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EVALUATION OF THE CHARGING CHARACTERISTISCS OF PARTICLES IN TRIBOELECTRIFICATION

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ABSTRACT

The charging behavior of particles is of great importance in triboelectrostatic separations. In this article, the tribocharging characteristics of the coal and mineral samples were studied using a new in-situ charge-measuring device that combines an in-line static mixer with a Faraday cage. Experimental data obtained using this device show that coal particles become positively charged during triboelectrification, while common mineral impurities (pyrite and quartz) become negatively charged. The data also suggest that the coal and mineral samples exhibit the maximum difference in charge at the highest air velocity and the lowest particle feed rate. Other parameters that influenced the magnitude of the charge density were particle size, humidity and feed composition.

INTRODUCTION

Numerous advanced coal beneficiation processes have been developed in recent years. Many of these are capable of removing substantial amounts of both ash- and sulfur-forming minerals from coal. However, most of the widely used physical coal cleaning technologies (Yoon, 1991) are wet processes. As such, the dewatering step constitutes a large part of the processing cost. One way to avoid this problem would be to develop dry separation processes.

Electrostatic separation for coal beneficiation has received a great deal of attention in recent years. In this process, particles to be separated are selectively charged and passed through an electric field to effect the separation (Inculet, 1984). The electrostatic separation processes depend heavily on the methods used to charge the particles (Inculet, 1984; Ralston, 1961). For this reason, the design of a separating machine is usually a reflection of the charging mechanism. Although there are many ways to cause the particles to acquire electric charge, only three charging mechanisms have been applied to the commercial electrostatic separations (Yoon, 1991; Inculet, 1984; Ralston, 1961, Kelly and Spottiswood, 1982; Harper, 1967): i.e., i) ion or electron bombardments, ii) conductive induction, and iii) contact or friction electrification (triboelectrification).

Tribocharging is the process in which one type of material (particle) selectively acquires charge when it comes in contact with a dissimilar material. The two materials can be any combination of conductor, semiconductor, or insulator (dielectric). Usually, the contact electrification mechanism is explained by means of the work function. When two materials with different work functions are brought into intimate contact, electrons will flow from the one of lower work function to the one of higher work function. Charge will flow in a direction determined by this work function parameter until the Fermi levels of the two materials become equal. The work function of a material is defined as the energy lost when an electron moves from just outside to inside the material. It is governed by the energy of the Fermi level. Although it is ordinarily thought that contact charging is the result of electron transfer from one body to another (Robinson, 1969; Seanor, 1972; Lowell and Rose-Innes, 1980; Kelly and Spottiswood, 1989; Rose-Innes, 1980), there is evidence that the charge transfer in contact charging can occur by ions (Harper, 1967; Gaudin, 1971) or by transferred materials which carry charge (Salanek, 1976). In the analysis of the charge remaining after contact electrification, it is conceivable that the magnitude of the final charge on the materials is the result of two processes: i.e., i) the charge transfer that occurs during the contact, and ii) the charge backflow that occurs as the materials are separated (Inculet, 1984; Lowell and Rose-Innes, 1980; Kelly and Spottiswood, 1989).

For electrostatic beneficiation of coal, the triboelectrification method for particle charging dates back to the early part of this century (Blacktin, 1931). It is based on the premise that coal and mineral matter can be triboelectrostatically charged selectively when a material is appropriately chosen to be the contact surface. Early triboelectrostatic separators commonly had particles sliding down, or transported through chutes, pipe, or nozzles (Lockhart, 1984), then followed by free-fall through an electric field that deflects the particles according to the sign and magnitude of their charge. The application of this type of particle tribocharging system has been the subject of many studies (Nieh and Nguyen, 1987; Schaefer et al., 1994; Link, et al., 1990; Finseth et al., 1993).

During the past decade, numerous studies have been conducted in an attempt to improve the charging efficiency of particles. Cyclone chargers (Carbini et al., 1982; Mazuda et al., 1983) and fluidized bed chargers (Inculet et al., 1980a; 1980b) have become the techniques of choice for particle charging in coal triboelectrostatic beneficiation. These devices are known to provide good particle-wall and particle-particle contacts. For coal desulfurization, Gidaspow et al. (1987) pioneered a design concept called an "electrostatic sieve", which is based on the principle of fluidization. More recently, in-line static mixers have been successfully employed for particle charging (Finseth et al., 1993).

In this paper, an experimental study was carried out to examine the charging characteristics of coal, quartz and pyrite. The charge measurements were performed using an in-situ charge-measuring device specially developed for this purpose. The effects of several important parameters were examined including particle velocity, solids feed rate, particle size and mixture composition.

EXPERIMENTAL

Apparatus

The charge-measuring device is the most important component in any study of the charging behavior of particles. Many techniques for measuring charging (Schaefer et al., 1994; Gidaspow, et al., 1987; Lawver and Wright, 1968; Kittaka et al., 1979; Secker and Chubb, 1984; Gajewski et al., 1987; Mazumder et al., 1991) have been discussed in the technical literature. Static charge is normally measured by induction and the classic method of measuring the static charge is by use of a "Faraday cage" or "pail", coupled to a suitable monitoring circuit. A typical Faraday pail consists of inner and outer cages made of metal. The inner cage is electrically connected to an electrometer while the outer cage is grounded to serve as shield against surrounding electronic interference. Ideally, a Faraday cage should surround the sample whose charge is being measured to prevent interference from external electrical noise.

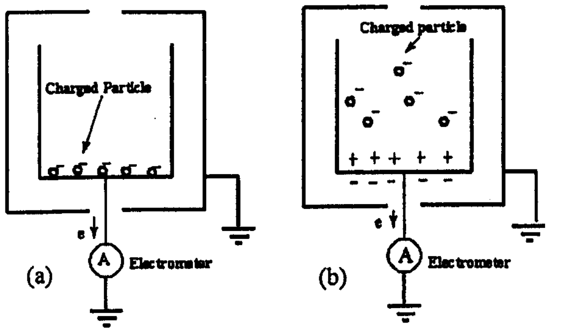

Fig. 1. Schematic of the principle of particle charge measurement using a Faraday cage.

The mechanism of charge measurement using a Faraday cage is illustrated in Figure 1. Let us assume that particles are charged negatively, and consider the case in which particles touching the wall of the inner cage, as shown in Figure 1(a). The free electrons of the particles will flow from the particle surface to the walls, resulting in a flow of electric current from the Faraday cage to the electrometer. Consider also the case of the negatively charged particles not touching the walls, as depicted in Figure 1(b). In this case, the particles will polarize the inner cage in such a manner that the inner wall is positively charged while the outer wall is negatively charged. The free electrons will flow from the negative charge sites of the inner wall to the electrometer, generating a current. Hence, in both cases, the presence of negatively charged particles will result in a current flowing from the Faraday cage to the electrometer.

To facilitate the in-situ measurement of particle charge, a tribocharge analyzer was developed which combines a Faraday cage mechanism with a static mixer charger (Figure 2). The charge-measuring device consists of a copper in-line static mixer (2.22-cm diameter and 0.15-m length) and an outer isolation tube made of copper. The in-line static mixer is electrically connected to an electrometer (Keithly Model-642) by means of a coaxial cable, while the outer copper cylinder is grounded to reduce interference from nearby electrostatic fields or charges.

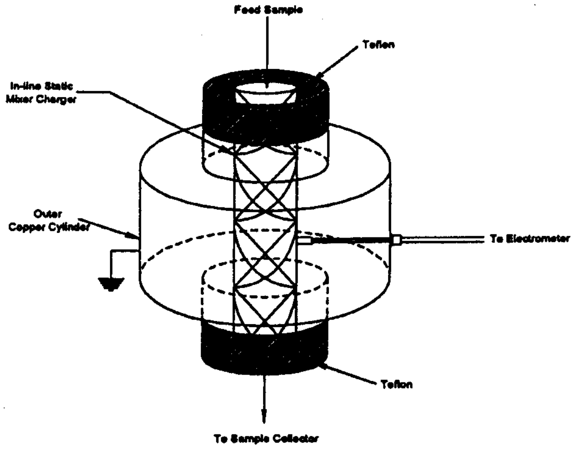

Fig. 2. The on-line charge measurement device developed for the experiments.

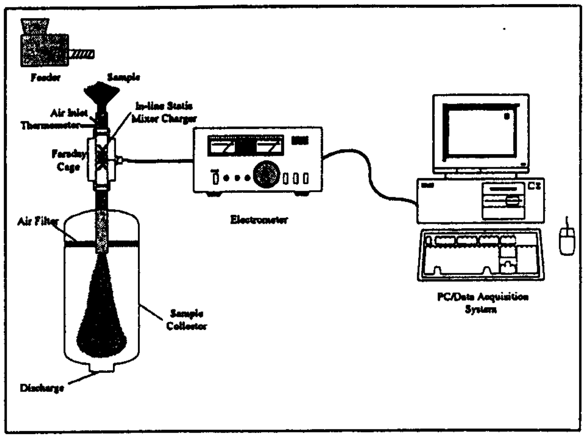

Fig. 3. Schematic of the on-line tribocharge analyzer and data acquisition system.

Teflon rings were placed between the static mixer and the outer tube at both ends to avoid a short circuit. A schematic of the overall setup for the on-line tribocharge analyzing system is shown in Figure 3.

Procedure

In a given experiment, the particulate sample was stored in a vacuum oven before being placed on the feed hopper. The sample was subsequently fed into the on-line tribocharge analyzer system by means of a compressed air, which is heated by use of a heating tape before entering the system. An air filter was placed on the top of the sample collection chamber to eliminate the back-flow of particles. When the particles passed through the tribocharger, the charge analyzer acquired and digitized the analog signal using a data acquisition system. The Fast Fourier Transformation (FFT) procedure was applied to the digitized information for noise reduction. Figure 4 shows a typical set of output data from the analyzer.

Five main parameters that may influence particle charging were investigated during this study. These included air velocity, particle feed rate, particle size, feed mixture composition (ash content), and temperature. The air pressure was maintained at 40 psi during each experiment. Unless stated otherwise, the system temperature was held in the range of 28-30°C for all experiments. In each test run, the measurement was repeated at least three times to ensure that the results were reproducible.

Materials

In order to obtain information on the charging mechanisms of both coal and the ash-forming minerals, samples of Pittsburgh No. 8 coal, quartz, and pyrite were studied. Two different coal samples were used, i.e., a clean coal sample assaying 6.27% ash and a run-of-mine coal assaying 19-22 % ash. The coal sample was crushed, pulverized to minus 40 mesh, and then dry-screened to provide three different size fractions (40 x 65, 65 x 100 and 100 x 200 mesh).

The quartz and pyrite samples were both obtained from a commercial vendor. The pyrite sample, which originated from Huanzula, Peru, was crushed and ground manually by means of the cast iron mortar and pestle. The sample was then dry-screened to obtain the size fractions of 40 x 65, 65 x 100 and

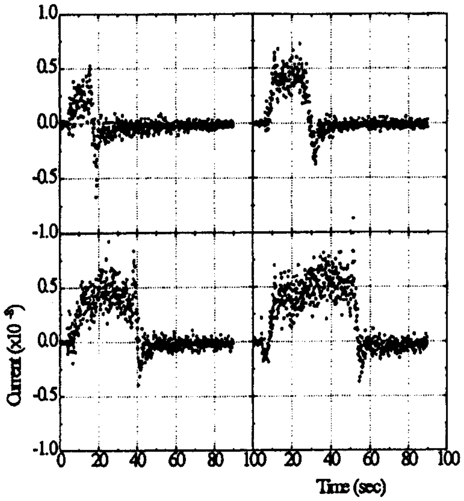

Fig 4. A printout from the data acquisition system used in conjunction with the on-line charge-measurement device.

100 x 200 mesh. The pure quartz sample (SiO_2) was obtained directly from the supplier in two different size fractions (40 x 65 and 65 x 100 mesh).

RESULTS AND DISCUSSION

Effect of Air Velocity

Figure 5 shows the effect of air velocity on the magnitude of the charge density of the various samples. The experiments were carried out at air pressure of 40 psi, particle feed rate of 0.2 kg/min, and temperature of 28-30°C. As shown, the coal sample acquired a positive charge after contact with copper surface, while ash-forming minerals, such as quartz and pyrite, acquire negative charges. These results can be explained by the fact that the work function of copper is higher than that of coal, but lower than that of the minerals.

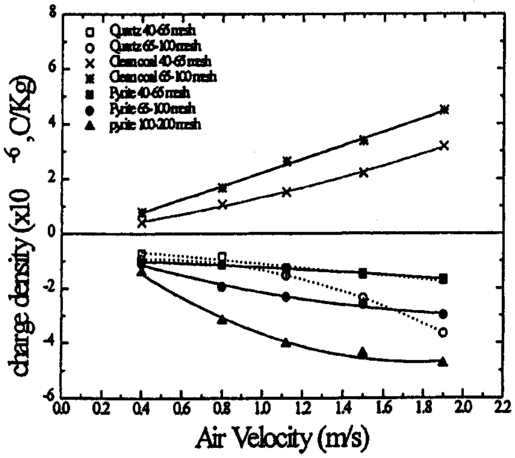

Fig. 5. Effect of air velocity on charge densities of clean coal (6.27% ash), quartz and pyrite samples.

An average charge per unit mass for all samples increased with an increase in air velocity, regardless of the particle size. The increased air velocity causes an increase in the impact velocity of the particles when they impinge on the copper walls and blades of the in-line static mixer charger. The higher impact velocity results in better particle-wall contact. This observation is consistent with other findings reported in the literature (Ban et al., 1993).

The data also show that the charge density for the coal samples is much higher than that of the quartz and pyrite samples. The pyrite sample tends to be more negatively charged than quartz. This finding agrees with the previous work done by Finseth et al. (1993), which shows that the dry triboelectrostatic-separation process can remove pyrite better than other ash-forming minerals. In addition, the results indicate that the charge densities of the particles increase with decreasing particle sizes.

Effect of Feed Rate

The effect of the particle feed rate on the magnitude of the charge density is shown in Figure 6. The experiments were carried out at an air pressure of 40 psi, air velocity of 1.9 m/sec, and temperature of 28-30°C. For all samples, an increase in the particle feed rate decreased the magnitude of charge density, regardless of particle size. At a given air velocity, the decrease in particle velocity often happens when the population of the particles in the charger is high and the chance of particles hindering each other is elevated.

At a given air velocity, the pyrite and quartz do not exhibit large differences in their charge densities. It should be noted that pyrite (a semi-conductor) may lose its charge upon contact with another conductor (Rose-Innes, 1980). The loss of charge may have contributed to the lower charge density of pyrite. In addition, the clean coal sample acquires about 3-4 times higher charge density either quartz and pyrite.

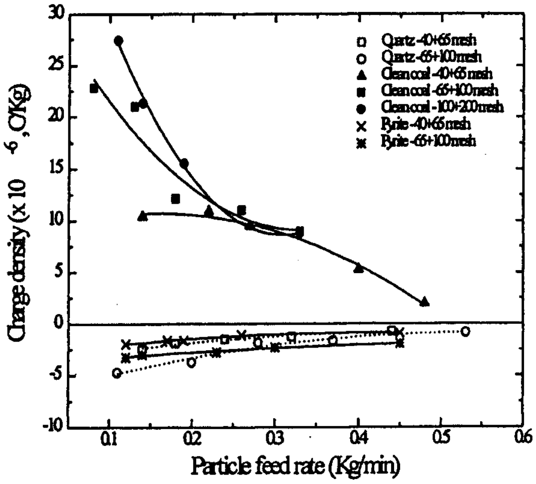

Fig. 6. Effect of particle feed rate on charge densities of clean coal (6.27% ash), quartz and pyrite samples.

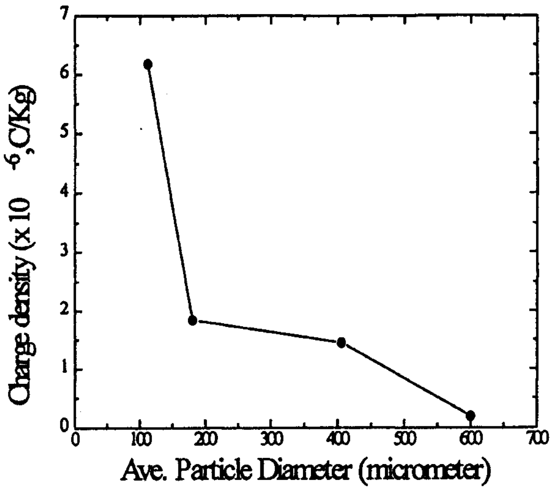

Fig. 7. The effect of particle size on charge density of coal (19-22% ash).

Effect of Particle Size

The effect of particle size on charging behavior is shown in Figure 7. These experiments were conducted using Pittsburgh No. 8 coal sample (6.27% ash) with a particle feed rate of 0.08 m/sec, air velocity of 2.0 m/sec, air pressure of 40 psi, and temperature of 28-30°C. Not surprisingly, a decrease in the charge density of the coal sample is observed with increasing mean particle diameter. This trend can be attributed to the higher surface area-to-mass ratio of the finer particles, creating larger contact area at a given mass. Note that the effect of particle size can also be seen in Figures 5 and 6.

Effect of Feed Composition

Figure 8 shows the results of the charge measurements conducted on the Pittsburgh No. 8 coal samples of different ash contents. The experiments were conducted using a particle size fraction of 65 x 100 mesh, particle feed rate of 0.2 kg/min, air velocity of 1.9 m/sec, air pressure of 40 psi, and temperature of 28-30°C. The results show that the lower the ash content, the higher the charge density becomes.

To obtain a better understanding of the charging behavior of mixtures, a series of experiments with known feed compositions were conducted. The feed composition was arbitrarily varied by mixing known amounts of the clean Pittsburgh No. 8 coal (assaying 6.27% ash) and quartz sample. The particle sizes of both clean coal and quartz were 40 x 65 mesh. Figure 9 shows the net charge measured for the different mixtures. The data were obtained at an air velocity of 1.9 m/sec and at a particle feed rate of 0.3 kg/min. As shown, the net particle charge decreased when the ash content in the feed increased. Note that the charge polarity of the mixture altered at an ash content of approximately 85% (by weight). A statistical analysis of the data indicate that the charge density obtained by the charge-measuring device is approximately a weighted average of the net charge of the positively charged coal particles and negative charged mineral particles in the feed stream.

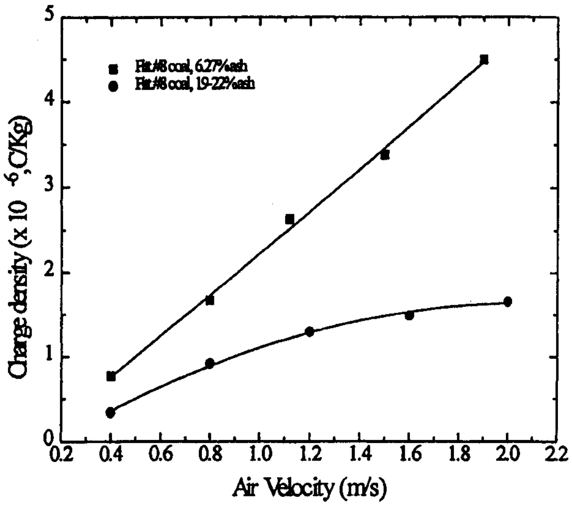

Fig. 8. Effect of ash content on the charge density of coal of different ash contents.

Effect of Temperature

Figure 10 illustrates the charge densities obtained when the system temperature was varied. The experiments were conducted at a particle size of 65 x 100 mesh, air velocity of 1.9 m/sec, air pressure of 40 psi, particle feed rate of 0.3 kg/min, and temperature of 28-30°C. The results show that the charge densities of clean coal and quartz samples increased with increasing temperature. It is well known that humidity is one of the critical factors in electrostatic separation. Water adsorbed onto the particle surface may increase the surface electrical conductivity. Accordingly, the charge that originated by contact electrification in a humid environment will dissipate rapidly

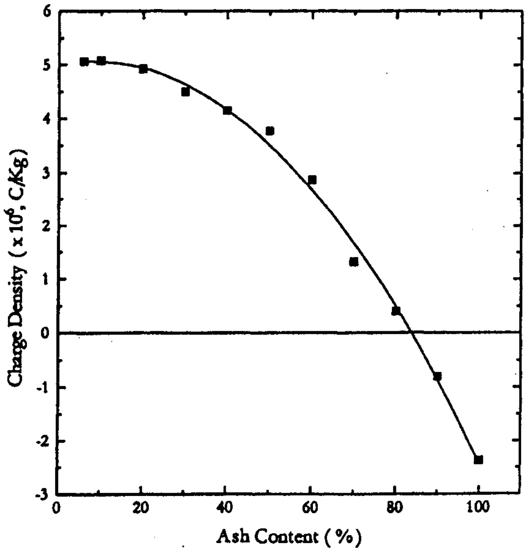

Fig. 9. Correlation between sample ash content and net charge for 40x65 mesh coal and quartz mixtures.

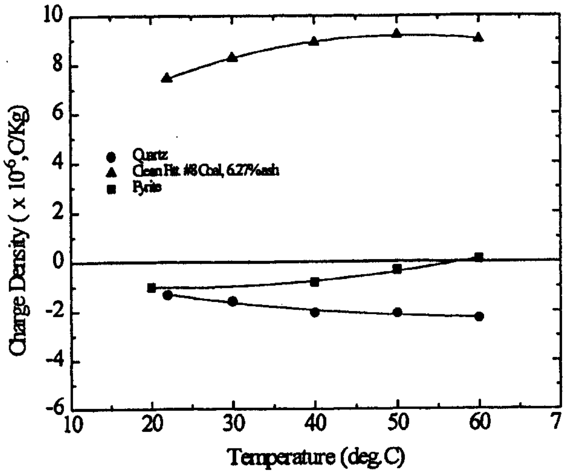

Fig. 10. Effect of temperature on charge densities of coal (6.27% ash), quartz, & pyrite samples

when touched by other particles due to the higher surface conductivity created by the surface moisture. Therefore, for insulators, an increase in temperature may reduce surface moisture and increase charge density.

In contrast, the charge density of the pyrite sample decreased with increasing temperature. It is well established that pyrite possesses some degree of conductivity (although less than pure metals). Conductivity can be expressed by:

$$\sigma = Ne^2\tau / m^* \quad [1]$$

where N is the concentration of the conduction electrons, τ is the relaxation time, and m^* is the effective mass of the electron. Conductivity increases as N increases since there are more current carriers. According to statistical mechanics, the concentration of conduction electrons increases exponentially with temperature (Omar, 1993). Thus, as the temperature is raised, a greater number of electrons become excited and the conductivity rises accordingly. For this reason, the pyrite sample becomes more conducting with increasing temperature, resulting in a decrease in the charge density. As mentioned earlier, the conductivity permits the charge to drain away from the contact area when two conductors are contacted (Rose-Innes, 1980).

CONCLUSIONS

1. A new charge-measuring device has been developed which combines an in-line static mixer with a Faraday cage. The analyzer can be used to determine the in-situ charging characteristics of fine particles in flowing streams.

2. Experimental data show that the in-line static mixer constructed from copper can produce a high charge density on both coal and ash-forming minerals (i.e. quartz and pyrite). This suggests that triboelectrostatic separations can be satisfactorily accomplished using an in-line static-mixer for particle charging.

3. The charging behavior of fine particles of coal, quartz and pyrite were evaluated using the in-situ charge analyzer. The experiment data indicate that coal becomes positively charged during triboelectrification, while pyrite and quartz become negatively charged.

4. Several important parameters that impact the charging behavior of particles were evaluated using the in-situ analyzer (i.e., air velocity, solids feed rate, particle size, ash content, and temperature). The test data suggest that the coal and ash-forming mineral samples exhibited the maximum difference in charge per unit mass at the highest air velocity and the lowest particle feed rate, regardless of particle size. However, the magnitude of the particle charge decreased with an increase in the particle size. Humidity and ash content also influenced the magnitude of the charge density for the coal samples. Increasing temperature had relatively little effect within the observed temperature range.

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