Effect of Moisture on Smouldering Combustion Characteristics of Indian Coals

S. K. Ray[1,*], D. C. Panigrahi[2] and G. Udayabhanu[3]

[1]*Central Institute of Mining & Fuel Research, Barwa Road, Dhanbad, India*
[2]*Department of Mining Engineering, Indian School of Mines, Dhanbad, India*
[3]*Department of Applied Chemistry, Indian School of Mines, Dhanbad, India*

Received January 20, 2013; Accepted March 17, 2013

Abstract: Coal mine fire interrupts sustainable mining, and the major cause for this is smouldering combustion. Therefore, it is essential to assess the self-heating susceptibility of coal seams so that precautionary measures can be taken against the occurrence of fire. The paper describes effect of moisture content of coal on its smouldering combustion. Moisture content of coal samples was increased by subjecting them to enhanced aqua vapor pressure. A new electrochemical method, viz., wet oxidation potential (WOP) technique, is used for assessing the susceptibility of coal to smouldering combustion. In the present investigation, 152 experiments using seventy-six coal samples collected from fiery and non-fiery seams in India were carried out. The WOP method demonstrates that rate of reduction of potential difference (RPD) increases in coal samples with enhanced moisture, indicating that oxidation rate is higher. Results of the study corroborate well with the field observations.

Keywords: Coal, moisture content, wet oxidation potential, self-heating

1 Introduction

Coal is the most abundant fossil fuel in the world. 40% of world electricity is produced using coal. Coal mine fire, a major problem worldwide, is caused primarily due to smouldering combustion. Smouldering combustion is defined as the slow, low-temperature flameless form of combustion sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel [1]. Typically, in smouldering at ambient conditions, the peak temperature is around 500–700°C and the average heat of combustion is 6–12 kJ/g. Smouldering propagates at velocities in the range of 10–30 mm/h [2]. This is an incomplete oxidation reaction

**Corresponding author*: santoshray8@gmail.com

DOI: 10.7569/JSEE.2013.629512

and thus emits toxic gases, including carbon monoxide, sulfur dioxide, and methane. Self-heating would be facilitated in conditions where a 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 [3]. Self-heating leading to coal mine fire causes huge loss of coal, environmental pollution, hindrance to normal production and productivity, and subsidence of surface infrastructure such as roads, pipelines, electric lines, bridge supports, buildings, and homes. Thereby, safety and economic aspects of a mine are jeopardized. Around 1.8 billion T of coking coal are locked in by fire in Jharia coalfields in India. In China, coal fires consume an estimated 20–200 million tons of coal a year, accounting for about 1 percent of the global carbon dioxide emissions from fossil fuels [4]. Thus it can be stated that smouldering combustion results in huge loss of coal, affecting conservation of fossil fuels; additionally, it damages the environment, emitting greenhouse gases and causing soil and water pollution. Sustainable mining balances economic growth, conservation of minerals, environmental protection, safety, and social development. Coal mine fire thus disturbs sustainable mining.

The increasing international trade in both metallurgical and steam coal has led to renewed interest in the potential for smouldering combustion occurring during transport, particularly by bulk carriers. Coal stockpiles are prone to smouldering combustion, especially where large quantities are stored for extended periods. Analysis of the occurrence of these fires reveals that most of them could have been averted if suitable preventive measures had been taken. The first step for taking such measures is to assess the susceptibility of coal seams. Attempts have been made to determine self-heating tendency of coal based on their constituents obtained from proximate and ultimate analyses. Gradations are made particularly by using inherent moisture content, volatile matter content, and oxygen percentage. Moisture plays an important role in smouldering combustion of coal. A number of studies have been reported on the effect of moisture on self-heating susceptibility of coal seams. From the studies on oxidation kinetics and DTA, Banerjee *et al*. [5] concluded that the release of moisture from coal facilitates air entry due to the opening up of active centers in the coal matrix. High moisture coals should thus have a higher tendency of self-heating, which is also an observed fact. The effects of the gas flow rate, the moisture of coal piles, humidity of the air, and particle size on smouldering combustion of coal samples were examined using the crossing point temperature (CPT) method [6], and this study revealed that CPT values increased with the humidity of air, indicating the occurrence of some reaction inhibiting mechanism. Kadioğlu *et al*. [7] observed that CPT values increased as moisture content and particle size of lignite samples increase. Vance *et al*. [8] studied the effect of moisture content and drying methods on self-heating rate of a sub-bituminous coal in the temperature range 40–140°C. They reported that at a medium moisture content of ~7 wt%, the self-heating rate is highest, predominantly at temperatures below 80°C. McPherson [9] explained the effects of moisture content of coal on self-heating. He observed that the moisture content of

DOI: 10.7569/JSEE.2013.629512

coal is driven off by evaporation during early stage of heating. Hence, some of the heat is removed in water vapor as latent heat of evaporation, leading to inhibition of rise in temperature of coal. Bhattacharyya [10] described the role of desorption of moisture from coal on its initial stage of self-heating under isothermal conditions at 30–35°C. The data suggest that moisture desorption acts as an inhibitor to the self-heating of coal. Nandy *et al*. [11] reported that CPT obtained by passing air of varying relative humidity (20–80% RH) did not show any definite trend with the changes in the relative humidity. In addition, some researchers carried out wet oxidation potential experiments to predict smouldering combustion characteristics of coal. Tarafdar and Guha [12] conducted wet oxidation experiments with seven coal samples and observed that the higher the potential difference, the more susceptible would be the coal towards smouldering combustion. Panigrahi *et al*. [13] conducted experiments with 12 coal samples from Indian coalfields. They suggested that the method has the potential to predict susceptibility of coal to self-heating more accurately than CPT. It is reported that the mechanism of coal oxidation is not the same above 70°C as at lower temperatures [14]. At temperatures above 70°C, the oxidation of coals occurs more readily in dry air than in moist air. Further, it has been found that coal reacts with oxygen more rapidly when wet than when dry at room temperatures [15].

From the above discussions, it is evident that there is a necessity to assess self-heating susceptibility of coal seams so that advance precautionary measures can be taken against the occurrence of fire. The present investigation deals with assessing self-heating susceptibility of 76 coal samples with wide variation in moisture content.

2 Experimental Investigation

Seventy-six (76) coal samples covering fiery and non-fiery seams of twelve mining companies of India were collected for this investigation. The companies are Eastern Coalfields Ltd., Bharat Coking Coal Ltd., Central Coalfields Ltd., Mahanadi Coalfields Ltd., South Eastern Coalfields Ltd., Northern Coalfields Ltd., Western Coalfields Ltd., North Eastern Coalfields, Singareni Collieries Company Ltd., IISCO Steel Plant SAIL, Monnet Ispat & Energy Ltd., and Tata Steel Ltd. Details of coal samples, i.e., sample code, name of the mine, and the seam and mining company, are presented in Table 1. The coal samples were collected following channel sampling procedure [16–17] and were brought to the laboratory in sealed condition for analysis. Samples were ground and sieved to –212 μ. Moisture content of fresh coal samples was determined following the procedure as mentioned in IS 1350- Part 1, 1969 [18], and wet oxidation potential analysis was carried out to assess the susceptibility of coal. Fresh coal samples of each mine were then kept in a vacuum desiccator containing water at the base. A vacuum pump (rotary-type single-stage, 20 l capacity) was run for 5–6 min to evacuate the desiccator partially, and samples were subjected to

DOI: 10.7569/JSEE.2013.629512

Figure 1 Experimental set up for moisture enhancement of coal samples.

enhanced aqua vapor pressure for 4 days. Four coal samples at a time were used for moisture enhancement experiment (Figure 1). Humidity inside the vacuum desiccator was maintained above 95%. A duly calibrated portable humidity meter was kept inside the desiccator to monitor humidity inside it. Moisture enhanced coal samples were then tested for moisture content and wet oxidation potential analysis.

2.1 *Wet Oxidation Potential Analysis*

Wet oxidation potential analysis was carried out with potassium permanganate ($KMnO_4$) as oxidizer in potassium hydroxide (KOH) solution. The equivalence factor of $KMnO_4$ in this case was taken as 158.04/3 = 52.68. Experiments were conducted with 0.2 N $KMnO_4$ in 1N KOH at 45°C, as these conditions gave optimum results [19]. In that study, 600 experiments with fifty coal samples were carried out. Experiments were carried out with different concentrations of $KMnO_4$, in 1 N KOH at 27, 40, and 45°C. Analysis of the results indicated that the experiments of the WOP method should be carried out with 0.2N $KMnO_4$ solution in 1N KOH at 45°C to achieve optimum results. The study in detail is reported in Ray *et al*. [19]. 100 ml of alkaline $KMnO_4$ solution was taken in a beaker, 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 using a millivoltmeter after attaining a stable reading. 0.5 g of coal sample of –212 μ size was added to this solution and was continuously stirred using a magnetic stirrer. The potential difference was recorded until 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 takes about an hour. The difference between potential difference (PD) of

DOI: 10.7569/JSEE.2013.629512

the mixture before adding the coal sample and after complete oxidization of coal sample was calculated for each sample and total time taken for each experiment was recorded, and thus rate of reduction of potential difference was calculated. This rate was considered as a parameter for susceptibility of coal towards smouldering combustion.

3 Field Observations on Occurrence of Fire in Different Seams

- Blazing fire/heating has been observed in the following mines: Ghuggus OCP, Meyo Bottom, WCL; Ghuggus OCP, Meyo Middle, WCL; Naigaon OCP, Meyo Middle, WCL; KD Hessalong OCP, Dakra Seam, CCL; Central Kajora Colliery, Seam RVIII, ECL; Jhanjra Project, Seam RVIIA, ECL; Umrer OCP, Seam IV, WCL; Kamptee OCP, VB Seam, WCL; New Majri III, Majri Seam, WCL; Jingurda Mine, Seam Jhingurda, NCL; Amlohri OCP, NCL; and Jayant OCP, NCL. Blazing fire/heating of KD Hessalong OCP, CCL; Naigaon OCP, WCL; Jayant OCP, NCL, Ghuggus OCP, WCL, Kamptee OCP, WCL, and Amlohri OCP, NCL are shown in the photograph (Figure 2). RPD of these mine samples are found to be 8.51, 11.85, 9.02, 10.84, 10.77, and 9.45 mV/min, respectively.
- Bastacolla, Seam O, Seam I & Seam II; Bansdeopur, Seam VIII; Kalyani OCP, Seam Karo (Major); and 6&7 Pits, Seam IX are considered to be poorly susceptible as no evidence of fire / heating is observed in these mines.

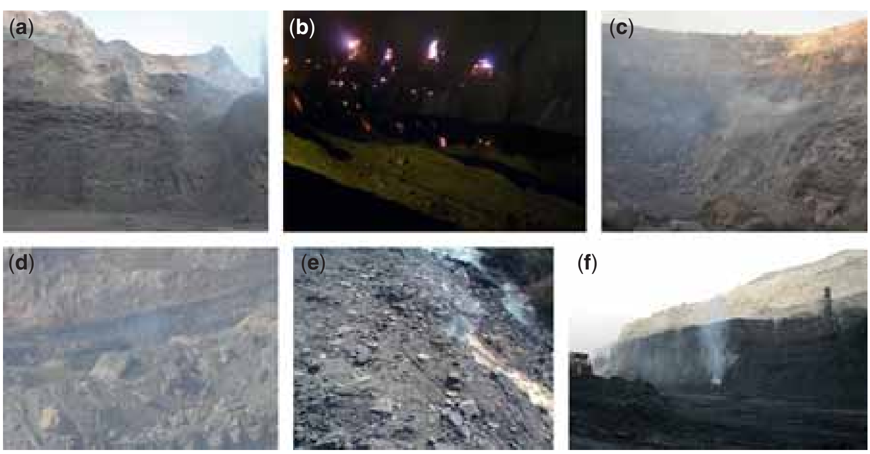

Figure 2 Blazing fire/smoke seen in different Indian mines **(a)** Smoke coming out from KD Hessalong, Dakra, **(b)** Blazing fire in Ghuggus OCP, Meyo middle, **(c)** Blazing fire in Naigaon OCP, Meyo Bottom, **(d)** Smoke coming out from Kamptee OCP, VB, **(e)** Smoke coming out in Jayant OCP, Purewa Top, **(f)** Blazing fire in Amlohri OCP, Purewa Merge.

DOI: 10.7569/JSEE.2013.629512

4 Results and Discussions

The moisture content of coal samples (as received) and rate of change of PD (RPD) are observed in the range of 0.40–14.85 wt% and 1.3–19.03 mV/min, respectively. With the increase of moisture content of coal samples, these values changed to 0.51–15.22 wt% and 2.05–20.54 mV/min, respectively (Table 1). Maximum and minimum RPD in wet oxidation potential analysis in the present investigations are found to be 20.54 (S40, Umrer OCP, Seam IV) and 1.3 mV/min (S68, Kalyani OCP, Seam Karo (Major)), respectively. Graphs are plotted between moisture and RPD of fresh coal samples, and enhanced moisture and RPD of treated coal samples (Figure 3). In general, as moisture increases, RPD increases, indicating more susceptibility to smouldering combustion. For fresh and treated coal samples, this trend is observed up to a moisture content of 12 wt%. The correlation coefficient of fresh and treated coal samples is observed to be 0.87. With increase in moisture of fresh coal samples, RPD values in general have increased, indicating that coal becomes more susceptible to smouldering combustion. But no definite trend

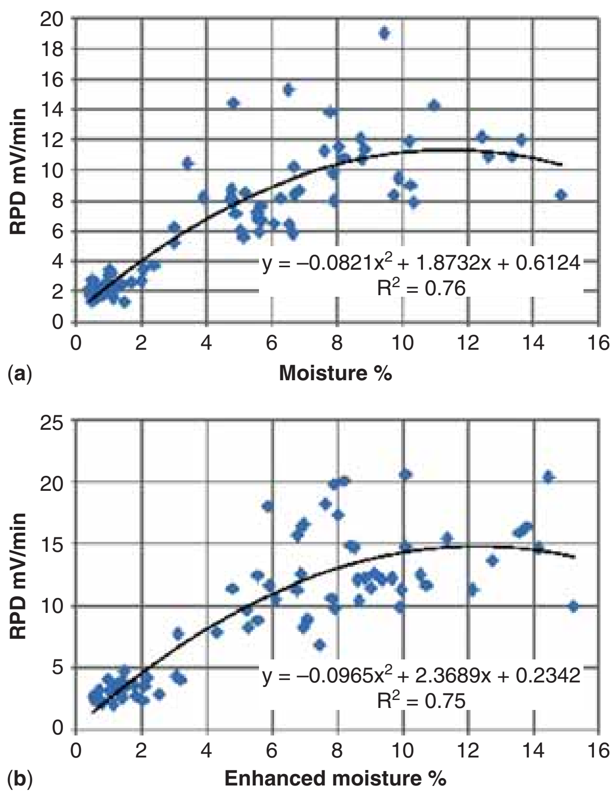

Figure 3 Variation of RPD with moisture of **(a)** fresh coals **(b)** moisture enhanced coals.

DOI: 10.7569/JSEE.2013.629512

Table 1 Variation of RPD with moisture.

Colliery/Seam/Company	Sample code	As received condition		Moisture enhanced condition		M% increase	RPD% increase
		RPD	M	RPD	M		
Central Kajora/RVIII, ECL	S1	7.64	5.66	18.0	5.86	3.53	135.60
Parascole East/RVII, ECL	S2	8.17	6.27	15.69	6.77	7.97	92.04
Shyamsunderpur/RVII, ECL	S3	8.37	9.74	9.9	9.88	1.44	18.28
Bansdeopur/VIII, BCCL	S4	1.78	0.73	2.73	1.82	149.32	53.37
Lakhimata/Kalimati, ECL	S5	1.58	1.15	3.44	1.20	4.35	117.72
Milupara/ II, Monnet Ispat & Energy Ltd.	S6	14.39	4.82	18.21	7.62	58.09	26.55
Chasnalla/XII, ISP, SAIL	S7	2.47	1.29	2.52	1.41	9.30	2.02
Rajnagar RO/ 8A2, SECL	S8	5.93	5.61	8.82	7.07	26.02	48.74
5&6 Incline/Index, SECL	S9	6.46	6.52	8.98	7.07	8.44	39.01
Kakatiya LW / I, SCCL	S10	8.43	6.69	11.24	6.75	0.90	33.33
Victoria West/Ramnagar, BCCL	S11	2.47	1.40	3.51	1.49	6.43	42.11
NCPH/ III, SECL	S12	6.85	5.53	16.57	6.98	26.22	141.90
Kumardhubi/Singpur Top, ECL	S13	2.50	1.27	3.86	1.35	6.30	54.40
Lakhimata/Metadih, ECL	S14	1.81	0.86	3.33	1.06	23.26	83.98
Western Quarry/ XIII/ XIV, ISP, SAIL	S15	1.76	0.84	3.19	1.25	48.81	81.25
Anjan Hill Mine/ III, SECL	S16	6.49	6.06	9.79	7.92	30.69	50.85
Sudamdih Shaft Mine/ XI/XII, BCCL	S17	1.32	1.48	2.34	2.03	37.16	77.27
Kondkel/ III, Monnet Ispat & Energy Ltd	S18	7.23	5.57	10.64	7.81	40.22	47.16
Kakatiya LW / III, SCCL	S19	7.12	4.88	9.67	5.21	6.76	35.81
Kottadih/ RV, ECL	S20	7.79	4.82	16.41	6.91	43.36	110.65
Jhanjra/ RVIIA, ECL	S21	13.79	7.79	17.3	8.0	2.70	25.45
MIC unit, Jhanjra/RVI, ECL	S22	11.33	8.85	11.45	9.03	2.03	1.06
Bastacolla/ II, BCCL	S23	1.73	0.43	2.05	1.13	162.79	18.50
Jhanjra/ RVII, ECL	S24	12.08	8.73	12.23	9.67	10.77	1.24
Kottadih/ RIII/II, ECL	S25	5.54	5.13	8.27	5.25	2.34	49.28
Khaskajora/ RVIIIA, ECL	S26	8.12	4.80	10.55	6.11	27.29	29.93
Khaskajora/ RVIIIB, ECL	S27	6.69	5.68	6.84	7.40	30.28	2.24

(*Continued*)

DOI: 10.7569/JSEE.2013.629512

Colliery/Seam/Company	Sample code	As received condition		Moisture enhanced condition		M% increase	RPD% increase
		RPD	M	RPD	M		
Saoner Mine 1/IV (M), WCL	S28	10.71	8.76	12.19	8.82	0.68	13.82
Saoner Mine 3/V, WCL	S29	15.30	6.51	19.79	7.90	21.35	29.35
Mudidih/IX, BCCL	S30	2.02	0.82	4.09	0.97	18.29	102.48
Moonidih/ XVI Top, BCCL	S31	2.35	0.49	3.17	0.71	44.90	34.89
Kamptee OCP/VB, WCL	S32	10.77	8.22	12.63	9.12	10.95	17.27
Sijua/XIII, Tata Steel Ltd.	S33	1.75	0.75	2.14	0.81	8.00	22.29
Churcha West/V, SECL	S34	2.72	2.0	4.32	3.06	53.00	58.82
Tipong Colliery/ 20′, NEC	S35	2.60	1.7	4.01	3.19	87.65	54.23
Churcha East/V, SECL	S36	2.08	1.2	3.61	1.61	34.17	73.56
6&7 Pits/IX, Tata Steel Ltd.	S37	2.78	0.49	2.88	0.72	46.94	3.60
Tipong/60′(B), NEC	S38	2.17	0.70	3.06	1.05	50.00	41.01
Tipong/60′(T), NEC	S39	3.06	1.03	3.50	2.07	100.97	14.38
Umrer OCP/IV, WCL	S40	19.03	9.44	20.54	10.09	6.89	7.93
Tirap OC/60′(T) N Limb, NEC	S41	3.42	1.02	4.68	1.47	44.12	36.84
Tirap OC/8′ N Limb, NEC	S42	3.23	1.07	4.17	2.17	102.80	29.10
Bastacolla/I, BCCL	S43	2.18	0.40	2.20	0.69	72.50	0.92
6&7 Pits/XI, Tata Steel Ltd.	S44	2.09	0.66	3.23	1.04	57.58	54.55
Tirap OC/20′N Limb, NEC	S45	1.87	0.56	2.87	1.10	96.43	53.48
Sijua/XIV, Tata Steel Ltd.	S46	2.19	1.15	2.87	1.38	20.00	31.05
Bastacolla /0, BCCL	S47	1.93	0.45	2.23	0.63	40.00	15.54
Adriyala Shaft Project/I, SCCL	S48	8.21	3.90	12.39	5.54	42.05	50.91
Kakatiya LW /II, SCCL	S49	6.22	3.0	7.74	3.11	3.67	24.44
Kakatiya LW /IA, SCCL	S50	8.13	4.71	11.38	4.78	1.49	39.98
Jingurda/Jhingurda, NCL	S51	10.86	13.36	14.64	14.16	5.99	34.81
New Majri III/Majri, WCL	S52	11.48	8.04	12.10	9.36	16.42	5.40
Ghuggus OCP/Meyo Bottom, WCL	S53	12.18	12.45	13.60	12.73	2.25	11.66
Ghuggus OCP/Meyo Middle, WCL	S54	10.84	12.63	20.36	14.45	14.41	87.82

DOI: 10.7569/JSEE.2013.629512

Colliery/Seam/Company	Sample code	As received condition		Moisture enhanced condition		M% increase	RPD% increase
		RPD	M	RPD	M		
Naigaon OCP/Meyo Bottom, WCL	S55	11.85	10.21	15.39	11.35	11.17	29.87
Lilari OC/Lajkura Top, MCL	S56	14.26	10.98	15.86	13.56	23.50	11.22
Belpahar OCM/IB, MCL	S57	5.81	6.64	10.46	8.66	30.42	80.03
Belpahar OCM/Rampur Top, MCL	S58	8.01	7.91	14.8	8.39	6.07	84.77
Belpahar OCM/Rampur Bottom, MCL	S59	8.69	6.83	14.73	10.07	47.44	69.51
Lakhanpur OCP/Lajkura Top, MCL	S60	9.75	7.88	11.34	9.95	26.27	16.31
Naigaon OCP/Meyo Middle, WCL	S61	8.36	14.85	10.01	15.22	2.49	19.74
Jayant OCP/Turra, NCL	S62	11.98	13.64	16.36	13.80	1.17	36.56
Amlohri OCP/Purewa Merge, NCL	S63	9.45	9.88	11.64	10.71	8.40	23.17
Jagannath OCP/III, MCL	S64	8.72	4.77	12.57	6.87	44.03	44.15
Jayant OCP/Purewa Bottom, NCL	S65	11.23	7.62	12.07	8.61	12.99	7.48
Amlohri OCP/Turra, NCL	S66	7.89	10.33	12.50	10.54	2.03	58.43
Jayant OCP/Purewa Top, NCL	S67	9.02	10.24	11.32	12.14	18.55	25.50
Kalyani OCP/Karo (Major), CCL	S68	1.30	0.5	2.68	0.65	30.00	106.15
Argada Colliery/I, CCL	S69	3.70	2.38	7.86	4.30	80.67	112.43
Hesagora OCP/X Bottom, CCL	S70	3.45	2.05	4.16	3.13	52.68	20.58
Halibari/XB, SECL	S71	6.05	5.04	8.28	6.95	37.90	36.86
Ravindrakhani New Tech Incline/IA, SCCL	S72	10.41	3.42	11.65	5.90	72.51	11.91
Churi/ Lower Bachra, CCL	S73	10.18	6.66	20.05	8.20	23.12	96.95
KD Hessalong OCP/ Dakra, CCL	S74	8.51	5.18	14.68	8.52	64.48	72.50
Argada/J, CCL	S75	5.18	2.99	8.83	5.55	85.62	70.46
Kuju/VII, CCL	S76	2.61	0.92	3.68	1.77	92.39	41.00

RPD: Rate of change of PD at 0.2N $KMnO_4$ with 1N KOH solution, mV/min., M-Moisture, %

DOI: 10.7569/JSEE.2013.629512

is observed between percent increase of moisture with percent increase of RPD (Table 1). 25 samples show very low moisture content, i.e., 0.4 to 1.5%. In general, these coal samples have low RPD (1.32–2.78 mV/min). These samples exhibit a slight increase in RPD after moisture enhancement. In spite of having low moisture content, NEC samples (S38, S39, S41, S42, and S45) are observed to have slightly higher values of RPD. This is because most of these samples have high volatile matter and sulfur content. 5 samples with moisture content of 1.5–3%, 9 samples with moisture content of 3–5%, and 20 samples with moisture content of 5–8% all show remarkable increase in RPD after treatment for enhancing moisture content. 17 samples have moisture content above 8%, and these do not exhibit any significant increase in RPD after treatment. Therefore, it may be concluded that samples having moisture content between 1.5–8% show significant increase in RPD after treatment for enhancement of moisture.

Repeatability of experimental results was verified with two coal samples in moisturized condition, carrying out 5 experiments each for a sample. S52 (New Majri III, Majri Seam) gives RPD of 12.3, 12.7, 12.45, 13.0, and 12.0 mV/min, whereas S67 (Jayant OCP, Purewa Top) shows RPD of 11.42, 11.18, 11.65, 11.5, and 12.92 mV/min. So, standard deviation of these two samples comes out to be 0.33 and 0.61, respectively.

5 Conclusions

The following conclusions may be drawn from the present investigations:

- All of the treated coal samples exhibit enhancement of moisture content. Therefore, the proposed system can be considered to be efficient (Figure 1).
- RPD in wet oxidation potential analysis gives a very good correlation with moisture ($r = 0.87$) for fresh as well as moisture-enhanced coals, indicating that the method is suitable for assessing the effect of variation of moisture on smouldering combustion of coal.
- As RPD increases, susceptibility of coal to self-heating enhances, which has been corroborated with the field observations (Figure 2).
- Coal samples having moisture content between 1.5–8% show significant increase in RPD after treatment for enhancement of moisture.
- Generally, with increase of moisture, susceptibility of coal increases. RPD increases with enhanced moisture in coal samples, indicating that the coal is becoming more susceptible. This is in agreement with findings of earlier investigations. However, no definite trend is observed between percent increase of moisture with percent increase of RPD.

Keeping all the above points in view, it may be concluded that wet oxidation analysis is a suitable method for determining the effect of moisture on self-heating susceptibility of coal samples.

DOI: 10.7569/JSEE.2013.629512

References

1. T.J. Ohlemiller: *SEPE fire protection handbook, chapter 9: smouldering combustion*, 3rd Edn., pp. 2.200–2.210, National Fire Protection Association, Quincy, MA (2002).
2. G. Rein, Smouldering combustion phenomena in science and technology. *Int. Rev. Chem. Eng*. **1**, 3–18 (2009).
3. S.C. Banerjee: *Coal catogorisation vis-à-vis spontaneous fire risk, prevention and combating mine fires*. Special Indian Edn., pp. 67–113, Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi (2000).
4. http://en.wikipedia/wiki/coal_seam_fire
5. S.C. Banerjee, B.D. Banerjee, and R.N. Chakravorty, Rate studies of aerial oxidation of coal at low temperatures (30 to 170°C). *Fuel* **49**, 324–331 (1970).
6. A. Kücük, Y. Kadioğlu, and M.S. Gülaboğlu, A study of spontaneous combustion characteristics of a Turkish lignite: particle size, moisture of coal humidity of air. *Combust Flame* **133**, 255–261 (2003).
7. Y. Kadioğlu and M. Varamaz, The effect of moisture content and air-drying on spontaneous combustion characteristics of two Turkish lignites. *Fuel* **82**, 1685–1693 (2003).
8. W.E. Vance, X.D. Chen, and S.C. Scott, The rate of temperature rise of a sub-bituminous coal during spontaneous combustion in an adiabatic device: the effect of moisture content and drying methods. *Combust Flame* **106**, 261–270 (1996).
9. M.J. McPherson: *Subsurface ventilation and environmental engineering* chapter 21, pp. 836, Chapman & Hall, London (1993).
10. K.K. Bhattacharyya, The role of desorption of moisture from coal in its spontaneous heating. *Fuel* **51**, 214–220 (1972).
11. D.K. Nandy, D.D. Banerjee, S.C. Banerjee, and R.N. Chakravorty, Effect of moisture on the self heating characteristics of coal. *J. Min. Met. Fuels* **314**, 297–301 (1967).
12. M.N. Tarafdar, D. Guha, Application of wet oxidation processes for the assessment of the spontaneous heating of coal. *Fuel* **68**, 315–317 (1989).
13. D.C. Panigrahi, H.B. Sahu, G. Udayabhanu, and V.K. Saxena, Wet oxidation method for predicting the spontaneous heating susceptibility of Indian coals. *CMTM* June-August, 13–21 (2004).
14. S.L. Chakraborty, Auto-oxidation of Indian coals, Part II - Mechanism of oxidation. *J. Min. Met. Fuels* November, 10–15 (1960).
15. K.K. Bhattacharyya, D.J. Hodges, and B. Hinsley, The influence of humidity on the initial stages of the spontaneous heating of coal. *Mining Eng*. **77,** 274–284 (1969).
16. W.C. Peters: *Exploration and mining geology*, pp. 416–425, John Wiley and Sons Inc, New York (1978).
17. Methods of sampling of coal and coke. *Indian Standard* **436**, 1–24 (1964).
18. Methods of Test for Coal and Coke: Proximate Analysis, Indian Standard: 1350, Part-I, pp. 5–18 (1969).
19. S.K. Ray, D.C. Panigrahi, G. Udayavhanu, and V.K. Saxena, Assessment of spontaneous heating susceptibility of Indian coals - A new approach. *Energy Source Part A* (2012).

DOI: 10.7569/JSEE.2013.629512

