

New learnings and strategies for meeting future recovery boiler particulate emission limits with existing electrostatic precipitators

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ABSTRACT: It is foreseeable that recovery boiler particulate emission limits in the United States and Canada will continue to get more stringent with time. Because of this, continued improvement of emission control equipment, as well as a better understanding of how operating parameters affect performance, are necessary.

Although electrostatic precipitators (ESPs) are often viewed as a mature technology, many improvements in ESP technology continue to be developed. In recent years, academic efforts have improved the understanding of recovery boiler operating conditions on ESP performance. Additionally, advancements in materials, power supplies, and design continue to improve the efficiency and reliability of ESPs.

This paper discusses how recovery boiler and electrostatic precipitator (ESP) operating factors affect ESP performance based on process simulations and practical experience, and how these learnings can be implemented to improve future operation of existing ESPs.

Application: This work builds on the extensive research performed by the University of Toronto on ESP emissions from recovery boilers. This analysis links the findings from laboratory research to the implementation of these learnings in the day-to-day operation of kraft pulp mills. The ultimate goal is to find a method of improving ESP performance and to minimize emissions of particulate matter to the surroundings in the most manageable and economically feasible manner.

In the United States, the Environmental Protection Agency (EPA) mandates that existing recovery boiler particulate emissions must not exceed 0.044 grains per dry standard cubic foot (gr/dscf) at 8% O₂, and new or rebuilt furnace emissions must not exceed 0.015 gr/dscf at 8% O₂ [1]. Similarly, in Canada, the recommendations in the Code of Practice for Management of Air Emissions from Pulp and Paper Facilities issued by Environment and Climate Change Canada state that total particulate emissions should be less than 2 kg of particulate matter (PM)/metric tons of production, and that local point-of-impingement requirements generally result in stack emissions <100 mg/Nm³. In both the United States and Canada, opacity limits are determined on a case-by-case basis and are commonly limited to 20%. Depending on stack geometry, this can sometimes be the critical parameter driving the need for higher electrostatic precipitator (ESP) efficiency, as it could correspond to a concentration lower than the previously mentioned concentration limits.

Many existing ESPs at North American mills are more than 20 years old, and have been sized and designed for the original boiler operating conditions and emission requirements at the time of installation. Additionally, many mills have modified their process conditions (increased black liquor solids (BLS) content or increased firing rate)

such that the operating characteristics have changed over time, and the resulting flue gas and dust may present more difficult conditions for particulate removal in the ESP. In some cases, an increase in ESP emissions over time can be attributed to the changes in operating conditions, while in other cases, it can be attributed to aging of the precipitator and deterioration of the internals. As emission requirements continue to become more stringent, maintaining and improving the efficiency of ESPs is more important than ever. Effects of process modifications, strategies for maintaining particulate emission compliance, and methods of improving ESP performance are presented in this paper.

GENERAL THEORY OF ESP OPERATION

The general theory of ESP operation has been studied extensively for many years. The fundamental Deutsch-Anderson equation, derived from a dust mass balance around the electrostatic precipitator, allows us to express ESP dust removal efficiency as follows [2]:

$$\eta = 1 - e^{-\frac{A_p \cdot w_d}{Q}}$$

where η is the fractional theoretical collection efficiency, w_d is the average migration velocity for the given applica-

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tion (m/s), A_p is the collection surface area (m²), and Q is the volumetric flow rate of the exhaust gas (m³/s).

The average migration velocity describes the average rate at which charged dust particles move towards the collecting electrodes due to the electrostatic force imposed by the presence of an electric field. The equation demonstrates that the higher the migration velocity, the more efficiently an ESP will operate, given that all other parameters remain constant. The migration velocity is a complex function of dust particle size, dust material resistivity, electric field strength, and flue gas viscosity. The dust resistivity, commonly expressed in units of $\Omega\cdot\text{cm}$, is defined as a material's tendency to oppose the flow of electrical current. In an ESP operational context, it determines the rate at which ash can be charged and the magnitude of charge that an ash particle can carry. In general, the higher the resistivity of the material, the more difficult it is to charge and the lower the resulting migration velocity. This plays a large role in ESP performance and is further discussed in the following section.

The Deutsch-Anderson equation also shows that flue gas volumetric flow rate will have a pronounced effect on ESP efficiency, and thus the outlet dust concentration. Additionally, since efficiency is defined as:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}}$$

where C_{in} and C_{out} are dust concentrations in the same units, we can deduce that the outlet dust concentration will be linearly proportional to the inlet dust concentration for a given ESP efficiency. This means that theoretically, an ESP

will operate at a given efficiency, independently of the inlet dust concentration, and that an increase in the inlet concentration will result in a linearly proportional increase in the outlet dust concentration.

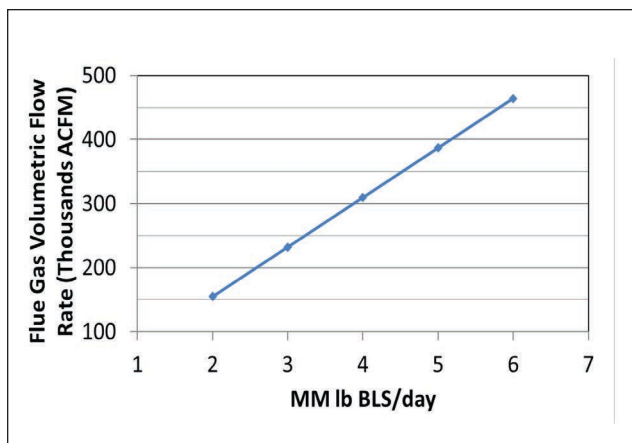
The previous equations indicate that exhaust gas volumetric flow rate, inlet concentration, ESP collecting area, and migration velocity will have a large effect on the ESP outlet dust emissions. However, the equations also make some ideal behavior assumptions that may not always apply to recovery boiler precipitator ash. Particles are not of uniform size or composition, and particle re-entrainment occurs during discharge electrode cleaning, releasing collected particles back into the exhaust. These non-idealities are not considered in the Deutsch-Anderson equation, which presents some challenges for predicting ESP emissions, despite extensive developments in modeling ESP operation.

The most recent work in this field has found that the main parameters affecting recovery boiler ESP particulate emissions are gas volumetric flow rate, inlet dust loading, dust resistivity, and particle size [3,4]. The effect of these parameters on ESP operation is summarized in **Table I**.

Please note that the effects described in Table I specifically refer to recovery boiler precipitator applications. Parameters deemed to have “minor” effects in Table I can have much more significant effects in other applications. For example, in coal and biomass ashes, there is much more variation in particle composition and particle size than recovery boiler ash. This makes it easier to identify and attribute changes in ESP performance to variations in these parameters; however, due to a smaller magnitude of variation of these parameters in recovery boiler applications, they play a seemingly smaller role in recovery boiler ESP operation.

Parameter	Magnitude of Effect on ESP Operation	Type of Effect on ESP Operation
Flue gas volumetric flow rate	Significant	Emissions increase exponentially with increase in gas volumetric flow rate.
Dust loading	Significant	Emissions increase linearly with increase in inlet concentration.
Moisture content*	Moderate	Migration velocity decreases with a decrease in moisture content (increase in resistivity), thus emissions increase.
Particle size	Minor	Migration velocity may decrease with a smaller particle size for particles > 0.5 μm in diameter; thus, emissions may increase. However, below 0.5 μm , decrease in size may actually increase migration velocity.
Particle composition*	Minor	Migration velocity may decrease with a higher chloride content (increase in resistivity); thus, emissions may increase.
Note: Parameters denoted with (*) indirectly affect ESP operation due to their effect on dust resistivity.		

I. Operating parameters affecting electrostatic precipitator (ESP) operation.



1. Effect of boiler firing capacity on flue gas volumetric flow rate (ACFM = actual cubic ft/min; BLS = black liquor solids).

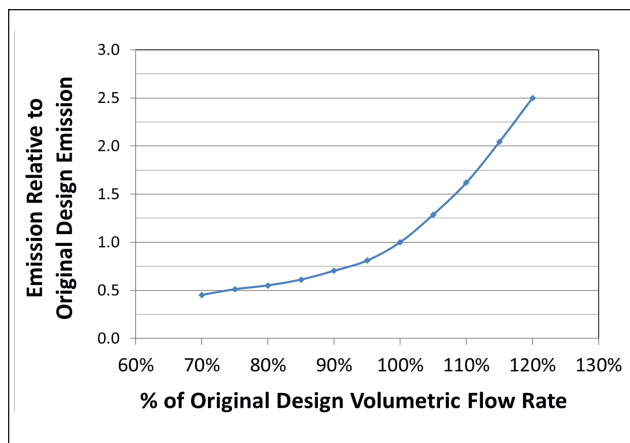
EFFECT OF INCREASING BOILER FIRING RATE

It is not uncommon for boilers to be upgraded during their lifetime in order to increase throughput to accommodate larger production capacities. Generally, this leads to a proportional increase in flue gas exhaust flow rate as shown in **Fig. 1**. Depending on the combustion properties, the resulting dust loading may also be affected.

When designing a new ESP, the flue gas volumetric flow rate is considered to establish the required internal collecting surface area. For all modern high efficiency ESPs, the required flue gas velocity is <4 ft/s. Most ESPs on existing recovery boilers were sized for the original boiler capacity and designed to achieve a lower performance efficiency than required to meet today's emission requirements. In addition, older ESPs were commonly designed with gas velocities ~ 4 ft/s, which was appropriate to achieve the removal efficiencies required at the time. The increase in gas volumetric flow rate associated with boiler upgrades presents a two-fold problem for existing units sized for the original boiler capacity:

- 1) The removal efficiency is decreased, as there is a higher gas flow being treated (i.e., the denominator Q is increased in the exponent term in the Deutsch-Anderson equation, leading to a lower removal efficiency).
- 2) The gas velocity is increased proportionally to the flue gas flow rate, resulting in a shorter treatment time and more particle re-entrainment (this decreases the average particle migration velocity, w_p , in the Deutsch-Anderson equation, leading to a lower removal efficiency).

The resultant effect of increasing flue gas volumetric flow rate on emissions is enormous. An increase of 10% in the flue gas flow can increase emissions by more than 50%, while an increase of 15% in the flue gas flow can double the emissions. A material balance for a typical recovery boiler as described in *Kraft Recovery Boilers* (3rd edition)



2. Effect of flue gas volumetric flow rate on ESP particulate emissions.

[5] was performed as a part of this study, and the effects of varying boiler load on flue gas volume and PM emissions are shown in **Fig. 1** and **Fig. 2**, respectively. Note that the following assumptions were made in performing the calculations in these figures:

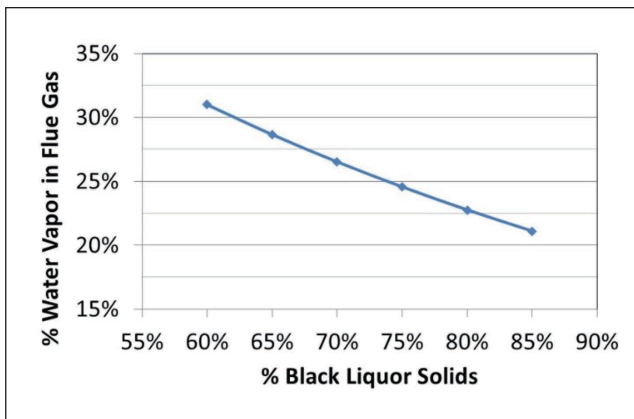
- Black liquor solids (as-fired): 70%
- Flue gas temperature at ESP inlet: 320°F (160°C)
- Flue gas pressure at ESP inlet: 5 in. H₂O (1.25 kPa)
- Total excess air: 15% of stoichiometric
- ESP original design specific collecting area (SCA): 265 ft²/1000 actual cubic ft/min (acfm)

EFFECT OF INCREASING BLACK LIQUOR SOLIDS

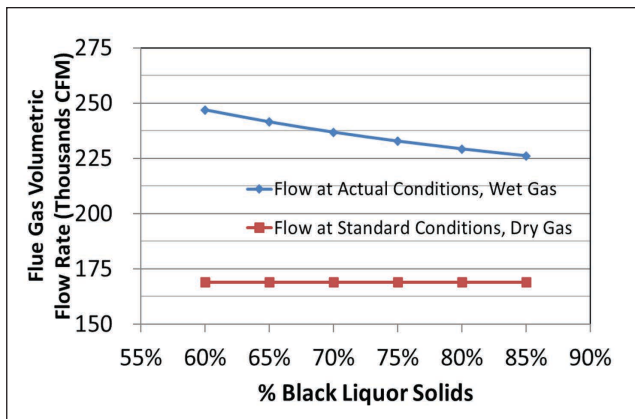
A recent trend of mills has been to increase the concentration of BLS being fired to achieve better thermal efficiency and a more stable char bed [6]. The effect of increasing BLS on ESP efficiency has not been studied extensively. From a mass balance on the recovery boiler, it can be deduced that an increase in liquor solids (for a given solids firing rate) would lead to the same flue gas composition and flow rate on a dry basis but would lead to a decrease in the moisture content, resulting in a lower actual flue gas flow rate. This decrease in the actual flue gas flow rate is attributed to the decrease of moisture in the flue gas stream. Modeling the effects of varying BLS on flue gas moisture content and volumetric flow rate is straightforward, and the results are presented in **Fig. 3** and **Fig. 4**, respectively. Please note that the following assumptions were made in performing the calculations in these figures:

- Flue gas temperature at ESP inlet: 320°F (160°C)
- Flue gas gauge pressure at ESP inlet: 5 in. H₂O (1.25 kPa)
- Total excess air: 15% of stoichiometric
- Standard reference temperature: 68°F (20°C)
- Standard reference pressure: 1 atm (101.325 kPa)

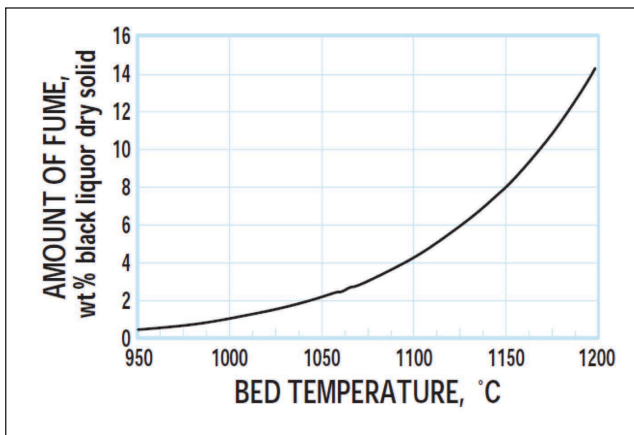
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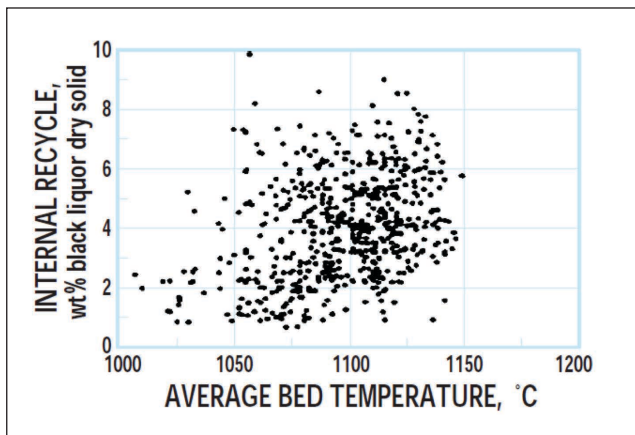
3. Effect of BLS concentration on flue gas moisture content.



4. Effect of BLS concentration on flue gas volumetric flow rate.



5. Predicted effect of bed temperature on amount of dust. Courtesy of: A. Tavares et al. [7].



6. Measured effect of bed temperature on amount of dust. Courtesy of: A. Tavares et al. [7].

However, it is more difficult to model the effects of varying BLS on dust loading, particle size, and particle composition. These three parameters are a function of temperature, black liquor composition, and a myriad of other dynamic parameters that vary from boiler to boiler. From previous works, it can be concluded that increasing BLS inevitably increases the char bed temperature, which in turn results in a higher dust loading and higher carbonate content in the fume, as shown in **Fig. 5** and **Fig. 6**, respectively [7]. The amount of fume generated and the amount of internal recycle are representative of the amount of dust going to the ESP. It can be seen that the actual amount of dust as a function of the bed temperature is difficult to predict, but there is an evident trend that a higher bed temperature leads to an exponentially higher amount of dust leaving the boiler.

The individual effects of modifying BLS content on various ESP operating parameters are summarized in **Table II**. The effect of these changes on ESP particulate emissions are also summarized. As previously mentioned, the parameters that have the highest impact on ESP emissions are flue gas volumetric flow rate and dust loading. However, as they have opposite effects on performance (and as there

are other factors that affect performance that are also affected by varying BLS), it is difficult to determine the net result of varying black liquor solids content on ESP efficiency. Case-by-case modeling and analysis are required to establish the collective effect of all mentioned parameters on ESP operation and particulate emissions for each individual scenario.

Whether the reason is an increased boiler flue gas volumetric flow rate, higher dust loading, more stringent emission regulations, or a deteriorating ESP, many mills are faced with the issue of trying to maintain compliance with particulate matter emissions with their existing equipment. The following section of this paper discusses strategies for maintaining and improving the efficiency of existing ESPs.

STRATEGIES AND RECOMMENDATIONS FOR IMPROVING RECOVERY BOILER ESP EMISSIONS

Boiler operation optimization

The first step toward improved ESP operation is optimizing boiler operation. The following is a list of boiler operational modifications that can improve ESP performance [5]:

Parameter	Effect of Increasing BLS on Given Parameter	Most Likely Effect of Parameter Change on ESP Particulate Emissions
Flue gas volumetric flow rate	Decrease	Decrease
Dust loading	Increase	Increase
Moisture content	Decrease	Increase
Resistivity (due to change in moisture content)	Increase	Increase
Particle size	Decrease	Increase

II. Effects of increasing black liquor solids (BLS) on ESP operating parameters and emissions.

- Reduce flue gas volumetric flow rate by reducing excess O₂ with improved gas mixing. The downside of this is that a lower amount of excess air may increase other harmful airborne emissions such as total reduced sulfur (TRS) and carbon monoxide (CO). Flue gas volumetric flow rate can also be reduced by minimizing air ingress into the system through ducting, dampers, etc.
- Optimize the liquor solids content such that the flue gas volumetric flow rate is decreased without a substantial increase in the particulate loading. As discussed previously, the combustion characteristics will vary from boiler to boiler, and there is no straightforward answer on the optimum solids content for minimizing ESP emissions.

Precipitator maintenance

Maximizing the performance of ESPs can be achieved with sound service, maintenance, and operational procedures. The following list is a summary of the main maintenance items that should be addressed in each outage:

- Have a good record keeping program. Log operating parameters such as flows, temperatures, loads, etc., as well as precipitator parameters such as current, voltage, and spark readings.
- Keep a good inspection and maintenance log. Monitor the behavior of the ESP over time and identify recurring issues. This may be a good diagnostic tool in identifying whether issues are process-related, mechanical, or electrical.
- Ensure that discharge and collecting electrodes are being cleaned properly. This includes inspecting all gas passages for irregular or biased dust buildups. Optimizing precipitator rapping sequences and frequencies to avoid such buildups can easily improve performance.
- Ensure that ESP internals are well aligned. Electrode misalignment is the most common reason for reduced power readings and deteriorated performance. Well-aligned internals will allow for maximum efficiency and reliability.
- Make sure that gas flow is optimized in order to

achieve a good velocity profile across the face of the precipitator. This will maximize particulate collection and minimize risk of undesired buildup at the base of the precipitator inlet perforated plate, at turning vanes, or within gas passages.

Precipitator modifications

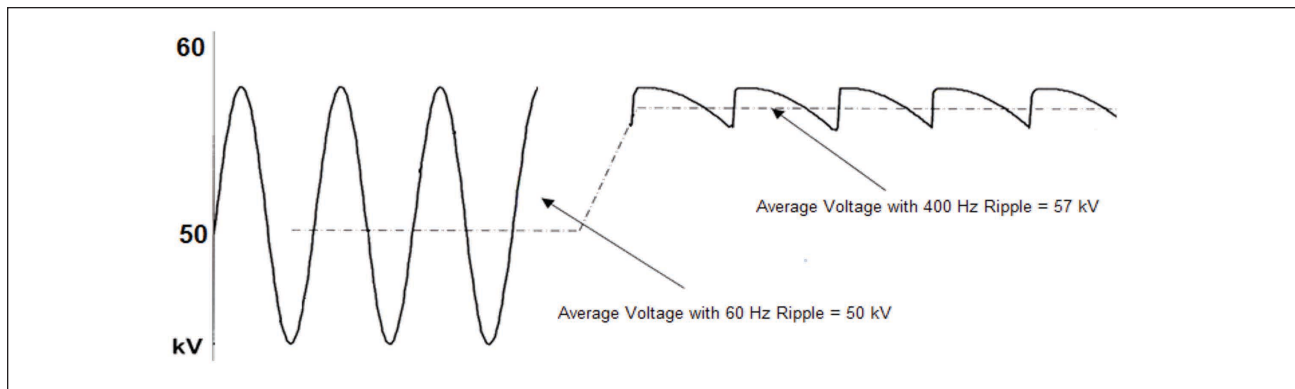
In addition to the regular maintenance items listed in the previous section, ESP modifications are sometimes necessary to achieve required removal efficiencies. Possible modifications include: low capital cost improvements that can be performed online and lead to marginal increases in performance; in-kind replacements of deteriorated components; and even more extensive modifications requiring longer outages that increase collecting area and lead to an appreciable reduction in emissions. The following is a brief list of possible precipitator modifications that may be implemented in order to increase removal efficiency.

Power supply upgrades

ESP power supplies provide the required DC high voltage to ionize flue gas and charge dust, which allows for it to be collected on collecting plates. The higher the average voltage in the ESP, the higher the effective migration velocity. Power supply controllers regulate ESP secondary voltages in response to process conditions that cause sparking and arcing. Because the voltage waveform is not a true DC (a small voltage ripple is inevitable with any power supply and controller), the function of the power supply controller is to minimize this ripple and maximize the average voltage.

Technological improvements in power supply controllers, such as the development of reliable insulated gate bipolar transistors (IGBTs), have allowed for an increase in the frequency (400 Hz or more) of the voltage ripple and a decrease in the amplitude of the voltage waveform over conventional 60 Hz transformers (**Fig. 7**). This results in a higher average voltage to the precipitator and improved collection efficiency. Power supply controls upgrades can be performed by retrofitting IGBTs on existing transformer rectifier sets at fairly low cost and without any process downtime.

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7. ESP voltage ripple with 60 Hz vs. 400 Hz power supplies [8].

Gas flow modifications

As previously discussed, gas flow distribution is extremely important within an ESP. Flow distribution can change due to failed or poorly designed flow distribution devices, like perforated plates or turning vanes. This can cause dust buildup in areas of the precipitator, deteriorating local electrical performance, plugging sections of the unit, and increasing dust re-entrainment. With the use of computational fluid dynamic modeling, gas flow can be optimized within ESPs in order to address present operating conditions and indicate the required modifications to flow distribution media. Such modeling efforts and modifications can improve performance to approach the maximum theoretical ESP removal efficiency; however, the maximum efficiency is still limited by the existing ESP collecting area. Further improvements can only be gained by modifying the internal plate and electrode arrangement to achieve a higher total collecting area.

Internal plate/electrode modifications

Precipitator performance can be improved by replacing existing internals. Novel electrode designs, such as rigid discharge electrodes, provide superior reliability and electrical characteristics over wire electrodes and older rigid electrode designs. However, the most effective way of increas-

ing ESP performance is by increasing total collecting area.

For most recovery boiler precipitators, an increase in precipitator collecting area by 25% can typically reduce emissions by up to 50%. The relationship between increasing collecting area and particulate emissions is shown **Fig. 8**. Please note that the following assumptions were made in performing the calculations in this figure:

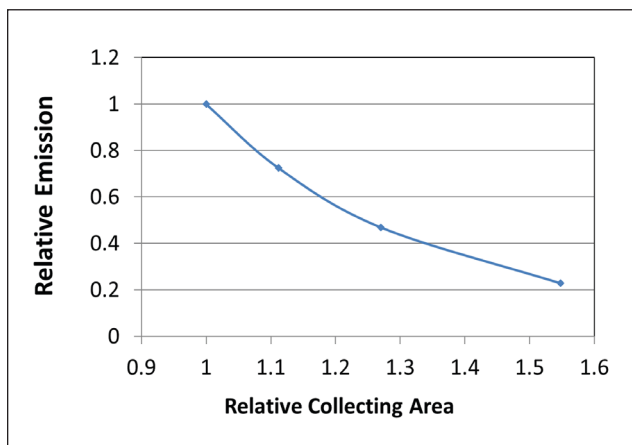
- ESP original design specific collecting area (SCA): 265 ft²/1000 acfm
- ESP original design velocity: < 4 fps

Several common ways of increasing collecting area are:

- Increasing the total collecting length by adding rows of collecting plates in the direction of gas flow (“adding fields”) or adding a new ESP as a secondary collector.
- Increasing the number of gas passages by adding width to an existing ESP chamber or adding a new chamber in parallel.
- Increasing the height of collecting plates, while keeping the same number of fields and gas passages.

Although increasing collecting area is an extremely effective way of reducing emissions, the main challenges of the described solutions are the high capital cost of implementation and space limitations. With this in mind, most mills rely on more cost-effective solutions described previously to remain within emission compliance.

However, an effective way of increasing the collecting area of European style ESPs with internal tumbling hammer rappers has been successfully implemented numerous times by several North American OEMs over the years. This method entails removing existing walkways and internal tumbling hammer rappers and replacing them with top rapped systems located outside of the precipitator casing. The additional space created after removing internal rapping systems allows for more plates and electrodes to be installed in the existing precipitator casing, increasing the effective collecting area by up to 25% while keeping the same equipment footprint. The biggest advantage of this modification is the ability to reuse ex-



8. Relative collecting area vs. relative particulate emissions.

isting precipitator structural steel, casing, and ash removal systems, saving appreciable material and labor costs. This strategy may be worth careful consideration for facilities that have the opportunity to make such modifications on their ESPs and require performance improvements to meet emission criteria.

CONCLUSION

The performance of an electrostatic precipitator was modeled, and a sensitivity analysis was performed to investigate the effects of ESP operating conditions (such as flue gas flow rate and inlet dust loading) on resulting PM emissions. The sensitivity analysis was coupled with a mass balance on a recovery boiler to study the relationship between boiler operating parameters on ESP operating parameters and to provide insight on the indirect effects of parameters such as black liquor solids content and liquor firing rate on ESP emissions.

The analysis provides a quantifiable relationship between boiler firing rate and ESP emissions. This relationship shows a remarkable (exponential) relationship between ESP particulate emissions as a function of boiler firing rate. The analysis also reveals the complexity of quantifying the effects of liquor solids content on ESP performance, as liquor solids content affects flue gas volumetric flow rate, inlet dust loading, moisture content, and particle size, all of which have effects on the efficiency of the electrostatic precipitator. Further work, including a field study, is required in order to establish a quantitative relationship between ESP performance and liquor solids firing.

ABOUT THE AUTHORS

Lots of work has been done on ESP performance in the past, but mostly on coal-fired utility applications. I would like to focus more efforts on improving the performance of ESPs for recovery boiler applications through research and data collection from facilities. Improving ESP performance by fine tuning boiler operation is a more effective method than costly equipment rebuilds or upgrades.

The focus of previous research (my own and that of others) was based on laboratory experiments. I would like to implement learnings from previous work in the field and to focus future efforts on measuring and validating the hypotheses that have resulted from laboratory experiments. Ultimately, the goal is to come up with a way to improve ESP operation as effectively as possible.

The most difficult part of this work was finding a way to analyze the effect of multiple parameters (i.e., ESP operating conditions) as a result of changes in one parameter (either firing rate or liquor solids) on the boiler. I found that the effect of some individual parameters had a much more pronounced effect

than originally thought. Other parameters did not have as big of an impact.

The effect of volume was the most surprising. Although the effect of volume on ESP operation is well known, performing a sensitivity analysis to investigate the effects of firing rate on volume, and in turn the effect on ESP efficiency, revealed a surprising increase in expected emissions.

Especially for mills that are load limited due to their ESP's performance, this work may offer possibilities for obtaining much faster and more cost-effective ways of achieving emission compliance.

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Finally, practical cost-effective approaches to improving ESP performance are offered. These include items related to optimization of boiler operation, ESP maintenance, and ESP modifications. In most instances, a combination of these factors will allow a facility to meet its recovery boiler emission requirements using its existing electrostatic precipitator, without sacrificing production capacity. **TJ**

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