling slab (m^2).

The constant, C, can be determined from the initial conditions, $P = P_0$, $z = z_0$ then C can be determined.

$$C = P_0 z_0{}^k \qquad \dots (3)$$

where P_0= air pressure over the falling slab (Pa).

The corresponding air temperatures are given by the adiabatic process and the equation is as follows:

$$T = T_0 \left[\frac{P}{P_0}\right]^{\frac{k-1}{k}} K \qquad \dots (4)$$

where, T = absolute temperature under the falling block (K); T_0 = initial temperature when roof fall commences (K); P = air pressure under the falling slab (Pa), P_0 = Initial atmospheric pressure.

Absolute temperature can be tracked numerically to show the variations of roof height (z), pressure (P), and temperature (T_0) with respect to time (t) where initial atmospheric air pressure (P_0) = 100 KPa; initial ambient temperature = 32ºC (T_0 = 293K). By changing the goaf height into three different heights i.e. extracted height of coal (z_o) = 5.4m for the panel and to assume other two heights i.e. 4.0m and 3.0m goaf ignition temperatures were determined to assume floor gap of 10cm. The results shown in Fig.3 reveal that expected GIT for a height of 5.4m, 4.0m and 3.0m would be of the order of 157, 140 and 125ºC respectively considering a loose coal dust layer of 10cm on the floor. Incidentally, the crossing point temperature of coal is 116ºC, therefore it is most likely to initiate heating/fire due to roof fall in the goaf. The results also reveal that to bring down the friction ignition temperature below CPT (116ºC) the height of loose coal dust layer above the floor should be 0.3m. Similarly, to bring down the friction ignition temperature below critical oxidation temperature (65ºC) the height of loose coal dust layer above the floor should be 1.0m. From the safety point of view, in no case, the GIT should reach the critical oxidation temperature i.e. 65ºC. Therefore, it is suggested to fill the goaf floor area up to a height of 100 cm with incombustible material.

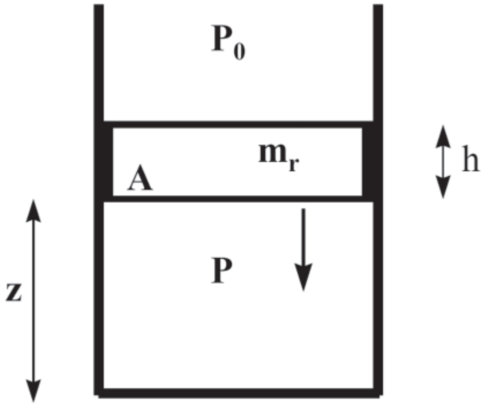


Fig.2 Air is compressed beneath a falling mass in a bounded system (no leakage) (McPherson, 1995a)

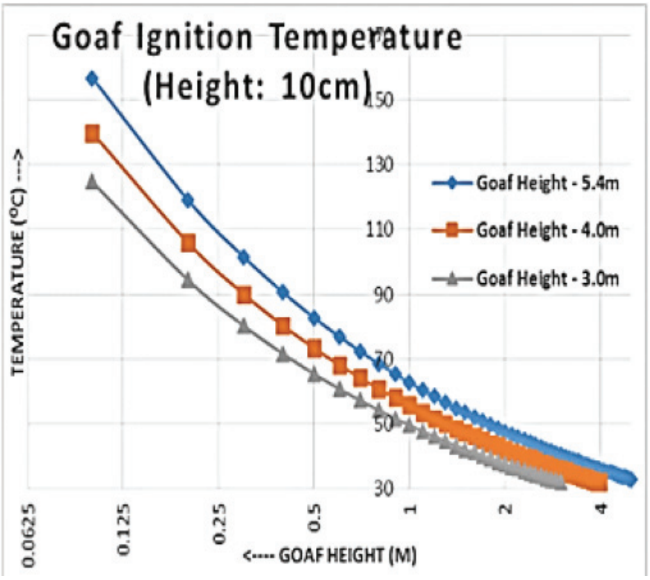


Fig.3 Goaf ignition temperature having floor gap of 10cm

Field study

Field investigations have been carried out in the B2A panel of RVI seam at Khottadih colliery which includes limited air quantity measurement, hygrometric survey, temperature and gas monitoring in main return airway. The ventilation system of the mine is of exhaust and antitropal type, achieved by an axial flow fan (make Voltas Model VF-3000) installed at surface connected with a mine shaft through fan drift. The experimental panel B2A in RVI seam is ventilated with an air quantity of 2000 m^3/m in which is ascentional towards the apparent rise. Panels 20D, 19D and 18D were used as intake airway while 17D and 16D act as return airways. Results of the hygrometric survey revealed that intake air temperature (wet bulb -WB/dry bulb -DB) was of the order of 29.0/31.5°C. The panel was stopped after 90 days of working. The panel was stopped for 35 days due to a large area of the roof hanging of beyond statuary limit. The area of exposure of the hanging roof during that period was more than 5000 m^2. After 35 days induced blasting was started from goaf edge. After a week main fall took place. The symptom of heating was noticed 5 days after the main roof fall and subsequently, release of CO from goaf was observed. The GIT after roof fall due to induced blasting was estimated to be in the order of 157°C. Accordingly, ventilation control technique using computational fluid dynamic modelling was applied in addition to the application of water through pipeline over the fallen material and pressure loss across the panel was reduced to 1-2 mmwg. This resulted in full extraction of the panel and CO was kept under control and maintained to the tune of 20-30 ppm in the return airway of the panel.

Computational fluid dynamics (CFD) simulation

CFD is widely used in mining industries to solve mine ventilation, fire and explosion, dust movement and methane control related problems [12, 13]. In order to design a perfect ventilation system for underground mine, it is necessary to improve the quality and quantity of air for workplace safety to suppress the dust and gas in the underground mine [14, 15]. CFD simulation has been used in this study to visualize the airflow behaviour in goaf i.e. velocity distribution in different parts inside the panel for a better understanding of the airflow [16]. The basic governing equations which describe the fundamental physical principles of fluid dynamics, conservation of mass, momentum, energy, and Navier-strokes equation are given below through equations 5-14 [17].

The conservation of mass (continuity equation)

Rate of increase of mass in fluid element = Net rate of flow of mass in fluid element

$$\frac{\partial \rho}{\partial t} + div(\rho u) = 0 \qquad \text{... (5)}$$

Where ρ is the density of fluid, t is the time, u is the velocity

Equation 5 is unsteady, three-dimensional mass conservation equation or continuity equation at a point in a compressible fluid. For an incompressible fluid, the density ρ is constant, so div u = *zero* means $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} + \frac{\partial w}{\partial x} = 0$.

The conservation of momentum (Newton's second law of motion)

Rate of increase of momentum of fluid particle = Sum of forces on fluid particles.

$$\frac{\rho\,(Du)}{Dt} = \frac{\partial(-p + \tau_{xx})}{\partial x} + \frac{\partial(\tau_{yx})}{\partial y} + \frac{\partial(\tau_{zx})}{\partial z} + S_{Mx} \qquad \text{... (6)}$$

$$\frac{\rho\,(Dv)}{Dt} = \frac{\partial(\tau_{xy})}{\partial x} + \frac{\partial(-p + \tau_{yy})}{\partial y} + \frac{\partial(\tau_{zy})}{\partial z} + S_{My} \qquad \text{... (7)}$$

$$\frac{\rho\,(Dw)}{Dt} = \frac{\partial(\tau_{xz})}{\partial x} + \frac{\partial(\tau_{yz})}{\partial y} + \frac{\partial(-p + \tau_{zz})}{\partial z} + S_{Mz} \qquad \text{... (8)}$$

Where τ is viscous shear stress for a Newtonian fluid; p is the pressure (normal stress); suffices *i* and *j* indicate that stress acts in the *j* direction on a surface normal to *i* direction. The terms S_{Mx}, S_{My}, S_{Mz} indicates contributions due to body forces; *u*, *v*, and *w* are the velocities in *x*, *y*, and *z*-direction respectively.

Conservation of energy

$$\rho \frac{DE}{Dt} = -\, div(pu) + \left[\frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(v\tau_{zz})}{\partial z}\right] + div(k\ grad\ T) + S_E \qquad \text{...(9)}$$

E is the specific energy, *T* is the temperature, S_E is the source of energy per unit volume per unit time, *k* is the thermal conductivity coefficient

Navier-strokes equation

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + div(\mu\ grad\ u) + S_{Mx,}\ \textit{in the direction of X} \qquad \text{...(10)}$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + div(\mu\ grad\ v) + S_{My,}\ \textit{in the direction of Y} \qquad \text{...(11)}$$

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + div(\mu\ grad\ w) + S_{Mz,}\ \textit{in the direction of Z} \qquad \text{...(12)}$$

Standard k-ε model of turbulent equation

The standard *k-ε* model solves two additional transport equations which are for turbulence kinetic energy (13) and rate of dissipation of turbulence (14) that compute the Reynolds stresses.

$$\frac{\partial\ (\rho k)}{\partial t} + div(\rho kU) = div\left[\frac{\mu_t}{\sigma_k}\ grad\ k\right] + 2\mu_t S_{ij}.S_{ij} - \rho\epsilon \qquad \text{...(13)}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + div(\rho\varepsilon U) = div[\frac{\mu_t}{\sigma_\varepsilon}\ grad\ \varepsilon] + C_{1\epsilon}\frac{\varepsilon}{k} 2\mu_t S_{ij}.S_{ij} - C_{2\varepsilon}\,\rho\,\frac{\varepsilon^2}{k} \qquad (14)$$

ρ is the density; k is the turbulent kinetic energy; ε is the turbulent dissipation; μ_t is the eddy viscosity; S_{ij} is the mean strain rate tensor.

where and are given by; $\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$

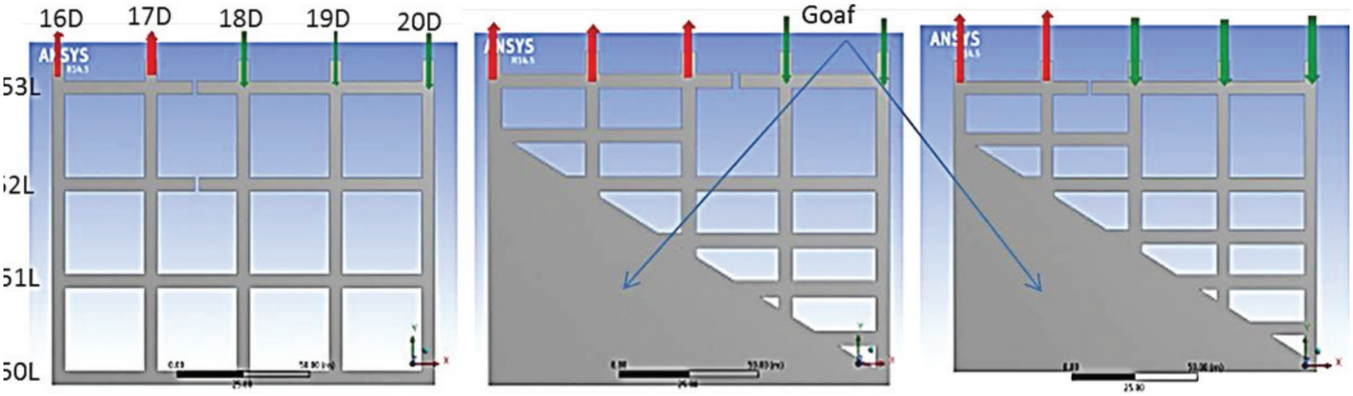
The values of adjustable constants are given by C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k, σ_e are given by (C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k, σ_e) = (0.09, 1.44, 1.92, 1.0 and 1.3).

BOUNDARY CONDITIONS

For this study, finite volume based Fluent-Ansys was used. For turbulence K–ε model has been used to determine the flow behaviour and distribution of temperature inside the galleries and at the working face [10]. The k–ε turbulence model has better agreement with experimental data [12]. The panel B2A of RVI seam, Khottadih colliery, ECL has been used for CFD modelling. Two models were used in this study. First one was without extraction of the panel and other with a partial extraction of the panel to design ventilation system. In the first model, three intake and two returns were considered (Fig.4a). At the intake the air velocity component, turbulent energy and dissipation rate were specified. Blockages were defined to serve the purpose of stoppings and walls were specified for a non-slip condition. Coal pillar size: 30m × 30m, gallery size (width): 4.8m, gallery height: 3.0 m and goaf height: 5.4m were considered for simulation. The coal properties used were 1450 kg/m^3, 1489J/kgk and 1.6w/mk for density, specific heat and thermal conductivity respectively. Air inlet temperature was taken as 32^{o}C. Nine case studies were applied to simulate the velocity, pressure and temperature distribution in goaf area (Table 2 and Fig.4b, 4c). For simulation purpose, goaf ignition temperatures 157^{o}C, 101^{o}C and 65^{o}C have been used. Three different amount of mesh of approximately 4.8×10^5(2.48×10^6 elements), 5.0×10^5 (2.50×10^6 elements) and 5.6×10^5(2.57×10^6 elements) are implemented to ensure a mesh independent solution [18, 19]. It is observed that the mesh amount of around 5.6×10^5 gives about 5.0% deviation. Therefore, a mesh of around 5.6×10^5 nodes is found to be sufficient for this simulation study. All computational iterations are solved implicitly. The scaled residuals for solution convergence of the continuity, energy and velocity equations are 10^{-4}, 10^{-4} and 10^{-3} respectively.

Analysis and interpretation

The results of CFD simulation for different cases are shown in Figs.5 to 14. Fig.5 shows the scaled residuals of continuity, energy, and k–ε with respect to the number of the iterations. As the scaled residuals are converging the results obtained from the case are considered to be significant. Fig.6 (case A1)indicates the distribution of air velocity and total pressure (absolute) in the panel for an air quantity of 2000 m^3/min in the panel. It is found that predicted air velocity within the goaf of the panel lies between 0.01m/s and 1.0m/s (Fig.6a). It also indicates higher air velocity through 1st intake gallery and lower air velocity through the 2nd intake. The air velocity



(a) (b) (c)

Fig.4 Geometry of the panel having a. three intakes and two return without goaf; b. two intakes and three return with goaf; c. three intakes and two return with goaf

TABLE 2: INLET BOUNDARY CONDITIONS APPLIED

Cases		Air quantity (m^3/min)		
		I	II	III
Case A	Total air quantity (m^3/min) in three inlets and two return without goaf	2000		
Case B1	Total air quantity (m^3/min) in three inlets and two return with goaf and without GIT	1200	1500	1800
Case B2	Total air quantity (m^3/min) in two inlets and three return with goaf and without GIT		1800	
Case C1	Total air quantity (m^3/min) in three inlets and two return with goaf and GIT of 157 ^{0}C		1800	2100
Case C2	Total air quantity (m^3/min) in two inlets and three return with goaf and GIT of 101 ^{0}C			2100
Case C3	Total air quantity (m^3/min) in two inlets and three return with goaf and GIT of 65 ^{0}C			2100

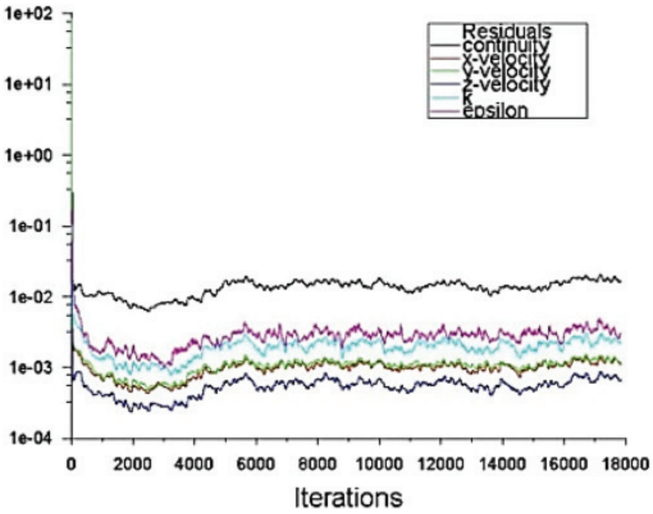
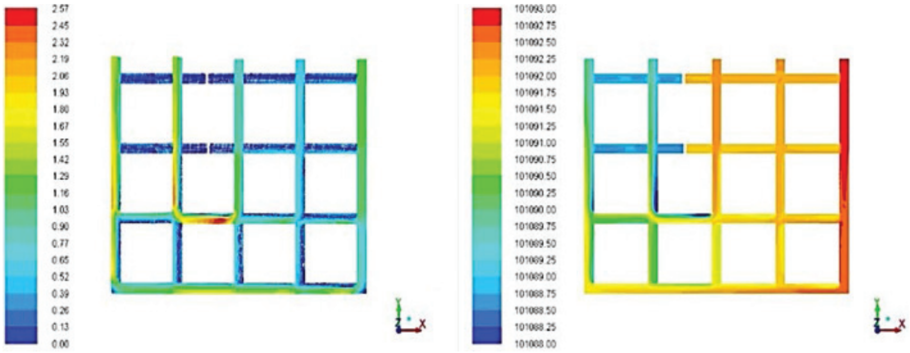


Fig.5 Residuals of iteration



(a) (b)

Fig.6 Velocity and total pressure profile for the panel

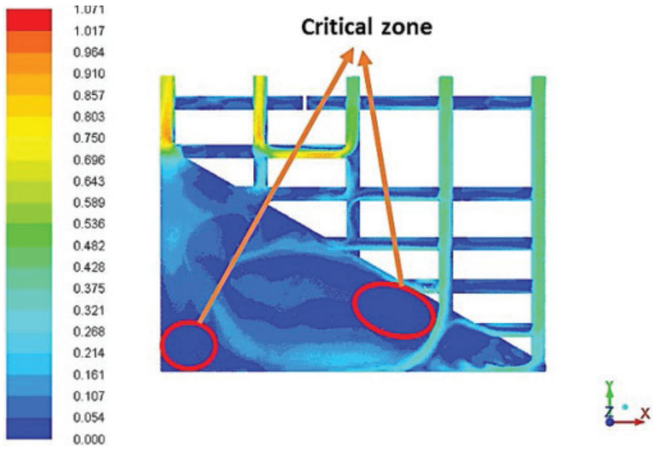


Fig.7 Velocity profile of air quantity 1200 m^3/min having three intakes and two return

in the 3rd intake is observed to be in between 1st and 2nd intake. The second return of the panel (near to the boundary of the panel) has high velocity as compared to the 1st one.

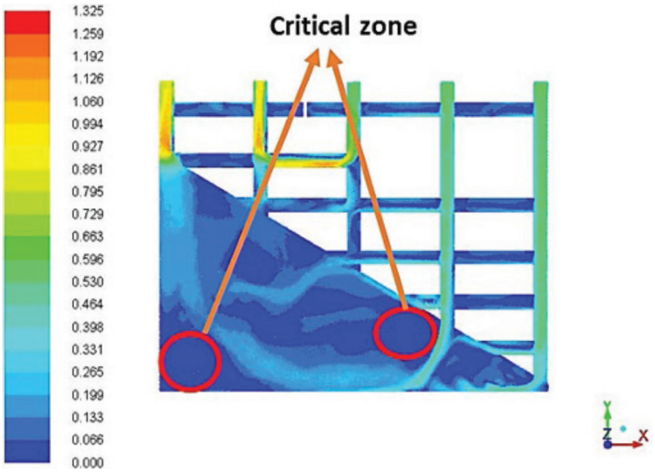


Fig.8 Velocity profile of air quantity 1500 m^3/min having three intakes and two return

The objectives of this simulation study is to find out the minimum air quantity requirement for the panel to maintain safe workplace environment and optimize the number of intakes and returns of ventilation system i.e. whether three intake-two return or two intake-three return system is better for prevention of spontaneous heating in goaf areas. Initially, three intakes and two returns are considered with air quantity 1200 (case B1-I, Fig.7), 1500 (case B1-II, Fig.8) and 1800 m^3/min (case B1-III, Fig.9) (Table 2). Fig.7 indicates the distribution of air velocity and pressure in the goaf for an air quantity of 1200 m^3/min in the panel. It is found that predicted air velocity within the goaf of the panel lies between 0.01m/s and 0.321m/s (Fig.7). It also indicates higher air quantity through 1st intake. There are critical zones (having velocity in the range of 0.1-0.9 m/min.) in goaf area (behind junction of 50L-18D) where air velocity comes down to even below 0.054m/s. The sluggish

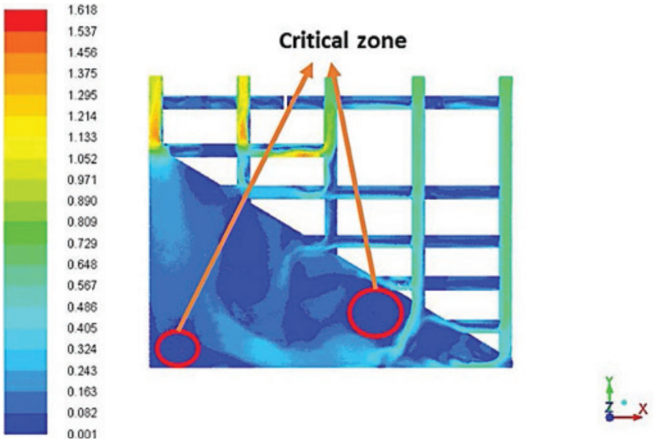


Fig.9 Velocity of air quantity 1800 m^3/min having three intakes and two return

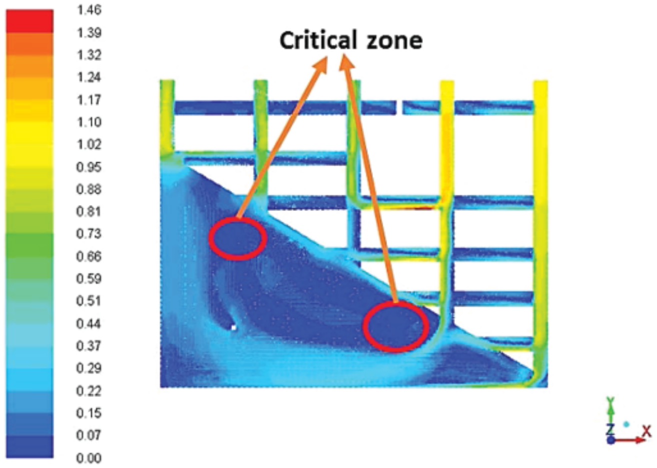
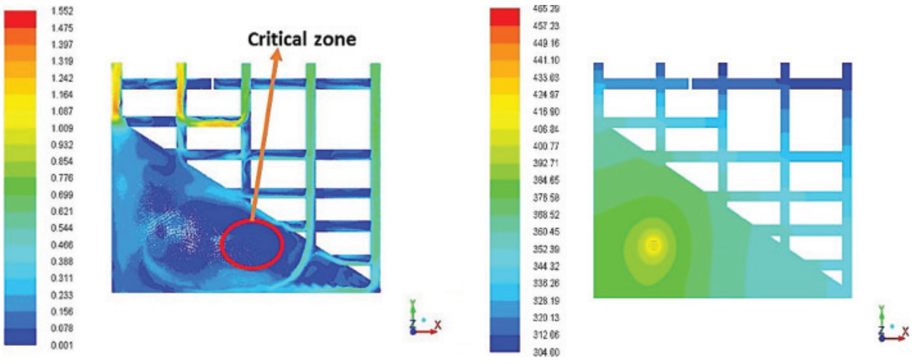
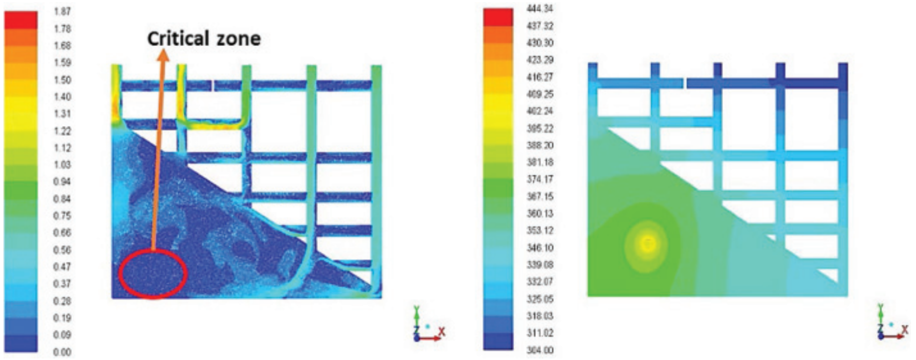


Fig.10 Velocity profile of air quantity 1800 m^3/min having two intakes and three return



(a) (b)

Fig.11 Velocity & temperature profile of air quantity 1800 m^3/min having three intakes and two return with goaf ignition temperature



(a) (b)

Fig.12 Velocity and temperature profile of air quantity 2100 m^3/min having three intakes and two return with goaf ignition temperature

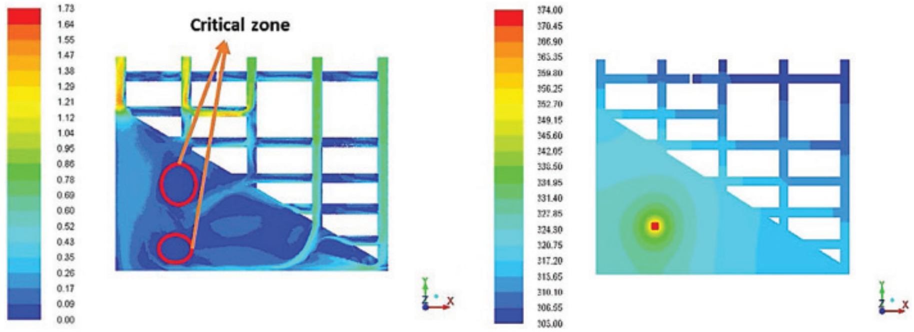
ventilation in the critical zone (air velocity within the range of 0.1 to 0.9m/min) and corner of the panel is very prominent which may increase the proneness of coal to spontaneous heating.

Similarly, Fig.8 (case B1-II) indicates the distribution of air velocity and pressure in the goaf for an air quantity of 1500 m^3/min in the panel. It is found that predicted air velocity within the goaf of the panel lies between 0.01m/s and 0.331 m/s (Fig.8). It also indicates higher air quantity through 1st intake gallery. There are critical zones in goaf area (behind junction of 50L and 18D) where the velocity of air comes down to even below 0.066m/s.

Fig.9 indicates the distribution of air velocity and pressure in the goaf for an air quantity of 1800 m^3/min in the panel (Case B1-III). It is found that predicted air velocity within the goaf of the panel lies in the range of 0.01m/s to 0.405m/s. It also indicates higher air quantity through 1st intake gallery. The critical zone in goaf area is found behind junction of 50L-18D where velocity is below 0.082m/s. The critical zone area has decreased as compared to the Figs.7 and 8. The sluggish ventilation zone in the corner of the panel is reduced and ventilation in the face zone increases which may help in decreasing the proneness of coal to spontaneous heating.

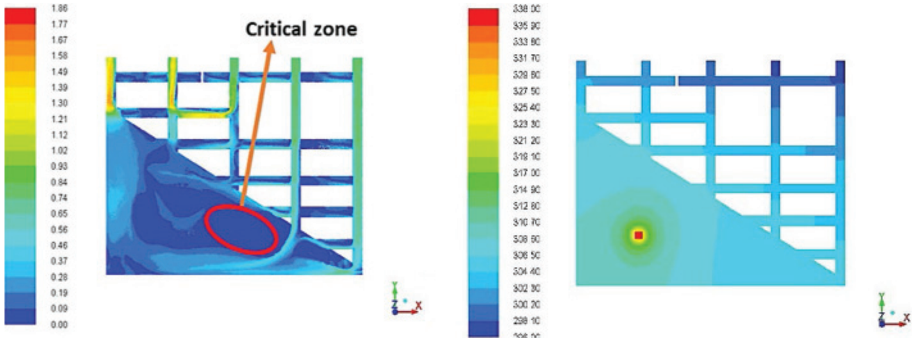
The ventilation system of the panel was changed to two intakes and three returns keeping air quantity 1800 m^3/min (case B2-II) (Fig.10). The velocity profile in critical zone (behind junction of 50L-18D) shows that mostly air velocity lies below 0.037m/s which indicate the sluggish ventilation near the working face (Fig.10). So, there may be chances of increase in proneness of coal to spontaneous heating near working face. The pressure (gauge) difference between intake and return airways is 0.87 Pa and pressure within goaf varies from 0.47 to 0.63 Pa. It is inferred from the Figs.9 and 10 that the panel should have three intakes and two returns having air quantity 1800 m^3/min which has the least area of critical zone in goaf.

The third objective of simulation study is to investigate the temperature profile of goaf with goaf ignition temperature (GIT) after roof fall. In this case, initially having three intakes and two returns with goaf ignition temperature (157^{o}C) is applied for two different air quantities 1800m^3/min (case C1-II, Fig.11) and 2100m^3/min (case C1-III, Fig.12) to achieve safe workplace environment. It is found that predicted air velocity within the goaf of the panel varies between 0.078m/s and 0.466 m/s for air quantity 1800 m^3/min (Fig.11a). There are a few critical zones in goaf area (behind junction of 50L-18D) where air velocity is below 0.078m/s. The sluggish ventilation in the above zone and corner of the panel is very high which may increase the proneness of coal



(a) (b)

Fig.13 Velocity and temperature profile of air quantity 2100 m^3/min having three intakes and two return with goaf ignition temperature 101°C



(a) (b)

Fig.14 Velocity and temperature profile of air quantity 2100 m^3/min having three intakes and two returns with goaf ignition temperature 65°C

to spontaneous heating. The temperature near working face is found to be (380°K) 107°C (Fig.11b). Similarly, for air quantity 2100 m^3/min (case C1-III) (Table 2), air velocity within the goaf of the panel varies between 0.09m/s to 0.466 m/s (Fig.12a), the temperature near working face is found to be 97°C (370°K) (Fig.12b).

Considering GIT of 101°C (case C2-III, Fig.13) having partial stowing of 30 cm and GIT of 65°C (case C3-III, Fig.14) having partial stowing of 100 cm after roof fall. The cases have been simulated with an air quantity of 2100m^3/min separately to achieve safe workplace environment. Figs.13 and 14 indicate the velocity, and temperature profile considering GIT of 101°C and 65°C respectively. The predicted air velocity within the goaf of the panel varies from 0.09m/s to 0.43 m/s for GIT 101°C (Fig.13a). There are a few critical zones in goaf area (behind junction of 50L and 18D) where velocity shows below 0.09m/s. The temperature near working face is found to be 57°C (330 K). Similarly, for an air quantity of 2100 m^3/min with GIT of 65°C the simulation results show that air velocity within the goaf of the panel varying between 0.09m/s and 0.46 m/s (Fig.14a) and the temperature near working face is found to be 33°C-35°C (306-308K) (Fig.14b). It reveals from the above two case studies i.e. Cases C2-III and C3-III (Figs.13 and14) that after increasing the partial stowing height from 30 cm to 100cm the temperature at working face comes to near ambient temperature. Thus it may be concluded that partial stowing with the incombustible material in the goaf area up to a height of 100 cm is beneficial to prevent spontaneous heating due to roof fall.

Conclusions

Laboratory and field investigations followed by CFD simulation reveals that problem of heating in the depillaring panel of the fairly thick seam is mainly due to nature of coal, addition of heat from the surface through intake air, generation of heat during roof fall from greater height and thickness of coal bed lying in the goaf. Dissipation of heat in goaf areas, generated due to roof fall with suitable ventilation control technique may be a viable solution for the safe liquidation of the thick seam in general and Raniganj coalfields in particular.

The following points emerge from the study:

- The moisture content of coal is close to the critical value (5-8%). Critical oxidation temperature and crossing point temperature determined earlier in laboratory study of coal is found to be of 65°C and 116°C respectively. This indicates that coal is more prone to spontaneous heating. In addition of heat from any other source scan cause the temperature of coal to rise more than 65°C which will support spontaneous heating and combustion. CFD simulation study is very helpful for prediction of velocity and temperature distribution of air in goaf. The simulation study reveals that partial stowing with the incombustible material in the goaf area up to a height of 100 cm is beneficial to prevent spontaneous heating due to roof fall with an air quantity of 2100 m^3/min maintaining three intakes and two return airways.

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