Factors affecting the electrical resistivity of kraft recovery boiler precipitator ash

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ABSTRACT: The electrical resistivity of ash particles is an important parameter that determines the efficiency of electrostatic precipitators. This systematic study examines the resistivity of recovery boiler precipitator ash as a function of electrical field strength, time of exposure, particle composition, and gas composition and temperature. Synthetic ash and actual ash samples from several pulp mills are used. The results show that most ash samples tested had a resistivity between 10^9 and 10^{10} Ω·cm, but one of the samples had an unusually high resistivity, 10^{12} Ω·cm. The resistivity increases with temperature up to about 140°C, then decreases. At a given temperature, the resistivity decreases with increasing moisture and sulfur dioxide concentration in the gas. Resistivity also increases with an increase in chloride content in the ash, but is not affected by the carbonate, sulfate, and potassium contents. The results imply that recovery boilers burning liquors with high solids and high chloride contents produce ash with higher resistivity, making it more difficult for electrostatic precipitators to capture.

Application: Pulp mills can minimize particulate emissions from recovery boilers by better understanding how ash composition and boiler and electrostatic precipitator operating conditions affect the electrical resistivity of ash particles.

The recent development of more stringent environmental regulations on particulate emissions in North America has called for an improvement in the performance of particulate control devices. Environmental Protection Agency regulations for kraft pulp mills, for example, allow for particulate emissions of 0.044 gr/dscf for existing recovery boilers and 0.015 gr/dscf for new recovery boilers [1]. Since electrostatic precipitators (ESPs) are the most commonly used devices for removing particulate matter from recovery boiler stacks, it is essential for kraft pulp mills to operate their ESPs at the highest efficiency possible to maintain the maximum production rate and meet compliance requirements.

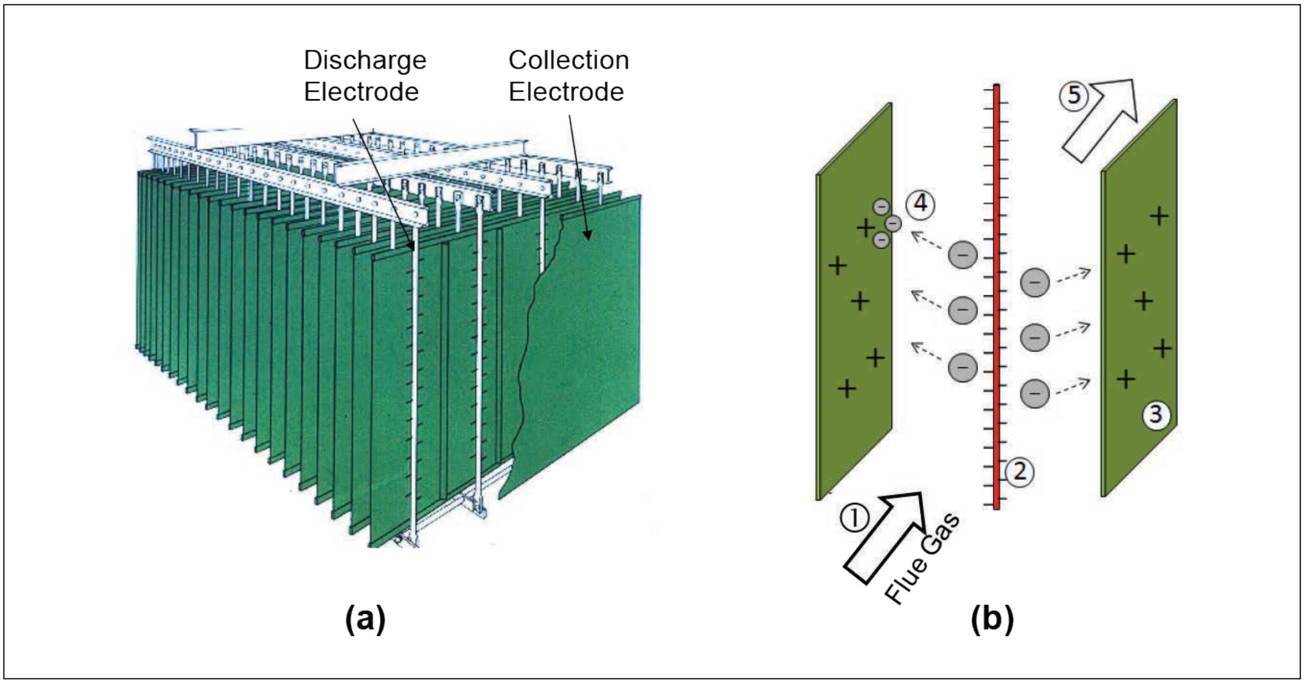
For ash particles to be removed from a gas stream, they must be sufficiently charged as the gas passes through a high-voltage electrostatic field in the ESP. The ability of ash particles to be charged depends on the electrical resistivity of the ash [2–4]. While electrical resistivity is an important property, only limited information is available in the literature, particularly with respect to recovery boiler ash [5,6]. It is not well understood how the electrical resistivity of recovery boiler ash changes with composition, particle size, gas composition, temperature, and other parameters. It is also not well understood how such change may affect the ESP performance.

In recent years, an increasing number of recovery boilers have been firing high solids black liquor (>75%) to help stabilize the char bed, minimize carryover, and maximize the boiler thermal efficiency. The practice inevitably results in a flue gas with low water and sulfur dioxide (SO_2) concentrations and precipitator ash with high carbonate content [7]. It is not known how these changes may affect the ash resistivity and hence the ESP performance. A systematic study was conducted to examine the resistivity of recovery boiler ash as a function of electrical field strength, particle composition, temperature, and flue gas composition. This work was the master's thesis project of Sretenovic [8] at the University of Toronto. This paper discusses the principles of ESPs and the role of ash resistivity, as well as experimental procedures and main results obtained from the thesis project.

PRINCIPLES OF ESP OPERATION

Electrostatic precipitators remove fly ash particles entrained in the flue gas by applying an electric field between the discharge and collection electrodes. Discharge electrodes are thin tubes or wires that are negatively charged, while collection electrodes are positively charged and grounded (**Fig. 1a**).

The charging process is schematically illustrated in **Fig. 1b**. As the flue gas (1) passes between two collection plates, the applied high voltage causes the gas molecules near the discharge electrode (2) to ionize. The negatively charged gas molecules then adhere to surface sites of ash particles, making them negatively charged. The charged ash particles are subsequently attracted to the positively charged collection



1. (a) Plate-type electrostatic precipitator (Courtesy of Clyde Bergemann) and (b) charging process.

electrodes or plates (3) and form an ash layer on the plates (4), resulting in a cleaner outlet gas stream (5). The collected ash layer is periodically removed by rappers or vibrators, which mechanically drop the ash layer to the collecting hoppers at the bottom of the precipitator. A thick ash build-up on electrode surfaces can deteriorate the electrical conditions and compromise the precipitator performance [2–4].

There are two paths for electrical current to conduct through a particle, and they can affect the ability of the particle to be charged. One is through the bulk of the material and the other is through a layer of a flue gas constituent adsorbed on the particle surface. Because of this, both ash and gas compositions can affect particle charging [2]. Once the ash particles are charged, they migrate toward the collection electrode at a velocity (the migration velocity) that varies with particle size; field strength; flue gas viscosity; and more importantly, with the ability of the particles to become charged, which is quantified by ash resistivity. The theoretical migration velocity (m/s) is derived from a force balance around an individual dust particle and can be expressed as Eq. (1):

$$w_p = \frac{q \cdot E_p \cdot C}{6 \cdot \pi \cdot a \cdot \mu} \qquad (1)$$

where q is the electrical charge on the particle (C), E_p is the field strength (V/m), C is a dimensionless Cunningham slip correction factor, a is the particle diameter (m), and μ is the gas viscosity (Pa·s) [9]. In practice, the migration velocity used for sizing a precipitator depends on the application and is based on databases of existing installations and the given operating conditions. The precipitator collection efficiency is expressed by the Deutsch-Anderson equation, Eq. (2):

$$\eta = 1 - e^{-\frac{A_p \cdot w_d}{Q}} \qquad (2)$$

where η is the fractional theoretical collection efficiency, w_d is the migration velocity for the given application and operating conditions (m/s), A_p is the collection area (m²), and Q is the volumetric flow rate of the exhaust gas (m³/s) [10]. To achieve a high collection efficiency, there must be sufficient collecting area in the ESP for the given gas flow rate and particle migration velocity.

ASH RESISTIVITY

Resistivity is a material property that describes its tendency to resist the flow of current. The higher the resistivity of a material, the more difficult it is for the material to become charged. In the context of ESP operation, resistivity is one of the most important ash properties that determines the particle migration velocity and hence the required size of the precipitator. The resistivity of a material sample is defined as Eq. (3):

$$\rho = R \cdot \frac{A}{l} \qquad (3)$$

where ρ is the resistivity (Ω·m), R is the electrical resistance of the sample (Ω), A is its cross-sectional area (m²), and l is its length (m), according to IEEE Standard 548-1984 "IEEE standard criteria and guidelines for the laboratory measurement and reporting of fly ash resistivity." In the literature, the resistivity ρ is often expressed in Ω·cm.

Ash resistivity can affect ESP performance in several ways.

It determines the magnitude of the particle charge and the charging rate. A higher resistivity particle requires a longer exposure time to become charged and cannot achieve as high of a charge as an identical particle of lower resistivity. This, in turn, will result in a lower migration velocity and a lower ESP collection efficiency [10,11]. Ash resistivity also determines how strongly an ash layer adheres to the collection electrode. Particles with high resistivity are difficult to charge; however once collected on the plate, they do not discharge readily and so are more difficult to remove by rapping due to their stronger electrostatic attraction to the plate [6]. Ash resistivity also affects the electrical field strength across the ash layer on the collecting plate. The field strength in an ash layer is crucial, since excessive breakdown in this layer can deteriorate electrical conditions in the ESP and lead to poor performance. The field strength is expressed by Eq. (4):

$$E_{ash} = j \cdot \rho \qquad (4)$$

where E_{ash} is the field strength in the ash layer (V/m) and j is the current density in the ash layer (A/m^2) [11]. The field strength at which electrical breakdown occurs, leading to localized excessive sparking, is about 12 kV/cm. The resistivity beyond which excessive sparking and deteriorated electrical conditions may begin to occur in normal ESP operating mode is between 10^{10} and 10^{11} Ω·cm [12]. In cases of extremely high dust resistivity, a condition known as back corona can occur, whereby the sparking in the dust layer leads to a net migration of positive ions into the interelectrode space, neutralizing the desirable negative charge and significantly reducing performance [12,13]. Resistivity ranges are categorized in **Table I**.

While resistivity has been extensively studied for fly ash from coal fired boilers [3,4], no study has been done on recovery boiler precipitator ash, other than the work of Samuelsson [5], who studied the constituent compounds typically found in ash, namely sodium sulfate (Na_2SO_4), sodium carbonate (Na_2CO_3), and sodium chloride (NaCl). It was reported that NaCl has a peak resistivity of more than 10^{12} Ω•cm compared to only 10^8 to 10^9 Ω•cm for Na_2SO_4 and Na_2CO_3.

Ash resistivity can be affected by the operating conditions of the boiler and the ESP, and by ash particle characteristics [4]. Changes in temperature can increase or decrease the ash resistivity depending on its composition. Electrical conductivity on the surface of dust particles generally decreases with increased temperature, while throughout the bulk of the dust increases with increased temperature. There exists a temperature range in which ash exhibits a peak resistivity, where surface and volume conductivity are both relatively low. This temperature range is typically 120°C–200°C for most materials [3,4,9].

Several components in the flue gas, such as water vapor, SO_2 and sulfur trioxide (SO_3) can lower the ash resistivity by adsorbing onto the particle surface. These components are commonly used as gas-conditioning agents to increase the ash removal efficiency of ESPs in utility boilers [3,4,9,12,13].

Ash particle size and size distribution can also affect the way the particles pack as they form deposits on the collection electrode, as well as the magnitude of charge the particles can attain as they pass through the electrical field [14]. Increasing the particle packing density increases the contact between particles. In turn, this creates more volume conduction paths for the current to flow, resulting in a lower ash resistivity.

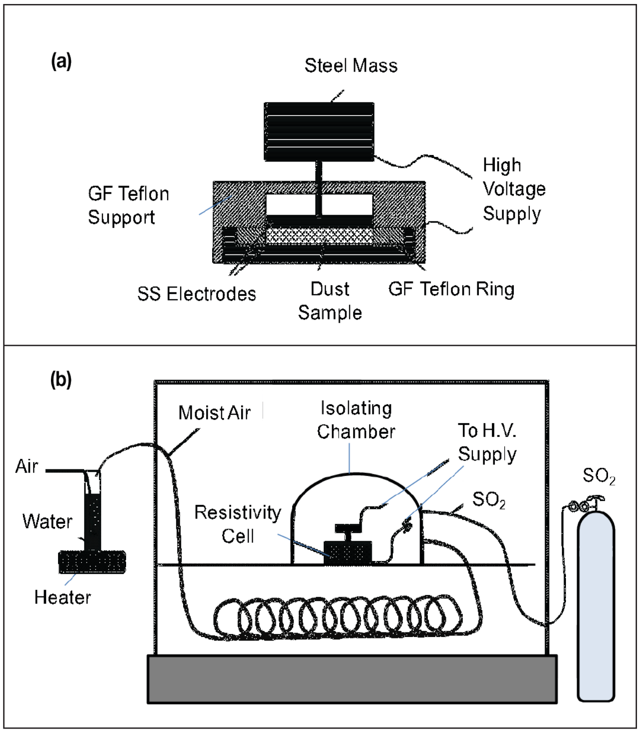
Unlike coal ash, which consists of mainly oxides (e.g., silicone dioxide, aluminum oxide, calcium oxide, magnesium oxide, iron oxide, sodium oxide, potassium oxide) with a small amount of alkali salts [3,4], precipitator ash in recovery boilers contains more than 99% alkali salts, mainly Na_2SO_4, Na_2CO_3, NaCl, and potassium salts [15]. Such a large difference in composition suggests that recovery boiler ash behaves differently and has a different effect on ESP performance.

EXPERIMENTAL

In this study, synthetic ash samples prepared from pure chemicals and actual precipitator ash samples from a number of recovery boilers were used. The measurements were performed following procedures for testing bulk resistivity of powders outlined in IEEE Standard 548-1984. **Figure 2** shows the ash resistivity apparatus used. It consists of a resistivity cell, a high voltage supply, an electrical oven, a gas conditioner, and a data acquisition system. In the resistivity cell (Fig. 2a), an ash sample was placed between two cylindrical stainless steel electrodes, across which a high potential was applied. Glass-filled Teflon was used as a mechanical support for the top electrode and as a means to linearize the flow of

Resistivity	Range (Ω·cm)	Impact on Electrostatic Precipitator Performance
Low	10^4–10^7	Low capture efficiency, high risk for particle re-entrainment
Normal	10^7–10^{10}	Ideal, high capture efficiency
High	>10^{10}	High risk for excessive sparking, insufficient particle charging, rapping problems, possibility of back corona

I. Ash resistivity and possible impact on electrostatic precipitator performance.



2. Ash resistivity apparatus.

current through the ash sample. The resulting current through the ash layer was measured and used to calculate the resistivity of the ash sample.

The bulk density of the samples was measured by placing a fixed mass of the sample in a graduated cylinder and tapping it gently to allow the dust to settle, then taking the volume reading. The resistivity was measured by placing a fixed volume of the sample into the cup of the resistivity cell. The top of the sample was leveled by drawing a straight edge across the surface of the cup. The disk electrode was gently lowered onto the surface of the sample, making sure not to press down and pack the dust sample. The effect of packing was investigated by changing the weight on the top electrode.

Tests were performed at different sample temperatures between 20°C and 280°C. To test the effects of gas moisture content on resistivity, the resistivity cell was placed in an isolating chamber made of polymethyl-pentene (PMP) inside a temperature-controlled oven (Fig. 2b). An electrical feedthrough was installed on the oven wall to connect the apparatus to the high voltage power supply. Air was bubbled through a humidification unit, which was filled with water controlled at a fixed temperature to get the desired moisture content in the gas stream. This moist gas stream was then fed to the oven through a copper coil so that it was preheated before entering the isolating chamber. The dust sample was exposed to the test conditions in the isolating chamber by raising the top disk electrode and allowing the moisture to adsorb onto the dust particles for 15 min, after which it was lowered and the voltage was applied.

The effect of SO_2 on ash resistivity was examined by feeding the gas from a pressurized gas cylinder (1000 ppm SO_2 in air) into the oven along with a stream of dry or moist air. The flow rates of two gas steams were adjusted to achieve the desired SO_2 concentrations in the isolating chamber. After the system had reached a steady state, the top disk electrode was lowered onto the dust and the voltage was applied.

The effect of ash composition was studied using synthetic ash samples prepared from mixtures of pure chemicals as follows: Na_2SO_4, Na_2CO_3, NaCl, potassium chloride (KCl), potassium carbonate (K_2CO_3) and potassium sulfate (K_2SO_4). The molar ratio of Na_2SO_4 to Na_2CO_3 was kept constant at 4:1, while the other components were changed to produce mixtures of synthetic ash with different chloride (Cl) and potassium (K) contents.

RESULTS AND DISCUSSION

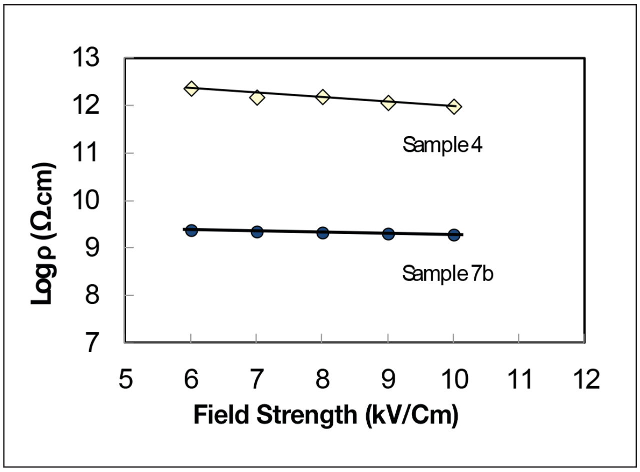
Resistivity of recovery boiler precipitator ash

Eleven precipitator ash samples from seven kraft pulp mills were tested for resistivity under various operating conditions. The effects of field strength, particle size, particle packing, temperature, ash composition, and gas stream composition on resistivity were studied. For each sample, repeated measurements were made at 100°C in air under an electric field at 90% of the breakdown field strength of the sample (i.e., 9–10 kV/cm).

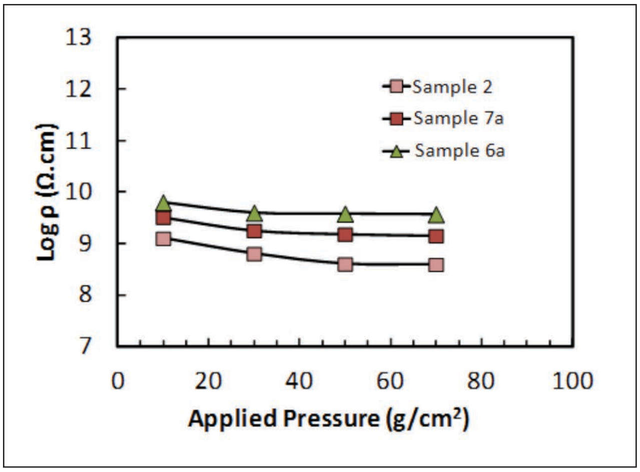
Table II summarizes the measurement results. No apparent correlation between the ash bulk density and resistivity was noticed. Most ash samples had resistivity between 10^9 Ω·cm and 10^{10} Ω·cm. Only one (sample 4) had extraordinarily high resistivity, 10^{12} kΩ·m, which is well

Sample ID	Mill and Boiler ID	Bulk Density (g/cm³)	Log Resistivity (Ω·cm)
1a	Mill 1 Boiler A	0.37	9.4
1b	Mill 1 Boiler B	0.27	9.0
1c	Mill 1 Boiler B	0.15	9.0
2	Mill 2 Boiler	0.25	8.9
3	Mill 3 Boiler	0.27	9.6
4	Mill 4 Boiler	0.23	12.0
5	Mill 5 Boiler	0.21	9.3
6a	Mill 6 Boiler A	0.21	9.7
6b	Mill 6 Boiler B	0.20	10.1
7a	Mill 7 Boiler A	0.26	9.2
7b	Mill 7 Boiler B	0.27	9.3

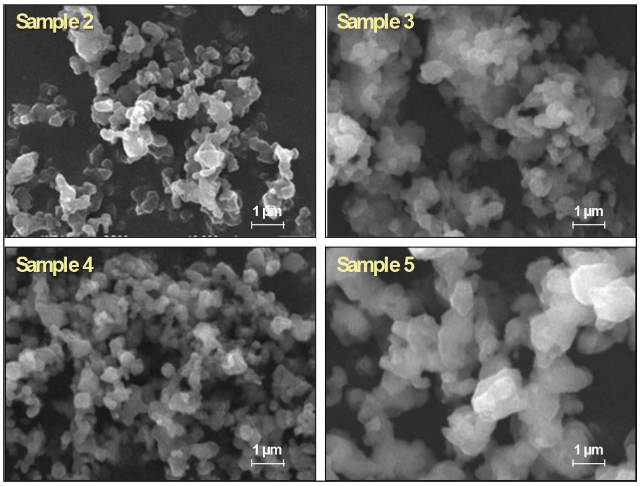
II. Resistivity of ash from various recovery boilers (measured in air at 100°C.)



3. Effect of field strength on recovery boiler ash at 100°C.



5. Effect of packing density on ash resistivity.



4. Scanning electron micrographs of various recovery boiler ash samples.

above the critical value of 10^{10} Ω·cm shown in Table I. Interestingly, this sample came from a mill where particulate emissions from its recovery boiler have been a chronic problem.

Effect of field strength

The applied field strength in an electrostatic precipitator is directly responsible for the charging of ash particles in the flue gas, and hence affecting the particle migration velocity. **Figure 3** shows the resistivity of sample 4 (high resistivity) and sample 7b (average resistivity) at 100°C under different field strengths. A slight decrease in resistivity with increasing field strength was observed, particularly for sample 4. This suggests that the recovery boiler does not obey Ohm's law, also known as non-ohmic behavior. A similar behavior has been observed previously for coal ash [4].

Effect of particle size and particle packing

Figure 4 shows scanning electron micrographs (SEM) of several recovery boiler ash samples (2, 3, 4, and 5) that have a comparable bulk density. The particle size varied between 0.3 µm and 1 µm. Of these samples, 4 had the smallest particle size (<0.3 µm) but the highest resistivity (≈ 10^{12} Ω·cm). Other samples had a larger particle size (0.5–1 µm) and lower resistivity (10^9–10^{10} Ω·cm). Although the compositions of these ash samples may play a role, this SEM analysis implies that ash with a smaller particle size has a higher resistivity than ash with larger particle size. It should be noted that particle size may have a greater effect on particle migration, as it is directly proportional to migration velocity, than on particle resistivity or charging.

The effect of particle packing density on resistivity was examined for several ash samples. The packing density was increased by mechanically increasing the pressure applied on the stainless steel mass placed on the top of the ash sample holder (Fig. 2a). As shown in **Fig. 5**, increasing the applied pressure on the ash decreases its resistivity. This is understandable since a closer contact between particles under an increased pressure would allow more current to flow through the bulk of the ash material. The results imply that the more loosely a dust layer packs on the surface of the collection electrode, the higher its resistivity and the more likely an electrical breakdown can occur.

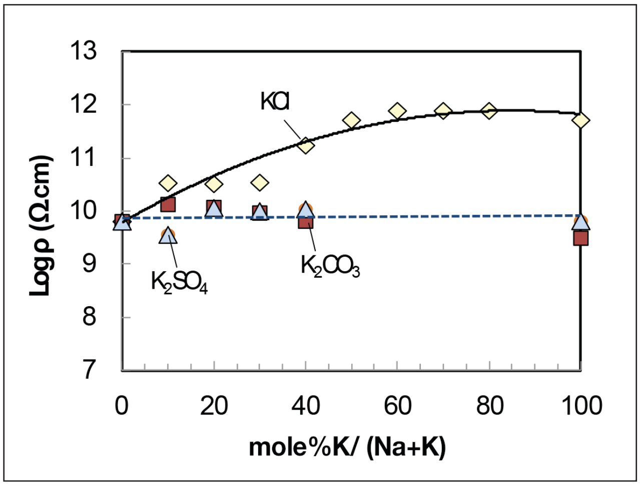
Effect of ash composition

Recovery boiler precipitator ash consists of sodium (Na) and potassium (K) salts; mainly sulfate (SO_4), carbonate (CO_3) and Cl. The effect of composition on ash resistivity was examined using mixtures of pure chemicals as follows: Na_2SO_4, Na_2CO_3, NaCl, K_2SO_4, K_2CO_3, and KCl.

Because K in the ash can be in the form of K_2SO_4, K_2CO_3, or KCl, its effect on ash resistivity was studied by adding each of these three compounds separately to a mixture of Na_2SO_4 and Na_2CO_3 with a SO_4:CO_3 molar ratio of 4. The addition increased the K content, expressed as mole% K/(Na+K), by replacing the Na in the mixture with K, while keeping the SO_4:CO_3 molar ratio of the initial mixture the same. A few examples of such additions for each compound are shown in **Table III**. Such an addition method was needed to enable

Compounds Used	Potassium Content	Na_2SO_4	Na_2CO_3	K_2SO_4	K_2CO_3	KCl
	mole% K/(Na+K)	mole %	mole%	mole%	mole%	mole%
K_2SO_4	0	80	20	0	0	0
	20	64	16	20	0	0
	40	48	12	40	0	0
	100	0	0	100	0	0
K_2CO_3	0	80	20	0	0	0
	20	64	16	0	20	0
	40	48	12	0	40	0
	100	0	0	0	100	0
KCl	0	80	20	0	0	0
	20	64	16	0	0	20
	40	48	12	0	0	40
	100	0	0	0	0	100

III. Compositional matrix for increasing the potassium content in synthetic ash made from mixtures of pure chemicals.



6. Effect of potassium on ash resistivity.

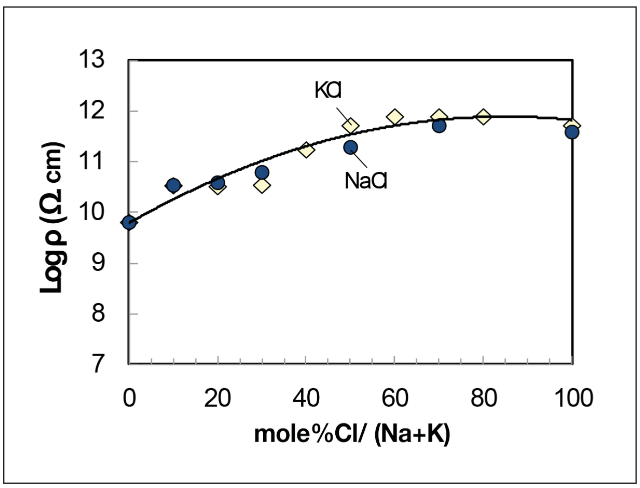
Chloride Content	Na_2SO_4	K_2SO_4	Na_2CO_3	NaCl
mole% K/(Na+K)	mole %	mole%	mole%	mole%
0	80	0	20	0
20	54	10	16	20
40	38	10	12	40
100	0	0	0	100

IV. Compositional matrix for increasing the chloride content in synthetic ash made from mixtures of pure chemicals.

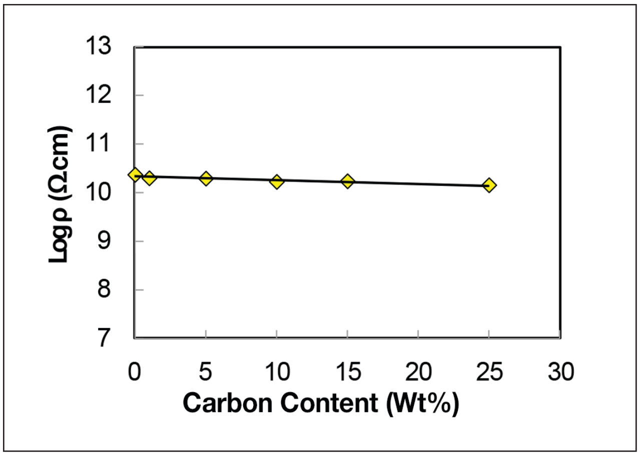
the comparison between results obtained with different potassium compounds.

As shown in **Fig. 6**, when K_2SO4 or K_2CO_3 was used to increase the K content of the mixture, no appreciable change in ash resistivity was observed, as it remained the same at about 10^{10} Ω·cm. When KCl was used to increase the K content, however, the resistivity increased significantly from about 10^{10} Ω·cm at 0 mole% K/(Na+K) to about 10^{12} Ω·cm at 60 mole% K/(Na+K) and then levelled off at that value. These results suggest that it was not the high potassium content that increased the ash resistivity; it was the high chloride content that did.

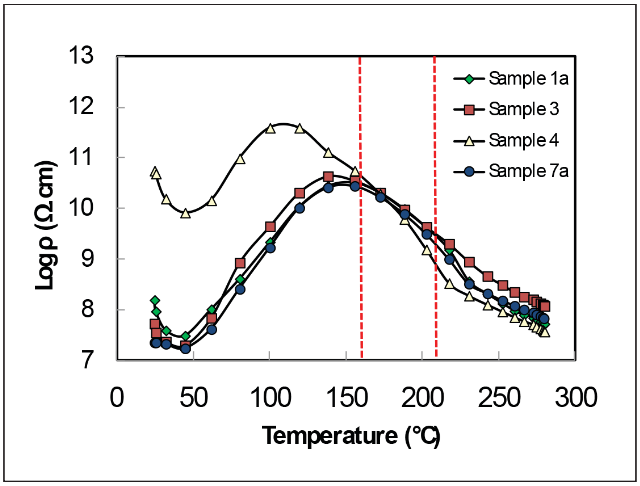
To confirm the effect of chloride on ash resistivity, another series of tests was performed in which NaCl was added to a mixture of Na_2SO_4, K_2SO_4, and Na_2CO_3 to increase the Cl



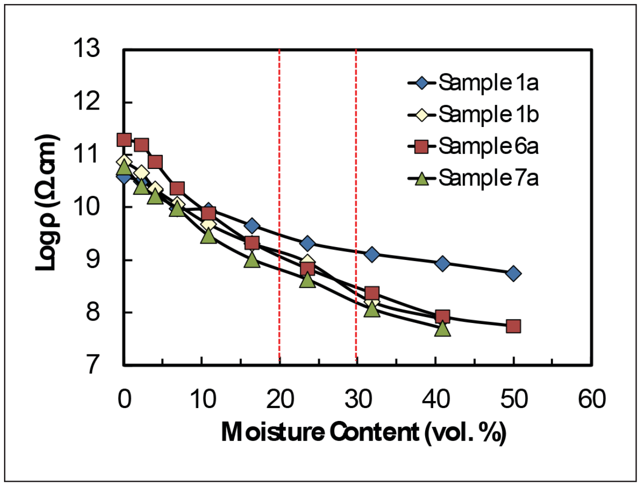
7. Effect of chloride on ash resistivity.



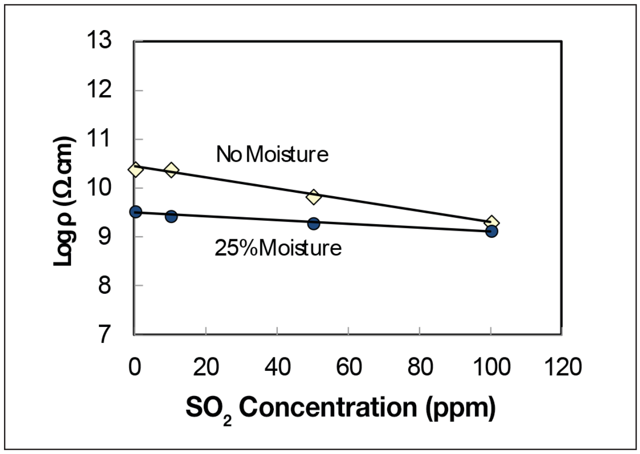
8. Effect of char on ash resistivity.



9. Effect of temperature on resistivity.



10. Effect of moisture content on resistivity at 150°C.



11. Effect of sulfur dioxide concentration in the gas on ash resistivity at 150°C.

content, while keeping the SO_4:CO_3 molar ratio the same at 4 (**Table IV**). The results are shown in **Fig. 7**. Increasing the chloride content in the mixture with NaCl addition significantly increased the ash resistivity.

Note that since the numbers of moles of K and Cl in KCl are equal, the mole% K/(Na+K) in the case of KCl addition shown in Fig. 6 is the same as mole% Cl/(Na+K). This means the same data can also be used to indicate the effect of chloride on ash resistivity, as shown in Fig. 7. The close agreement between these two sets of data confirms that the high ash resistivity was caused by Cl, not by K.

Effect of char

Unburned carbon that reaches the ESP is known to have a low resistivity in coal fired boilers [12]. It can be beneficial for high resistivity ash since it lowers the ash resistivity, making it easier to become charged and collected. However, it can also lead to carbon re-entrainment. In this study, the effect of unburned carbon inclusion in recovery boiler ash was also tested by adding varying amounts of charred black liquor to a recovery boiler ash sample. As shown in **Fig. 8**, the presence of carbon decreases the ash resistivity slightly. The effect, however, is expected to be negligible since the char content in recovery boiler ash is typically less than 0.1 wt%.

Effect of gas temperature

As shown in **Fig. 9**, the resistivity of all ash samples tested reaches a peak at a certain temperature, after which it decreases with temperature. This peak resistivity occurs between 100°C and 150°C for most samples. Since the flue gas temperature in most recovery boiler ESPs ranges between 160 °C and 210°C (dotted line), it can be concluded that in this temperature range, the ash resistivity decreases significantly as the gas temperature increases.

Effects of moisture and SO_2

The moisture content in the recovery boiler flue gas typically ranges from 20% to 30% depending on the solids content of the black liquor fired in the boiler. As shown in **Fig. 10**, increasing the moisture content lowers the ash resistivity significantly. Sulfur dioxide also lowers the resistivity of recovery boiler ash (**Fig. 11**). The effect, however, is more pronounced in a dry atmosphere than in the presence of 25% moisture.

SUMMARY AND CONCLUSIONS

A systematic study was performed in the laboratory to determine the resistivity of recovery boiler ash as a function of electrical field strength, particle size, particle composition, temperature, and moisture and SO_2 contents in the flue gas. The results show that most of the recovery boiler ash samples tested had a resistivity between 10^9 and 10^{10} Ω·cm. One sample had an abnormally high resistivity (10^{12} Ω·cm). Increasing electrical field strength decreased resistivity slightly. This suggests that higher field strengths in electrostatic precipitators are beneficial for increasing charging rates and migration velocities and lowering the resistivity of the deposited ash layer, making it easier to discharge.

The chloride content has an impact on resistivity, while carbonate, sulphate, potassium, and carbon contents have little or no effect. Under the normal ESP operating temperature range of 160°C–210°C, the ash resistivity decreased with increasing temperature. Finally, increasing both moisture and SO_2 concentrations in the flue gas resulted in a lower ash resistivity. This implies that recovery boilers burning liquors with high solids and high chloride contents produce ash with a higher resistivity, making it more difficult for ESPs to capture. **TJ**

ACKNOWLEDGEMENTS

This work was conducted as part of the Increasing Energy and Chemical Recovery Efficiency in the Kraft Process-II research program, jointly supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and a consortium of the following companies: Andritz, Babcock & Wilcox, Boise Paper, Carter Holt Harvey, Celulose Nipo-Brasileira, Clyde-Bergemann, DMI Peace River Pulp, Fibria, International Paper, Irving Pulp & Paper, Metso Power, MeadWestvaco, StoraEnso Research, and Tembec.

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Electrostatic precipitators (ESPs) have been widely used to efficiently reduce particulate emissions from kraft recovery boilers. We chose to do this research because as particulate emission limits become more stringent, it is important to understand factors that influence the ESP performance to maximize the ash removal efficiency.

This research greatly complements previous research on recovery boiler ash resistivity that others have done. The difference is that our research was more systematic and covered a wide range of ash composition, ash compactivity, and ESP operating conditions. We found that electrical resistivity measurements of ash samples are very sensitive to ash compactivity, temperature, and ambient gas composition. To deal with this challenge, the measurements had to be carried out in a well-controlled environment to achieve reproducible results. Regular calibration of the instruments used to measure low currents through the dust layer was also necessary.

We found that the sample with the highest resistivity happens to come from the boiler that experienced poor opacity problems. This implies that ash electrical resistivity plays an important role in ESP performance.

Knowledge of how ESP operating conditions and particle characteristics affect ash resistivity can help mills to establish the most favorable boiler operating conditions to allow ash resistivity to be in the desirable range for maximum ESP removal efficiency.

Our next step is to construct a miniature ESP and install it at the outlet stream of our bench-scale combustor. We hope this will enable us to simulate the effects of boiler and precipitator operating conditions and particle characteristics.

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