



Recent Development in Determining Spontaneous Heating Susceptibility of Indian Coals and Its Correlation with Intrinsic Parameters of Coal

Santosh Kumar Ray · Durga Charan Panigrahi

Received: 7 January 2015 / Accepted: 9 March 2015 / Published online: 12 April 2015
© The Institution of Engineers (India) 2015

Abstract The paper describes a new electro-chemical method called wet oxidation potential technique for determining the susceptibility of coal to spontaneous combustion. Altogether 78 coal samples collected from thirteen different mining companies spreading over most of the Indian coalfields have been used for this experimental investigation. Experiments have also been carried out for proximate and ultimate analyses of coal. Susceptibility index obtained from wet oxidation potential was correlated with intrinsic parameters of coal. It has been found that susceptibility index bears a good correlation with moisture content, volatile matter, oxygen, hydrogen and carbon content of coal.

Keywords Spontaneous heating · Wet oxidation potential method · Proximate and ultimate analyses

Introduction

Spontaneous combustion is largely responsible for coal mine fire. This is an incomplete oxidation reaction and thus emits toxic gases, including carbon monoxide, sulfur dioxide and methane. Self-heating would be facilitated in conditions where large mass of coal is involved and ventilation is neither too little to restrict coal–oxygen

interaction nor too high to dissipate away all the heat generated from above [1]. Self-heating leading to coal mine fire causes huge loss of coal, environmental pollution, methane emissions, hindrance to normal production and productivity, subsidence of surface infrastructure such as roads, pipelines, electric lines, bridge supports, buildings and homes [2]. Thereby, safety and economic aspects of a mine is jeopardized. Around 1.8 billion tonne of coking coal are locked in by fire in Jharia coalfields in India. In China, coal fire consumes about 20 million tonne of coal a year, equal to Germany's annual hard coal production [3], which contributes 0.1 % of all global human induced CO₂-equivalent greenhouse gas emissions [4]. Thus it can be stated that spontaneous combustion results in huge loss of coal affecting conservation of fossil fuels; damages the environment emitting green house gases, causes soil and water pollution. From the analysis of occurrence of these fires, it was revealed that most of them could have been averted if suitable preventive measures were taken. The first step towards such measures is to assess the susceptibility of coal seams.

In India, susceptibility of coal to spontaneous combustion is determined by using Crossing Point Temperature (CPT) method. It has been observed by earlier researcher [1] that in case of high moisture coals usually with high susceptibility, there is a shift of the CPT to a high value, because of release of moisture during heating, indicating that the coal is poorly susceptible, but in reality it is a highly reactive coal. Therefore, some researchers advocate that susceptibility of a particular coal should be determined by different methods to ascertain its liability fairly accurately. This idea did not gain its ground as some of the methods require elaborate and costly experimental set ups.

Wet oxidation potential method, a new electro-chemical method, was adopted for assessing the susceptibility of coal

S. K. Ray (✉)
Central Institute of Mining & Fuel Research, Barwa Road,
Dhanbad 826001, India
e-mail: santoshray8@gmail.com

D. C. Panigrahi
Department of Mining Engineering, Indian School of Mines,
Dhanbad 826004, India

to spontaneous heating. This method provides reliable and reproducible results [5, 6]. In the wet oxidation potential method, emphasis is given to change in potential difference during the oxidation process. It has been investigated that 0.2 N KMnO_4 with 1 N KOH solution is the optimum mixture to carry out wet oxidation potential method for obtaining best response to spontaneous heating of coal [7].

78 coal samples covering fiery and non-fiery seams of thirteen mining companies of India were collected for this investigation [8]. The companies are Eastern Coalfields Ltd. (ECL), Bharat Coking Coal Ltd. (BCCL), Central Coalfields Ltd. (CCL), Mahanadi Coalfields Ltd. (MCL), South Eastern Coalfields Ltd. (SECL), Northern Coalfields Ltd. (NCL), Western Coalfields Ltd. (WCL), North Eastern Coalfields (NEC), Singareni Collieries Company Ltd. (SCCL), IISCO Steel Plant (ISP) SAIL, Monnet Ispat & Energy Ltd., Neyveli Lignite Corporation (NLC) and Tata Steel Ltd. The coal samples were collected from different mines following channel sampling procedure [9, 10] and brought to the laboratory in sealed condition for analysis. This paper addresses wet oxidation potential method in detail and correlation of susceptibility index with intrinsic parameters obtained from proximate and ultimate analyses of coal.

Wet Oxidation Potential Method

This method involves low temperature oxidation process. The schematic diagram of experimental set-up for the wet oxidation process is presented in Fig. 1. The experimental set up consists of a beaker, one saturated calomel electrode ($\text{Hg}/\text{Hg}_2\text{Cl}_2/\text{KCl}$) and one carbon electrode. The calomel and the carbon electrodes are connected to a milli-voltmeter to measure the potential difference during the oxidation process. The beaker along with electrodes and

the chemical solution are placed over a magnetic stirrer and Teflon coated fish of the magnetic stirrer is placed inside the beaker. Temperature of the mixture is measured with a calibrated temperature recorder.

Wet oxidation potential (WOP) analysis was carried out with potassium permanganate (KMnO_4) as oxidizer in potassium hydroxide (KOH) solution. Equivalence factor of KMnO_4 in this case was maintained as $158.04/3 = 52.68$. 100 ml KMnO_4 solution of 0.2 N was prepared in 1 N KOH solution. This mixture was taken in a beaker of 250 ml capacity and a calomel reference electrode and a carbon electrode were immersed in it. The potential difference, i.e. EMF, in mV, was measured between these electrodes by using a digital millivoltmeter (Range 0–2000 mV, Accuracy $\pm 0.1\%$) after attaining a stable reading. 0.5 g of coal sample of -212 micron size was added in this mixture and was continuously stirred using a magnetic stirrer. The potential difference was recorded over a period of time till a nearly constant value was attained. Temperature of the mixture was measured with a calibrated temperature recorder. Potential difference and temperature were recorded at an interval of 1 min. Each experiment took about one and half hour. Experiments were carried out at 45°C . Wet oxidation provides a measure of ambient temperature reactivity that is relevant to the very initial stages of oxidation in self heating, but of course cannot fully capture the complexity of kinetics that might be relevant for taking the materials to full self-heating behavior. In other words, the Arrhenius type temperature dependence should be given importance [11]. Earlier studies have shown that the rearrangement of peroxides on the surface can involve significant thermal effects [1], and that these occur only at slightly higher than ambient temperatures. That is the reason wet oxidation potential experiments have been carried out at 45°C , slightly more than ambient temperature available in this part of the country. The difference between

Fig. 1 Experimental set up for wet oxidation potential method

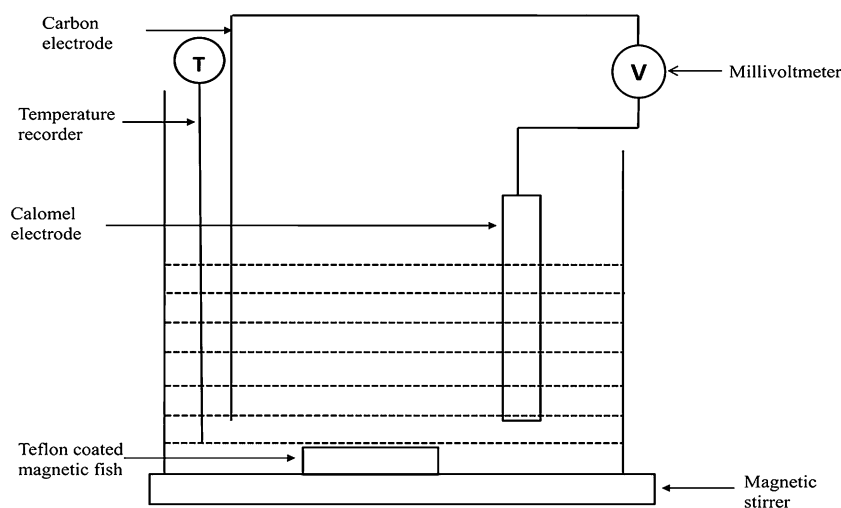


Table 1 Wet oxidation potential analysis results

S. no.	Colliery and seam	PD, mV	S. no.	Colliery and seam	PD, mV
1	Central Kajora, RVIII	115	41	Haldibari, XB	127
2	Parascole East, RVII	139	42	Kamptee, VB	140
3	Shamsunderpur, RVII	126	43	Saoner Mine 1, IV(M)	128
4	Lakhimata, Metadih	51	44	Saoner Mine 3, V	153
5	Lakhimata, BII	33	45	Umrer, IV	152
6	Jhanjra, RVIIA	138	46	New Majri III, Majri	115
7	MIC unit Jhanjra, RVI	136	47	Ghuggus, Meyo (B)	134
8	Jhanjra, RVII	121	48	Ghuggus, Meyo (M)	98
9	Kottadih Project, RV	117	49	Naigaon, Meyo (B)	130
10	Kottadih, RIII/II	105	50	Naigaon, Meyo (M)	100
11	Khaskajora, RVIIIA	114	51	Jhingurda, Jhingurda	98
12	Khaskajora, RVIIIB	147	52	Jayant, Turra	120
13	Kumardhubi, Singhpur Top	62	53	Jayant, Purewa (B)	146
14	Bansdeopur, VIII	37	54	Jayant, Purewa (T)	117
15	Victoria West, Ramnagar	96	55	Amlohri, Purewa Merge	123
16	Sudamdih shaft, XI/XII	41	56	Amlohri, Turra	118
17	Bastacolla, 0	42	57	Tipong, 20'	120
18	Bastacolla, I	46	58	Tipong, 60'(B)	74
19	Bastacolla, II	38	59	Tipong, 60'(T)	104
20	Moonidih, XVI(T)	40	60	Tirap, 8' N Limb	136
21	Mudidih, IX	46	61	Tirap, 60'(T) N Limb	106
22	Kalyani, Karo (Major)	34	62	Tirap, 20'N Limb	82
23	Argada, I	104	63	Kakatiya LW, I	135
24	Argada, J	124	64	Kakatiya LW, IA	122
25	Hesagora, X (B)	114	65	Kakatiya LW, II	118
26	Churi, Lower Bachra	132	66	Kakatiya LW, III	128
27	KD Hessalong, Dakra	128	67	Adriyala Shaft, I	123
28	Kuju, VII	104	68	RK New Tech inc, 1A	146
29	Lilari, Lajkura Top	128	69	Sijua, XIII	42
30	Belpahar, IB	93	70	Sijua, XIV	52
31	Belpahar, Rampur (T)	112	71	6&7 Pits, IX	39
32	Belpahar, Rampur (B)	113	72	6&7 Pits, XI	48
33	Lakhanpur, Lajkura (T)	107	73	Milupara, II	158
34	Jagannath, III	122	74	Kondkel, III	123
35	Anjan Hill, III	117	75	Chasnalla, XII	64
36	NCPH, III	96	76	Western Quarry, XIII/XIV	58
37	Rajnagar RO, 8A ₂	118	77	Neyveli Mine 1A, Lignite	113
38	5&6 Incline, Index	116	78	Barsingsar, Lignite	98
39	Churcha West, V	109			
40	Churcha East, V	110			

S No Sample No., S. Nos: 1–13:ECL, 14–21:BCCL, 22–28:CCL, 29–34:MCL, 35–41:SECL, 42–50:WCL, 51–56:NCL, 57–62:NEC, 63–68:SCCL, 69–72: Tata Steel Ltd., 73–74:Monnet Ispat & Energy Ltd., 75–76:ISP,SAIL, 77–78: NLC

potential difference (PD) of the mixture before adding coal sample and after complete oxidization of coal sample was calculated for each sample and this parameter was

considered as susceptibility index of coal towards spontaneous combustion. The results of the experiments are furnished in Table 1.

Physico-Chemical Analysis

Samples were prepared for various analyses namely proximate (moisture, volatile matter yield, ash yield and fixed carbon), ultimate (carbon, hydrogen, nitrogen, sulphur and oxygen), following standard procedures i.e. IS, 1969 [12]; ASTM 1993 [13].

Proximate Analysis

The proximate analysis of coal is used widely as the basis for coal characterization. It was developed as a simple means of determining the distribution of products obtained when the coal sample is heated under specified conditions. While moisture, ash, volatile matter are determined experimentally, fixed carbon is determined indirectly.

Moisture

Approximately 1 g of coal (–72 mesh or –212 micron) was weighed in pre-weighed empty pair of watch glasses. The coal sample was spread over evenly with the help of nichrome wire and camel hair brush. The pair of watch glasses was transferred to an air oven maintained at a temperature of about 108 ± 2 °C for a period of 1 h with the upper watch glass slightly opened. After 1 h of heating the lower watch glass was covered by upper watch glass and placed in a desiccator for about 15 min for cooling. The pair of watch glasses was then weighed and the percentage content of moisture was determined as follows:

$$\text{Moisture content (\%)} = (Y - Z)/(Y - X) \times 100 \quad (1)$$

where, X is the weight of empty pair of watch glasses, g; Y is the weight of empty pair of watch glasses + coal, g; and Z is weight of watch glasses + coal after heating, g.

Volatile Matter

For the determination of volatile matter, an empty volatile matter crucible of specific size (38 mm in height, 25 mm external diameter and 22 mm internal diameter) made of silica, with lid uncovered was heated at 800 °C in the muffle furnace for an hour. Then the volatile matter crucible (VM crucible) was taken out and cooled to room temperature. The empty VM crucible was then weighed. Approximately one gram of fresh coal sample was weighed in VM crucible. The crucible was transferred to the furnace at 900 °C and heated for exactly 7 min. After that crucible was removed and cooled in a desiccator and weighed.

$$\% \text{VM content} = [(Y - Z)/(Y - X) \times 100] - M\% \quad (2)$$

where, X is the weight of empty crucible with lid, g; Y is the weight of crucible + coal, g; Z is the weight of

crucible + residue (coke) after heating, g and M is percent of moisture content.

Ash

In order to determine the ash content, an empty silica dish was weighed. Approximately one gram of fresh coal was weighed in the dish. The dish was placed in a muffle furnace and the temperature was raised to 450 °C and subsequently it was kept at that temperature for 30 min. Then the temperature of the furnace was raised to 800 ± 20 °C. The dish was kept at this temperature for another 1 h. It is to be ensured that the coal is completely burnt. Complete combustion of coal was determined by repeated weighing of the burnt sample. After that the dish was taken out from the muffle furnace and cooled in a desiccator and weighed.

$$\% \text{Ash content} = [(Z - X)/(Y - X)] \times 100 \quad (3)$$

where, X is weight of empty silica dish, g; Y is weight of silica dish + coal, g; Z is the weight of silica dish + residue (ash) after incineration, g.

Fixed Carbon

Fixed carbon is the difference between 100 % and the sum of the percentages of moisture, ash and volatile matter.

$$\text{FC} = 100 - (\text{VM} + \text{M} + \text{A})\% \quad (4)$$

where, FC is percentage of fixed carbon, VM is percentage of volatile matter, M is percentage of moisture and A is percentage of ash.

Ultimate Analysis of Coal

Vario EL III CHNS analyser from Elementar Germany was used for determination of carbon, hydrogen, nitrogen and sulphur. Oxygen was calculated using the following relations:

$$\text{O}\% = 100 - (\text{C}\% + \text{H}\% + \text{N}\% + \text{S}\% + \text{M}\% + \text{Ash}\%) \quad (5)$$

The experimental procedure in brief is as presented subsequently [13].

To start the analysis, first of all, the carousel from the Vario EL III was removed and the position of carousel hole was adjusted to zero. The main power of analyser was switched on, after a while the carousel of the analyser started moving and came to original position, i.e. zero. Now the carousel was placed at top at original position. Before performing the sample analysis, the analyser is first run with few blank determinations (no sample) and thereafter a few samples of standard sulfanilic acid (whose composition is known) is run to calibrate the analyser. It is to be ensured that calibration factor of the analyser should not

be less than 90 %. To perform the ultimate analysis of coal, pre-manufactured tin boat was weighed in precision digital balance. Few milligram (say 4–5 mg) of tungsten oxide, which acts as a catalyst, is mixed with approximately 10 mg of coal sample of –200 mesh size. The pellets were prepared by using tin boat containing tungsten oxide and coal sample with the help of pellet maker. The pellet is transferred to the slots provided in the carousel (upper portions) of Vario EL III CHNS analyser. There are 79 slots in the analyser.

Two types of gases namely helium and oxygen are used for the analysis. Helium is used as carrier gas and oxygen for combustion purpose. During the experiment, helium gas flow is maintained at the rate of 200 ml/min and oxygen dosage is 90 s for each sample. Requirement of oxygen per sample is 40 ml. Before the gases come into contact with the pellet it is passed through drying agents. Vario EL III CHNS analyser consists of various parts and instrumentation which includes; oxidation tube, reduction tube and absorption columns for absorbing N_2 , CO_2 , water vapour, SO_2 . In the oxidation tube there is ash finger. Oxidation tube is placed in the oxidation furnace, the temperature of which goes to around 1150 °C. The product gas which is emitted from oxidation tube passes through reduction tube having temperature of 850 °C first and then these gases pass to absorption columns for absorbing N_2 , CO_2 , water vapour, SO_2 . Thermal conductivity detector (TCD) detects the presence and quantity of these gases by measuring the peaks and the area under peaks. The quantity of gases absorbed under the peaks is converted into the elemental composition, i.e. N, C, H, and S, in the instrument itself by way of a machine dedicated programme. The results are displayed in the computer attached to analyser machine and after completion of analysis, the result was printed. Approximately one sample takes 15 min for complete analysis. Photograph of Vario EL III CHNS analyser is shown in Fig. 2.

Discussion of Results

The correlation studies have been carried out between the susceptibility index, PD and the coal characteristics as obtained from proximate and ultimate analyses. MS Office

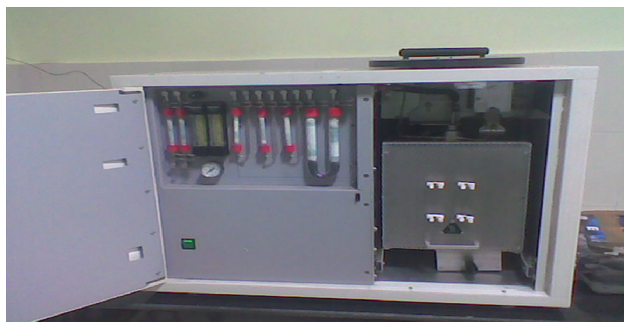


Fig. 2 Photograph of Vario EL III CHNS analyser

Excel 2007 is used for the statistical analysis of experimental results. Efforts are made to get the best fit curve after achieving maximum correlation coefficient.

It has been observed by different researchers in the past that the susceptibility of coal to spontaneous combustion depends upon the different intrinsic characteristics of the coal. Synthesizing all the studies of the past, the independent variables have been chosen. The coal characteristics have already been studied by carrying out different experiments. From these experiments the following critical parameters affecting the susceptibility of coal to spontaneous combustion are chosen as independent variables for this correlation study:

Proximate Analysis

- Moisture content, M (wt%)
- Volatile matter on dry ash free (daf) basis, VM_{daf} (wt%)

Ultimate Analysis

- Carbon content on dry ash free (daf) basis, C_{daf} (wt%)
- Hydrogen content on dry ash free (daf) basis, H_{daf} (wt%)
- Oxygen content on dry ash free (daf) basis, O_{daf} (wt%)

Potential difference (PD) obtained from WOP analysis as presented in Table 1 and intrinsic properties of coal like M , VM_{daf} , O_{daf} , H_{daf} , and C_{daf} as depicted in Table 2 are correlated by statistical analysis. Figures 3–7 represent correlation graph. Correlation coefficient (r) for each graph along with empirical relation is recorded. It may be mentioned here that nitrogen has no effect on the spontaneous heating tendency of coal. The total sulphur content of maximum number of samples is less than 1.90 wt% (except 3 coal samples where the values are 7.18, 5.04, 5.07 wt%). Therefore, these parameters are not taken into consideration in these analyses. Analysis of results with principal components analysis shows that ash and fixed carbon do not have any correlation with PD [7]. It has been observed that PD increases with increase in moisture content of coal indicating higher susceptibility to spontaneous heating of coal. Beyond 8–9 % of moisture content of coal this trend is not observed (Fig. 3). Correlation coefficient is observed to be 0.78. This result conforms to the findings of other researchers. Nandy et al. [14] observed that CPT, which is widely used in India, decreases with increase in moisture content of coal and they have indicated that beyond 4–6 % moisture content—there is not much change in CPT [1]. Figure 4 indicates that PD increases with increase in volatile matter (on daf basis) of coal indicating higher

Table 2 Results of Proximate and Ultimate analysis of coal

S. no.	M (%)	VM _{daf} (%)	FC (%)	A (%)	C _{daf} (%)	H _{daf} (%)	N _{daf} (%)	S _{daf} (%)	O _{daf} (%)
1.	5.66	40.08	48.46	13.47	80.81	5.43	1.88	1.04	10.84
2.	6.27	42.47	48.55	9.34	80.46	5.94	1.84	1.00	10.77
3.	9.74	39.11	50.26	7.72	78.70	5.56	1.96	0.91	12.87
4.	0.86	28.98	52.46	25.29	86.08	5.01	2.06	1.11	1.16
5.	1.15	29.68	59.01	14.93	85.72	5.12	1.97	0.80	6.39
6.	7.79	40.55	46.5	13.99	78.53	5.82	2.07	0.74	12.84
7.	8.85	39.15	46.79	14.26	78.36	5.81	2.05	0.72	13.06
8.	8.73	42.45	35.63	29.36	71.98	6.67	2.49	0.81	18.06
9.	4.82	40.66	34.59	36.89	76.24	6.26	2.35	0.55	14.60
10.	5.13	41.14	48.74	12.07	81.64	5.79	1.75	0.57	10.25
11.	4.80	42.76	44.60	17.28	79.76	5.97	2.13	0.87	11.27
12.	5.68	42.67	44.13	17.35	79.99	5.87	2.14	0.81	11.19
13.	1.27	30.40	52.28	23.61	85.46	5.43	1.98	1.03	6.11
14.	0.73	23.41	63.56	16.28	88.78	4.78	2.07	0.98	3.39
15.	1.40	31.04	55.51	18.10	85.84	5.14	2.00	1.01	6.01
16.	1.48	29.14	65.57	5.99	87.61	5.18	1.71	0.82	4.68
17.	0.45	20.44	70.28	11.21	89.27	5.04	1.45	0.63	3.61
18.	0.40	24.18	57.33	23.99	86.38	5.12	1.59	0.56	6.36
19.	0.43	21.17	52.54	32.92	87.44	4.73	1.85	0.68	5.31
20.	0.49	28.69	55.49	21.69	86.92	5.28	1.77	0.91	5.11
21.	0.82	22.80	59.86	21.64	88.25	4.81	1.84	0.86	4.23
22.	0.5	18.62	69.17	14.5	89.56	5.04	1.52	0.52	3.36
23.	2.38	34.90	47.61	24.49	79.94	6.02	1.64	0.46	11.94
24.	2.99	38.45	47.37	20.05	80.02	6.17	1.82	0.58	11.41
25.	2.05	41.53	45.23	20.59	80.93	6.93	2.37	0.94	8.83
26.	6.66	34.41	49.88	17.29	76.42	6.02	1.66	0.32	15.58
27.	5.18	44.23	42.9	17.9	73.79	6.29	1.40	0.85	17.67
28.	0.92	36.05	58.11	8.21	83.69	6.03	1.86	0.62	7.80
29.	10.98	46.53	33.89	25.64	77.82	7.81	1.72	1.09	11.57
30.	6.64	47.18	36.66	23.95	78.46	6.60	1.51	0.62	12.81
31.	7.91	48.25	31.56	31.11	77.35	6.84	1.44	0.64	13.73
32.	6.83	44.56	42.39	16.71	79.05	6.98	1.94	0.78	11.25
33.	7.88	47.93	27.94	38.46	71.73	6.90	1.40	0.86	19.12
34.	4.77	48.68	30.89	35.04	79.50	7.34	1.98	0.88	10.30
35.	6.06	40.10	49.15	11.89	79.87	6.53	2.24	0.77	10.59
36.	5.53	33.09	54.34	13.26	83.04	5.05	1.92	1.13	8.85
37.	5.61	38.92	50.25	12.12	81.37	5.51	2.02	0.91	10.20
38.	6.52	36.12	51.35	13.10	82.48	5.16	1.97	0.93	9.46
39.	2.00	36.62	57.82	6.77	76.37	8.25	1.58	1.18	12.62
40.	1.20	33.78	57.93	11.32	79.29	5.73	1.75	1.17	12.07
41.	5.04	36.14	49.4	17.6	79.68	6.51	1.59	1.85	10.37
42.	8.22	39.73	48.31	11.63	75.25	6.20	1.42	0.30	16.83
43.	8.76	42.42	43.2	16.21	77.97	7.30	1.71	0.60	12.42
44.	6.51	46.79	30.68	35.83	75.53	6.16	2.27	1.02	15.02
45.	9.44	46.35	45.44	5.87	73.07	7.18	1.39	0.43	17.94
46.	8.04	37.64	50.82	10.46	82.10	6.26	1.72	0.43	9.50
47.	12.45	44.45	41.7	12.48	81.51	7.34	2.14	0.37	8.63
48.	12.63	40.78	45.54	10.47	79.78	6.84	2.04	0.36	10.98

Table 2 continued

S. no.	M (%)	VM _{daf} (%)	FC (%)	A (%)	C _{daf} (%)	H _{daf} (%)	N _{daf} (%)	S _{daf} (%)	O _{daf} (%)
49.	10.21	41.07	47.6	9.01	77.93	6.55	1.57	0.78	13.17
50.	14.85	47.34	40.06	9.07	79.35	7.33	1.96	0.93	10.42
51.	13.36	43.74	38.84	17.60	78.98	6.89	1.46	0.56	12.09
52.	13.64	45.62	42.91	7.45	84.59	7.58	2.00	0.51	5.32
53.	7.62	40.93	43.80	18.23	80.46	6.81	1.25	0.46	11.02
54.	10.24	39.83	45.09	14.82	82.13	6.87	1.44	0.52	9.03
55.	9.88	46.93	38.34	17.87	75.83	6.73	1.54	0.64	15.27
56.	10.33	42.42	46.93	8.17	78.96	6.75	1.69	0.42	12.18
57.	1.70	45.34	53.00	1.34	70.02	6.92	1.06	7.18	14.82
58.	0.70	46.00	52.53	2.03	81.74	6.79	1.21	0.57	9.69
59.	1.03	48.52	48.89	4.01	76.25	6.77	1.16	3.69	12.13
60.	1.07	47.53	51.11	1.52	77.28	6.40	0.95	5.04	10.33
61.	1.02	42.22	56.68	0.88	80.10	6.61	1.33	1.40	10.57
62.	0.56	45.85	53.46	0.71	77.31	6.43	1.17	5.07	10.01
63.	6.69	42.27	43.22	18.45	79.84	5.38	2.26	0.81	11.70
64.	4.71	39.99	44.73	20.75	80.47	6.04	1.65	0.71	11.13
65.	3.00	46.02	38.12	26.38	81.38	6.63	1.64	0.69	9.66
66.	4.88	34.28	42.93	29.80	80.37	5.16	2.54	1.26	10.67
67.	3.90	47.96	41.64	16.08	75.54	6.84	1.54	1.09	15.00
68.	3.42	45.37	41.35	20.89	75.89	7.20	1.61	0.74	14.56
69.	0.75	24.13	68.48	8.99	87.72	5.09	1.50	0.88	4.82
70.	1.15	23.83	64.61	14.03	88.60	4.93	1.63	0.81	4.03
71.	0.49	23.40	51.48	32.30	86.56	5.03	1.65	0.61	6.14
72.	0.66	26.62	63.47	12.85	88.31	5.12	1.49	0.65	4.43
73.	4.82	34.34	53.47	13.74	82.99	5.28	1.89	1.08	8.75
74.	5.57	36.21	46.31	21.83	81.89	5.21	2.38	1.14	9.38
75.	1.29	34.32	54.09	16.35	83.50	5.28	1.64	0.67	8.91
76.	0.84	31.15	59.83	12.26	87.02	5.13	1.70	0.79	5.35
77.	15.71	55.22	36.4	2.98	74.42	6.37	1.69	0.85	16.68
78.	11.10	44.26	43.44	10.97	73.04	6.25	1.62	0.80	18.30

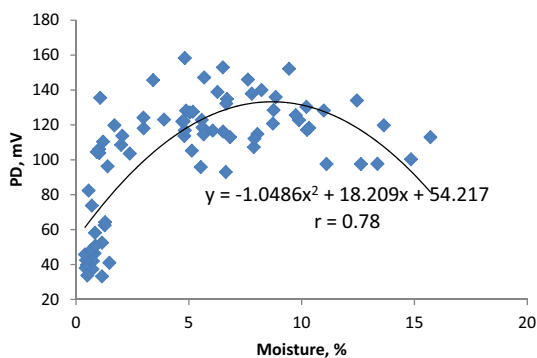


Fig. 3 Variation of PD with moisture

susceptibility to spontaneous heating of coal. This trend is not observed beyond 45–47 % of volatile matter of coal. Correlation coefficient is observed to be 0.81. This result also conforms to the findings of other researcher. Nandy

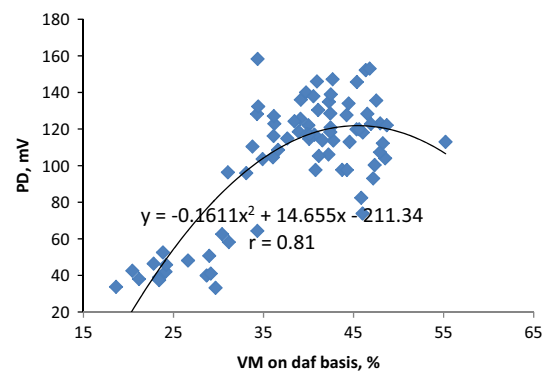


Fig. 4 Variation of PD with VM on daf basis

et al. [14] observed that CPT decreases with increase in volatile matter of coal and they have indicated that beyond 35 % volatile matter- there is not much change in CPT [1]. Correlation between PD and O_{daf} are shown in Fig. 5.

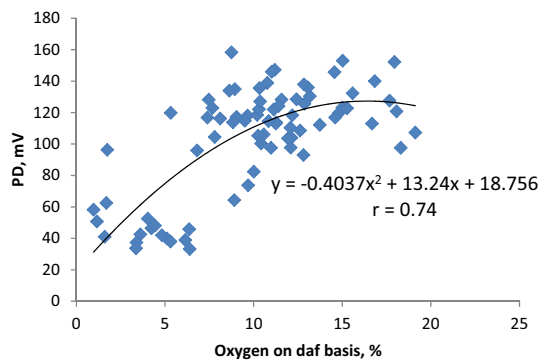


Fig. 5 Variation of PD with oxygen on daf basis

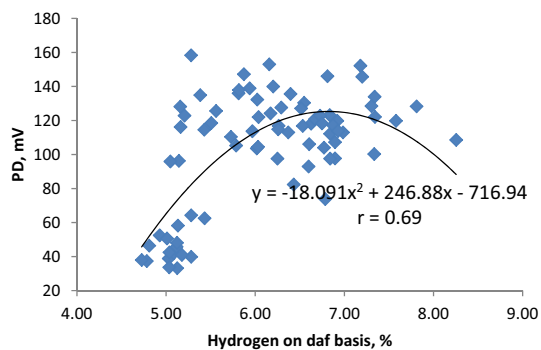


Fig. 6 Variation of PD with hydrogen on daf basis

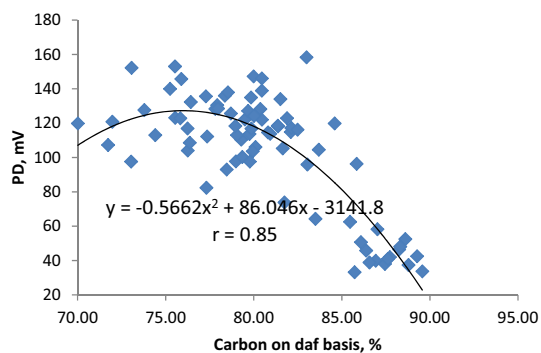


Fig. 7 Variation of PD with carbon on daf basis

PD increases with increase in O_{daf} , indicating higher susceptibility. Correlation coefficient in this case is found to be 0.74. Beyond 15–17 % of O_{daf} this trend is not observed. This result also conforms to the findings of other researcher [14]. They observed that CPT decreases with increase in oxygen in coal and they have indicated that beyond 9 % oxygen—there is not much change in CPT [1]. PD is found to increase with increase in H_{daf} indicating higher susceptibility to spontaneous heating of coal. Beyond 6.6–6.8 % of hydrogen this trend is not observed. Correlation coefficient is observed to be 0.69 (Fig. 6).

Relationship between PD and C_{daf} is shown in Fig. 7. PD increases with increase in C_{daf} up to 77 % carbon and after that PD decreases with increase in C_{daf} . Correlation coefficient is found to be 0.85 (Fig. 7).

Conclusions

The following conclusions emerge from the investigation:

- Since WOP method takes less time (about one and half hour) and it poses no problem with high moisture coals, it can be used for routine analysis by practicing engineers working in mines for ascertaining the susceptibility of coal to spontaneous combustion.
- It has been found that susceptibility index (PD) bears a good correlation with moisture content, volatile matter, oxygen, hydrogen and carbon content of coal.
- PD increases with increase in moisture content, volatile matter, oxygen and hydrogen content of coal. But beyond 8–9 % moisture content, 45–47 % volatile matter, 15–17 % oxygen—this trend is not observed.
- PD decreases with increase in carbon content. This trend is observed from 77 % carbon content of coal.

References

1. S.C. Banerjee, *Prevention and Combating Mine Fires. Coal Categorisation vis-à-vis Spontaneous Fire Risk* (Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, 2000), pp. 67–113. Special Indian Edition
2. B.T. Qin, L.L. Zhang, D.M. Wang, Q. Xu, The characteristic of explosion undermine gas and spontaneous combustion coupling. *Proc. Earth. Planet. Sci.* **1**, 186–192 (2009)
3. C. Kuenzer, J. Zhang, A. Tetzlaff, S. Voigt, D.P. Van, W. Wagner, H. Mehl, Uncontrolled coal fires and their environmental impacts: investigating two arid mining regions in north-central China. *Appl. Geogr.* **27**, 42–62 (2007)
4. D.P. Van, J. Zhang, W. Jun, C. Kuenzer, K.H. Wolf, Assessment of the contribution of in situ combustion of coal to greenhouse gas emission; based on a comparison of Chinese mining information to previous remote sensing estimates. *Int. J. Coal Geol.* **86**, 108–119 (2011)
5. M.N. Tarafdar, D. Guha, Application of wet oxidation processes for the assessment of the spontaneous heating of coal. *Fuel* **68**, 315–317 (1989)
6. D.C. Panigrahi, H.B. Sahu, G. Udayabhanu, V.K. Saxena, Wet oxidation method for predicting the spontaneous heating susceptibility of Indian coals. *Coal Min. Technol. Manag.* **9**(6–8), 13–21 (2004)
7. S.K. Ray, D.C. Panigrahi, A.K. Varma, An electro-chemical method for determining the susceptibility of Indian coals to spontaneous heating. *Int. J. Coal Geol.* **128–129**, 68–80 (2014)
8. S.K. Ray, Development and standardization of a method for studying the susceptibility of coal to spontaneous heating. Unpublished Ph.D. Thesis, Indian School of Mines, India, 2013

9. W.C. Peters, *Exploration and Mining Geology* (Wiley, New York, 1978), pp. 416–425
10. IS (Indian Standard): 436, *Methods of sampling of coal and coke* (Indian Standard, Dhanbad, 1964), p. 13
11. https://miningandblasting.files.wordpress.com/2009/09/spontaneous_combustion_guidelines.pdf. Accessed 15 Oct 2013
12. IS (Indian Standard): 1350, *Part—I. Methods of Test for Coal and Coke—Proximate Analysis* (Indian Standard, Dhanbad, 1969), pp. 5–18
13. ASTM D 5373-93, in *Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Laboratory Samples of Coal and Coke*, (ASTM D 5373-93), pp. 493–496
14. D.K. Nandy, D.D. Banerjee, R.N. Chakravorty, Application of crossing point temperature for determining the spontaneous characteristics of coals. *J. Mines, Metals Fuels*. 41–48 (1972)