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How to Design Effective Mercury Capture Systems at Coal-Fired Power Plants

David Schowalter, PhD, ANSYS, Inc.

INTRODUCTION

Mercury emissions have become a concern in recent years, particularly in relation to fish contamination in fresh water in the eastern United States. Between 1990 and 1999, man-made mercury emissions in the US decreased by about 50%. Nearly all of the improvement, however, came through reductions in medical and municipal waste incinerator emissions. Mercury is an inherent element in coal, and the emissions from coal-fired power plants decreased by just 4.3% in the same time period. In order to address this situation, the EPA released the Clean Air Mercury Rule (CAMR)¹ in early 2005. CAMR establishes standards limiting mercury emissions from both new and existing coal-fired power plants. It also creates a market-based cap and trade program, and comes in two phases.

The additional SO₂ (sulfur dioxide) and NO_x (nitrous oxides) control equipment that will be required by the Clean Air Interstate Rule (CAIR), also released in 2005, will cause some reduction in mercury emissions. This is typically referred to as the “co-benefit” of SO₂ and NO_x reduction. The first phase mercury cap is 38 tons (as compared to the current emission level of 48 tons), and it is expected that this may be accomplished via CAIR co-benefits. The second CAMR phase is due in 2018 and entails a 15 ton cap. New coal-fired power plants (for construction starting after January 30, 2004) must meet new source performance standards, while also being subject to these caps. In its original form, the rule specifies that caps are distributed among the states, with each state deciding how to achieve the required reductions, including source control determination, and whether or not to join a trading program.

Some uncertainty remains, however, since the EPA reopened CAMR for public comment on October 21, 2005. Specifically, the agency is responding to complaints from some states and environmental groups, and is seeking further comment on the cap and trade program, as well as the decision not to regulate hazardous air emissions from utilities under Section 112 of the Clean Air Act that would have required the use of the “Maximum Achievable Control Technology” (MACT) to control mercury.

Whatever the outcome of the public comment, one thing is clear: mercury control regulation on coal-fired power plants is inevitable, and the utilities that are most prepared will avoid costly last minute solutions.

ACTIVATED CARBON INJECTION TECHNOLOGY

Most coal has between 50 and 300 micrograms of elemental mercury per kilogram. After the coal is combusted, some of this elemental mercury is oxidized as the flue gas cools in the convection pass of the boiler. The result is flue gas with trace amounts of gaseous elemental mercury, gaseous HgCl₂, and particulate mercury. The particulate mercury will be removed through the power plant’s particulate control system, but the gaseous components must be eliminated in another manner.

Proposed methods for capturing oxidized mercury in the flue gas of traditional coal-fired power plants include standard coal-fired power plant equipment, such as wet flue gas desulfurization (FGD) systems and spray dryers (traditionally used to remove SO₂), and wet electrostatic precipitators (ESP). It is the elemental form of mercury that is more challenging. Some methodologies exist to oxidize more of the mercury, such as using ultraviolet light and oxidizing agents, enabling more capture via the aforementioned methods. Activated Carbon Injection (ACI), however, has been the most widely studied and most common method of removing both elemental and oxidized mercury. It involves injection of pulverized carbon into the flue gas to adsorb gaseous elemental mercury upstream of the electrostatic precipitator (ESP) or fabric filter, which will in turn remove the carbon. The porous carbon structure is ideal for this adsorption process. The vapor phase mercury compounds migrate to the surface of the particles, followed by adsorption into the pores. Advantages of this approach are that installation requires no plant outages, capital equipment costs are generally under \$1 million, capture includes both elemental and oxidized mercury, and it is effective on both bituminous and subbituminous coals. Because of the necessity to replenish the activated carbon continually, however, the operating costs become a more important consideration than the capital costs.

Equipment installation is also not without its technical difficulties. Because the time-limiting step in this process is the diffusion of mercury in the flue gas to the solid particle, the particle distribution throughout the flue gas duct must be maximized. Additionally, a sufficient residence time must be achieved so that the diffusion process has time to take place. In some cases, the available space for a retrofitted system yields more than enough residence time for this process to complete. Other sites are more challenging, and the optimal location of injection points needs to be determined.

SIMULATING MERCURY CAPTURE

When there are space limitations in the installation of an ACI system, a trial and error approach to determine the injection locations and the required injection rate can be prohibitively expensive. A more cost-effective approach is to use virtual engineering to build a digital computer model of the duct and lances, then to simulate the motion of the flue gas, the activated carbon motion, and the subsequent adsorption of the mercury.

The Solution Process

There are two stages of analysis: generating a three-dimensional flow solution within the duct of interest and tracking activated carbon particles through the flue gas. The first stage involves three steps: 1) creating a three-dimensional computer model of the duct geometry, 2) generating a computational mesh, and 3) using a computational fluid dynamics (CFD) solver to render the 3-D flow field. After importing computer-aided design (CAD) files defining the duct, or creating this geometry from scratch using 3D geometry generation software, a mesh generation tool splits the flow volume into small cells, each of which will act as a control volume in the flow solver. Tools are currently available which provide a very high level of automation in this process.

For the third step, the flue gas material properties and boundary conditions are specified in the flow solver, and the computational work begins as an iterative process. Figure 1 illustrates the geometry of a retrofit duct between two ESP's in this process, with the final result showing flue gas pathlines through the duct. From this last image, it can be observed that there is a large recirculation zone in the top portion of the duct.

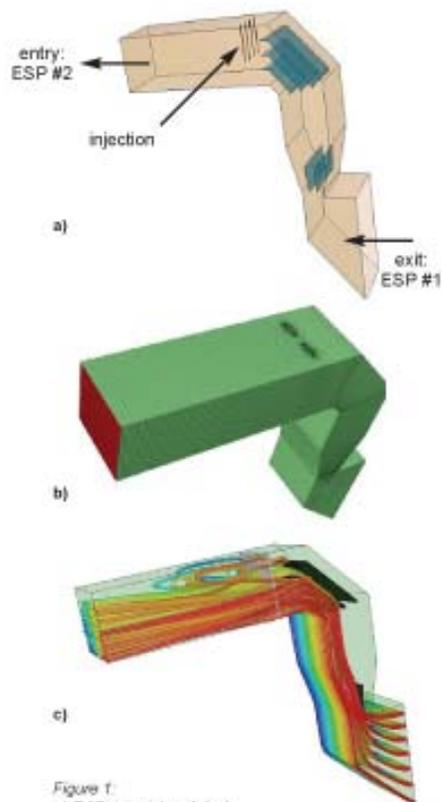
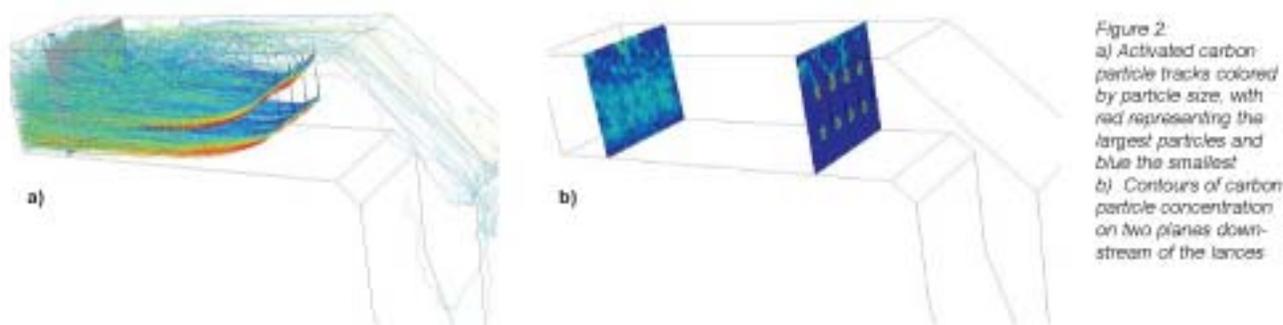


Figure 1:
a) CAD geometry of duct
b) Computational mesh
c) Flow field simulation showing gas flow pathlines

The second stage of analysis involves the simulation of activated carbon particle tracks within the flow domain. These tracks will depend upon particle properties, including material and size. The flow solver will use these properties, the coefficient of restitution at the walls, and the effect of the surrounding fluid to calculate the particle tracks. In some cases, a simple residence time calculation or a plot of carbon distribution may be sufficient. In other cases, it may be necessary to estimate the level of mercury capture three-dimensionally in the duct. In that case, it will also be necessary to incorporate mercury adsorption model.

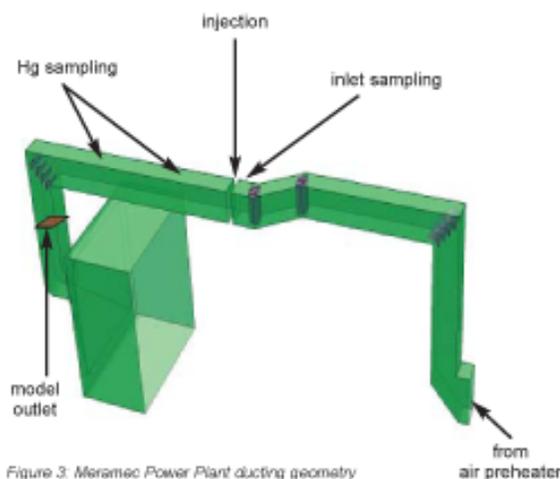
Figure 2 shows the final stage of the analysis, the activated carbon particle tracks along with particle concentration for the duct from Figure 1. The gray plane in 2 a) and the second downstream contour plane to the left in 2 b) represent the position at which mercury sampling takes place in the physical duct. Note that there is a poor velocity distribution in this duct, which causes a recirculation at the top, pulling some smaller particles upstream of the lance positions. This condition actually enhances residence time for these particles.



Determining Effective Mercury Capture

Fluent Inc. and the Department of Energy's (DOE) mercury control technology research, design and development program at the Office of Fossil Energy are developing a mercury capture model to estimate the adsorption of gaseous mercury onto the activated carbon particles throughout the particle's history. In fact, the example used in Figures 1 and 2 is ADA Environmental Solutions' injection system at Dominion Generation's Brayton Point Power Plant, one of the facilities coordinating with the DOE on a full-scale testing program. The detailed capture model helps engineers visualize bulk mercury capture within the flue gas, as well as local mercury concentrations.

Even without such a detailed model, however, much can be learned about coverage of the duct cross-section by activated carbon particles. Figure 3 shows a three-dimensional rendering of the duct downstream of the air preheater at Ameren UE's Meramec Power Plant, another of the full-scale testing facilities in the DOE's RD&D program. The chosen activated carbon injection location is shown in the figure, along with inlet and downstream sampling points. A computational model of this duct was constructed, ending at the plane labeled "Model Outlet." Particle paths are colored by residence time in Figure 4. Unlike the situation at Brayton Point, the particle tracks at Meramec are smooth and straight.



One method to determine the level of cross-duct coverage of the activated carbon particles is to display where the concentration of particles is greater than 10% of the mean concentration value. If the mixing of particles across the duct is poor, then a significant portion of the duct cross-section will be below this 10% cut-off. If there is sufficient mixing of the particles, then most of the duct cross-section will be above the cut-off. Figure 5 a) shows coverage of the duct cross-section 20 feet downstream of the bend, which is more than 100 feet from the injection lances. The red color indicates particle concentrations above 10% of the mean value. Because the particle tracks are so straight, the particles do not have a strong migration to the sides and corners of the duct. By contrast, Figure 5 b) shows the same plot for Brayton Point just 30 feet downstream of the injection lances, indicating a much higher level of coverage.

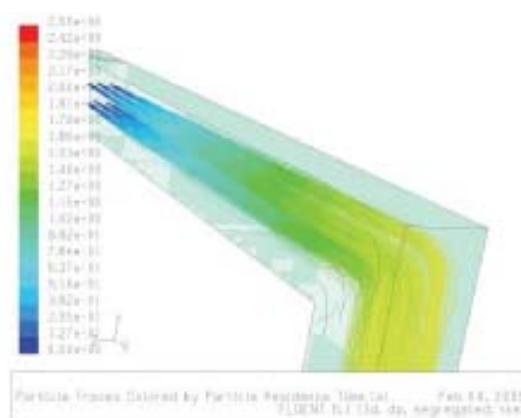


Figure 4: Activated carbon particle tracks at the Meramec plant colored by residence time

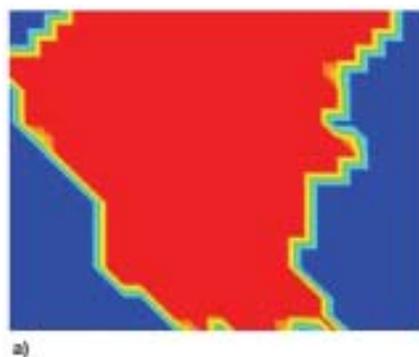
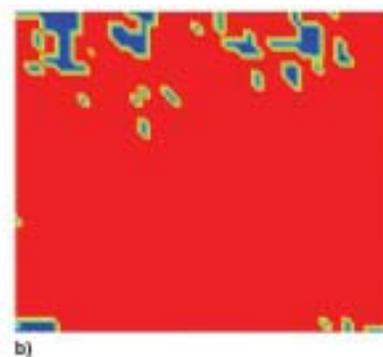


Figure 5: a) Carbon particle coverage 20 feet downstream of the bend in the duct at Meramec (more than 100 feet from the injection lances), with red indicating a particle concentration greater than 10% of the mean value, and blue being less than 10%
 b) Carbon particle coverage at the outlet of the Brayton Point Plant 30 feet downstream of the injection lances, at the outlet of the modeled domain



It is important to note that coverage and contact time both play a major role in mercury adsorption. It turns out that Meramec had a higher rate of mercury removal, largely because the duct is much longer, increasing the overall contact time between particles and flue gas, even though the carbon particle coverage was not as extensive. For this level of detail and comparison, it is necessary to include the mercury adsorption physics in the model. When comparing different injection scenarios for the same duct, however, the simple coverage calculation will indicate the optimal choice.

CONCLUSION

While the specifics of mercury control at US coal-fired power plants are still being determined, it is certain that limits or caps will be enacted, and that utilities need to strategize to determine the most cost-effective approach to capture flue gas mercury. Flow distribution is a key factor in the success of an activated carbon injection system. In searching for the optimal location of injection lances for maximum carbon coverage throughout the duct, computational flow modeling is a low-cost alternative to physical prototyping. For comparing performance for varying injection lance positions, it is sufficient to simulate particulate motion only. When the goal is to determine the mercury capture process and the three-dimensional mercury concentration within the duct, however, it is necessary to include a mercury adsorption sub-model.

1 Source: Web seminar presentation by Roman Kramarchuck, Office of Air and Radiation, USEPA, "Virtual Prototyping to Improve Power Plant Emissions," hosted by Fluent Inc., April 28, 2005.



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ANSYS, Inc.	Toll Free U.S.A./Canada:
Southpointe	1.866.267.9724
275 Technology Drive	Toll Free Mexico:
Canonsburg, PA 15317	001.866.267.9724
U.S.A.	Europe:
724.746.3304	44.870.010.4456
ansysinfo@ansys.com	eu.sales@ansys.com