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A Review on Fly Ash Resistivity: A Concept to Develop Mathematical Model for Calculating Fly Ash Resistivity of Indian Coals

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Abstract

Recent years have seen no radical changes in predicting fly ash resistivity from Indian perspective. There have been no significant advances in developing new techniques in the field of fly ash resistivity for low sulphur coals which becomes a basic parameter to design an(ESP). However, arise from time to time which depress performance; a particular example is that due to high resistivity dust which has tended to become more troublesome in Indian power stations, especially with low sulphur coals. Practical solutions to such problems are being vigorously sought.

Introduction

Interest in the subject of fly ash resistivity is of prime importance in the thermal power plants because of the importance of this material property with respect to the electrostatic precipitator collection and performance. Fly ash resistivity is the key factor utilized in the sizing precipitators, troubleshooting in efficient operation and anticipating problems associated with changes in coal supply. There are several key factors either independently or in combination affect the magnitude of the resistivity values. These include mainly

- Specific surface area
- Particle size distribution
- Ash layer porosity
- Environmental chemical composition
- Ash layer field strength
- Temperature
- Moisture content
- Chemical composition

While considering the general case with a narrow temperature range for ashes produced from low sulphur coals, the fly ash chemical composition is a dominant factor. The relationship between resistivity and chemical composition is also important with respect to developing and understanding of the conduction mechanism, the selection of condition agents and in the prediction of resistivity for ashes from heretofore unburned coals and cleaned coals. Today, electrostatic precipitators (ESPs) have been widely applied in industries, and a number of ESPs need to be upgraded for matching the latest emission standards. Our knowledge for predicating ESP performances, however, are still poor because of lack of reliable ESP models. Many factors influence ESP performance, such as flue gas velocity, gaseous temperature and compositions, electrical power sources, ESP configuration and fly ash characteristics [1-5]. Ash resistivity is one of the critical parameters to affect ESP' s collection efficiency and power consumption. For higher than 10^{12} ohm.cm and smaller than 10^{4} ohm.cm ashes, ESP performance significantly deteriorates due to ash reentrainment. A small value of resistivity leads the collected ash to lose its charge too fast. A higher value, however, hardly leads to discharge its charges but to the so-called back corona [1, 6]. As a result, ash reentrainment occurs in these cases. So far, many works have been performed to limit the reentrainment and/or back corona by optimizing electrode rapping [7], electrode construction [8], flue gas conditioning [9,10] and upgrading the power sources [11,12]. Ash resistivity models have been very useful for selecting and/or blending coals and sizing ESP in order to achieve a better ESP performance. Ash and gaseous compositions, electric field strength and temperature play key roles for determining its value. As a pioneer, R.E. Bicklhaupt proposed one analytical model to derive the resistivity in terms of ash compositions, electric field and gaseous temperature [13]. V. Arrondel and G. Bacchiega recently reported a comprehensive ESP model and also developed the ORCHIDEE, by which the ash resistivity and the particle grade collection efficiencies can be evaluated in terms of coal characteristics and ESP specifications [14]. After Bicklhaupt' s model, Chandra proposed a revised one with new coefficients according to Indian utilities [15]. These three empirical models present the state of the art of theoretical investigations on the ash resistivity. Unfortunately, those models hardly match each other when considering ash effects on the resistivity. Its final objective is to develop an industrial ESP model for upgrading ESPs to control fine particle emissions Rigorous new regulations in dust emission by power plants and industrial processes have caused new demands for dust control devices. These new regulations will require maximum particle emissions on the level of 10– 50 mg/ Nm3 and restrictions to the emission of fine particles smaller than 2.5 mm. To meet these requirements, new methods of gas cleaning with collection efficiency higher than 99 % have been developed and tested. The main components of fly ash emitted into the atmosphere by coal-fired power plants consist of Al_2O_3, SiO_2, and Fe_2O_3, which constitute about 80– 90% of the total mass. Other non-volatile trace elements in fly ash at levels higher than 1 mg/g include Ca, Na, Mg, K, Ti, S [16–19]. Toxic metals such as Se, As, Cd, Hg, Ni, Pb, Cr, Sr, Be, V, and U have also been found [16, 17, 19, 20-22]. The concentration of trace elements in particles larger than 1 mm is inversely related to particle diameter. The fraction of toxic metals is significantly higher in sub micrometer particles, and it is independent of particle size. Volatile elements such as Hg are usually depleted in the fly ash and are frequently ignored in the analysis [18]. The particles leaving the typical boiler are in the approximate size range of 20nm to 200 mm [23]. The fraction of particles of diameter smaller than 1 mm constitutes only 1% of the total mass, but 99 % of the number concentration [24]. At the outlet of an electrostatic precipitator (ESP), the size distribution of particles is usually bimodal, depending on the boiler load. Finer particles (first modal diameter of about 0.07 mm) contain vaporized and condensed matter, usually toxic elements. Larger particles (second modal diameter of 0.4 mm) contain unburned mineral materials, mainly SiO2 (about 1/2) and Al2O3 (about 1/4) [25]. The mean mass density of fly ash is about 2.45_103 kg/m3 [20, 24] which is close to the density of SiO_2 Large fly ash particles are usually spherical, whereas those smaller than 0.1 mm in diameter are irregular in shape and frequently form short dendrites attached to the larger ones. Submicrometer particles are formed by the bursting of large particles as an effect of gas release during their rapid heating. When cooled, the particles condense and adsorb volatilized elements to form particles in the size range 0.1– 1 mm [18]. Research in particulate control technology has tried to find new, improved, and less costly methods for collection of small particles that save energy and structural materials. Two general groups of dust removal devices—dry and wet [26]—can be distinguished. The category of dry devices includes cyclones, fabric filters, ceramic filters, electret filters, and ESPs. The wet devices include inertial, centrifugal, Venturi or electrostatic scrubbers, foam precipitators, and irrigated ESPs Cleaning devices usually use mechanical (mainly inertial and gravitational) forces to precipitate the particles from a gas, or molecular forces to capture particulate matter on a solid or liquid collector. Dense obstacles in the form of fibrous or porous media are also used for this purpose. ESPs utilize electrical energy to remove particulate matter from the gas. Over the past few decades, substantial progress has been made in the development of new electrical techniques for gas cleaning with the goal of increasing cleaning efficiency in the small particle size range. These particles, which are a potential danger to human airways, are very difficult to remove by conventional devices. The current state of development in ESPs and some of the unsolved problems in the field of gas cleaning were recently summarized by Mizuno [27] and Porle [28]. The paper by Hackam and Akiyama [29] focuses on gaseous pollution control by electrical discharges. Currently, there is a tendency in the gas cleaning industry to enhance the collection efficiency of conventional devices by using electrical forces. The simultaneous removal of gaseous contaminants and particulate matter is also a new trend in gas cleaning technology [30, 31].

1.1 Background

Electrical resistivity of fly ash is one of the critical properties required to make accurate predictions of ESP performance. Dr. Roy E. Bickelhaupt of Southern Research Institute developed a correlation relating the mineral composition of coal fly ash to its electrical resistivity in the late 1970s. Predictive software based on this correlation has been in general use for about twenty years. It is recognized, however, that the accuracy of the resistivity predictions made with the original correlation and its successors are sometimes marginal. The principle cause for the lack of accuracy is believed to be due to the limited number of ash samples, chemical composition and tests used to develop the correlation. Furthermore, there were only one or two ashes from blended coals in Dr. Bickelhaupt' s original study, and it is not known if the correlations produce accurate results for these ashes.

1.2. Early Work on Predictive Resistivity Correlations

Dr. Roy Bickelhaupt' s study of the electrical resistivity of coal fly ash began in the early 1970s. This work focused on the study of volume conduction and surface conduction in fly ash. Test data indicated that for fly ashes consisting principally of a glassy phase, the volume conduction process was similar to that of common glass. It was determined that conduction occurs by an ionic mechanism in which the alkali metal ions serve as charge carriers (in the absence of sulphuric acid vapour). His research showed that the electrical resistivity was inversely proportional to the combined molecular concentration of lithium and sodium [32]. Dr. Bickelhaupt conducted additional experiments demonstrating that surface conduction takes place by an ionic mechanism in which the alkali metal ions serve as the principal charge carriers. It was observed that the surface resistivity was inversely proportional to the concentration of these alkali metal ions (in the absence of sulphuric acid vapour). Previously, it had been generally accepted that surface conduction occurred by an electrolytic or ionic mechanism dependent principally on the physical and chemical adsorption of certain species on the ash surface to produce a conducting film. Dr. Bickelhaupt' s research showed that the role of the environment is no less important in that these factors control the release of the alkali metal ions [33]. The results of Dr. Bickelhaupt' s research on surface and volume conduction mechanisms provided the basic tools for developing a method for predicting fly ash resistivity based on the chemical composition of the ashes. To provide a complete set of data for developing these correlations, an exhaustive study of 35 coal fly ashes was conducted in the late 1970s. From this group, sixteen ashes were selected to investigate the effect of the variation in flue gas moisture concentration and ash layer electric field strength on resistivity. Eight of these ashes were further utilized in experiments to determine the effect of sulphur trioxide on resistivity. By combining the expressions defining the effects of these three factors on resistivity with the basic expression for resistivity as a function of ash composition, correlations were developed to allow the prediction of fly ash resistivity as a function of temperature knowing the ash composition, water and sulphur trioxide concentrations, and the ash layer field strength. This work was published in 1979 [34]. The laboratory tests showed that resistivity was strongly correlated to the concentrations of lithium, sodium, iron, calcium, and magnesium in the ashes. Strong correlations were also shown with moisture levels and sulphur trioxide concentrations. Mathematical expressions were developed relating volume resistivity to ash composition and surface resistivity to temperature and water vapours concentration. These were combined as a sum of parallel resistances. A mathematical expression was developed relating acid resistivity to temperature and sulphur trioxide concentration. Using the expression for parallel resistances, the surface-volume resistivity expression was combined with the acid resistivity expression to form the final predictive relationship

1.3. Refinements in the Original Model

The original model developed in 1979 was labelled Model 1. Between 1980 and 1985 laboratory data relevant to the resistivity prediction model were periodically obtained. Usually these data simply verified previous observations. However, a series of tests were conducted using fly ashes having high concentrations of calcium and magnesium that showed extra sensitivity to water vapour concentration with respect to resistivity. This deviation from the previous resistivity/water vapour correlation used in Model 1 was incorporated into the computer program. This new program was designated Model 1A [35]. In 1986 a new fly ash resistivity predictive tool was published, Model 2 [35]. The reason for this new model was a better understanding of the influence of sulphur trioxide on resistivity and the dependence of its influence on the concentration of alkali metals in the ash. The scope of the work for developing the new model was an evaluation of the quantitative effect of air environments containing water and sulphuric acid on the resistivity of fly ash. Ten new ashes were thoroughly characterized both chemically and physically. The parameters investigated included fly ash composition, sulphuric acid concentration (1 ppm to 10 ppm), water concentration (5% and 10%), temperature (115^{o}C to 200 ^{0}C), and field strength intensity (2 kV/cm to 12 kV/cm). The principal type of experiment was the determination of resistivity at three temperatures for three concentrations of sulphuric acid vapour (1, 4, and 10 ppm). In 1990 Dr. Bickelhaupt updated the program slightly to account for observations relative to the combined concentrations of magnesium and calcium. There are three criteria for the selection of the slope of the acid resistivity curve as a function of reciprocal absolute temperature. New data and observations made since Model 2 was published demonstrate that improved predictions occur when the concentration of magnesium plus calcium is 5.0% for the criteria listed. With this change, the model, now designated Model 2A [36], shows better agreement with observation, and it becomes somewhat more conservative. Between 1980 and 1984 a new predictive tool was developed by Dr. Bickelhaupt for predicting the effective volume resistivity of sodium-depleted fly ash layers in hot-side electrostatic precipitators. At hot-side ESP operating conditions fly ash resistivity is not dependent on either water vapour concentration or sulphuric acid vapour concentration, but solely on electric field strength and temperature since volume conduction is the only means of charge transfer through the ash layer. To create his data set, eight fly ashes were evaluated by subjecting 0.5-cm layers to a continuously applied voltage gradient of 4 kV/cm for periods of time up to 35 days at a temperature of 350 ^{0}C (662 ^{0}F). Resistivity was determined at temperature before the test started and after the long period of applied voltage used to create the sodium-depleted condition. Sodium depletion was determined to have gone to completion when current measurements made at regular intervals did not change by more than 10% in a 100-hour period. The temperature was then reduced to 536 ^{0}F and current measurements were repeated. The voltage was then increased to electrical breakdown of the fly ash layer. This procedure was used to provide data to determine the effects of temperature, time (and therefore sodium depletion), and electric field strength on resistivity. The model developed from this study was designated as Model SD [37].

1.4. Volume Resistivity

Until several years ago, the volume conduction mechanism was thought to be electronic and particulates were considered intrinsic semiconductors [38, 39] or impure insulators. Efforts were made to identify the specific electronic mechanism and little attention was given to the fly ash composition. This view point was probably encouraged by the assumption that the ashes were principally crystalline, by the observation that log rho vs. I/T is linear and that the numerical value of experimental activation energy is commensurate with semi conduction and by the tendencies of investigators to explain conduction for all materials subjected to electrostatic precipitation using one mechanism

About 1970 there was evidence that investigators [40-42] were observing the pronounced in resistivity for fly ashes containing large amounts of sodium. In late 1971and early 1972 an effort was made to determine the mechanism for volume conduction [43, 44]. It was hypothesized that the conduction mechanism was ionic and that the charge carriers were alkali metal ions.

In the subsequent years extensive research programmes associated with the resistivity-fly ash composition relationship has been carried and the pronounced effect of sodium on resistivity for lignite and sub-bituminous coals mined in the western United States [45-47]. These studies have led to development of a correlation that can be used to determine resistivity from ash composition for these coals. Bickelhaupt [48] attempted to expand the earlier work on volume resistivity to include a general cross section of ash composition produced throughout the country of united stated. It was found that excellent correlation existed between resistivity and iron concentration [48,] same effect was observed by other workers [25, 49] a number of experiments were conducted to elucidate the effect of iron. The obvious suggestion that iron introduces an electronic contribution to the total conduction process could not be demonstrated. Transference experiments using ashes having four levels of iron concentration yielded useful information [48]. It was found that for a constant amount of electrical energy passed the ratio of the alkali metal migrated to that amount present in the ash increased with increasing iron concentration. As a result it was speculated that the iron in the glassy structure of the ash permitted as a greater number of the alkali metals ions to be mobile. As a result of this research an empirical expression was developed to estimate resistivity from ash composition for high temperatures. Emphasizing the role of sodium in the volume conduction process it has been demonstrated that sodium can be injected as an agent to enhance conduction and lower resistivity values [20].

1.5. Surface resistivity

Until the recent years the role of ash composition with respect to surface resistivity received little attention. This was true principally because the generally accepted mechanism for surface conduction does not require the ash composition specifically to be operative [51]. This electrolytic mechanism suggest that conduction takes place through an adsorbed film, one or more molecular layers thick, of water and/or sulphuric acid. In a manner analogous to that for bulk aqueous solutions, conduction occurs by electrolysis of the adsorbed agents or by a proton jump process [52]. In these cases, the hydrogen ion would be the principal charge carrier. Many investigations have shown that the composition of the fly ash has a vital role in the surface conduction process. Included are the observations of improved performance when coals high in sodium concentration were burned ,test demonstrating the effect of sodium as condition agent and laboratory studies relating resistivity and ash composition [42, 53, 55]. Some other workers have previously cited to the discussion that the effect of ash composition on surface resistivity [45, 47]. These authors have shown that surface resistivity under constant environmental test conditions decreases over 3 orders of magnitude as the sodium concentration increases with in the normal limits for ashes produced from western coals. High coefficients' of correlation were found for relationships between resistivity and expression derived to predict resistivity from ash composition. It was pointed out that in the cases of high sodium coals, volatilized sodium appears on the surface of fly ash as Na_2So_4 readily available for participation in the conduction process [54]. Bickelhaupt [55] studied surface resistivity as a function of a broad range of ash composition to determine of ash composition to determine a correlation between these two factors and to establish the role of ash composition with respect to the conduction process. The effect of iron and potassium was particularly clarified using chemical transference experiments. It was observed that after extended periods of time under applied electrical field at a temperature at which only surface conduction was operative, a concentration gradient for the alkali metals lithium, sodium and potassium has been established. Bickelhaupt extended of surface conduction mechanism is given that accentuates the role of ash composition. It was suggested that the conduction mechanism for glassy ash is analogous to that recorded for silicate glasses [56]. Keeping For the general case one can visualize an ion exchange process in which H^+ replaces Na^+ in the surface structure of the ash thereby freeing the sodium ion to migrate. In India, however, there are varieties of coal used in different power plants across the country. They differ significantly from those used in USA. The composition of fly ash is too different from those generated in power plants in USA. There fore the correlation developed by Bickelhaupt does not fit the criteria for resistivity calculation predications and new approach for predicting fly ash resistivity for low sulphur coals has an attempt in the future study

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