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Investigation on the Combustion Behavior of Coal at Various Level of Washing in TGA and Drop Tube Furnace

Santi Gopal Sahu, Pinaki Sarkar,* Uday Sankar Chattopadhyay, Ashis Mukherjee, Manish Kumar and Thonangi Gouri Charan

CSIR-Central Institute of Mining and Fuel Research, Digwadih Campus, P.O. F.R.I., Digwadih – 828108, Dhanbad, Jharkhand, India

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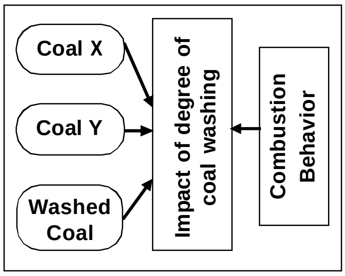
ABSTRACT

Cleaning of coal resulted in ash reduction, heat value enhancement, increased reactive maceral content and change in ash composition influencing combustion performance. With washed fractions, trends of improved combustion behavior were observed in thermo-gravimetric analyser, which was not always reflected correspondingly in bench scale combustor, i.e. drop tube furnace (DTF). Lower burnout efficiency in DTF was observed when top port char particles were totally masked by defused mineral matter. Higher burnout efficiency was observed with tenui ballon/ sphere type of char structure partially covered by defused mineral matter. Overall improvement of combustion performance also led to CO_2 emission reduction.

[Keywords: Washed coal, Coal combustion, Char morphology, DTF, TGA]



Introduction

Coal is the most easily available and important fossil fuel used for electricity generation worldwide. In the Indian context, since the average ash content is significantly high, the use of washed coal for power production is becoming a general trend. The purpose of beneficiation of thermal coals is not only to minimize the abrasive materials but mainly to improve its combustion characteristics. Clean and efficient combustion is being demanded nowadays to meet serious environmental stipulations and one of the routes to achieve efficient combustion is through coal washing, more particularly through proper/ judicious selection of specific gravity cut. Desired qualities to the beneficiated coal may be imparted through such selection. The environmental, technological and economical benefits accrued from the use of consistent cleaner fuel are well established now. Thus cleaning of coal has become one of the important action areas identified for conventional PF fired power generation for achieving reduction in CO_2 emission and many other benefits.

The properties of coal like heat value, volatile matter content, char characteristics, abrasivity, etc, govern the combustion performance of the coal in a boiler and the combustion performance has obvious dependence on some inherent properties like ash, maceral composition, etc. It is worth to study how the changes in these parameters affect the overall burning efficiency and other related issues. Although various studies are there in the literature to report impact of these basic parameters on burning efficiency of coal,[1–4] the area is very much complicated and still needs further attention of the researchers.

Several studies carried out on raw coal and their selected density fractions have been reported in the literature.[5–10] Changes in the maceral compositions influence the coal/char reactivity but conflicting results have been reported on the role of mineral matter on char oxidation. Mineral matter may sometimes contribute to lower down ash fusion temperature causing slagging or clinkering problem. Minerals may fuse and form a coating over burning char particles, finally inhibiting the combustion process. Mineral matters also contribute to alter particle size distribution of coal during pulverization and the altered particle size distribution has significant effect on burning performance. However, it has been observed by many researchers that mineral matters can exert a positive catalytic effect also.[11–14]

In the present paper variation of combustion characteristics of two Indian coals and their washed fractions at different ash levels have been studied and the analysis of results could be indicative of the issues to be addressed during washing of coal for power stations. This paper also attempts to indicate the opportunity of obtaining more uniformity in fly ash quality through coal beneficiation.

Experimental

Coal Selection and Sample Preparation

Two coals, viz. Coal X and Coal Y, of very close rank and ash levels have been chosen for the study. These

*Corresponding author; email: pscfri@rediffmail.com

coals are basically two typical Indian non-coking coals of same commercial grade G-12,[15] generally used in pulverized fuel (PF) fired power plants. These two coals are of comparable characteristics with respect to moisture content, volatile matter, ash content, carbon value, etc. However, due to low GCV (gross calorific value), utilization of both the coals demands either judicious blending with high-GCV coal/ imported coal or value addition through coal washing. As improper selection of Indian coal-foreign coal combination can impose serious slagging fouling problem, and for economic reasons, coal washing sometimes appears to be the preferred option. Accordingly, non-coking coal washing has become rapidly popular in Indian context and the scenario provokes researchers to find out avenues to extract maximum possible benefits out of coal washing. Keeping all these facts and situation-wise research needs under consideration, two samples of washed fractions from each coal at two different ash levels were prepared for the study. The Run of Mine (ROM) coals were first crushed to 75 mm and mixed thoroughly with undersize coals, followed by crushing to 3 mm. –3 mm sized samples were drawn for various tests after coning and quartering for getting the representative samples. Representative quantities of all the samples were taken for float and sink test at different relative densities to get the samples at different ash levels following standard procedures (BIS 13810:1993). Two ash levels of coals X and Y were named as X_1, X_2 and Y_1, Y_2, respectively and the nomenclature is mentioned in Table I.

Chemical Analysis

Proximate and ultimate analysis of parent coals and washed fractions were done using standard procedure (proximate analysis following IS: 1350: Part 1, 1984 and ultimate analysis for carbon and hydrogen following IS: 1350; Part 4, Sec 4, 1974). Gross calorific value (GCV) was obtained following IS 1350 (Part 2): 1970. Chemical data of the coals are shown in Table I.

Petrographic Analysis

Preparation of coal pellet and subsequent petrographic studies of parent coals and their washed fractions at two ash levels were done as per BIS/ISO (IS: 9127 Pt 1-1992, 2-1979, 3-1992 & 5-1986) and (ISO 7404 Pt 1-1982, 2-1985, 3-1994, 4-1988 & 5-1994). Polarized light microscope (Leitz MPV and DMRXP HP systems) was used for measuring the mean R_0%, maceral distributions and the latter was measured using both white light and fluorescent light irradiation. Petrographic analysis data of coals are shown in Table II. Two drop tube furnace (DTF) char samples were microscopically studied using an oil objective of ×50 magnification and categorization of char particles was made conforming to the generalized classification scheme of common char types.

Ash Analysis

Chemical analyses of ash of different samples were done by standardized XRF technique and the data for ash composition are shown in Table III.

Table I : Chemical analysis of coal samples (wt%, air dry basis)

Sample ID	Nomenclature of gravity cuts	M	A	VM	FC	C	H	GCV (kcal/kg)
Coal X	NA	8.1	36.3	24.8	30.6	42.5	2.62	3760
X_1	Gravity cut-1 of Coal X	11.7	21.4	27.5	39.4	55.2	3.22	4820
X_2	Gravity cut-2 of Coal X	11.6	29.7	23.3	35.4	47.8	2.23	4050
Coal Y	NA	7.9	36.4	25.3	30.4	43.0	2.80	3910
Y_1	Gravity cut-1 of Coal Y	6.1	24.4	28.7	40.8	53.1	3.30	4960
Y_2	Gravity cut-1 of Coal Y	5.5	29.1	27.3	38.1	49.2	2.90	4560

Table II : Petrographic composition of coals (wt%)

Sample ID	Vitrinite	Semi-vitrinite	Liptinite	Inertinite	Mean R_0%
X	28.3	–	14.2	57.5	
X_1	34	–	14.5	51.5	0.38
X_2	28.8	–	16.8	54.4	
Y	9.8	–	23.3	66.9	
Y_1	20	0.2	20.4	59.4	0.44
Y_2	12	–	22.2	65.8	

Table III : Ash composition of the samples (wt%)

Sample ID	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	SO_3	CaO	MgO	Na_2O	K_2O	I.D.T
X	57.48	25.34	11.98	1.12	0.26	0.86	1.36	0.52	0.2	0.87	1390
X_1	55.9	21.75	14.37	2.08	0.65	0.81	2.42	0.89	0.3	0.81	1280
X_2	57.46	22.64	13.17	2.24	0.25	0.52	2.03	0.69	0.2	0.78	>1400
Y	56.86	27.46	9.38	1.92	0.34	0.54	1.41	0.49	0.47	1.11	1280
Y_1	46.6	30.05	15.77	1.44	0.79	0.39	2.58	0.71	0.67	0.99	1320
Y_2	53.04	27.53	12.77	2.24	0.26	0.38	1.78	0.72	0.24	1.02	1200

Thermal Analysis, DSC/TGA/DTG

Combustion behavior of the samples were studied using simultaneous thermal analyzer (model: STA 409C; NETZSCH, Germany). The experiments were carried out in differential scanning calorimetry/thermogravimetry (DSC/TG) mode with ~20 mg of accurately weighed sample (–212 μm) at a heating rate of 10^{o}C/min under a constant air flow rate of 50 mL.min^{-1}. The thermograms were analysed to determine the relevant combustion parameters like derivative thermogravimetry (DTG) peak temperatures (PT, which corresponds to the maximum rate of weight loss) and burnout temperature (BOT, the temperature at which the rate of combustion diminishes to 1%/min at the terminal phase of combustion). TGA results are shown in Table IV.

Table IV : Thermogravimetric analysis of the samples

Sample ID	DTG1 (^{o}C)	BOT (^{o}C)
X	408.9	448.1
X_1	395.3	415.7
X_2	406.7	421.2
Y	395.3	500.5
Y_1	317.6	476.9
Y_2	316.0	500.9

Drop Tube Furnace Study

The drop tube furnace (DTF) used in this study consists of a cylindrical ceramic tube of 2500 mm length and 100 mm internal diameter having five zones.[16] All the five zones have provision to be heated electrically by externally heated canthal wire; the temperature of all the five zones can be raised up to 1100^{o}C. After each zone there is provision of sample collection (solid and gas) through water cooled probe having vacuum pump and cyclone. A schematic diagram of the drop tube furnace is presented in Fig. 1.

Pulverized coal, initially dried at 110^{o}C separately in air oven for 1 h, was fed into the DTF through vibratory feeder at the rate of 1.5 kg/h. 30% primary air and 70% secondary air preheated to 180^{o}C, considering 20% excess air, were fed into the DTF. All the relevant parameters including air flow were kept constant during the experiment for parent coals and their two ash levels. Furnace middle temperature, wall temperature and gas

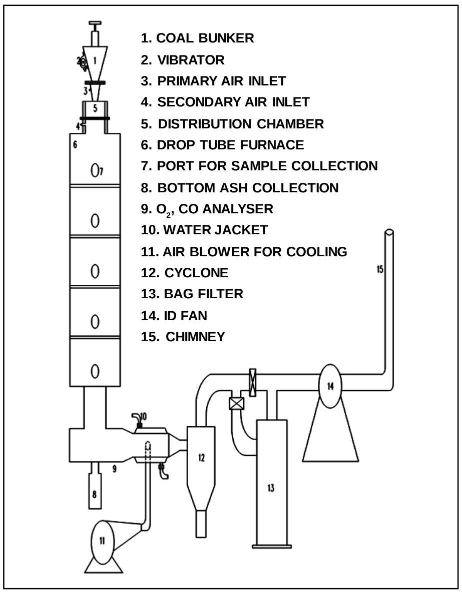


Fig. 1 – Schematic diagram of drop tube furnace

temperature were measured by thermocouples inserted through the DTF. Samples were collected after ensuring the steady state condition through online carbon monoxide and oxygen gas analyzer. To calculate the burnout efficiency (BE) following formula was used:

$$BE = [1–A_0(100–A_c)/(A_c(100–A_0)]\times100$$

where A_0 and A_c are the dry ash percentages of the parent coal and char, respectively. DTF combustibility data is shown in Table V. The DTF tests were standardized with

Table V : Burnout efficiency (BE) of the samples at different ports of DTF

Sample ID	Top port BE	Bottom port BE
X	89.50	98.50
X_1	94.90	99.70
X_2	69.70	98.40
Y	88.30	96.20
Y_1	86.56	94.77
Y_2	96.59	97.15

several runs on the same samples under identical conditions, which showed excellent repeatability of the results.

Results and Discussion

Both Coal X and Coal Y are inertinite rich with total reactive macerals content (vitrinite + liptinite) of 42.5% and 33.1%, respectively. In the washed samples increase in reactive maceral content was observed, although in X_2 it was not found to be significant. In Coal Y, liptinite is the major reactive maceral.

The variation in ash compositions of the washed fractions of the coals shows a pattern of increasing content of basic oxides with decreasing ash content (Table III).

Combustion Behavior

From TGA observations it was found that the DTG peak temperatures decreased in washed coal fractions indicating higher reactivity than the respective parent coal (Table IV). It was observed that burnout temperature (BOT) generally decreased on coal washing, although Y_2 was found to retain the same BOT as its parent coal. This indicates that time taken for complete burning of a coal may be reduced by coal washing. The reason behind retaining the same BOT in case of X_2 as in the parent Coal X may be attributed to almost the same inertinite content of both the samples; inertinite burns in terminal phase of combustion, mostly contributing to arriving at BOT. The BOT of Coal X and its washed fractions are found to be lower than the corresponding values of Coal Y showing higher reactivity of lower rank Coal X. Effect of rank was also reflected in DTG peak temperature. Substantial reduction in DTG peak temperature was observed in washed fraction of Coal Y, whereas in case of Coal X extent of reduction was much less. Therefore, reactivity enhancement may not be close with similar kind of coals and with ash level of gravity cut. Therefore, ash level of a gravity cut may be carefully chosen to improve the combustion property of washed coal. Combustion studies of different gravity cut of a given coal help to arrive at the decisions on selection of appropriate ash level of the gravity cut. Another observation was that X_2 had almost the same DTG peak temperature as that of Coal X. This is due to the similar reactive content (vitrinite + lipnite) of both the samples. Reactive macerals contribute to major combustion zone and hence almost same DTG peak temperatures were observed for X_2 and Coal X.

From Table V it appears that burnout efficiency (BE) of washed coal fraction X_1 was higher than that of another washed coal fraction X_2. This result corroborates well with the TGA reactivity data both in terms of DTG peak temperatures and BOT. For Y_1 fraction the scenario of BE does not match well with the observed TGA characteristics. Burnout efficiency of Y_1 is lower than that of the parent coal which does not match with the TGA results where improvement in combustion reactivity was noticed. Improvement in combustion reactivity was also noticed for Y_2 fraction in the major combustion zone, which appeared from sharp lowering of DTG peak temperature (Table IV), although total time taken for complete burnout was found to be similar to the parent coal. Top port and bottom port burnout efficiencies (BE) of the coals and their washed fractions are presented in Table V. Bottom port BEs indicate overall burnout performances of the coals. Like bottom port burnout efficiencies, top port burnout efficiencies are also very important, because combustion at top zone of DTF is dominated by volatile combustion with sudden release of heat which influences the rest of the combustion process, i.e. the char combustion process. In the real boiler system, the volatile combustion is the fastest step and results in sudden heat release to sustain the desired flame structure. Top port burnout efficiencies give indication of relative initial heat release in boiler operation and this heat release pattern should be suited for maintaining the desired temperature profile in the boiler. Among the washed coals, X_2 and X_1 show low burnout efficiencies (BE) in the top port. Bottom port BE for all the parent coals and washed fractions samples are quite good. It is to be noted that bottom port BE of Y_1 is less than that in the parent Coal Y, whereas bottom port BE of X_2 is almost same as that of the parent Coal X. Microscopic images of top port char of X_2 and Y_1 are presented in Figs. 2a and 2b, respectively (BE in top port is low in these two cases).

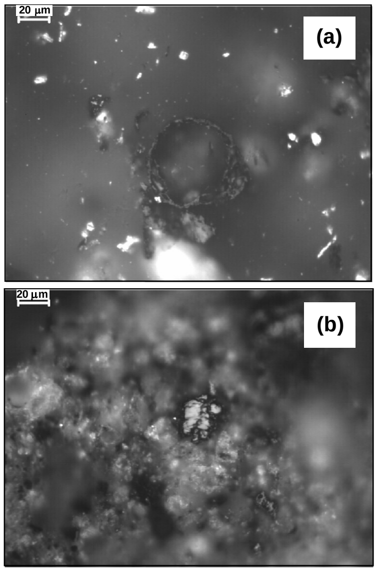


Fig. 2 – Photographs of top port char of (a) X_2 and (b) Y_1 (crossed nicol X800)

As such, combustion performance of any coal is largely dependent on morphological features of char formed in different stages. There are three basic structures of chars found in Indian coals: Cenosphere, Network and Solids.[17] Cenophere and Network structures may be tenui- or crassi-type and thin walled structures (tenui-structures) of char are known to be more reactive than corresponding crassi- or thick-walled structures. A char morphology system with applications to coal combustion has been described by Bailey *et al.*[18] Chars with large pore diameter and thin wall contribute to fast burning. As such, investigation with char generated in a combustor like drop tube furnace is very important because residence time of pulverized coal resembles with the real boiler.

Figure 2a shows that the pore space of a tenui ballon/sphere is partially covered by defused mineral matter and Fig. 2b shows that char particle is totally masked by defused mineral matter. Char having tenui ballon/sphere structure (partially covered by defused mineral matter) is expected to be more reactive than the char totally masked by defused mineral matter, which have been reflected in BE results of these two char samples. Due to such char morphological features bottom port BE is less in Y_1 than in X_2. Mineral matter association in Y_1 is quite different (Table III) from the parent Coal Y causing substantial masking of char particles in top port char of Y_1. Lowering of BE of Y_1 as compared to parent Coal Y is possibly due to this masking effect.

Washed fractions of coals normally bring out benefits in terms of increased gross calorific values, increased combustion reactivity in major combustion zone and decreased burnout time. Burnout efficiency may also be improved on coal washing. The ash level of gravity cut should be judiciously selected so that maximum positive effects in burning behavior may be obtained. Combustion studies on cleans at different ash levels may give clear picture towards proper selection of ash level for gravity separation where yield of the gravity cut will also be economically viable. The use of washed non-coking coals obviously brings out improvement of thermal efficiency and reduction of CO_2 emission. But to extract maximum benefit, combustion performance evaluation has been found to be an important criteria to fix the level of washing for a specific non coking coal. On the other hand, use of beneficiated coals in power plants additionally ensures more uniformity in fly ash quality, i.e. more consistency in quality of fly ash on long term basis and that is very much desirable for development or production of fly ash based ‘geopolymer concrete’, ‘crockery and novelty wares’, unglazed semi vitreous tiles,[19–21] etc with better control over the final product quality. Fly ash has pozzolanic property due to which fly ash chemically reacts with calcium hydroxide (lime) in presence of water at ordinary temperature and develops cementitious bond. Therefore fly ash is blended in cement to produce Portland pozzolana cement (PPC) conforming to IS:1489 Part-1 in place of ordinary Portland cement (OPC). As coal washing improves burning performance or combustion efficiency leading to reduction of unburned carbon in resultant fly ash, it finally contributes to qualitative improvement of fly ash enhancing its acceptability for manufacturing of PPC.

Conclusions

- On judicious selection of washed fractions of noncoking coals, significant improvements in combustion performance parameters are possible in terms of heat release, reactivity, burnout efficiency and burnout time.
- Combustion studies with cleans at different ash levels helps to select effective gravity cut(s) for a specific non coking coal and abrupt selection may not be fruitful.
- Relative maceral content in the washed fractions influences combustion performance of beneficiated coals.
- Char morphology is important consideration to assess combustion reactivity.
- Use of washed coals improves power generation efficiency and reduces CO_2 emission per unit electricity generation. Moreover, in the process of burning washed coals, fly ash quality improves ensuring more consistency in quality parameters of fly ash on long term basis. Consistency in quality parameters is desirable in development or production of fly ash based value added items.
- Improvement of fly ash quality is possible through improvement of burning performance through coal beneficiation. Coal beneficiation, therefore, leads to value addition in marketing of fly ash enhancing its acceptability in cement industry for manufacturing of PPC.

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