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An oxygen balancing approach to determine the extent of fire in an underground coal mine

Coal can easily be oxidized and has a prominent self-heating capacity. In underground coal mine, coal has a tendency to combust spontaneously under sufficient oxygen through ventilation. Uncontrolled spontaneous combustion of coal in an underground coal mine is a very serious problem. Spontaneous combustion of coal is one of the major hazard in any underground coal mining operations. If not detected early and managed properly, it can seriously affect the safety of workers and productivity. Thus, fire in underground coal mines need to be detected at an early stage so that effective measures can be taken before the fire assumes a very advanced stage. But detection of spontaneous heating or oxidation to know the status of heating is not a simple task. Gaseous products of spontaneous combustion, such as carbon monoxide, ethylene and hydrogen, are commonly used in coal mines as indicators to reflect the state of the spontaneous combustion. However, use of machineries, gases released from strata and other sources inside the mine also emits carbon dioxide, carbon monoxide and other gases when gets intermixed with the gases emitted from spontaneous combustion makes it difficult to assess the extent of fire in the mine. However, combustion of coal is not possible without its oxidation. Underground mines are ventilated by regulated supply of air containing oxygen causing oxidation, which is an exothermic reaction. When the heat released due to oxidation is not dissipated, temperature of coal goes on increasing, and thereby further increasing the rate of oxidation, till it reaches the ignition temperature of coal and cause spontaneous combustion. This study is an attempt to develop an approach to detect the extent of fire in underground mine is developed based on the amount of oxygen consumption or rate of oxidation. Other conventional approaches based on the presence of different gaseous products of combustion like CO, CO_2 have the limitations of their sources other than spontaneous combustion or the different gas ratios based on these gases may indicate the stage of heating but the size of fire or in other words, quantity of coal involved in the process of oxidation cannot be estimated or assessed. The proposed approach of determining the extent of fire based on oxygen consumption is more appropriate and helpful in fire emergency planning and reducing the risk due to mine fire hazards.

Keywords: Underground mining; coal; spontaneous combustion; oxygen; fire.

1.0 Introduction

The majority of fires that occur today in various coalfields are caused by spontaneous coal combustion. The auto oxidation of coal eventually leads to spontaneous combustion, which is the primary cause of coal mine disasters in major coal-producing countries such as the United States, China, Australia, India, and Germany. The process is sluggish, and the heat produced is taken away by the air. “Spontaneous heating” or “auto oxidation” refers to the process of coal or other carbonaceous materials self-heating and eventually igniting. At room temperature, coal can interact with oxygen in the air, releasing heat. Allowing heat to be accumulated increases the interaction rate, gradually reaching to the stage of auto-ignition

Spontaneous heating and fire in coal mines is a major problem worldwide and has been a great concern both for the industry and researchers in this field. In terms of both safety and productivity, spontaneous coal combustion is a major concern in underground coal mining operations (Qin et al. 2009). Despite the fact that most studies point out oxidation of organic matter as the primary cause of spontaneous combustion (Stracher and Taylor 2004; Querol et al. 2008), the exact mechanism of spontaneous combustion is still unknown due to the presence of numerous internal and external factors influencing spontaneous combustion initiation and development (Beamish and Jabouri 2005). As a result, accurately predicting the beginning of spontaneous combustion is challenging. However, the majority of researchers agree that the reaction of oxygen with coal is a surface event that occurs through a loosely bound coal-oxygen-water complex, with subsequent phases consisting of the complex’s breakdown into simpler molecules such as CO,

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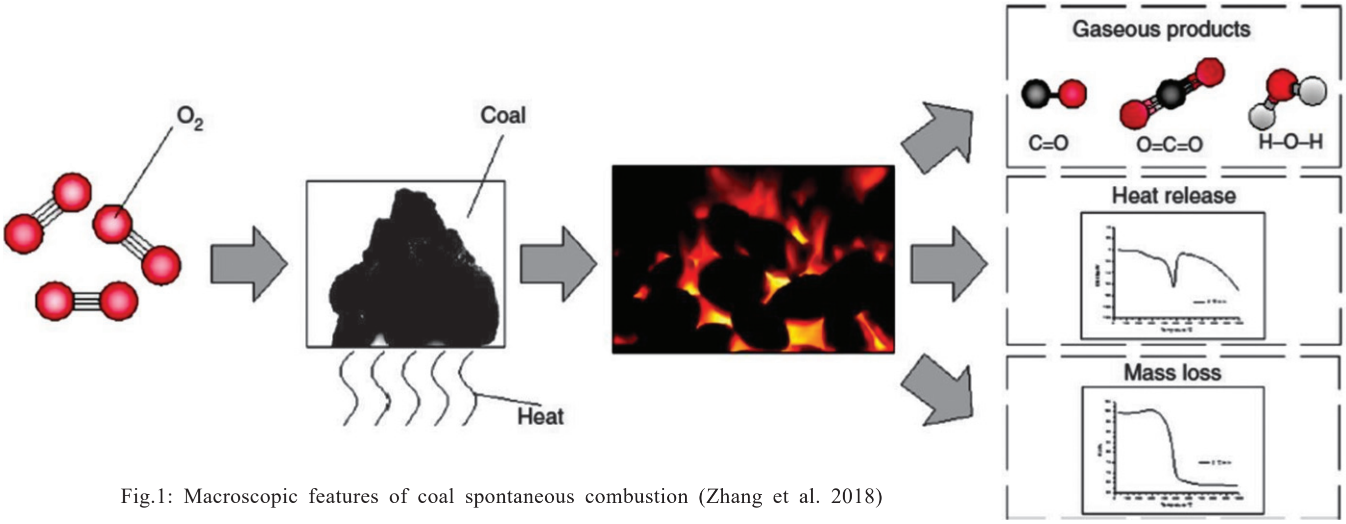

Fig.1: Macroscopic features of coal spontaneous combustion (Zhang et al. 2018)

CO_2, and H_2O. The most widely accepted theory is that the reaction is carried out in a chain, with moisture favouring the creation of free radicals, which act as chain carriers.

Coal mine operators frequently use detection methods to assess the state of spontaneous combustion in practice. As a result, a number of technologies for detecting spontaneous combustion in coal mines have been developed. Temperature or heat measurements (Kim 2004; Zhang and Kuenzer 2007), index gases (Singh et al. 2007), numerical modelling (Klika et al. 2004; Wessling et al. 2008), and the radon approach are among these methods (Xue et al. 2008). In coal mines, index gases are the most popular approach for detecting spontaneous combustion and determining its stage of development. The steps involved or macroscopic features of coal spontaneous combustion is presented in Fig.1.

1.1 Mechanism of Spontaneous Heating

The oxidation of coal, alike all oxidation reactions, is exothermic in eccentric. The exact mechanism of the reaction is still not well observed. The low-temperature reaction that leads to spontaneous combustion has been thoroughly investigated, but due to its complexity, the specific reaction mechanism of the process is still unknown (Wang et al. 2003; Pone et al. 2007). The interaction between coal and oxygen is mostly due to physical adsorption and chemisorption of oxygen in coal pores at temperatures below 40°C. The creation of unstable surface oxygen-coal complexes, which produce peroxides and hydro-peroxides, is the following stage (Lopez et al. 1998). At these temperatures, gaseous products do not evolve much. When the temperature rises over 40°C, the unstable oxy-compounds decompose into gaseous products and stable oxy-complexes. When temperatures rise over 70°C, stable oxy-complexes disintegrate, resulting in new active sites for coal oxidation and the production of more gaseous products. Carbon dioxide, carbon monoxide, methane, hydrogen, ethane, ethylene, and other higher hydrocarbons, as well as numerous organic volatiles, are among the gases produced (Beamish and Jabouri 2005; Nelson and Chen 2007). It is worth noting that the order in which gases appear and the temperature at which they appear can differ from coal to coal (Xie et al. 2011).

Not all gaseous products of coal oxidation at low temperatures are acceptable for use as index gases in coal mines. It is determined by the chemical composition of the coal as well as the presence or absence of naturally occurring gases within a coal seam. For example, if hydrogen occurs naturally in a coal seam, it cannot be utilized. Because both methane and carbon dioxide are commonly found in coal seams, they are not suited as index gases. In coal mines, index gases including carbon monoxide, hydrogen, and ethylene are commonly used to detect the start of spontaneous combustion. Carbon monoxide and ethylene, for example, are widely utilized in Australia and China, whereas carbon monoxide and hydrogen are the most commonly used index gases in the United States. Carbon monoxide as an index gas has a number of drawbacks, one of which is that, its detection in coal mines does not always imply spontaneous combustion because it can be produced at ambient pit temperatures also (Moreby 2005). Lu et al. (2004) studied the composition and quantity of carbon monoxide and ethylene generated by different coals at different temperatures(Lu et al. 2004). They discovered that ethylene could be used as an index gas, and that the presence of ethylene (at a concentration of 0.01 ppm) indicated a temperature of 64°C in the goaf area. Dai (2007) observed that the initial temperature of ethylene appearance rose with coal rank: 90°C for brown coal, 120°C for high volatile bituminous coal, 140°C for low volatile bituminous coal, and 210°C for anthracite (Dai 2007). In general, the presence of ethylene is regarded as a good indicator of advanced heating in coal mines or a temperature of between 100°C and 160°C (Yang et al. 2008). When ethylene is found in coal mines, it usually means that spontaneous combustion has progressed to an advanced stage. This is due to dilution of ventilation air and the detection limits of ethylene analysis tools used in coal mines.

Similarly, there is lack of confidence in each index gas as discussed above, either due to sources other than oxidation or dilution. Therefore, in this study an attempt has been made to consider the other most important parameter of spontaneous heating i.e. oxidation and consumption of oxygen. As oxygen is neither seam gas nor can be produced from other sources and consumption of oxygen indicates oxidation only. The balancing of amount of oxygen supplied through intake ventilation air and in return air will provide the amount of oxygen used for the spontaneous heating. The other oxygen consuming factors such as human respiration, machinery etc. is insignificant and may be ignored. Hence, based on the consumption of oxygen, the extent of fire in underground coal mines can be predicted. This will help in better emergency, reopening planning and enhance in overall safety and productivity.

2.0 Oxygen balancing approach to detect the extent of fire

Based on the principles of combustion and oxygen consumption during the combustion, an approach to detect the extent of fire in an underground coal mine is discussed below.

2.1 Principles of Heat of Combustion

Combustion is an exothermic oxidative reaction i.e. it produces heat and consumes oxygen. Exothermic reactions produce heat whereas endothermic reactions absorb heat.

The heat of combustion (HC) is the heat released when a unit quantity of fuel (at 25°C and atmospheric pressure) is oxidised completely i.e. all the carbon is converted to CO_2 and all the hydrogen to H_2O.

Table 1: Proximate analysis of coal

Physical property	Percentage
Moisture	2.81 %
Ash	45.25 %
Volatile matter	16.54 %
Fixed carbon	35.40 %
Calorific value	3995.37Kcal/Kg~16780KJ/kg

For example, the oxidation of propane (C_3H_8)

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \qquad \text{... (1)}$$

The equation (1) mentioned above is exothermic and the value of the heat of combustion (HC) depends on whether the water in the products is in the form of a liquid or vapour. The two values

HC_{liq} (C_3H_8) = 2220 $kJmol^{-1}$

HC_{vap} (C_3H_8) = 2044 $kJmol^{-1}$ (for water in its vapour state)

where,

HC_{liq} is the heat of combustion for water in its liquid state

HC_{vap} is the heat of combustion for water in its vapour state

The difference between these two values is the latent heat of vaporisation of water i.e.

$HC_{vap} - HC_{liq}$ (C_3H_8) = 2044 – 2220 = –176 $kJmol^{-1}$

Within flames the water remains as a vapour and so it is more appropriate to use the value of HC_{vap} = 2044 $kJmol^{-1}$. From now on HC refers to HCvap.

The heat of combustion (HC) may be expressed either as energy per mole or energy per gram (or kilogram). As the molecular weight of C_3H_8 is 44 then the energy per gram equivalent to the value 2044 is = 2044/44 = 46.45 $kJgram^{-1}$.

Calculating the heat released in a fire can be difficult as there are generally a large number of products of combustion.

One way to do it is to estimate the amount of oxygen consumed rather than the amount of fuel oxidised.

2.2 Calculation on the basis of amount of oxygen consumed

For most common fuels the heat released per unit mass of oxygen is remarkably constant. The so-called 'Heat of combustion for oxygen', HCO_x, has been found to have the approximate values:

Typical organic liquids and gases HCO_x = 12.72 (± 3%) kJgram-1 of O_2

Table 2: Ultimate analysis of coal sample per 100 kg sample

Elements/composition	Kg/100 kg coal (adb)	Kmol/100 kg of coal	Kmol of O_2 required	Kmol of flue gases	
Carbon (C)	41.81	3.48	3.48	CO_2	3.48
Hydrogen (H_2)	3.35	1.675	0.8375	H_2O	1.675
Oxygen (O_2)	6.50	0.204	- 0.204	O_2	-
Nitrogen (N_2)	0.78	0.027	-	N_2	0.027
Sulphur (S)	0.50	0.01	0.01	SO_2	0.01
Moisture (H_2O)	2.81	0.156	-	H_2O	0.156
Ash	45.25	-	-		
Total			4.12		5.348
N_2 from Air	= 4.12*3.76 (Nitrogen is 3.76 times the oxygen in air)				15.50
			Total		20.83

And for most polymers $HCO_x = 13.02$ (± 4%) $kJgram^{-1}$ of O_2 As an overall estimate, $HCO_x = 13.1$ $kJgram^{-1}$ may be taken.

As Avagadro's Law states that equal volumes of all gases contain equal numbers of molecules at the same temperature and pressure, we can use volumetric proportions of gases to calculate the rate of heat release (Q). As the initial proportion of oxygen in air can be taken to be 0.21 the value of Q and may be assumed to be given by: rate of heat release

$$Q = (0.21 - \eta O_2) \times V \times 1000 \times \rho O_2 \times HC_{ox} \quad \text{... (2)}$$

where,

Q = Rate of heat release (in kJ/Sec or kW)

ηO_2 = mole fraction of oxygen in exhaust gases from fire V = Volumetric flow rate of air in m^3/Sec

ρO_2 = Density of oxygen at standard temperature and pressure in Kg/m^3 H_{Cox}= Heat of combustion for oxygen.

The approach can be well explained with the following example:

2.2.1 Proximate analysis of coal sample

The physical properties of coal can be tested in laboratory by conducting proximate analysis of coal sample. Table 1 presents a report of proximate analysis of coal.

Few ideal values are considered to explain the calculations:

1. Volume percentage of flue gases in exhaust gases = 16%
2. Volumetric flow rate of air = 500 m^3/min = 500*60 m^3/hr
3. Percentage of O_2 in air = 21%
4. Density of O_2 = 1.3 kg/m^3

Using the Equation (2), the value of rate of burning can be obtained as:

Q = (0.21 – 0.16) * 500 *60 * 1.3 * 1000 * 13.1

= 25545000 KJ/hr

Rate of burning = (rate of heat release)/(calorific value of coal)

Therefore, rate of burning = 25545000/16780 kg/hr = 1522 Kg/hr =1.52 tonne/hr

This indicates that 1.52 tonnes of coal is spontaneous heating per hour in an underground coal mine. Higher the value of tonnes of coal under spontaneous heating, higher will be the risk of hazard and therefore accordingly the planning should be done to deal with the fire.

2.3 COMBUSTION STOICHIOMETRY AND THERMODYNAMICS

The chemical composition of coal can be tested in laboratory by conducting ultimate analysis of coal sample. Table 2 presents a report of ultimate analysis of coal per 100kg sample.

Assumptions:

1. Volumetric flow rate of air = 500 m^3/min
2. Volume of air at standard temp and pressure = 22.4 m^3/Kmol
3. Air/oxygen ratio = 4.76
4. Excess air factor = 1.5

On the basis of ideal gas law: $PV=nRT$ ... (3)

At constant pressure, $\frac{V_1}{V_2} = \frac{n_1 T_1}{n_2 T_2}$ ... (4)

2.3.1 Based on capacity of blower

The calculations of oxygen consumption based on the capacity of blower can be performed in the following manner:

Capacity of air blower = (kmol theoretical O_2 requirement) × $\left(\frac{\text{Air}}{\text{Oxygen}}\text{Ratio}\right)$ × (Volume of air) × (excess air factor) × $\frac{T2}{T1} \times \frac{\text{Coal Burning rate}}{100}$ ... (5)

Therefore, by applying the values of parameters in Equation (5),

500 = 4.12 * 4.76 * 22.4 * 1.5* (273+30)/273 * coal burning rate (Kg/min)/100

The coal burning rate comes out to be = 68.38 Kg/min = 4102 Kg/hr = 4.1 tonne/hr

This indicates that 4.1 tonnes of coal is spontaneous heating per hour in an underground coal mine.

2.3.2 B. Based on flow rate of flue gases

The calculations based on flow rate of flue gases can be performed in the following manner: Considering flow rate of flue gases as = 504 m^3/min

Flow rate of fluw gases = (Kmol of flue gases) × (volume of air) × $\frac{T2}{T1} \times \frac{\text{Coal Burning rate}}{100}$ ... (6)

Therefore, by applying the values of parameters in Equation (6),

504 = 20.83 * 22.4 * (273+30)/273 * coal burning rate (Kg/min)/100

The coal burning rate = 97.32/min = 5839.35 Kg/hr = 5.8 tonne/hr

This indicates that 5.8 tonnes of coal is spontaneous heating per hour in an underground coal mine.

3. Discussion and Conclusion

The approach discussed in section 2 above are basic in nature and can be utilized for predicting the stage of heating or for determining the extent of fire in terms of quantity of coal taking part in the oxidation process. The developed approach will provide a fair idea of the extent of fire in mine and get an idea of the rate of burning of coal to indicate the stage of fire. This will further help in planning different actions by the mine management and rescue team. Knowing the chemical composition of coal with the help of ultimate analysis, the coal burning rate can be calculated based on capacity of blower and on flow rate of flue gases.

This approach may be used for the following purposes:

- To regularly monitor the stage of spontaneous heating in any section or panel in underground mine so that appropriate measures can be taken to reduce the hazards and improve the productivity of mine.
- To assess the stage of fire by the rescue team in decision making in any emergency situation.
- While re-opening of any old panel of mine closed/sealed/isolated due to fire.
- To adjust the flow of air quantity or air velocity in case of fiery conditions.
- To know the rate of burning of coal.

There is a huge scope of further research and development on the methodology discussed in this paper.

Conflict of interest

The authors state no conflict of interest.

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