Research Journal of Applied Sciences, Engineering and Technology 5(6): 2284-2288, 2013
DOI:10.19026/rjaset.5.4778
ISSN: 2040-7459; e-ISSN: 2040-7467
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Submitted: August 31, 2012 Accepted: October 02, 2012 Published: February 21, 2013

Research Article

Influence of Chemical Composition on the Electrical Resistivity of Fly Ash Generated from Indian Coal Based Thermal Power Plants

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Abstract: Electrostatic Precipitators (ESP) are control devices widely used for collection of fly ash in Indian coal based thermal power plants. The design, performance, sizing, collection and operation of ESP depend largely on the properties and quality of the coal burned and the fly ash generated in the boilers. This study presents the influence of fly ash composition on the resistivity of Indian fly ash generated from coal based power plants, which is one of the critical parameter required to make accurate predictions of ESP in terms of their collection efficiency. The fly ash electrical resistivity measurements were conducted over a wide range of temperature in both ascending and descending cycles in the range of 90 to 455ºC at 9% moisture as per IEEE-Standard 548 (1991). The earlier developed Empirical relations used for calculating fly ash electrical resistivity for western coals were modified for the calculations of electrical resistivity of Indian fly ashes and new empirical relations have been developed based on experimental results and chemical composition of fly ash samples collected from different coal based power plants in India which have different chemical composition in comparison to western coals. Results in the newly developed correlations show better agreements with experimentally determined resistivity compared to those developed by Bickelhaupt and others.

Keywords: Chemical composition, electrostatic precipitation, fly ash, resistivity, thermal power plant

INTRODUCTION

Electrostatic Precipitator (ESP) is still one of the most cost effective means of controlling particulate emissions from large industrial process plant. Traditionally, ESP's used metal plates as collecting surfaces for capture of particles in flue gas. However, back corona and re-entrainment of particles into flue gases hinder with the performance of ESP in collection of fine particulate matter $PM_{2.5}$ (Zhao and Zheng, 2008). In order to meet the stringent emission levels from power plant, it is necessary to have knowledge of the properties of fly ash for sizing and operation of ESP. Retrofit methods can be applied to an ESP depending on the electrical and chemical properties of the fly ash. China and India have large plants of expanding coal-based power plants. At present India has got 61,175 MW installed coal based power capacity which is expected to rise 1,14,500 MW by the year 2012 (Shah *et al*., 2006). The design and operation of ESP depends largely on the properties of coal burned and fly ash generated in the boilers.

The properties of coal used in difference plants across India vary widely. In many of the power plants, the ash contents of coal are high up to 45% and the coals have low calorific values (3500-4200) Kcal/kg (Liqiang and Yongtao, 2011). As a result Indian coal generates about 6 to 7 times more ash to collect compared to U.S. or European coal for similar electricity generation. Besides, low sulphur content (≤0.5%) which results in the resistivity is (100-1000) time higher as compared to desired range of resistivity 2×10^{10} ohm.cm; the inlet dust loading to ESPs is also high for efficient ESPs Table 1 summarizes the effect of Resistivity on the conduction, migration and efficiency of electrostatic precipitator. Resistivity can be described as the resistance to charge transfer by the dust. Dust resistivity values can be classified roughly into three groups of low resistivity ($<10^4$ ohm.cm), normal resistivity (10^4-10^{10} ohm.cm) and high resistivity regime ($>10^{10}$ ohm.cm). The efficiency of an ESP strongly depends on the resistivity of fly ash. Particle resistivity refers to the condition of particles in a gas stream that can alter the actual collection efficiency of an ESP design (CPCB, 2004). Particle resistivity is a condition of the particle in the gas stream that can alter the actual collection efficiency of an ESP design. The most economical design and operation of an ESP are obtained when the electrical resistivity of the particulate is kept within certain limits (Liqiang and Yongtao, 2008). There is no such signification research data available for the electrical properties of fly ash

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Table 1: Chemical composition of the typical fly ash samples (weight % as the oxide)

Element	1	2	3	4	5	6	7	8	9	10
Al_2O_3	33.87	28.48	39.55	34.23	43.70	37.65	43.95	36.58	39.96	24.63
CaO	10.92	10.55	1.80	2.89	5.32	1.35	1.30	9.34	4.58	0.90
Fe_2O	4.89	6.06	5.70	9.35	6.28	4.28	5.49	4.89	7.10	4.69
MgO	0.77	0.89	1.01	0.87	0.92	0.56	0.29	0.56	0.40	0.29
P_2O_5	0.19	0.19	0.35	0.37	0.31	0.41	0.27	0.45	0.38	0.48
K_2O	0.15	0.15	0.01	0.02	0.05	0.04	0.03	0.45	0.29	28.19
SiO_2	39.26	48.70	49.82	51.01	36.65	48.33	45.15	32.23	22.21	21.39
Na_2O	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.64	0.37	1.54
TiO_2	0.42	0.54	0.05	0.11	0.31	0.12	0.13	0.48	0.35	0.50
SO_3	0.31	0.25	0.30	0.37	0.35	0.25	0.17	0.24	0.26	0.27

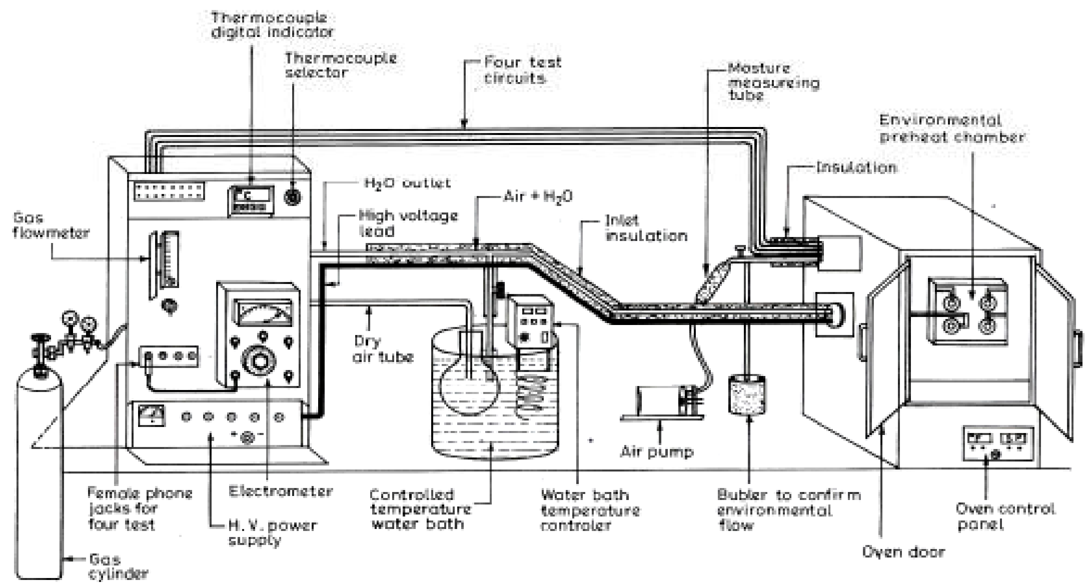

Fig. 1: Schematic diagram of apparatus setup for fly ash resistivity measurement

generated in indian coal based power plants. Therefore, a research was undertaken to study the effect of ash properties on the efficiency of ESPS. A laboratotary set up was established to measure electrical resistivity (IEEE-Standard 548, 1991) of fly ash generated by indian power plants using different coal found in different parts of India jointly by Sounthern research institute Birmingham USA and IIT Delhi In India.

A significant number of samples with known chemical composition were provided by National Thermal Power Corporation (NTPC) and chemical analysis for other samples were carried out at SGS laboratotry. Based on the electrical properties and chemical composition a correlation was developed to study the effect of chemical composition on the resistivity of fly ash.

EXPERIMENTAL

An experimental test arrangement was set up at Indian Institute of Technology, New Delhi, India as per the IEEE standard criteria and guidelines (Chandra, 2008) for the fly ash resistivity measurements as shown in Fig. 1.

The test apparatus includes four electric resistivity test cells enclosed in such a manner that the test cells are housed in a thermally controlled chamber so that resistivity can be determined at temperature range of 90 to 455ºC and at specific 9% moisture. A dc high voltage power supply was used to impress the required magnitude of electric field strength. The environment was maintained as per the standard. The environmental water concentration was introduced by bubbling a portion of dry gas through distilled water maintained at a selected temperature in a thermostatically controlled water bath. It was 9% by volume at the specified temperature in the present study. The oven is capable of operating in the desired temperature range, within 0.01ºC accuracy. The resistivity test cell has parallel plate construction made from SS 304 steel. The resistivity cell current was measured using a sensitive electrometer capable of reading current in the range o 10^{-3} to 10^{-11} amp. with an accuracy of ±2% of the full-scale reading. Fly ash samples were prepared in accordance with the IEEE standard and placed in the test cell in a grounded environmental chamber. The upper electrode is gently placed on the top of ash with a defined pressure. The oven is started and once the desired temperatures are reached, the readings are taken for the temperature, voltage and current using the instrumentation provided in the test facility. The fly ash resistivity ρ is calculated from standard relation:

$$\rho = (V/I)\,(A/l) \quad (1)$$

where,

V & I : The voltage and current across the fly ash sample

l & A : The thickness and area of cross-section of sample of fly ash cell

The resistivity is calculated for more than 50 different fly ash samples from Indian coal fired thermal power plants for the temperature range of 90 to 460ºC.

Prediction of fly ash resistivity: Bickelhaupt (1979) proposed correlations to calculate the fly ash resistivity from the results of coal and the fly ash analysis. The correlation fly ash resistivity in terms of volume resistivity, surface resistivity and adsorbed acid resistivity is:

- The volume resistivity is:

$$\rho_V = \exp\begin{bmatrix}(-1.8916\ln X - 0.9696\ln Y + 1.237\ln Z + 3.62876) - \\ (0.069078)E + \left(9980.58/T\right)\end{bmatrix} \quad (2)$$

- The surface resistivity is:

$$\rho_S = \exp\begin{bmatrix}27.59774 - 2.233348\ln X - 0.00176W - 0.069078E - \\ 0.00073895W(\exp)\left(2303.3/T\right)\end{bmatrix} \quad (3)$$

- The adsorbed acid resistivity is:

$$\rho_a = \exp\begin{bmatrix}59.0677 - 0.854721CSO_3 - 13049.47/T \\ -0.069078E\end{bmatrix} \quad (4)$$

For Z>3.5% or K<1.0%

- The resultant resistivity is:

$$\frac{1}{\rho_{vsa}} = \frac{1}{\rho_{vs}} + \frac{1}{\rho_a} \quad (5)$$

where,

$$\frac{1}{\rho_{vs}} = \frac{1}{\rho_v} + \frac{1}{\rho_s} \quad (6)$$

A new set of correlations have been developed for predicting ash resistivity for Indian fly ashes based on the Bickelhaupt relations developed. It has been observed that Bickelhaupt model results differ appreciably from experimental values in the lower temperature range (90-160ºC at 9% moisture. It may be due to significant difference in concentration of elements like sulphur, lithium, sodium and moisture contents as well as alumina plus silica components among the Indian and US coals (Chandra *et al*., 1996). The sulphur concentration in coal regulates the surface resistivity by adsorbing forming acid. The fly ash resistivity for Indian coals we re-calculated in terms of surface and volume conduction as a function of temperature and moisture as per IEEE standards. The sulphur content is very less in Indian coals, therefore it is worthwhile to consider little or zero adsorbed acid conductivity is present. The negligible adsorption of Sulphur trioxide (SO_3) conduction may also be due to formation of glassy alumina-silicate surface that hinders the adsorption of SO_3 on the fly ash, therefore the total conduction in fly ash is thus considered entirely due to surface and volume conduction. The earlier Bickelhaupt correlations for surface and volume resistivity are therefore, modified for the Indian coals and a new model is developed for predicting resistivity of fly ashes to give the best fit results between the proposed correlations and the experimental data. The experimental values in the range (90-200ºC) were used to develop empirical relaxations for surface resistivity and those in the range (210-440ºC) were used for volume resistivity as per IEEE guidelines for measuring the resistivity (Walker, 1968). The modified correlation for the volume and surface resistivity is developed:

- Correlation for the volume resistivity:

$$\rho_V = \exp\begin{bmatrix}(-1.5193\ln X - 1.12633\ln Y + 1.89907\ln Z + 3.62368) \\ -(.06884)E + \left(9635.16/T\right)\end{bmatrix} \quad (7)$$

- Correlation of the surface resistivity:

$$\rho_S = \exp\begin{bmatrix}25.516 - 2.7319\ln X - (.00176)W - (.06884)E \\ -(.000793)W(\exp)\left(2303.3/T\right)\end{bmatrix} \quad (8)$$

The resultant resistivity is:

$$\frac{1}{\rho} = \frac{1}{\rho_V} + \frac{1}{\rho_S} \quad (9)$$

where,

ρ_s = Surface resistivity
ρ_v = Volume resistivity
W = Moisture in flue gas (%)
T = Temperature
V = Applied d.c. potential (volts) and (E) applied electric field (kV/cm)
X = k + Na, Percent Atomic Concentration
Y = Fe, Percent Atomic Concentration
Z = Mg + Ca, Percent Atomic Concentration

Table 2: Effect of chemical composition and moisture on fly ash resistivity

Chemical constituents	Property	Effect on resistivity
Calcium oxide (CaO)	So_3 absorber, low conductive	Increase with increase in percentage
Magnesium oxide (MgO)		
Iron oxide (Fe_2O_3)	Increases alkali ion solubility and mobility	Decrease slightly with increase in percentage
Sodium oxide (Na_2O)	Ion contributor	Decreases with increase in percentage
Potassium oxide (K_2O)	Ion contributor	Low impact because of small percentage
Moisture (9-15%)	Conductor	Decreases with increase in moisture content

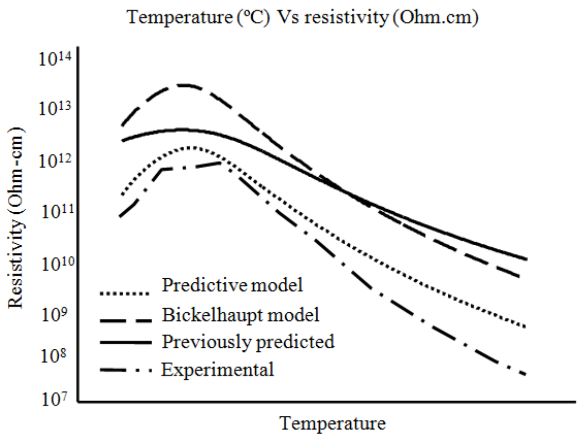

Fig. 2: A typical graphic representation for comparison of predicted model with the existing models in ascending mode of resistivity vs temperature

RESULTS AND DISCUSSION

The chemical compositions of fly ash samples collected from different power plants were used as input to a model for predicting resistivity for Indian coals. The collection efficiency of an electrostatic precipitator collecting fly ash from a coal-fired boiler is strongly influenced by the operating voltage and current in each of the precipitator's electrical sections. In turn, the spark-limited voltage and effective current for charging and collecting particles are strongly influenced by the resistivity of the collected particulate layer. The electrical resistivity of fly ash is dependent on physical and chemical characteristics of the ash and the flue gas physically, the particle sire distribution, specific surface and ash layer porosity are important. It is, therefore important to understand the relation between the chemical composition of fly ash like alkali metals, alkaline earth metals, iron concentrations and other elements coming out from the boiler and its electrical resistivity. Besides chemical composition, temperature and moisture contents also affect the magnitude of fly ash resistivity.

Table 1 shows the results of the chemical characterization of the fly ash generated from different coal based thermal power plants in India. The results of elementary chemical analysis are expressed in weight percent of oxides. The fly ash primarily consisted of CaO 1.54-2.54%, SiO_2 59.22-64.74%, Al_2O_3 25.09-30.87%, Fe_2O_3 5.19-6.79%, TiO_2 1.44-1.92%, Na_2O 0.2-0.54%. Major constitute of the fly ash are silica (SiO_2), alumina (Al_2O_3) and iron oxides (Fe_2O_3).

Electrical resistivity based on chemical composition and moisture: From the Correlation for the volume resistivity Eq. (7) and Correlation of the surface resistivity Eq. (8) it has been observed the fly ash chemical composition and moisture plays a vital role in decreasing and increasing resistivity of fly ash both volume conduction and surface conduction mode.

A resultant graphic representation of both volume and surface resistivity as a function of temperature and moisture at 9% is show in Fig. 2. It is observed that the resistivity at temperature from 90-170ºC there is an increase in resistivity with increase in temperature and it coincides the operating temperature of Indian Electrostatic precipitators which signifies there is high fly resistivity generated in ESP thereby decreasing the collection efficiency of Indian ESPs and increasing chances of high particulate pollution in the environment. It is also observed that resistivity values are decreasing after increase in temperature from 170 to 450ºC While calculating the resistivity in the newly developed correlations it was seen that moisture and composition plays a significant effect on the net resultant resistivity. The coefficients generated on the basis of experimental data of resistivity and chemical composition influence the resistivity range with increase and decrease in percentage quite significantly and is summarized in Table 2.

The coefficients (cv) generated for log Z which signifies that increase in calcium plus magnesium in a combine effect increases the resistivity. It is due to the low conductive nature of calcium and magnesium in a combine effect which aids in increase in resistivity with the increase in percentage. While the coefficient (bv) generated for log Y for the iron oxide, signifies that it increases alkali ion solubility and mobility and therefore in the conduction mechanism it decreases the resistivity effect when there is slight increase in percentage.

The coefficient (av) generated for log X which signifies that sodium oxide plus potassium oxide in combination has got very much importance in the resistivity effect as it decreases the resistivity with increase in percentage because sodium is mainly an ion contributor and aids in the conduction. Although potassium oxide is an ion contributor it is evident from the coefficient in correlation that it has got low impact

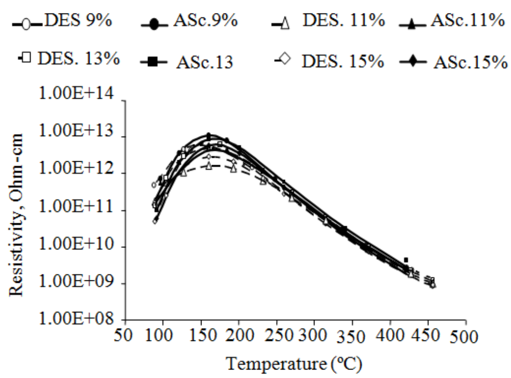

Fig. 3: Variation of resistivity vs temperature in ascending and descending modes at different moisture contents (9-15%)

on the resistivity calculation because the percentage of potassium oxide in the fly ash was quite low and therefore no evident effect was felt. The coefficients generated signify that increase in calcium percentage increases the resistivity effect of chemical composition on fly ash resistivity because of calcium is mainly the absorber of SO_3 and it has low conductive nature. While observing the effect of varying moisture 9-15% experimentally as a function of temperature, it is observed that at 9% moisture in the temperature range of 120-160 the resistivity values were in range of 1.11×10^{12}, at 11% the resistivity is in the range of 4.31×10^{12} and while at 13% it was found to be 8.62×10^{12} and that of 15% it is 5.97×10^{12}. Therefore, a significant effect is found by varying moisture as shown in Fig. 3.

CONCLUSION

The foregoing expressions developed for predicting resistivity represents is an initial attempt to predict volume resistivity as a function of ash chemistry and temperature and surface resistivity as a function of moisture and temperatures. The characterization of ashes representing a wide variety of coals suggests that 75-85% is glassy solid. It has been rationalized that the volume conduction takes place through a continuous matrix of these glassy particles. It has been verified that volume conduction is an ionic mechanism involving the alkali metal ions, principally sodium as charge carrier and iron contributes in decreasing the magnitude of resistivity with the increase in percentage. Sodium and potassium show inverse correlation with the resistivity. In surface conduction mechanism the moisture plays a significant role in decreasing the magnitude of resistivity with the increase in percentages.

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