Skewed Gas Flow Decreases Opacity From Kentucky Utilities E.W. Brown Station, Unit 1 Precipitator

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ABSTRACT
In 2003, Kentucky Utilities sought to reduce the opacity from their 110 MW coal fired Unit 1 generating plant at the E.W. Brown Station located in Burgin, KY. Kentucky Utilities selected Skewed Gas Flow Technology for the Unit 1 precipitator as the most cost effective alternative. Modifications to the gas flow distribution devices in the precipitator were designed using CFD computer modeling and were installed during the annual outage in November 2003. Gas flow testing was performed before and after the modifications, which verified that the desired Skewed Gas Flow profile was achieved. Operating data collected since startup confirms that the project achieved the predicted 30% reduction in opacity. This paper describes the process for improving electrostatic precipitator performance with Skewed Gas Flow Technology and reviews the before and after gas flow and operating data from this installation.

INTRODUCTION
Kentucky Utilities, is part of the LG&E Energy LLC which owns and operates seven regulated coal fired generating stations in Kentucky. This paper describes the installation and results of a Skewed Gas Flow precipitator improvement project completed on Kentucky Utilities’ Unit 1 at the E.W. Brown Station in 2003.

Unit 1, commissioned in 1957, has a front wall fired Babcock and Wilcox boiler with a divided back pass. The unit originally did not have a precipitator, however, a two-chambered Buell precipitator was installed in 1972.

The Unit 1 precipitator was designed for a collection efficiency of 98.5% at a gas flow of 430,000 ACFM. The precipitator has two chambers, each with 29 gas passages at 9 inch spacing. The precipitator has two mechanical fields (eight electrical fields) in the direction of gas flow, and a total treatment length of 24 feet. The collection plates are 30 feet high, with weighted wire high voltage electrodes.
Because the precipitator was installed later than the rest of the unit, its location and resulting ductwork are somewhat unusual for a utility precipitator as shown in Figure 1. The precipitator is located well above grade, with gas flow entering the inlet plenum from beneath the precipitator. The inlet plenum includes spreader vanes and horizontal turning vanes to help the gas flow make the 90-degree turn into the precipitator. At the outlet, the gas flow leaves the precipitator through an upward facing vertical plenum before turning and running back over the precipitator toward the ID fan, located in front of the precipitator at roughly the same elevation.

The station predominantly burns low sulfur central Appalachian coal and a small amount of northern Appalachian coal, delivered by rail car.

In 1993, a gas flow model study was implemented to improve the uniformity of the gas flow distribution through the Unit 1 precipitator. Airflow Sciences Corporation of Livonia, MI developed a Computational Fluid Dynamic (CFD) model for the precipitator. The baseline flow model showed the gas distribution was not uniform through the unit and recommendations were developed to modify the inlet and outlet gas flow control devices. Due to the difficulty in accessing and modifying the inlet distribution screen and turning vanes, only the new outlet distribution screen was installed at that time. An improvement in performance was noted as a result of the outlet screen changes.

In 2003, Kentucky Utilities sought to further reduce particulate emissions and opacity from Unit 1 and through discussions with the Electric Power Research Institute (EPRI) became aware of Skewed Gas Flow Technology offered by Stothert Engineering. At that time Stothert Engineering had completed over twenty Skewed Gas Flow Technology installations on coal fired generating units, with good performance results. After the completion of the project, NORAM Engineering acquired Skewed Gas Flow Technology from Stothert Engineering and hired the key personnel involved.
PROJECT IMPLEMENTATION AND RESULTS

During the initial project evaluation, the potential opacity reduction was estimated with a proprietary precipitator performance model using drawings for the unit, performance data provided by Kentucky Utilities and the Airflow Sciences 1993 CFD modeling report. Based on this information a 30% reduction in opacity and particulate emissions was predicted to be possible from installing Skewed Gas Flow when compared with uniform flow. A budget was prepared for the project, including all of the following items:

1. Anemometer tests to document the preexisting gas flow distribution
2. CFD modeling (by Airflow Sciences Corporation) and engineering to design the changes to the unit’s gas flow distribution devices. This model was used to design modifications to the distribution screens to achieve the desired Skewed Gas Flow Profile
3. Detailed design including fabrication and installation drawings
4. Material and labor to install the modifications (by a local contractor)
5. On site construction assistance
6. Post installation anemometer tests

The project was authorized to begin in June 2003 and was installed during the annual outage in November 2003. The total project was completed for less than $US 205,000.

Description of Skewed Gas Flow

Most precipitator vendors adhere to the industry standard calling for uniform flow throughout the precipitator. These standards are based on the assumption that there is a uniform top-to-bottom dust concentration as the gas flow passes through the precipitator, as shown in Figure 2.

Figure 2: Dust Distribution Assumed For Uniform Flow Standards

The uniform dust distribution shown in Figure 2 does not consider the re-entrainment that takes place as dust falls from the point of collection to the hoppers below. Some models have attempted to account for re-entrainment effects, however, these have typically assumed the dust is re-entrained at the same elevation as it is collected and therefore results in the same uniform top-to-bottom dust distribution.
Figure 3a illustrates the re-entrainment of dust as it is falling. Dust is often collected and re-entrained several times before finally being deposited in the hoppers. When dust is re-entrained at a different elevation than it is collected, it results in a dust distribution that increases towards the bottom of the precipitator as shown in Figure 3b. The gas flow is more heavily laden with dust towards the bottom of the precipitator as it is subject to the re-entrainment of dust falling from above.

The Skewed Gas Flow profile improves performance compared to uniform flow by recognizing the non-uniform dust distribution that is caused by re-entrainment and optimizing the gas flow profile to account for this non-uniformity. In general, a Skewed Gas Flow profile consists of a top heavy skew at the outlet of the precipitator, coupled with a bottom heavy skew at the inlet of the precipitator as shown in Figure 4.

The top heavy skew at the outlet increases performance by slowing the gas velocity in the lower region of the precipitator to increase the local collection efficiency where the dust concentration is highest. To maintain the same flow rate the velocity in the upper region of the outlet must then be increased, which reduces the local collection efficiency; however, the gas flow at the top has a much lower relative dust concentration and so contributes little to the total emissions. The net effect produced is a reduction in overall emissions.

The bottom heavy inlet skew increases performance by collecting dust at the top of the precipitator as early as possible to allow time for it to be collected again after it is re-
entrained. The bottom heavy inlet skew also increases the amount of dust entering near the bottom of the precipitator, thereby reducing the distance it has to fall and reducing subsequent re-entrainment.

It is important to find the optimum magnitudes and balance between the inlet and outlet skews to maximize performance. The optimal Skewed Gas Flow profile, and hence potential for increased collection efficiency, is different for each precipitator geometry. Factors affecting the available performance improvement with Skewed Gas Flow include the dimensions of the precipitator (a higher unit tends to increase the amount of re-entrainment), the gas velocity through the unit (higher velocity tends to increase re-entrainment) and the nature of the dust being collected (smaller particles are more likely to become re-entrained rather than fall into the hoppers below).

A proprietary precipitator model that accounts for the re-entrainment of falling dust is used to predict the optimal inlet and outlet skew for each precipitator based on its geometry and operating conditions.

**Implementation of Skewed Gas Flow**

The Skewed Gas Flow project was approved in June 2003. The first step in the project was to measure and document the existing flow distribution within the precipitator to validate the CFD modeling results and confirm the estimate of opacity reduction.

**Initial Flow Distribution**

During a weekend outage in August 2003, cold gas flow measurements were taken to document the preexisting flow distribution within the precipitator. For this testing, personnel inside the unit took measurements with vane anemometers while the FD and ID fans ran on cold, fresh air. Measurements were taken just after the outlet field, and at the center of the unit. Measurements were made every three feet vertically in every fifth gas passage. Due to the symmetry of the unit, only one chamber needed to be tested.

No measurements were taken at the inlet due to difficulty with safe access for the testing crew. Consistent inlet measurements are also difficult to make given the turbulence caused by the inlet distribution screen.

Figure 5 shows the preexisting vertical flow distribution that was measured at the center and outlet of the precipitator. Each data point represents the average velocity ratio measured at each elevation across the width of the precipitator. The data shows that the preexisting gas flow distribution was skewed towards the bottom of the precipitator at both the center and outlet of the precipitator. Note that for easier comparison between planes, the relative velocity (velocity ratio) has been used, which is simply the measured velocity divided by the average velocity from that measurement plane.
Because the preexisting flow was already skewed in the recommended direction at the inlet, but was skewed in the opposite direction to what is recommended at the outlet the overall precipitator performance was predicted to be quite similar to uniform flow, as was assumed for the original estimate of the potential opacity reduction.

Figure 6 shows the preexisting horizontal flow distribution at the center and outlet of the precipitator. On this chart, every data point represents the average relative velocity measured in each gas passage. The data shows that the preexisting horizontal flow distribution was reasonably uniform, with all of the measured gas passages at the center plane and most at the outlet plane having a flow within 20% of the average.
**CFD Modeling and Detailed Design**

Airflow Sciences Corporation was contracted to create the CFD model of the precipitator and ductwork. This model was initially used to simulate the preexisting flow distribution using the existing equipment. Results from the CFD model were compared with the measured flow data to confirm the model accuracy. The CFD model was then used to design modifications to the precipitator flow control devices.

During the design, it was determined that due to the preexisting inlet skew in the recommended direction, the benefit from further inlet skewing did not justify the additional expense required. It was decided, instead, to match the outlet skew to the preexisting inlet skew, and to limit the modifications to the outlet distribution screen to simplify the installation and reduce costs. The CFD model was then used to achieve the desired flow profile according to the following requirements:

- Modifications were to be made only to the outlet distribution screen without placing any baffles or other obstructions inside the precipitator
- The gas flow had to achieve the desired outlet design skew, while making an even and gradual transition between the inlet and outlet skew
- There was to be no noticeable increase in pressure drop through the precipitator
- The cost of the installation was to be minimized

Figure 7 compares two side view plots from the CFD model showing the model prediction for the preexisting flow distribution and predicted design flow. The plots show the preexisting inlet skew towards the bottom of the precipitator, as well as the new outlet skew that was developed in the design runs. Because no changes were made to the inlet, the flow in the first half of the unit is mostly unchanged in the design runs; however, after the midpoint the effect of the outlet screen becomes greater and the gas flow makes the transition to the top heavy outlet skew.

![Figure 7: CFD Modeling Results – Side View Plots](image)
The design modifications included full replacement of the existing outlet distribution screen with a new screen of variable porosity. The new screen had a slightly higher average open area than the existing screen, resulting in a similar or slightly lower pressure drop.

Once the porosity distribution of the outlet distribution screen was established, detailed drawings were prepared showing exactly how the new screen was to be fabricated and assembled inside the unit.

**Installation**
Kentucky Utilities contracted with a local fabrication and service company for the supply of material and installation labor based on the drawings provided.

Construction took place during the November 2003 outage and required six days to complete, based on one 10-hour shift per day with a crew of eight personnel.

Personnel from Stothert provided onsite construction assistance and field review during the installation.

**Final Gas Flow Distribution**
After the installation, cold gas flow anemometer tests were performed to confirm that the desired flow profile was achieved. Due to time constraints, only the outlet flow profile was measured, and as with the before testing, only one chamber of the symmetric unit was tested.

To illustrate the accuracy of the CFD modeling and design modifications an evaluation of the percentage deviation between the design and measured flows before and after the modifications are shown in Figure 8.
Figure 8 shows that before the modifications were installed there was a high level of variation between the design and measured gas flow profile with more than 55% of the data points being more than 30% above or below design.

After the modifications were installed, the agreement was much better, with approximately 60% of the measurement points within 10% of the design flow, 80% were within 20% and 96% within 30%. No measurements were greater than 30% above the design flow, and less than 3% were more than 30% less than the design flow.

During the design phase of the project, modifications were also incorporated into the design to improve the horizontal gas flow distribution. Figure 9 shows the average relative velocity in each gas passage measured before and after the modifications were installed. This data shows that the modifications improved the horizontal flow distribution somewhat at the outlet; however, since modifications were not also made to the inlet, the horizontal flow distribution throughout the first half of the precipitator will have remained mostly unchanged.

The measured data discussed above confirms that the CFD modeling was able to accurately predict the effect of modifications made to the precipitator and that the modifications achieved the desired Skewed Gas Flow profile.

Based on the achievement of the desired flow profile, the full predicted reduction in opacity was expected to be realized upon startup.
Performance Improvement

The key performance indicator for the project was to be the opacity meter installed on the Unit 1 stack. This instrument is used for environmental compliance monitoring and so has a very high level of operator attention and availability.

The daily average opacity was recorded over a ten-month period prior to the installation of Skewed Gas Flow. This data is compared with the seven months of data collected so far since the installation.

Station personnel have confirmed that the coal supply and properties have been consistent during the before or after periods. In addition, no modifications, besides regular maintenance, were made to the boiler or precipitator during the shutdown, such that any consistent improvement in performance is attributable to the gas flow changes that were made.

Figure 10 shows the daily average opacity and generation for ten months before and seven months after the installation in November 2003.

The average opacity in the before period was 17.3% compared with 11.6% in the after period. This is equivalent to an average 33% reduction in opacity.

The unit is not base loaded; its generation varies between approximately 60 and 100 MW depending on electricity prices and demand. The average generation was, however, very similar in the before and after periods (81 MW before, 82 MW after).
Opacity vs. Generation – All Data

Figure 11, shows that the stack opacity is related to generation in both the before and after periods. The average opacity is, however, 34% lower in the after period over the normal generating range (60 to 100 MW) as indicated by the difference between the two best fit straight lines.

As can be seen from Figure 11, the reduction in average opacity is fairly consistent over the normal generating range, varying only from 35% at 60 MW to 33% at 100 MW.

Note that the result is very similar if a best-fit exponential line, similar to the standard Deutsch equation, is used rather than the best-fit straight line shown above. When an exponential best-fit line is used the reduction in average opacity varies from 39% at 60 MW to 32% at 100 MW.

Maintenance Issues

As with most operating precipitators of similar age (> 30 years), the unit occasionally experiences maintenance related issues such as wire failures / grounded fields, ash conveyor failures, etc. Similar such failures have occurred during both the before and after modification measured period.

Due to the varying load operation of the unit it is possible to shutdown the unit to perform minor maintenance more frequently than is common for most base loaded coal fired power plants. The unit was brought offline for short periods (one to two days) three times in both the before and after periods in order to perform minor repairs.
**Opacity vs. Generation – Best Two Month Periods**

Although it is not possible to quantify the effect of the maintenance related issues on the before and after opacity, it can be shown that the improvement seen was not simply a result of less maintenance issues by comparing the performance during periods when no precipitator problems were encountered.

Figure 12 plots the opacity vs. generation for the best two months from both the before and after periods during which time there were no significant precipitator issues.

![Figure 12: Opacity vs Generation Before and After SGFT Best 2 Month Run Comparison](image)

Although the opacity measured during the best two month run periods is lower for both the before and after periods, the reduction in opacity observed is very similar to that seen when using all of the data. The average reduction in opacity as measured using only data from the best two-month run period is approximately 29%. As with a comparison using all of the available data, the reduction in opacity is relatively consistent over the normal generating range.
CONCLUSION

A CFD model was used to design a new outlet distribution screen and achieve a Skewed Gas Flow profile within the Unit 1 precipitator at the E.W. Brown Station. Cold gas flow anemometer testing confirmed that these modifications closely achieved the desired flow Skewed Flow profile. Approximately 60% of the measured values were within 10% of the design, 80% were within 20% of design and 96% were within 30% of design.

Station personnel have confirmed that the coal supply and properties have been consistent during the before or after periods. In addition, no modifications, besides regular maintenance, were made to the boiler or precipitator during the shutdown, such that any consistent improvement in performance is attributable to the gas flow changes that were made.

Stack opacity measurements over seventeen months as well as operator feedback have confirmed that the unit operates at an opacity level approximately 30% lower than it did prior to the implementation of Skewed Gas Flow.

As with most operating precipitators over 30 years old, the unit experiences ongoing maintenance related issues such as grounded fields due to wire failures. While it is impossible to prevent these issues, or accurately quantify their effect on opacity, a comparison of shorter periods where no significant failures occurred also indicates an approximately 30% reduction in opacity.

The opacity varied depending on the unit’s generation in both the before and after periods; however, the percentage reduction in opacity remained constant over the normal generating range (60 to 100 MW).

The proprietary precipitator model used to estimate the level of opacity reduction accurately predicted the reduction in opacity that would be achieved from the implementation of Skewed Gas Flow.

Kentucky Utilities considers the project a success, having been completed on time and on budget, and achieving the predicted reduction in opacity.

Skewed Gas Flow has been demonstrated to be a relatively low cost method of reducing opacity at an operating coal fired power station. Opacity was reduced by 30% for a cost of less than $205,000.