Project Title: **OPTIMIZING ELECTROHYDRODYNAMIC MASS TRANSFER AND MERCURY CAPTURE WITHIN ESPS**

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**ABSTRACT**

This research project fundamentally explores the potential for powdered mercury sorbents to collect preferentially on the discharge electrodes of electrostatic precipitators (ESPs), and the resulting impact on mercury capture within ESPs. First, a parametric series of lab-scale tests assess the collection behavior of various fly ashes and mercury sorbents within an ESP. Second, a separate wire-plate ESP provides the basis for evaluating the electrohydrodynamically enhanced mass transfer that would occur between the mercury-laden flue gas and the mass of mercury sorbent collected on the wire discharge electrodes. Planar laser-induced fluorescence (PLIF) images of the flows entering, exiting, and within the wire-plate ESP are made possible by seeding the air flow with acetone vapor. Activated carbon-impregnated cloth wrapped around the wire discharge electrodes provides the adsorptive surface, simulating an accumulated dust cake enriched in powdered mercury sorbent. By comparing PLIF images under different conditions, the rate of mass transfer to such sorbent-covered wire discharge electrodes can be measured as a function of thickness of the sorbent layer and strength of the electrohydrodynamic effects, providing the basis for developing an appropriately modified convective mass transfer correlation that adequately represents this secondary mercury capture mechanism within ESPs.
EXECUTIVE SUMMARY

Mercury emissions control from coal-fired power plants is growing in urgency at both the state and federal levels. The challenge is particularly daunting for mercury because there remain important unknowns and substantial variability in how mercury is transformed, captured or emitted as a result of coal combustion. This investigation addresses a key uncertainty among these, specifically, it seeks to elucidate additional, previously unidentified mechanisms by which mercury is removed from the flue gas within an electrostatic precipitator. The benefit to Illinois coal stems from the opportunity to improve fundamental understanding and advance analytical tools relating to the performance of mercury emissions controls, which enables higher performing and more cost-efficient mercury emissions control technologies, thereby encouraging coal further coal usage.

The investigation uses two separate lab-scale electrostatic precipitators (ESPs) to study differences in particle collection as a function of particle composition (i.e., fly ash versus powdered mercury sorbents) and ESP operating conditions. In addition, one of the lab-scale ESPs is constructed to be optically accessible, thereby allowing the acquisition of color-enhanced images within the ESP showing spatially resolved concentrations of a trace gas species. Together, results from these separate experiments provide needed insight into previously unidentified mechanisms of mercury capture within ESPs.

The results of the mass balance measurements reveal that, powdered activated carbon preferentially collects on the discharge electrode of an ESP, particularly at low electric field strengths. At low electric field strengths, fly ashes of varying carbon content collected exclusively on the discharge electrodes; however, with increasing electric field strength, fly ash begins to collect on the discharge electrode. The addition of PAC to fly ash produces an admixture that yields results similar to that of pure, untreated PAC, even at very low (1%) PAC concentrations that are reflective of values expected during the application of full-scale sorbent injection.
OBJECTIVES

The objective of this project is to evaluate and differentiate the behaviors of different mercury sorbents with respect to their preferential collection on the discharge electrodes of an ESP and degree to which such preferential collection leads to a secondary mechanism for mercury capture within ESPs. The investigation consists of three tasks:

Task 1: Parametric Evaluation of Differential Electrostatic Precipitation Behavior of Mercury Sorbents. Involves processing selected mercury sorbents (untreated, chemically treated, and non-carbon) through a cylindrical lab-scale ESP, and conducting a mass balance to identify the percentage of each sample collected on the ESP discharge electrode.

Task 2: Experimental Investigation of Trace Gas Adsorption by Sorbent-Covered Discharge Electrodes Subjected to Ionic Wind Effects within ESPs. Involves planar laser-induced fluorescent (PLIF) imaging of acetone-doped air flows into, through, and out of an optically accessible, lab-scale, wire-plate ESP. The wire discharge electrodes are encircled by adsorbent material that adsorbs acetone vapor. Differences in fluorescent intensity observed at different experimental conditions indicate different rates of mass transfer to the adsorbent material. In particular, the magnitude of the voltage applied to the wire discharge electrodes will induce electrohydrodynamically driven fluid flow patterns that will alter the convective mass transfer between the acetone-doped air flow and the cylindrical adsorbent material surrounding the discharge electrodes. Because acetone fluorescence intensity varies proportionately with acetone concentration, as the voltage applied to the discharge electrodes changes, its effects on the fluid flow pattern around and mass transfer to the adsorbent material will be evident in the observed acetone fluorescence intensity at the ESP outlet.

Task 3: Development of Mass Transfer Model Including Electrohydrodynamic Effects. Using the results of Task 2, conventional Nusselt and Sherwood number correlations for fluid flows over circular cylinders will be modified to incorporate the effect of the electric field and resulting electrohydrodynamically induced perturbations.

INTRODUCTION AND BACKGROUND

The U.S. EPA is expected to issue new rules pertaining to emissions of mercury, as well as other hazardous air pollutants, from coal-fired power plants. In anticipation of the new regulations and their expected performance requirements, mercury emissions control technologies have been under development for more than a decade. A leading mercury emissions control technology is the injection of powdered mercury sorbents upstream of the particulate control device. The injected sorbents disperse within the flue gas and collectively provide a large adsorbent surface for capturing gaseous elemental and oxidized forms of mercury. Sorbent injection, in the various forms in which it has been tested, is the most mature of the mercury emissions control technologies; still, several
physical phenomena remain poorly understood, preventing a optimization of the sorbent injection process.

One particular area of uncertainty is the process of mercury capture within electrostatic precipitators (ESPs). Most full-scale demonstrations of ACI have been conducted upstream of an ESP. More than two-thirds of U.S. coal-fired power plants (CFPPs) operate ESPs (1), and their prevalence is even greater in other dominant coal-powered economies of China and India: nearly 90% of power plants in China (2) and greater than 95% in India (3). However, the actual process by which mercury is captured within an ESP by injected powdered mercury sorbents remains unclear. Previous analyses have focused on mercury capture by the accumulated dust cake on the ESP collection electrodes (4) and in-flight capture while the powdered sorbent remains in suspension (5) (6) (7). Figure 1 shows evidence of an additional capture mechanism, separate from these, that is evident only once sorbent injection ceases. Figure 1 shows traces of sorbent injection rate (red) and the measured mercury concentrations at the ESP inlet and outlet during a full-scale test of activated carbon injection (ACI). Results show mercury concentrations at the ESP outlet that drop immediately when ACI commences, but that exhibit a slow recovery when ACI ceases. The mechanism for this long recovery after ACI shutdown, which does not occur universally, indicates a mechanism of mercury capture within the ESP that does not occur in-flight because of the long time scales of the phenomenon (hours) as compared to the characteristic fluid flow time through an ESP (seconds). Although it has been widely hypothesized that this slow recovery reflects mercury capture by the accumulated dust cake on the ESP collection electrodes, there are several reasons why this is not likely to be the case, our prior analysis (4) of mass transfer to ESP plate electrodes notwithstanding. The sorbent represents only a fraction of a percent of fly ash mass on the collection electrode. With such deep dilution of the powdered sorbent in the dust cake, its surface can only act as a weak adsorber of mercury.

![Figure 1: Time-resolved traces of sorbent injection rate, ESP inlet mercury concentration, and ESP outlet mercury concentration, during full-scale sorbent injection testing at We Energies Pleasant Prairie Power Plant (8).](image)

Further, after ACI shutoff, even this small amount of sorbent would be masked from the flue gas by a growing layer of fly ash that continues to collect on the collection electrode.
The present project follows the hypothesis that powdered mercury sorbents, particularly powdered activated carbon, may behave differently during electrostatic precipitation than fly ash, leading to an enriched concentration of the powdered mercury sorbent in the accumulated dust cake on the discharge electrode of an ESP.

EXPERIMENTAL PROCEDURES

The present investigation fundamentally explores the phenomena associated with the collection behavior of various sorbents during electrostatic precipitation, and the potential for substantial mercury capture from the flue gas by powdered sorbents retained on the wire discharge electrode. The expectation of substantial mass transfer of mercury from the flue gas to the sorbent-covered discharge electrodes is based on 1) knowledge of the superiority of the cylinder-in-cross flow configuration in the context of heat transfer, 2) the supposition of the validity of the heat-mass transfer analogy, and 3) awareness of the importance of fluid flow characteristics to heat and mass transfer and the potential for strong perturbation of fluid flows in the presence of strong electric fields such as those found within ESPs. Toward this end, the investigation consists of two experimental tasks, a first task to assess the electrostatic precipitation behavior of various powdered mercury sorbents under different conditions within a cylindrical lab-scale ESP, and a second task that uses planar laser-induced fluorescence (PLIF) imaging to evaluate the mass transfer and adsorption of a trace gas species by adsorbent material affixed to the discharge electrode of a lab-scale wire-plate ESP.

The first task involved suspending a variety of powdered mercury sorbents, as well as mixtures of sorbents and various fly ashes, in an air stream that then passes through and is treated by a cylindrical lab-scale ESP. For each powder mixture and under each experimental condition, a mass balance for the ESP was calculated by collecting and measuring the separate masses collected on the discharge electrode, the collection electrode, and the mass which passed through the ESP and went uncollected. The cylindrical lab-scale ESP is a vertically oriented 90 cm long, 12.5 cm diameter cylinder whose inner surfaces are covered with brass plating to comprise the collection electrode. A 1 mm diameter wire aligned along the cylinder axis serves as its discharge electrode. A DC power supply together with one of two separate power amplifiers (Trek Inc.) provides up to -40 kV and either 4 W or 30 W to the discharge electrode. The brass collection electrode plates are grounded. Powdered mercury sorbents of various forms (untreated, bromine impregnated, concrete-friendly non-carbon) and fly ashes generated from different rank coals were tested, both independently and as fly ash-sorbent mixtures. Experimental results from this task take the form of comparisons of the mass balances for different powdered mercury sorbents, fly ashes, and fly ash-sorbent mixtures when precipitated under different ESP voltages and power settings.

The second task used a second ESP of wire-plate design, constructed to provide optical access to the flow inside, allowing PLIF imaging to reveal changes in the concentration of the gas-phase acetone tracer as a result of mass transfer to and adsorption by the adsorptive material affixed to the wire discharge electrodes. In PLIF imaging of fluid
flows, acetone vapor serves as a tracer in the gas stream because it fluoresces when excited by UV radiation within a specific wavelength band. In the present experimental setup, a frequency-quadrupled Nd:YAG pulsed laser (Spectra Physics Lab 130), provides 50 mJ, 4 ns pulses at a wavelength of 256 nm and a repetition rate of 10 Hz. A set of lenses converts the UV beam into a planar sheet, which induces fluorescence of acetone vapor in the flow along its path of propagation. The resulting acetone fluorescence (\( \lambda = 350\text{-}550 \text{ nm} \)) is captured with an electron-magnifying CCD camera and its intensity at any point is proportional to the acetone molar concentration at that point. In this way, color-enhanced images taken of the fluorescence in the flow reveal spatially resolved acetone concentration, gradients of which are used to infer rates of mass transfer and adsorption by the adsorptive material affixed to the wire discharge electrodes of the ESP.

Figure 2: Schematic of planar laser-induced fluorescence (PLIF) imaging setup.
RESULTS AND DISCUSSION

TASK 1: Parametric Evaluation of Differential Electrostatic Precipitation Behavior of Mercury Sorbents

Figure 3 compares the measured mass balances after electrostatic precipitation for pure untreated PAC (Norit DARCO), two fly ashes from different ranks of coal (Eastern bituminous, lignite) and having different carbon content (LOI; 20% and 8%), and a fourth data set representing a 1:1 mixture of fly ash and untreated PAC. It is clear that the behavior of the 1:1 mixture of fly ash and PAC is very similar to that of pure untreated PAC, namely, that the particulate matter (PM) collects preferentially on the discharge electrode. The observed collection efficiency of the 1:1 fly ash-PAC mixture on the discharge electrode (4.3%) is very similar to that measured for pure untreated PAC (4.6%). Both fly ashes collected exclusively on the collection electrode, however this behavior was later found to be a function of the applied electric field (see Figure 8). It is notable that the very high LOI of the E. bituminous ash (20%) did not result in behavior similar to that of untreated PAC at this electric field strength.

Research in powder handling has shown that the charging behavior of particles can be affected by the surface chemical composition (1). Figure 4 shows a sampling of results comparing the precipitation behaviors of two PACs, one untreated and one brominated, under electric fields of different polarity. Within experimental accuracy, the results suggest that bromine impregnation of PAC results in increased collection on the discharge electrode, regardless of

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**Figure 3:** Comparison of mass balances for a) pure untreated PAC, b) E. Bituminous FA (LOI = 20%), c) lignite FA (LOI = 8%), and d) 1:1 mixture of FA and untreated PAC. $E_{\text{field}} = +5$ kV.

**Figure 4:** Comparison of percent of total sorbent mass collected on the discharge electrode of a lab-scale ESP for two different sorbents at applied voltages of +25 kV and -25 kV.
the polarity of the applied electric field. This result is relevant because the existing ESP population has a mixture of negative and positive polarity electric fields.

Figure 5 shows how the collection of particulate matter (PM) on the discharge electrode varies with the percentage of untreated PAC mixed with fly ash (Eastern bituminous). Clearly evident in the results are both a local maximum between 20 and 50% PAC and an apparent y-intercept that is non-zero; this indicates that at low PAC concentrations, the percentage of PM collected on the discharge electrode exceeds the percentage of PAC in the feedstock. Thus, the PM collected on the discharge electrode must consist of a mixture of PAC and fly ash that is enriched in PAC relative to the feedstock. This bolsters the likelihood that collected PM on the discharge electrodes of a wire-plate ESP could contribute non-negligibly to total Hg capture measured across an ESP. For the purposes of comparison, typical sorbent injection rates for chemically impregnated sorbents are 1-6 lb/MMacf, approximately 1% of fly ash loadings of 1-10 g/m³.

Figure 6 extends the results of Figure 5 to multiple mercury sorbents. When mixed in concentrations of 1% mercury sorbent to 99% fly ash (E. Bituminous), Figure 6 shows all sorbents appear to collect on the discharge electrode, with untreated PAC showing the least propensity and brominated PAC showing the greatest. And in-line with the results in Figure 5, all sorbents showed a greater percentage of PM collected on the discharge electrode than represented the concentration of sorbent in the feedstock. This suggests that the presence of small (1%) concentrations of mercury sorbents results in both sorbent and fly ash collecting on the discharge electrodes. Particle size analysis showed that the PM collected from the

Figure 5: Collected PM on the discharge electrode for fly ash (bituminous)-untreated PAC admixtures as a function of percent PAC. ESP electrification of -25 kV.

Figure 6: Collected PM on the discharge electrode for bituminous fly ash-sorbent admixtures. All compositions contain 1% mercury sorbent. ESP electrification of -25 kV.
discharge electrode has a particle size distribution that closely matches that of the PAC, suggesting that the presence of the PAC has the strongest effect on fly ash particles of similar size, leading to collection of both fine fly ash and fine PAC on the discharge electrode.

Figure 7 compares the percent PM collection on the discharge and collection electrodes with increasing total PM processed through the ESP. In all cases, the PM consists of 1% concentration of various mercury sorbents. For the discharge electrode, there is no discernable trend as the total PM mass processed by the ESP increases, or among the different mercury sorbents. However, for the collection electrode, it is clear that the substantial differences between the different mercury sorbents grow less pronounced as the total mass of PM processed by the ESP increases. This suggests that the increasing electrical resistance of the growing dust cake of fly ash and mercury sorbent on the discharge electrode tends to overwhelm the differences between the sorbents’ collection behaviors on the collection electrode. However, their collection on the discharge electrode appears to be unaffected by the increasing dust cake.

Figure 8 shows the effect of ESP power and voltage on the...
precipitation behavior of a 1% concentration of untreated PAC mixed with E. Bituminous fly ash. The results show that as power and voltage increase, the overall collection efficiency of the ESP increases (the “CE” fraction increases and the “out” fraction decreases), with the fraction collected on the discharge electrode at first increasing and then decreasing with power and applied voltage. Similar results were obtained for the chemically impregnated and non-carbon sorbents, as well as with fly ashes derived from other ranks of coal.

Figure 9 confirms the enrichment of the PM collected on the discharge electrode through measurements of LOI. For three samples of the PM collected on the discharge electrode of the ESP, LOI measurements indicate that two exhibited PAC enrichment by 25% and 50% above the 1% concentration in the feedstock. The LOI of the third sample indicated PAC content equivalent to that of the feedstock. This provides further evidence that electrostatic precipitation leads to the development of a dust cake on the discharge electrodes of an ESP that is enriched in PAC during ACI for mercury emissions control. It is likely that the degree of enrichment is dependent on the applied voltage and power, requiring additional studies of a similar nature conducted at voltages and power settings more typical of full-scale ESPs.
TASK 2: Experimental Investigation of Trace Gas Adsorption by Sorbent-Covered Discharge Electrodes Subjected to Ionic Wind Effects within ESPs

Figure 10: PLIF images obtained at the outlet of the wire-plate ESP: Left: upper elevation (avg. intensity = 0.1049); Right: mid-plane elevation (avg. intensity = 0.0116). $E_{\text{field}} = 0$, no adsorption.

Figure 10 compares color-enhanced PLIF images at the outlet of the wire-plate ESP: on the left, the image is taken at the upper elevation of the experimental apparatus while at the right the image is taken at the mid-plane of the apparatus. Both images represent exclusively fluid flow, i.e., no electric field is applied and no adsorptive surface is present inside the ESP. The images in Figure 10 are useful for assessing the degree of asymmetry in the baseline flow. Greater acetone concentrations are evident at the higher elevation, which is counterintuitive given the greater density of acetone vapor as compared to air, and the substantial cooling that occurs in the gas stream as liquid acetone is vaporized to produce the acetone-seeded air needed for PLIF imaging.

Figure 11 shows analogous images to those in Figure 10, with the key difference being the application of a variable $E_{\text{field}}$. As the applied voltage (for a fixed 4 W power) increases, the average PLIF intensity also increases, suggesting an alteration of the fluid flow pattern in response to the increasing electric field.

Figure 11: PLIF images obtained at the outlet of the wire-plate ESP for 15, 17, and 20 kV applied $E_{\text{field}}$. No adsorption.
**TASK 3: Development of Mass Transfer Model Including Electrohydrodynamic Effects**

Figure 12 compares values of the mean convective heat (mass) transfer coefficient over a cylinder ($\overline{h}_{cyl}$) and a flat plate ($\overline{h}_{plate}$), both exposed to the same fluid flow. To facilitate the comparison over a range of Reynolds numbers, the cylinder and the flat plate maintain equivalent surface areas with increasing Reynolds number for a given fluid velocity (i.e., the length of the plate and the diameter of the cylinder are related by $L_{plate} = \pi D_{cyl}$). The results in Figure 2 reflect commonly used Nusselt (Sherwood) number correlations for a flat plate ($\overline{Nu}_L = 0.644 Re_L^{1/2} Pr^{1/3}$) and a cylinder ($\overline{Nu}_L = [0.6664 Re_{x,c}^{1/2} + 0.037(Re_L^{4/5} - Re_{x,c}^{4/5})]Pr^{1/3}$) for mixed laminar and turbulent conditions\(^5\) and from Hilpert\(^9\), where $C$ and $m$ are functions of $Re_D$.

Figure 12 shows that, in the absence of electric field effects (so-called “corona wind” or “ionic wind”), the geometry of a cylinder in a cross-flow is much more effective than a flat plate for heat (mass) transfer between the fluid and the solid surface. Cylindrical forms outperform flat plates even as plate length $L$ and cylinder diameter $D$ increase (while maintaining equivalent surface areas, i.e., $L = \pi D$). Mean convective heat (mass) transfer coefficients for cylinders surpass those for flat plates by approximately a factor of 1.5 for shorter plates, and more than a factor of 2.5 for the longest plates and the highest gas velocities (3 and 5 m/s). The comparison of convective heat (mass) transfer coefficients in Figure 10 lends qualified support to the position that significant adsorption of mercury within an ESP is more likely to occur on cylindrical surfaces (e.g., sorbent-covered discharge electrode wires) than on planar surfaces (e.g., ash-covered collection electrodes). This inference must be qualified because a final correlation for mass transfer Sherwood number under conditions relevant to wire-plate ESPs has not yet been developed, due to ongoing, but as yet incomplete, experimental data collection in Task 2. A proper Sherwood number correlation for convective mass transfer under these conditions will require a full complement of experimental results over a wide range of experimental conditions. Without such data and correlation, a definitive statement cannot be made regarding the effect the electric field on the mass transfer to the collected mercury sorbent on discharge electrodes in wire-plate ESP configurations. Ohadi and co-
workers studied enhancements to heat transfer in response to a discharge corona. However, their configuration was a wire-in-tube type with heat transfer measurements made only along the tube surface. Thus, the results of Ohadi and co-workers cannot be used to infer enhancements to mass transfer to the wire electrodes in a wire-plate ESP.

CONCLUSIONS AND RECOMMENDATIONS

1. Small amounts of PAC enhance collection of fly ash (FA) on the discharge electrode of an ESP.
   - FA begins collecting on discharge electrode at higher electric field strengths (kV).
   - Non-carbon sorbents do not appear to exhibit this property.

2. Particulate matter (PM) collected on the discharge electrode is enriched in PAC and is finer as compared to the PM entrained in the flue gas.
   - Provides greater adsorption capacity for mercury than PM collected on collection electrodes, which contains more dilute concentrations of PAC.
   - Finer PM and higher PAC concentration on discharge electrode means higher rapping reentrainment into the flue gas.
   - Finer PM on discharge electrode means that after rapping, a greater percentage to remain in flue gas longer, be collected in the last fields of the ESP.

3. PAC collected on ESP discharge electrodes can capture Hg.
   - Flow over cylinders (i.e., PM-covered wire discharge electrodes) can have 2X or greater convective mass transfer coefficient as compared to flow over planar surfaces.
   - Greater PAC concentration in PM collected on discharge electrodes further enhances Hg capture as compared to planar surfaces of collection electrodes.
   - PM collected on discharge electrodes likely exposed for longer periods to flue gas due to less frequent rapping.
   - Affinity of PAC for discharge electrodes possibly means that rapping induces PAC to migrate to downstream discharge electrodes, resulting in a repeating cycle.

4. Need to evaluate:
   - Convective mass transfer in presence of ionic wind.
   - Electrical, adhesion characteristics of DE dust cake.
REFERENCES


DISCLAIMER STATEMENT

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