Experimental Study on Online Measurement of Unburned Carbon in Pulverized Fuel Boilers by Thermal Oxidation of Ash

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ABSTRACT The unburned carbon (UC) in the ash in Indian power plants is presently measured offline by manually collecting the samples and analyzing it by loss on ignition or thermogravimetric analysis methods. The manual collection and offline analysis of samples take 6–8 h. By this time, the existing operating conditions of the boiler may be different from the conditions when the samples were collected. The combustion optimization and corrective maintenance activities can be performed immediately by plant operation and maintenance team if the UC values are available online along with furnace flame intensity and the percentage of CO in flue gases at economizer outlet. The presence of high amounts of the UC in ash decreases the boiler efficiency and reduces the utilization of ash in cement industries. In this paper, 20 ash samples were collected from five Indian thermal power plants of range 150–500 MW. An experimental setup has been developed for the measurement of the UC using the percentages of CO_2 and CO obtained by thermal oxidation of ash. The experimental results were compared with the laboratory results. The maximum deviation between experimental and laboratory results was within the range of ± 0.30. The percentages of the UC is more accurate when CO_2 and CO both are considered in comparison to the present existing online measurement based on CO_2 only.

INDEX TERMS Carbon loss, unburned carbon, pulverized fuel boiler, bottom ash, fly ash.

ABBREVIATIONS

APH	Air preheater
ANN	Artificial Neural Network
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
BHEL	Bharat Heavy Electricals Limited
DCS	Distributed Control System
DOI	Digital Object Identifier
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator
FC	Fixed Carbon
HHV	Higher Heating Value
HEA	High Energy Arc Ignitor
IEA	International Energy Agency
LOI	Loss on Ignition
MOC	Material of Construction
NDIR	Non Dispersive Infrared
NTP	Normal Temperature and Pressure
PTC	Performance Test Code
SADC	Secondary Air Damper Control
SS	Stainless Steel
TGA	Thermogravimetric Analysis
TM	Total Moisture
UC	Unburned Carbon
VM	Volatile Matter

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I. INTRODUCTION

Steam generators of coal fired thermal power plants have various sources of losses viz. due to flue gas exit temperature, H_2O vapor from thermal oxidation of hydrogen, moisture in the air and coal, unburned combustibles (unburned carbon loss), pulverizer (mill) rejects, unburned hydrocarbons in flue gas, sensible heat of residue (ash), air infiltration, NOx formation, surface radiation and convection and heat credit as a negative loss [1]. Steam generators fired with pulverized

sub-bituminous Indian coal are designed for losses around 12-16%. Out of these, loss due to unburned carbon (UC) in ash accounts for 1.0-1.5%. In real practice, it has been observed that this loss may go up to 7% or even more if the parameters controlling UC in ash like coal fineness, total combustion air, coal to primary air ratio, operation of secondary air dampers, burner tilts are not properly maintained and controlled. The UC loss in stoker fired boiler may go up to 45% [2].

Conventional method of measurement of UC is collection of ash samples from ash hoppers and analyzing the same in the laboratory by Loss on Ignition (LOI) method or by Thermogravimetric analysis (TGA). Conventional methods are not real time measurements and take minimum processing time of 6-8 hrs. The delayed results of UC, reported from laboratory cannot be used accurately for real time combustion optimization. The plant operators can understand and optimize the combustion taking place inside the boiler furnace if the percentage of UC in ash will be available in Distributed Control System (DCS) along with furnace flame intensity and the percentage of CO in flue gases at economizer outlet. If UC in bottom ash and fly ash goes above 3.0% and 1.0% respectively, plant operation and maintenance team needs to look out for abnormalities in pulverizers, secondary air dampers and burner tilts to correct pulverized coal fineness, control combustion air distribution and optimize fireball of tangential firing respectively [3].

Finding land for disposing fly ash is a big concern for plant operators. Alternately, fly ash containing UC percentage up to 6% (as per ASTM) is used in the cement industries as a raw material.

Excess of carbon particles in fly ash are not suitable to use it as a raw material in the cement industries as it may absorb air entraining admixtures (vinsol resin, sodium dodecyl benzene sulfonate, sodium dodecyl sulfate, sodium cetyl sulfate, and sodium oleyl sulfate, oleic and caproic acid) which are added for entraining air bubbles of size 0.025 to 1 mm diameter to increase the durability and stability of concrete [4], [5]. Further, excess of carbon particles in cement may float to the top during concrete formation and may result in blackish surface. All power stations prefer to sell fly ash to cement industries rather than disposing it in the land. Thus, monitoring and controlling of UC in ash becomes important for controlling the boiler performance, increasing plant efficiency and utilizing ash in cement industries.

The offline (laboratory) measurement of UC includes LOI or TGA. ASTM D7348-13 Standard [27] provides complete guidelines for LOI test analysis. Fan and Brown [6] and Mohebbi *et al.* [7] compared LOI and TGA techniques while analyzing UC in coal fly ash. The online measurement of UC using Photoacoustic absorption spectroscopy was investigated and developed by Brown and Dona [8], Dykstra and Brown [9], Waller and Brown [10] and Fan and Brown [11]. Advanced microwave technologies were developed by Cutmore [12], Melick *et al.* [13], Haiyu *et al.* [14] and Smith *et al.* [15]. Noda *et al.* [16], Kurihara *et al.* [17],

Ctvrtnickova *et al.* [18], Pan *et al.* [19] and Shunchun *et al.* [20], [21] carried significant work towards development of online measuring instrument using Laser induced breakdown spectroscopy. Online measurement based on Infrared emissions was developed by Bonanno *et al.* [22]. Sathyanathan and Mohammad [23], Bilen and Kizgut [24] proposed the use of empirical relations for the prediction of UC in bottom and fly ash. Pallarés *et al.* [25] predicted UC in fly ash based on Artificial Neural Network (ANN) system. Zhu *et al.* [26] proposed artificial bee colony algorithm with support vector machine for forecasting the unburned carbon content in the fly ash from coal-fired utility boilers.

Clifford [27] had evolved instrument for online measurement of UC in fly ash by oxidizing ash thermally and measuring the percentage of CO_2 using Non dispersive infrared (NDIR) sensors. Many times, carbon particles in the ash may not be able to combust completely into CO_2 due to insufficient combustion air or combustion temperature. Since the incomplete thermal oxidation of ash in a closed furnace produces CO_2 and CO, the measurement of UC can be done more accurately if both CO_2 and CO percentages are considered in its calculation. UC in dry bottom and fly ashes can be measured by the methodology outlined in the present study.

An experimental setup is developed which can be used for online measurement of UC. Fly and bottom ash samples (20 nos.) are collected from five different Indian thermal power plants and divided into two sets. One set of the samples is thermally oxidized in the developed experimental setup to find out the percentages of CO_2 and CO. The percentage of UC in the ash samples is back calculated from the percentages of CO_2 and CO in the present study. Another set of the samples is analyzed in the laboratory. The experimental and laboratory results are compared. The root cause analysis has been carried out for the samples having a very high percentage of UC.

II. FUNDAMENTALS OF UC MEASUREMENTS

Ash is produced when coal is burned in the boiler furnace at a coal fired thermal power plant. The produced ash falls down into bottom hoppers below burners in furnace first pass as well as travels with flue gas from boiler second pass to Electrostatic precipitator (ESP). The former is known as bottom ash and later is known as fly ash. Fly ash has subdivisions based on collection hopper namely Economizer (ECO) ash, Air preheater (APH) ash and ESP ash. The distribution of Bottom, Economizer, APH and ESP ash is typically designed to 20, 5, 3 and 72% respectively for tangentially fired boilers firing pulverized sub bituminous Indian coal.

During tangential firing of pulverized coal, the UC particles in bottom ash get less time for exposure to higher combustion temperature than fly ash because bottom ash falls below the burners in the boiler furnace due to gravity while fly ash travels from burners to ESP due to the suction created by induced draft fans. This results in higher size of UC particles in bottom ash than fly ash. The normal types of UC particles in bottom and fly ash are vitrinite or inertinite
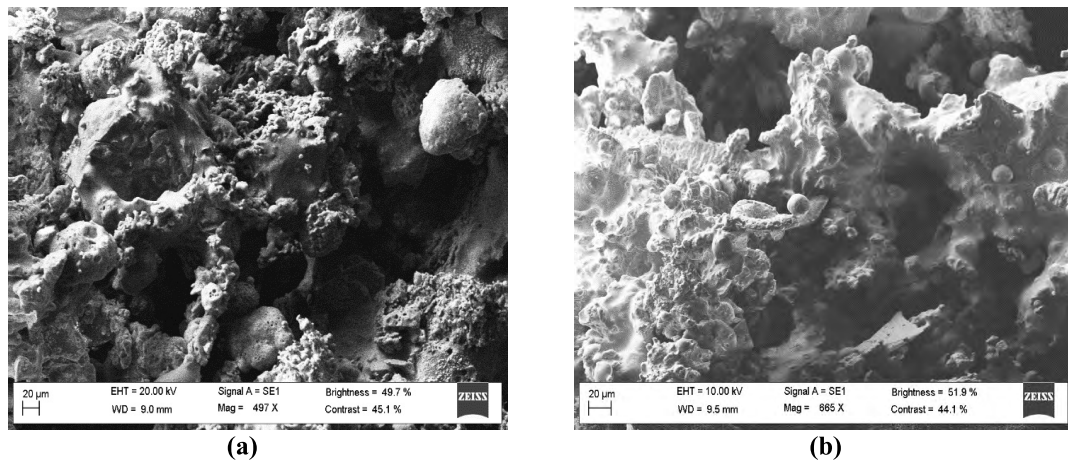
FIGURE 1. SEM Scans of bottom and fly ash samples for a typical 500 MW boiler. (a) Bottom ash. (b) Fly ash.
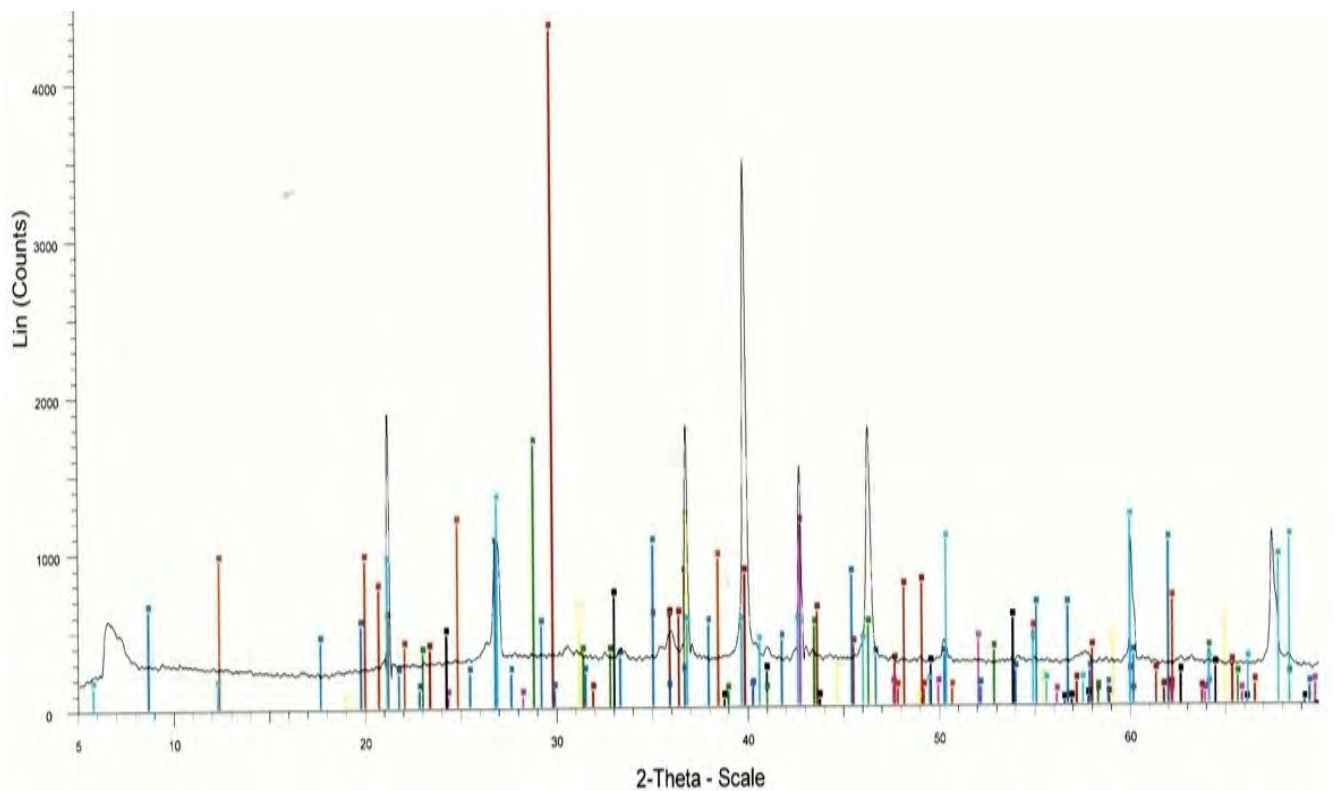

FIGURE 2. XRD Scan of a typical bottom ash sample of a 500 MW boiler.

macerals. The optical texture of particles may be cenospheres (hollow spheres) or network (honey comb). The structure of particles may be isotropic or anisotropic based on rank of coal [2], [22]. The SEM scans of bottom and fly ash samples for a typical 500 MW boiler were conducted in Coal Research Laboratory of BHEL Tiruchirappalli and shown in Figure 1(a) and Figure 1(b). The structure of bottom ash sample was highly porous, fused and fragmented due to presence of high unburned carbon particles. The optical texture of the UC particles was mainly honey combs. The structure of

fly ash sample was mainly solid, finer and made of rounded solid spheres, amorphous material and small amount of finer unburned carbon particles. The particles of bottom ash samples are relatively of larger size than the particles of fly ash samples.

A. METHODOLOGY USED IN INDIAN POWER PLANTS FOR UC MEASUREMENTS

The UC in ash is measured in laboratory mostly by LOI or TGA methods in most of Indian power plants.

TABLE 1. Minerals found in XRD Scan of a typical bottom ash sample of a 500 MW boiler.

| Mineral	ICDD PDF-2	Lattice Parameters (°A, Degree)
Quartz- SiO_2	00-003-0444 (D)	Hexagonal- a 4.90300, b 4.90300, c 5.39300, alpha 90.0, beta, 90.0, gamma-120.0
Calcite Magnesian- $(Mg.129Ca.871)(CO_3)$	01-066-2336 (C)	Rhombo.H.axes- a 4.93820, b 4.93820, c 16.8320, alpha 90.0, beta, 90.0, gamma-120.0
Germanium Nickel Vanadium- $V_3Ni_5Ge_2$	00-022-0310 (N)	Cubic- a 8.93700, b 8.93700, c 8.93700, alpha 90.0, beta, 90.0, gamma-90.0
Karelianite Chromium- $High.syn(Cr0.01V0.99)_2O_3$	01-071-0349 (C)	Rhombo.H.axes- a 4.99740, b 4.99740, c 13, alpha 90.0, beta, 90.0, gamma-120.0
Anorthite- $CaAl_2(SiO4)_2$	00-003-0559 (D)	Triclinic- a 8.21000, b 12.95000, c 14.16000, alpha 93.22, beta, 115, gamma-91.2
Spinal- $CoAl_2O_4$	01-082-2252 (C)	Cubic- a 8.10664, b 8.10664, c 8.10664, alpha 90.0, beta, 90.0, gamma-90.0
Illite- $(KAIFe)_2AISi_3O_{10}(OH)_2.H_2O$	00-015-0603 (D)	Monoclinic-a 5.1800, b 8.9800, c 10.3200, alpha 90.0, beta, 101.83, gamma-90.0
Kaolinite- $Al_2Si_2O_5(OH)_4$	00-001-0527 (D)	Triclinic- a 5.17000, b 8.93000, c 7.37000, alpha 91.8, beta, 104.5, gamma-89.8

(a)   (b)
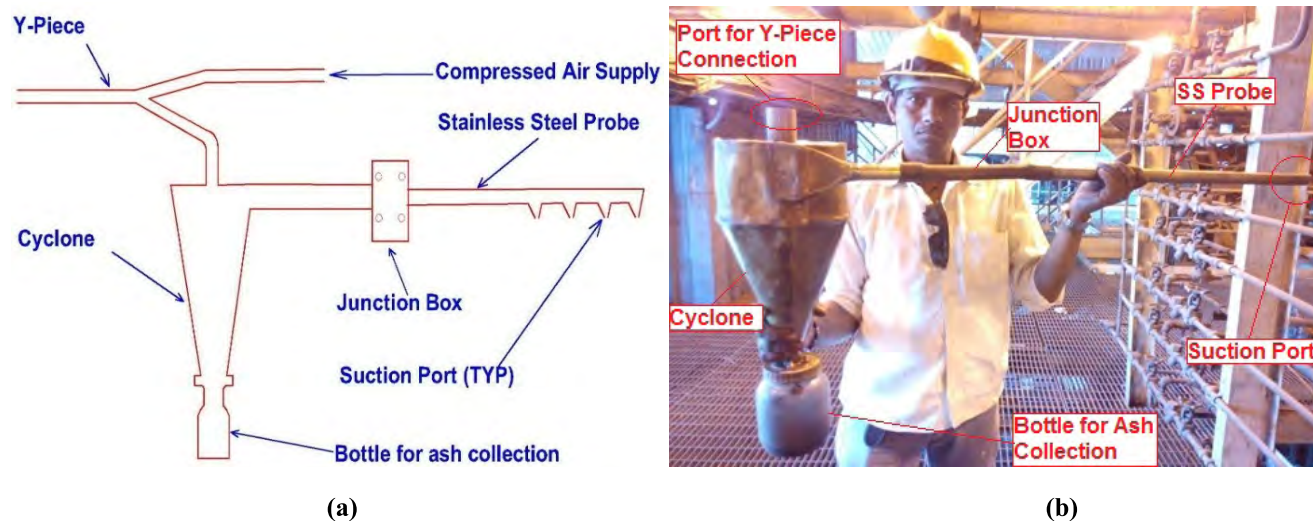
FIGURE 3. Sample extraction probe. (a) Schematic view. (b) Actual view.

1) LOSS ON IGNITION METHOD

In this method, 1 ± 0.0001 gram of dry ash sample (heated in drying oven at 104-110° C for 1 hour duration to remove moisture from the sample) is taken in a crucible and placed in a furnace having oxygen or air as furnace atmosphere. The temperature of the furnace is raised at a rate such that the furnace temperature reaches $660\pm10°$ C after one hour and $750\pm15°$ C after two hours. The sample is then cooled and weighed. The loss in weight is called Loss on Ignition (LOI) [28].

2) THERMOGRAVIMETRIC ANALYSIS

In TGA, known mass of dry ash is heated in an inert atmosphere (N_2/He atmosphere) in the same manner as done in LOI method. It is then cooled to 200° C and weighed. The inert gas is switched to O_2 or air and the sample is again heated to 750° C and kept for one hour. The sample is cooled and weighed. The weight loss is the loss due to UC [6].

B. NEED FOR ONLINE MEASUREMENT OF UC

The high percentage of UC in coal-ash becomes very detrimental to environment in following two ways [29]:

1. High values of UC in coal-ash directly reduce the boiler efficiency. A reduced boiler efficiency causes an increase in coal quantity to be burnt for the same output (MW). Increased burning of coal quantity results in increased emission of greenhouse gases (CO_2, N_2O), acid rain causing gases (SOx and NOx) and increased production of ash.

2. Higher values of UC in coal-ash make it unusable as a raw product for cement industries which forces plant
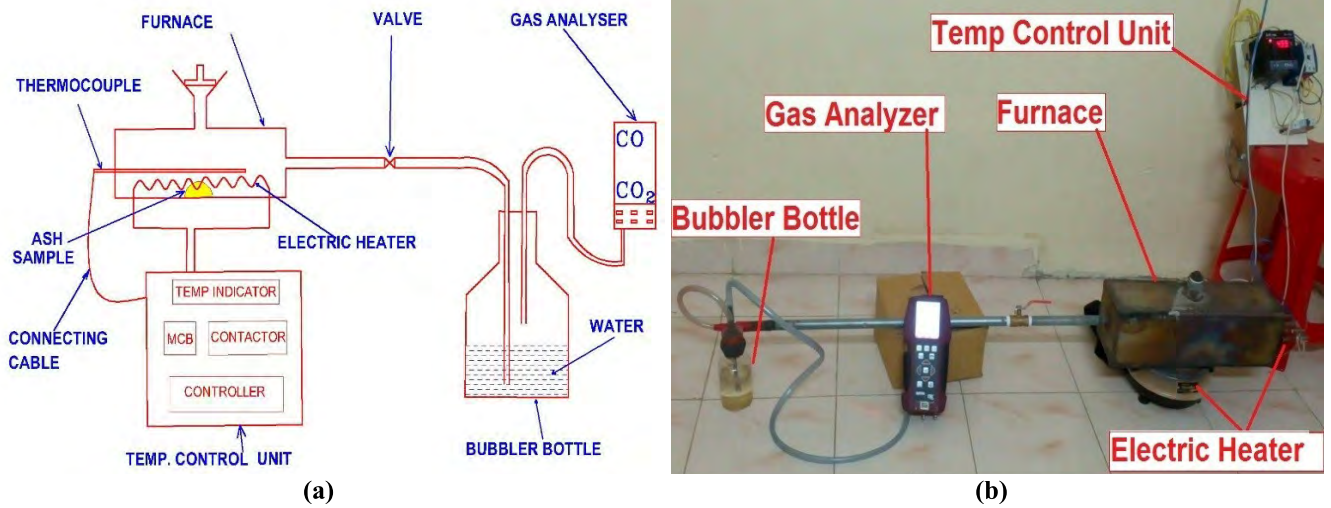
FIGURE 4. Ash analyzing system. (a) Schematic view. (b) Actual view.

TABLE 2. Specifications of the experimental setup.

Sample Extraction Probe	• 1 meter stainless steel probe with cyclone separator at one end and suction ports at other end • Air Supply at 8-10 bar pressure, clean and oil free • 2.5 meter reinforced compressed air hose for air supply • Sampling bottle - 400 ml size
Furnace	• 430×135×135 mm Size • Material of Construction (MOC) - Stainless Steel Plate, 8 mm thick • Gross volume - 6.75 liters
Heating Element	• 2×0.75 kW Ni-Cr steel tubular sheathed, 230 volts, • 1×2 kW, 230 Volts Ni-Cr steel
Temperature Control Unit	• Thermocouple- 1.5 mm K-Type- 2 nos. • Temperature Controller- I-therm AI-5941 • MCB • MNX 32, 3 pole contractor, coil voltage-240 V, 50 Hz, • High temperature compensating cables
Bubbler Bottle	• 300 ml. glass bottle containing demineralized water
Flue Gas Analyzer	• Optima 7 gas analyzer having electrochemical sensors, Make-Emission Monitoring System

operators to find the land to fill it. Sometimes agricultural land is also scarified to fill the coal-ash. Thus, real time monitoring and controlling of UC in ash becomes important from the environmental point of view. The project study carried in this paper will contribute in the development of more accurate online carbon in ash monitor based on thermal oxidation of ash than presently existing instruments.

Additionally, real time values of UC in ash can be used as a combustion quality index for the combustion taking place inside the boiler furnace. If the UC values go beyond permissible levels, the plant operators can look for the following plant operation and maintenance activities [30]–[32]:

• Maintaining of coal-air ratio for each coal mill as per design

• Adjusting of operational parameters to achieve designed mill outlet temperature
• Ensuring balanced coal-air flow through each coal pipe of a particular mill
• Mill maintenance for ensuring coal fineness of the order of minimum 72% passing through 200 mesh (75 μm) sieve and maximum 1% retention on 50 mesh (300 μm) sieve
• Ensuring proper condition of coal nozzles and burner tilts in all corners of the furnace
• Maintaining 20% of excess air or 3.56% of O_2 at economizer outlet
• Ensuring correct distribution of auxiliary air across furnace nozzles by ensuring correct
• Ensuring design coal firing in the boiler

TABLE 3. Sample wise details of UC obtained from experimental setup (both CO_2 and CO considered) and laboratory method.

Sample No.	Plant/MW	Sample Type	CO_2 %	CO %	UC % (Exp. setup)	UC % (Lab.)	Difference (Exp. setup ~ Lab.)
1	P1/150	Bottom Ash	7.50	0.6455	5.90	5.78	0.12
2	P1/150	ECO Ash	0.20	0.0174	0.16	0.10	0.06
3	P1/150	APH Ash	0.10	0.0312	0.09	0.01	0.08
4	P1/150	ESP Ash	0.80	0.0840	0.64	0.49	0.15
5	P2/200	Bottom Ash	16.00	2.4650	13.37	13.19	0.18
6	P2/200	ECO Ash	7.60	0.6455	5.97	5.90	0.07
7	P2/200	APH Ash	3.40	0.4174	2.76	2.63	0.13
8	P2/200	ESP Ash	2.90	0.2112	2.25	2.51	-0.26
9	P3/250	Bottom Ash	4.60	1.3840	4.33	4.06	0.27
10	P3/250	ECO Ash	4.50	0.7731	3.82	3.57	0.25
11	P3/250	APH Ash	2.40	0.0062	1.74	1.67	0.07
12	P3/250	ESP Ash	3.20	0.0044	2.32	2.28	0.04
13	P4/500	Bottom Ash	5.30	1.3114	4.79	4.53	0.26
14	P4/500	ECO Ash	0.40	0.0495	0.33	0.13	0.20
15	P4/500	APH Ash	0.62	0.4719	0.79	0.54	0.25
16	P4/500	ESP Ash	1.00	0.0227	0.74	0.67	0.07
17	P5/500	Bottom Ash	7.20	1.2164	6.09	6.15	-0.06
18	P5/500	ECO Ash	0.40	0.0250	0.31	0.11	0.20
19	P5/500	APH Ash	0.80	0.0353	0.60	0.53	0.07
20	P5/500	ESP Ash	0.60	0.0230	0.45	0.16	0.29

III. EXPERIMENTAL MEASUREMENT OF UC BY MEASURING CO_2 AND CO

Ash samples (20 nos.) including bottom as well as fly ash were collected from five coal fired Indian thermal power plants. The boilers of these power plants have tangentially fired furnace and designed for sub-bituminous/Indian coal, 3-5 sec. of coal particle residence time, 34-40% of ash content and Higher Heating Value (HHV) of around 14194-15827 kJ/kg.

The XRD analysis of ash samples was carried out in Coal Research Laboratory of BHEL Tiruchirappalli using Bruker D8 Advance Powder diffractometer with a copper sealed tube. The XRD scans were performed for 2θ Scale from 5-70° with a step size of 0.01°, scan speed of 1 sec/step and wavelength Cu Kα = 1.54060° A to find out the constituents in the ash. The constituents found in the ash samples were minerals of Si, Al, Fe, Ca, Mg, K, Co, Ti, Ni, V and Ga.

The constituents of minerals found in XRD analysis of all four types of samples (Bottom, ECO, APH and ESP ash samples) from a plant were matching which confirmed that they belong to a same coal origin. Thus, it was ensured that the collected ash samples from a plant are representative samples. XRD scan of a typical bottom ash sample of a 500 MW boiler is represented in Figure 2. Minerals found along with their ICDD PDF-2 database number and their lattice parameters are given in Table. 1.

The ash samples were divided into 4 categories, i.e. Bottom, Economizer, APH and ESP ash based on the location of collection hoppers. The volumetric percentage of CO_2 and
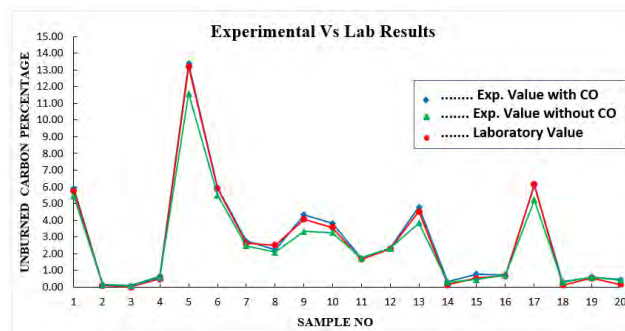
FIGURE 5. Comparison between experimental and laboratory results of the UC Percentage.

CO obtained by thermal oxidation of 5 grams of each sample in a closed electric furnace for 10 minutes at temperature around 700-750° C, were measured. The UC in ash is back calculated by analyzing the measured volumetric percentage of CO_2 and CO.

A. EXPERIMENTAL SETUP

The experimental setup consists of sample extraction probe and ash analyzing system.

1) SAMPLE EXTRACTION PROBE

The ash samples were collected from all five thermal power plants using sample extraction probe shown in Figure 3(a) and 3(b).

TABLE 4. Comparison of UC from experimental setup (without consideration of CO value) with laboratory results.

Sample No.	Plant/MW	Sample Type	UC without consideration of CO (%), {a}	Lab Result (%) {b}	Difference ({a}~ {b})
1	P1/150	Bottom Ash	5.43	5.78	0.35
2	P1/150	ECO Ash	0.14	0.10	-0.04
3	P1/150	APH Ash	0.07	0.01	-0.06
4	P1/150	ESP Ash	0.58	0.49	-0.09
5	P2/200	Bottom Ash	11.58	13.19	1.61
6	P2/200	ECO Ash	5.50	5.90	0.40
7	P2/200	APH Ash	2.46	2.63	0.17
8	P2/200	ESP Ash	2.10	2.51	0.41
9	P3/250	Bottom Ash	3.33	4.06	0.73
10	P3/250	ECO Ash	3.26	3.57	0.31
11	P3/250	APH Ash	1.74	1.67	-0.07
12	P3/250	ESP Ash	2.32	2.28	-0.04
13	P4/500	Bottom Ash	3.84	4.53	0.69
14	P4/500	ECO Ash	0.29	0.13	-0.16
15	P4/500	APH Ash	0.45	0.54	0.09
16	P4/500	ESP Ash	0.72	0.67	-0.05
17	P5/500	Bottom Ash	5.21	6.15	0.94
18	P5/500	ECO Ash	0.29	0.11	-0.18
19	P5/500	APH Ash	0.58	0.53	-0.05
20	P5/500	ESP Ash	0.43	0.16	-0.27

TABLE 5. Proximate analysis and fineness data of fired and design coal.

Plant	Condition	Coal proximate analysis					Average coal fineness analysis	
		TM (%)	FC (%)	VM (%)	Ash (%)	HHV (kJ/kg)	50 Mesh (300 μm)	200 Mesh (75 μm)
P1	Fired	11.68	27.03	20.15	41.14	14453.5	1.42	12.66
	Design	12.10	26.60	22.70	38.60	14193.9	≤ 1.00	≤ 28
P2	Fired	14.30	26.81	26.62	32.27	16492.6	2.52	20.54
	Design	10.50	29.20	21.60	38.70	15826.9	≤ 1.00	≤ 28
P3	Fired	12.25	30.15	21.23	34.62	15198.8	2.52	20.54
	Design	10.00	28.78	21.19	40.03	14654.5	≤ 1.00	≤ 28
P4	Fired	16.98	28.56	24.28	30.18	15261.6	1.3	15.86
	Design	15.00	29.00	22.00	34.00	14654.5	≤ 1.00	≤ 28
P5	Fired	16.60	28.25	21.79	33.36	14273.5	1.8	12.58
	Design	15.00	29.00	22.00	34.00	14654.5	≤ 1.00	≤ 28

Sample extraction probe contains a stainless steel tube with cyclone separator at one end and suction ports at the other end. The vacuum inside the cyclone was created to collect an ash sample by passing compressed air through one limb of the Y-piece connected to the cyclone separator.

2) ASH ANALYSIS SYSTEM

The collected ash samples of all five coal fired power plants were analyzed in the ash analyzing system shown in Figure 4(a) and 4(b). Stainless steel plates were welded to form an air tight furnace of volume 6.75 liters. Two heater elements
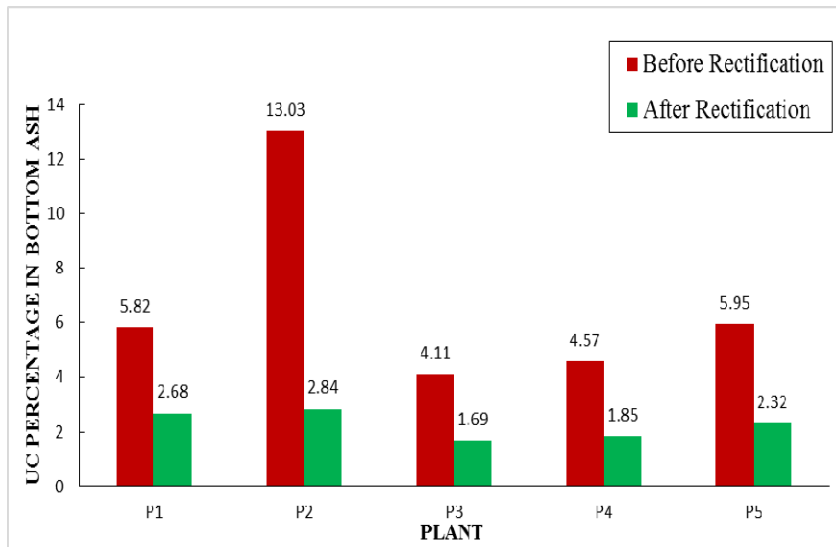
FIGURE 6. Comparison of UC results before and after rectification work.

of 0.75 kW each (internal) and one heater element of 2 kW (external) were installed to maintain the inside temperature of furnace around 700-800° C. Two K-type thermocouples of 1.5 mm thickness were installed to measure the furnace temperature. Electronic temperature control unit consisting of Miniature Circuit Breaker (MCB), contractor, controller and temperature indicator was used to control the temperature of furnace at a desired set point. Bubbler bottle consisting of demineralized water and gas analyzer were connected with this furnace to absorb moisture and analyze combustion gases respectively. Detailed specifications of the experimental setup are mentioned in Table 2.

3) PROCEDURE FOR CALCULATING UC

The collected 20 samples were divided into two sets. One set was analyzed based on present experimental setup, the second set was analyzed in the plant laboratory of BHEL Tiruchirappalli for the validation of the present results. Five grams of each sample of the first set were thermally oxidized for 10 minutes at temperature around 750° C in the furnace of the ash analyzing system. The thermal oxidation of ash resulted in the formation of combustion gases containing CO_2, CO, NOx, SOx, and H_2O vapor. Now, the combustion gases were passed through the bubbler bottle containing water with the help of suction created by a suction pump inbuilt in the gas analyzer. The H_2O vapor condensed in the bubbler bottle. After this, the flue gases were passed through the flue gas analyzer having electrochemical sensors to measure the volumetric percentage of CO_2 and CO gases. Thermal calculations are performed to back calculate the percentage of UC in ash from measured values of CO_2 and CO. A sample calculation has been done to estimate the percentage of UC for the first sample.

IV. SAMPLE CALCULATION

By the thermal oxidation of 5 grams of the first ash sample, 7.5% of CO_2 and 6455 ppm of CO were obtained on volumetric basis. The moles of CO_2 or CO can be calculated from equation (eq.) 1 given as:

$$M = \frac{V}{22.4} \times \frac{v}{100} \tag{1}$$

where M is the moles of CO_2 or CO, V is the total volume of the furnace (6.75 L) and v is the volumetric percentage of CO_2 or CO obtained.

A. CALCULATION OF UC FROM CO_2

From the reaction,

$$C + O_2 \rightarrow CO_2 \tag{r1}$$
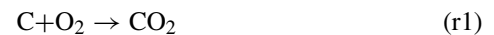
$$\text{Moles of C} = \text{Moles of } CO_2 \tag{2}$$

From the equations (eqs.) 1 and 2, moles of C = 0.0226.

Weight of C (in grams) can be calculated from eq. 3 given as:

$$W/A = m \tag{3}$$

where W is the weight of C (in grams), A is the atomic weight of C (12.011) and m is the moles of C.

Thus, from the eq. 3, weight of C from CO_2 = 0.2715 g.

B. CALCULATION OF UC FROM CO

From the reaction,

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{r2}$$

$$\text{Moles of C} = \text{Moles of CO} \tag{4}$$

From the eqs. 1 and 4, moles of C = 0.001945.

Thus, from the eq. 3, weight of C from CO = 0.02336 g.

C. CALCULATION OF THE PERCENTAGE OF UC

Total weight of UC = weight of C from CO_2+ weight of C from CO = 0.29486 g.

Thus, % of unburned C found in 5 g ash = 0.29486 × 100/5 = 5.90.
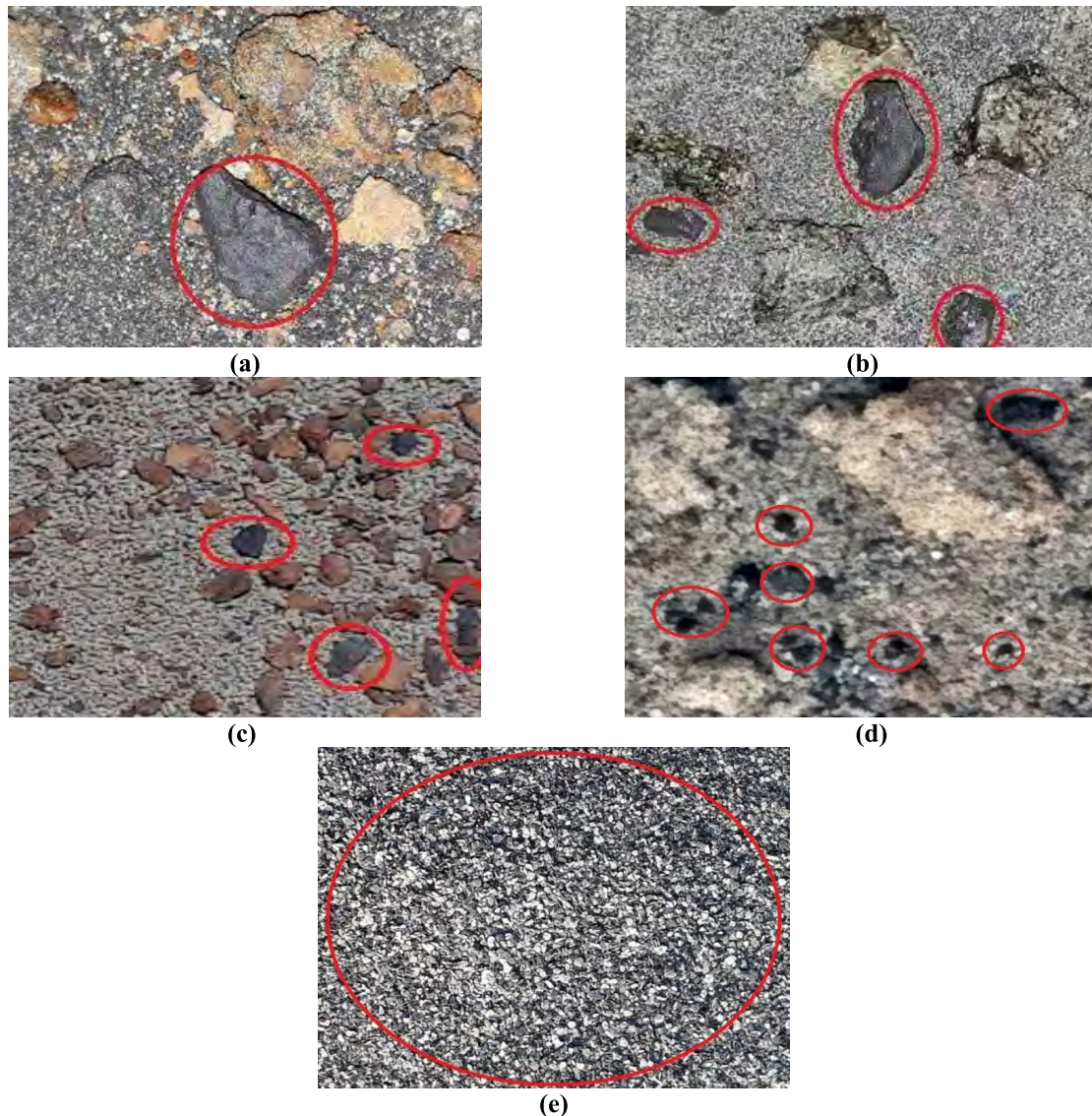
FIGURE 7. Bottom ash samples for plant no. P1, P2, P4, P5 and P3. (a) Bottom ash plant-P1. (b) Bottom ash plant-P2. (c) Bottom ash plant-P4. (d) Bottom ash plant-P5. (e) Bottom ash plant-P3.

D. AUTOMATION OF THE UC MEASUREMENT

Ash samples extracted from sample extraction probes can be fed into the furnace of the ash analyzing system after weighing by a mass measuring device like load cell. The percentage of CO_2 and CO values obtained by thermal oxidation of ash can be linked to DCS Controller. All thermal calculations can be incorporated in the DCS controller to obtain the real time values of UC percentage. The online values of UC percentage along with flame intensity data can be used to optimize the combustion in the boiler furnace. The implementation of the experimental setup is to be tested further for its accuracy of measurement in actual conditions at different coal fired thermal power plants.

E. VALIDATION

All the 20 ash samples were analyzed; thermal calculations were performed in the same manner as explained above to find out the percentage of UC. The LOI based results of UC obtained from the present experimental setup and plant laboratory of BHEL Tiruchirappalli are compared and shown in Table 3.

Table 4 compares the percentage of UC obtained from present experimental setup without considering the percentage of CO with the laboratory results and it has been observed that the differences have increased and vary in the range from -0.27 to $+1.61$. From Table 3, it is also observed that sample Nos. 1, 5, 9, 13 and 17 showing high values of UC are the bottom ash samples of plants P1, P2, P3, P4 and P5 respectively. The high density UC particles could not be carried along with the flue gas and hence fallen in the bottom ash hopper.

The comparison between the results of UC percentage measured by present experimental setup with CO, without CO and plant laboratory are also plotted in Figure 5. It is observed that the experimental results are more accurate

when percentages of both CO_2 and CO are considered in comparison to results when the percentage of CO is not considered. The experimental results vary from laboratory within the range of ± 0.30 when the percentages of both CO_2 and CO were considered in UC calculation. The range of this variation increased from ± 0.30 to -0.27 to $+1.61$ when CO was not measured.

Table 5 represents the fired and design data of coal proximate and average coal fineness (average sieve retention) analysis for plants P1, P2, P3, P4 and P5. Based on proximate analysis, it was observed that Total Moisture TM), Fixed Carbon (FC), Volatile Matter (VM) and Ash contents of fired coal were near to design and HHV of fired coal were within $\pm 5\%$ of design for all the five plants. The high values of UC in bottom ash for plant P1, P2, P4 and P3 were found mainly attributable to improper coal fineness through 200 mesh sieve (average retention $\geq 1\%$). The pulverizers were inspected and corrected for roller-bowl gap settings, classifier opening settings and roller-spring tension settings to achieve the designed coal fineness. The percentages of UC were found within the acceptable range (below 3%) and consistent after rectification work.

The pulverized coal fineness was found as per design for plant-P3 even though the UC in bottom ash was considerably high. The high values of UC in bottom ash for plant-P3 was attributable to improper combustion inside the boiler furnace. The reasons of improper combustion were examined and it was observed that the positions of auxiliary air dampers at field were not matching with the DCS-command. The positions of auxiliary air dampers at field were corrected to achieve perfect matching with DCS-command. It was observed that the percentage of UC after rectification work was consistent and within 3%. Figure 6 compares the results of UC in bottom ash before and after rectification work.

Bottom ash samples of plants P1 to P5 are shown in Figure 7. Circled big size coal particles were observed in the bottom ash samples of plants P1, P2, P4 and P5 due to improper coal fineness. Coal particles in the bottom ash sample of plant P3 were of smaller size, equivalent to the size of other ash particles and were uniformly distributed.

V. CONCLUSIONS

An experimental study was conducted for the online measurement of unburned carbon in ash. Ash samples were collected from five different power plants operating in India, analyzed using the present experimental setup and compared with the laboratory results of BHEL, Tiruchirappalli. The online measurement of UC by thermal oxidation of ash in a closed furnace can be done more precisely if CO_2 and CO both are considered which is not presently done that may lead to a reduction in the accuracy of measurement, particularly in the cases when UC do not combust to CO_2 completely. The variation between experimental and laboratory results was within the range of ± 0.30 when both CO_2 and CO were measured. This variation was much higher (-0.27 to $+1.61$) when CO was not measured.

The UC percentage in tangentially corner fired boilers using sub-bituminous coal is always higher in bottom ash than fly ash, irrespective of furnace size. The high value of unburned carbon in bottom ash was attributed to poor coal fineness ($+300$ micron) for plants P1, P2, P4 and P5 and poor combustion due improper position of auxiliary air damper for plant P3. Therefore, the developed experimental setup in the present work can be installed either in the dry bottom or fly ash hoppers for measuring and controlling the values of UC in ash in order to improve the plant efficiency and utilization of ash in cement industries.

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