Improved Control of Primary Fine Particulate Emissions with Electrostatically Augmented Fabric Filtration

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ABSTRACT

Southern Research Institute (SRI), under a cooperative agreement with the United States Environmental Protection Agency (USEPA), is reporting the results of an investigation of electrostatically stimulated fabric filtration (ESFF) for particulate control on a utility boiler fired with pulverized coal (2001-2003). In pilot-scale testing at the SRI Combustion Research Facility and in a long-term, pilot-scale demonstration of ESFF at a full-scale utility boiler, ESFF consistently outperformed conventional fabric filters (2001-2002). For these tests particle charging was accomplished with high voltage electrodes mounted outside of, but co-axially, with the pulsejet filter bags. With ESFF, total mass emissions without cleaning were one-fourth to one-fifth of those for a conventional pulse-jet fabric filter (FF). Penetration of particles smaller than one micrometer was about one order of magnitude less with ESFF. In addition, pressure drop increased about one-third as fast with ESFF as compared with FF, reducing the frequency of bag cleaning. Since a significant fraction of the total particulate emissions occur as a consequence of cleaning, the reduced cleaning schedule in itself leads to lower emissions of all particle sizes. Recently, additional testing (2003) has been completed using a cooled-pipe precharger to impart charge to the fly ash particles. The previous high voltage electrodes were replaced with large diameter electrodes intended to produce only a collection field. Improved baghouse performance was observed with this arrangement, producing filter drag values 50 to 60% lower than those experienced during normal baghouse operation. Of special note was the observation that significant performance improvement was measured with only the collection field energized (no precharging of the fly ash).

INTRODUCTION

The development of a commercially feasible technology for the use of Electrostatically Stimulated Fabric Filtration (ESFF) began at Southern Research Institute in 1999 with the installation of a pilot-scale ESFF baghouse in the SRI Combustion Research Facility (CRF). The initial research from 1998 through 2000 was supported by USEPA under Cooperative Agreement CR 826754-01-0. The CRF was fired at 3.6×10^6 Btu/hr producing a nominal flue gas flow rate of 1200 acfm, equivalent to a generation rate of 0.3 MWe. The testing comprised a series of discreet one-week operating periods with a variety of fuels. The fuels included eastern bituminous coal from three sources, Powder River Basin coal from two mines, a mixture of eastern bituminous coal and biomass (switchgrass), and three blends of an eastern bituminous coal and a Powder River Basin coal. This work demonstrated that, regardless of fuel, pressure drop was significantly lower with ESFF as compared to a conventional baghouse, total mass penetration was reduced when the high voltage array was powered and the penetration of fine particles was reduced by about one order of magnitude with ESFF.

The evaluation of ESFF at the SRI CRF indicated that several advantages would accrue from the use of ESFF provided that the performance gains persisted. The continuation of the development of the ESFF technology was performed under USEPA Cooperative Agreement R-82834201. This work was designed to confirm the performance of ESFF, to demonstrate the persistence of ESFF performance and to design and operate a two-stage ESFF system. The two-stage ESFF design incorporated a cooled pipe precharger to charge the particles ahead of a particle collection region containing the bags and large-diameter electrodes. The collector electrodes primarily established an electric field and generated little or no corona current.

METHODS

Fabric filter size is expressed as a combination of the air-to-cloth ratio (A/C), the ratio of the volumetric flow rate of flue gas to the face-area of the filter and the gross volumetric flow rate through the baghouse casing. Fabric filter performance, in addition to particulate collection efficiency or penetration, is expressed in terms of the filter drag, the ratio of pressure drop to the A/C. In the ESFF configuration demonstrated by SRI the current density at the electrified face of the filter and the electric field strength in the collection region are also important design criteria.

As with conventional fabric filters, the gas volume and the characteristics of the particulate, the overall face area of the filter, the selection of bag material and cleaning frequency influence the pressure drop across an ESFF. Pressure drop translates into the principle operating cost, power to operate the fan. The addition of electrostatics adds a second group of variables. These include the operating voltage and current and the electrical properties of the particles that are collected. We have found that this additional set of ESFF operating parameters also influence pressure drop.

The size of this set of independent variables can complicate the evaluation of the performance of an ESFF. Our approach for this work was to hold constant as many of the fundamental fabric filter variables as possible while comparing periods of operation as a standard fabric filter with periods of ESFF operation. In general, we found that the pressure drop across the filter increased three times faster for conventional baghouse operation than for ESFF operation. We quantified this effect by analyzing performance in terms of a filter drag model, sometimes called the Kozeny-Carman relation. This model describes pressure drop in terms of the gas volumetric flow rate, particulate loading, filter area and filtration properties of the particulate as it forms a dustcake on the bag surface.[1]

In the working form of the Kozeny-Carman equation,

$$\mathrm{S} = \mathrm{S_E} + \mathrm{K_2 W},$$

where S is the filter drag (quotient of ΔP and A/C), S_E is the effective residual drag or after-cleaning drag, W is the areal density of dustcake deposited during a filtering cycle, and K_2 is the specific drag coefficient described below. The drag immediately after cleaning is the sum of three terms: the drag due to the filter fabric, the drag due to the boundary where the dustcake is attached to the filter fabric and the drag due to the residual dustcake adhering to the fabric after cleaning. The after cleaning portion of the plot of S versus W is not linear, principally due to the uneven topography of the recently cleaned dustcake. As the fissures and thinner areas of the residual dustcake are refilled following cleaning, the relationship becomes linear. The effective residual drag, S_E, replaces the complex terms that would be needed to describe these processes. S_E is the y-intercept of the linear portion of the plot of drag versus areal dustcake density. The slope of the drag versus weight curve K_2, called the specific drag coefficient, is characteristic of a particular dust, gas, fabric and dustcake structure. The values of K_2 were used to compare conventional fabric filter operation with ESFF operation.

The analysis is further facilitated by the assumption of constant inlet mass loading, c, so that the product cK_2 becomes the slope of the line when drag is plotted versus the cumulative volume of gas passing through the filter. W, the areal density of the dustcake, is described by the following equation, where c is given in pounds per cubic foot, Q the volumetric flow rate in cubic feet per minute at baghouse temperature and pressure, and A_c the surface area of the filter in square feet,

$$\mathrm{W} = \int \mathrm{c}\frac{\mathrm{Q}}{A_c}dt \ \text{(lb/ft}^2\text{)}$$

or, assuming c is constant,

$$\mathrm{W} = \mathrm{c}\int (A/C)dt \ \text{(lb/ft}^2\text{).}$$

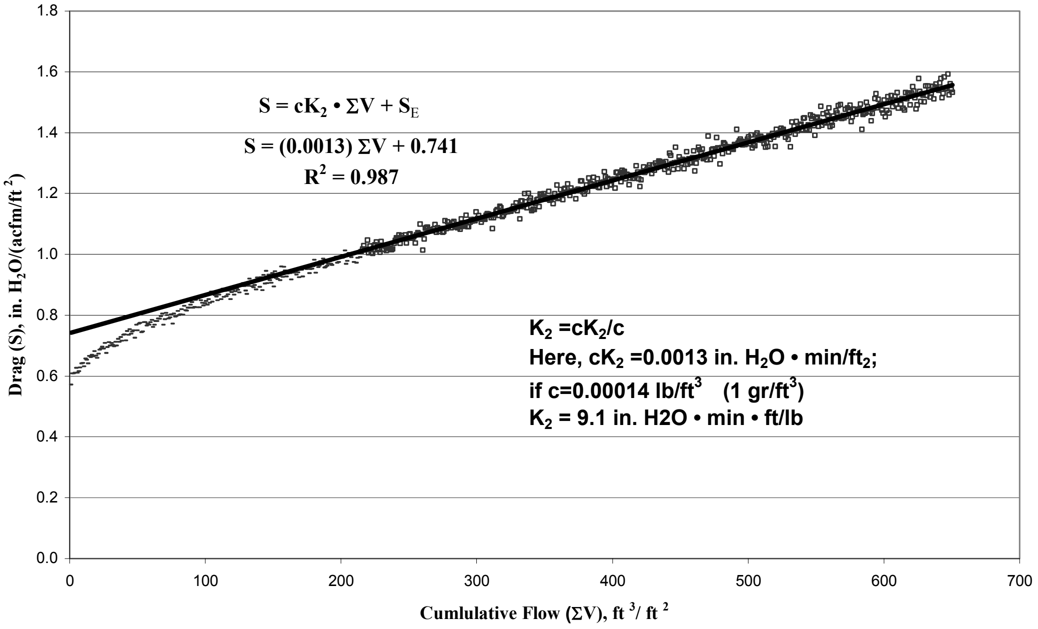
The term A/C is the baghouse air-to-cloth ratio or filtering face velocity. The filter drag model can then be rewritten as,

$$\mathrm{S} = \mathrm{S_E} + \mathrm{cK_2}\int (A/C)dt$$

Figure 1 illustrates the approach that we used to determine the value of K_2. Values of flow rate and pressure drop logged at ten-second intervals were used to calculate drag and A/C. Drag was plotted versus the cumulative gas volume as shown in the figure. In this example the data judged to be non-linear, shown by dashes, were excluded from the regression analysis. The data judged to be linear were included in the regression analysis and are shown by squares. The linear regression for the filtering cycle used for this illustration gave the values of S_E and cK_2 as shown. The value of K_2 follows from cK_2 when the inlet mass loading is known.

The specific drag coefficient, K_2, effectively describes fabric filter performance in terms of pressure drop. In this discussion the performance gains with ESFF are described as the ratio of K_2 with ESFF to K_2 without electrostatic stimulation. This ratio is called the pressure drop reduction factor (PRF). The PRF ranged from 0.27 to 0.45 during the testing of the ESFF at the Institute's Combustion Research Facility.[2]

Figure 1. Illustration of the method used to evaluate ESFF performance.



CRF TESTING

The data obtained in the CRF testing was used to develop a set of three-dimensional curves that illustrate the potential decrease in pressure drop that can be attained with ESFF. Examples of these curves are shown in Figure 2 and Figure 3. Each of the colored bands represents a tubesheet pressure drop interval of one inch of water.

During the CRF testing ESFF performance was evaluated at corona voltages up to 42 kV and corona currents giving a current density up to 26 μA/ft^2 of electrified fabric area. The PRF averaged 0.32 for these tests.

Emissions Reduction

A prototype TEOM® (tapered-element oscillating microbalance) 7000 continuous mass monitor, supplied by Rupprecht & Patashnick Co., Inc., was used to measure mass emissions while the ESFF operated as the primary particulate control device during a study of coal blends at the CRF. The blended coal was a mixture of an eastern bituminous coal and a Powder River Basin coal.

Figure 2. This plot shows the family of operating points for a conventional fabric filter with K_2 = 3 in. H20 · min·ft/lb.

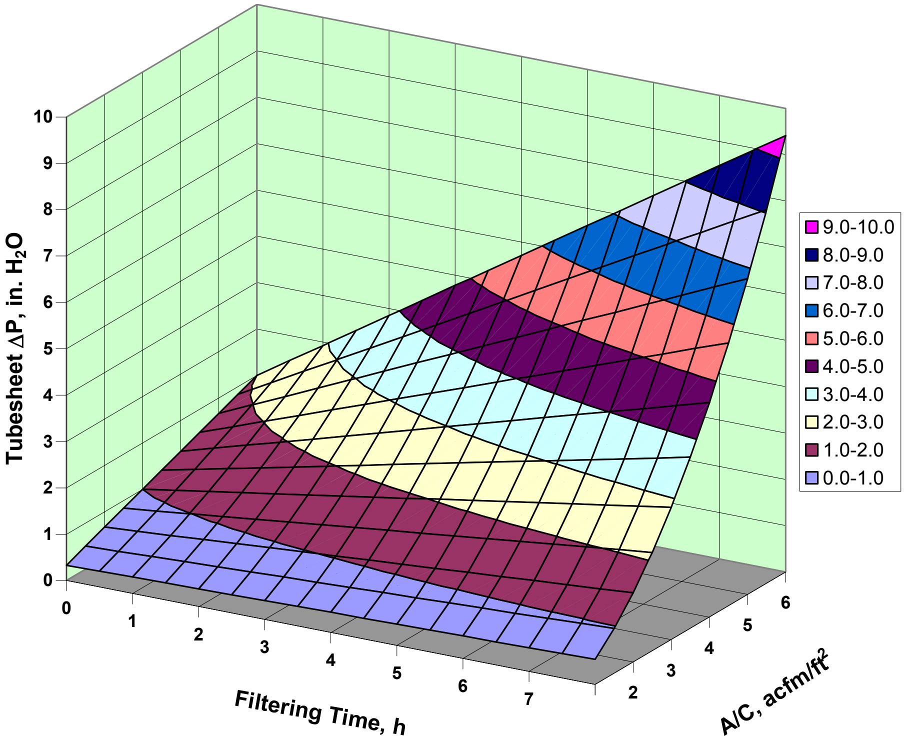


Figure 3. This plot illustrates the family of operating points for the same installation shown in Figure 2. For this example K_2 was reduced to 1 in. H_20 · min · ft/lb with ESFF.

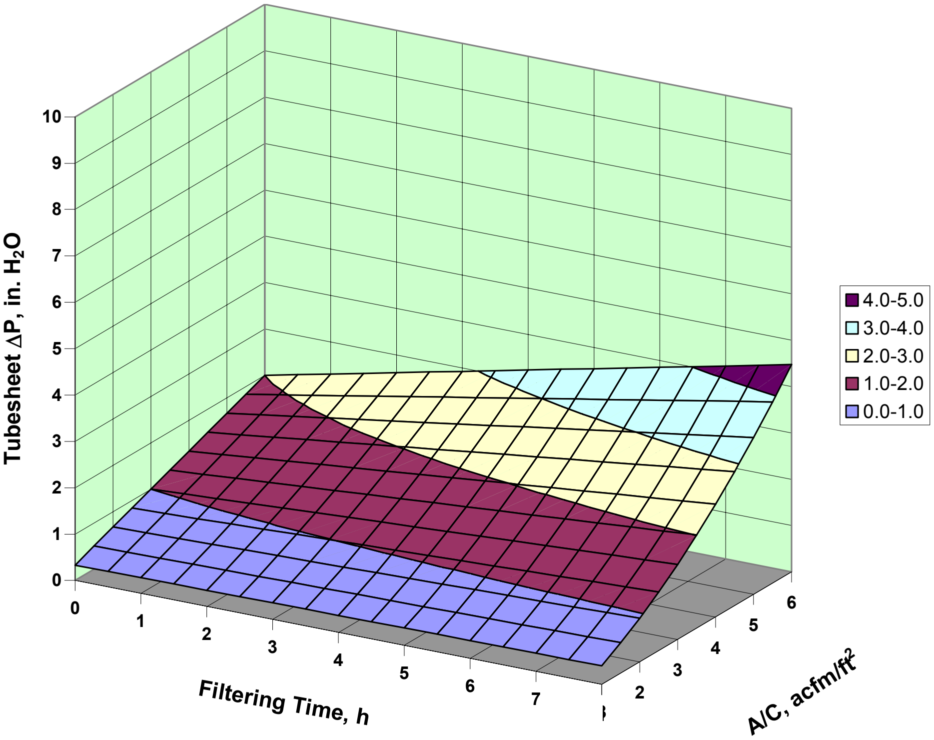


Table 1 shows outlet ESFF mass emissions data obtained during this testing. The total outlet mass concentration was reduced by 81% when power was on. A pre-cutter with a 2.5 micrometer D_{50} (physical particle diameter with 50% collection efficiency) was fitted to the probe for a portion of the test to measure the fine particulate matter fraction of the outlet emissions. $PM_{2.5}$ emissions were reduced 67% while the high voltage array in the baghouse was energized.

Table 1. Comparison of outlet emissions while the high voltage frame was energized for ESFF and with conventional baghouse operation with power off.

Power	Total PM	Fine PM
	$\frac{\text{mg}}{\text{acm}}$	$\frac{\text{mg}}{\text{acm}}$
off	2.035	0.666
on	0.384	0.217
Reduction	81%	67%

Figure 4 compares ESFF $PM_{2.5}$ and PM_1 penetration, the emissions expressed as a percentage of the inlet mass loading, with several particulate control configurations, some which are in use on full-scale utility boilers and others being tested at pilot scale. The data shown for ESFF performance are from the SRI research at the CRF. Table 2 identifies the labels used in the figure.

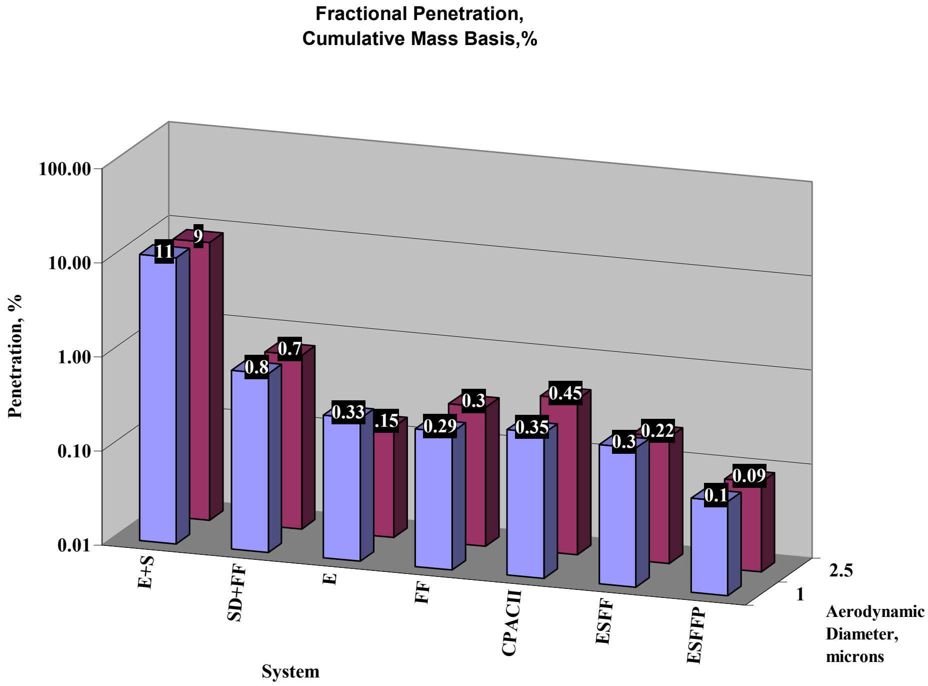
With the exception of the scrubber-ESP system, all of the systems shown achieved better than 99% control of the $PM_{2.5}$ mass fraction. Condensation of sulfuric acid to form an aerosol was apparently occurring in the scrubber downstream of the ESP at this location, thereby reducing its collection efficiency.[3] The ESFF with power on exhibited the highest collection efficiency (lowest penetration) of the systems considered for both $PM_{2.5}$ and PM_1 size fractions, with a collection efficiency of 99.9% for both size fractions.[4]

Table 2. System Label Key for Figure 4.

Label	Description
E+S	High-efficiency ESP+Wet Limestone Scrubber
SD+FF	Spray Dryer+Reverse-Gas Cleaned Fabric Filter
E	Large SCA* High Efficiency ESP
FF	Reverse-Gas Cleaned Fabric Filter
CPACII	Pilot Compact Hybrid Particle Collector (COHPAC II)
ESFF	ESFF Without Electrode Energization
ESFFP	ESFF With Electrode Energization

- Specific Collection Area, ft^2/1000 acfm

Figure 4. Fine particle penetration of several particulate control systems.



PILOT-SCALE, LONG-TERM DEMONSTRATION OF ESFF

An existing pilot-scale baghouse at Alabama Power Company's Plant Miller was adapted to continue the development of ESFF. The pulsejet baghouse was modified to accept a five-by-five bag array, each bag five inches in diameter and sixteen feet long. The bags were made of felted polyphenylene sulfide (PPS) fibers (Ryton^{TM}). The PPS fibers were 2.7 denier (9000 m of the fiber weighs 2.7 g) and the nominal weight of the finished felt was 16 oz./yd^2.

The baghouse casing is 63-5/8 in. square. An array of sixteen corona electrodes (0.109 in.-diameter steel wire) was suspended between the bags as shown in Figure 5. Bag-to-bag and electrode-to-electrode spacing that is shown in the scale drawing of the ESFF tubesheet is 10.5 in. For this research a pulsejet cleaning method utilizing intermediate pressure compressed air (nominally 30 to 40 psi) was selected.

The schematic drawing in Figure 6 illustrates the layout of the ESFF installation at Plant Miller. Plant Miller comprises four 700 MW units fired with Powder River Basin Coal. For the ESFF research the baghouse inlet ducts extract flue gas from two points in the Unit 2 system. The main ESFF inlet duct takes flue gas from the ESP inlet and a second duct extracts hot flue gas at the economizer outlet. This hot gas duct is fitted with a control valve and is used to boost the flue gas temperature at the baghouse inlet. Operating at a pre-selected, constant temperature eliminates the need to consider temperature-related resistivity issues.

The pilot-scale ESFF at Plant Miller was operated for a total of 3892 h. The baghouse was periodically operated as a conventional pulsejet fabric filter to compare performance with ESFF operation. The inlet and outlet mass concentrations measured with USEPA Method 17 mass trains are presented in Table 3. These data give mass collection efficiency of 99.89% for the conventional baghouse and 99.99% for ESFF. The resistivity of the fly ash as measured in-situ is given in Table 4. The ability to control the temperature at the baghouse inlet was utilized to examine the effect of temperature on resistivity. The resistivity data show a general trend to higher values as temperature increases.

Figure 5. Scale drawing of the ESFF tubesheet.

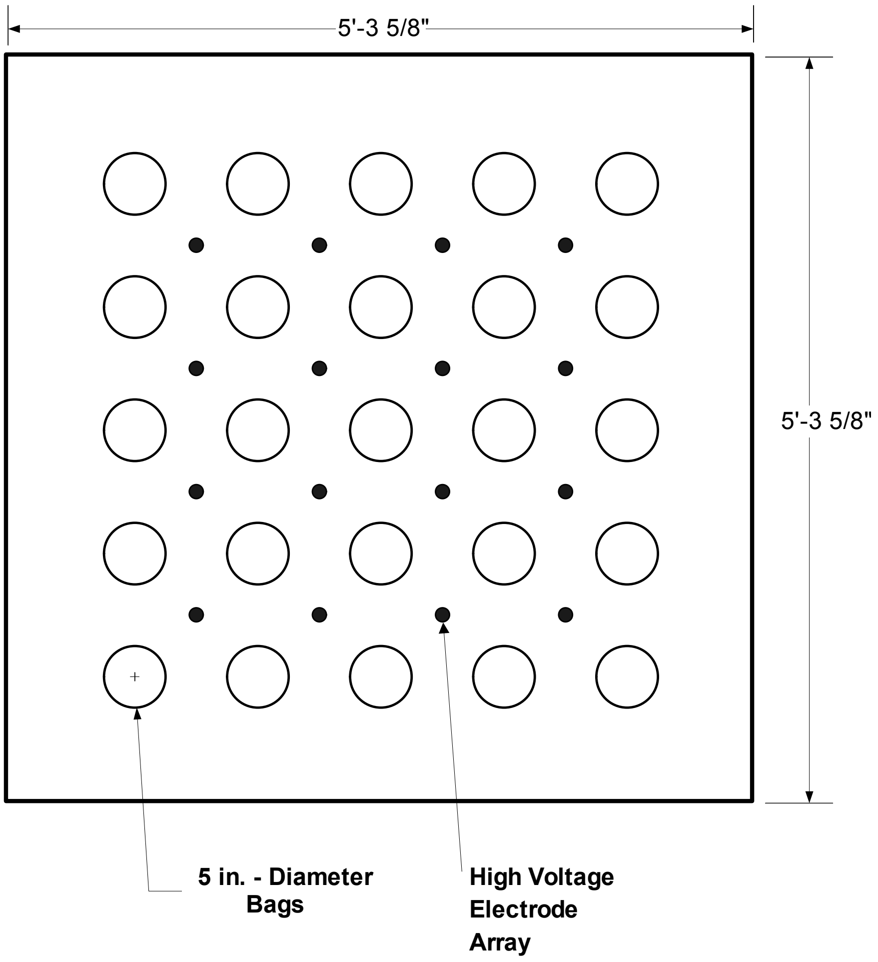


Figure 6. This drawing is a schematic representation of the ESFF installation at Plant Miller.

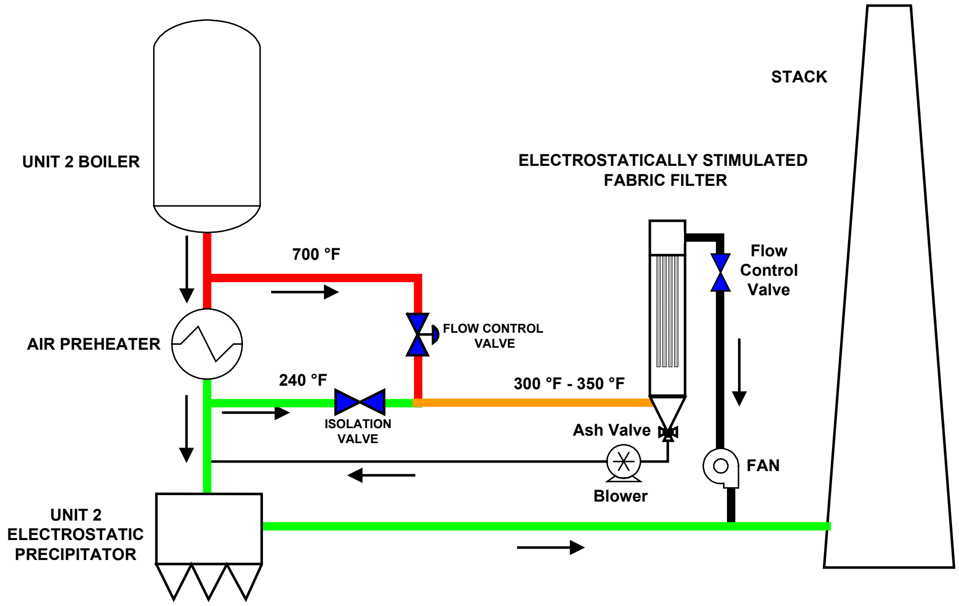


Table 3. ESFF inlet and outlet mass concentration.

Test I.D. #	HV on/off	gr/acf	gr/dscf	mg/acm	mg/dscm	$lb/10^6$ Btu
ESFF IN-1	na	1.10	1.83	2,520	4,210	3.69
ESFF IN-2	na	1.09	1.82	2,5005	4,180	3.69
ESFF IN-3	na	1.11	1.86	2,550	4,270	3.70
ESFF OUT-2	Off	0.00012	0.00019	0.270	0.445	0.0005
ESFF OUT-3	On	0.00010	0.00017	0.226	0.379	0.0004

Table 4. In-situ resistivity measurements.

Temperature, ^{o}F	Resistivity, ohm-cm
227	4.37×10^{10}
230	4.29×10^{10}
232	4.38×10^{10}
276	9.58×10^{10}
344	5.25×10^{10}
345	6.93×10^{10}
369	7.08×10^{10}

Figure 7 is a plot of the voltage and current on the secondary windings on the ESFF transformer. The ESFF was typically operated at approximately 35 kV and 3 mA giving a current density of 8.8×10^{-6} A/ft^2 (9.5×10^{-9} A/cm^2) at the surface of the bags.

Fine Particle Penetration

The penetration of particles with physical diameters less than 1 micrometer was determined with a TSI Scanning Mobility Particle Sizer (SMPS). The particle size distribution was measured at the inlet and outlet of the baghouse with the SMPS with and without electrostatic augmentation. These data were used to calculate the penetration of sub-micron particles as shown in Figure 8. The penetration of particles smaller than one micrometer physical diameter was reduced by 5% to 50% over the range of particle sizes detected by the SMPS.

Pressure Drop Reduction

Pressure drop and volumetric flow rate data were analyzed to determine representative values of S_E and K_2 to characterize ESFF operation over nearly 4000 h of baghouse operation. Unit 2 operation at full boiler load (700 MW) was the only criterion used to select operating periods for analysis.

Figure 7. Voltage – current performance for the ESFF.

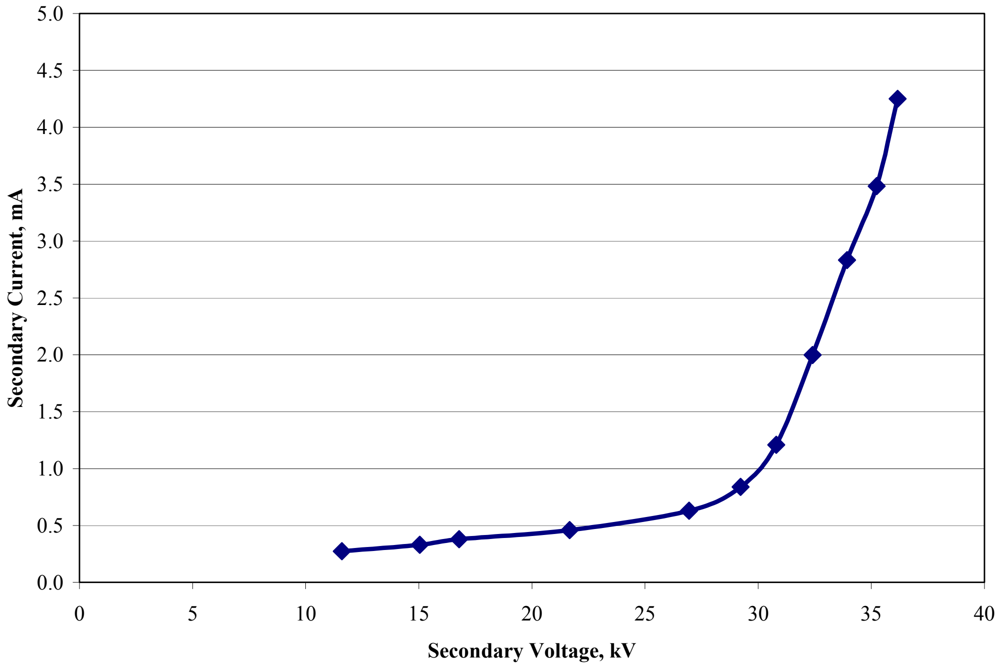
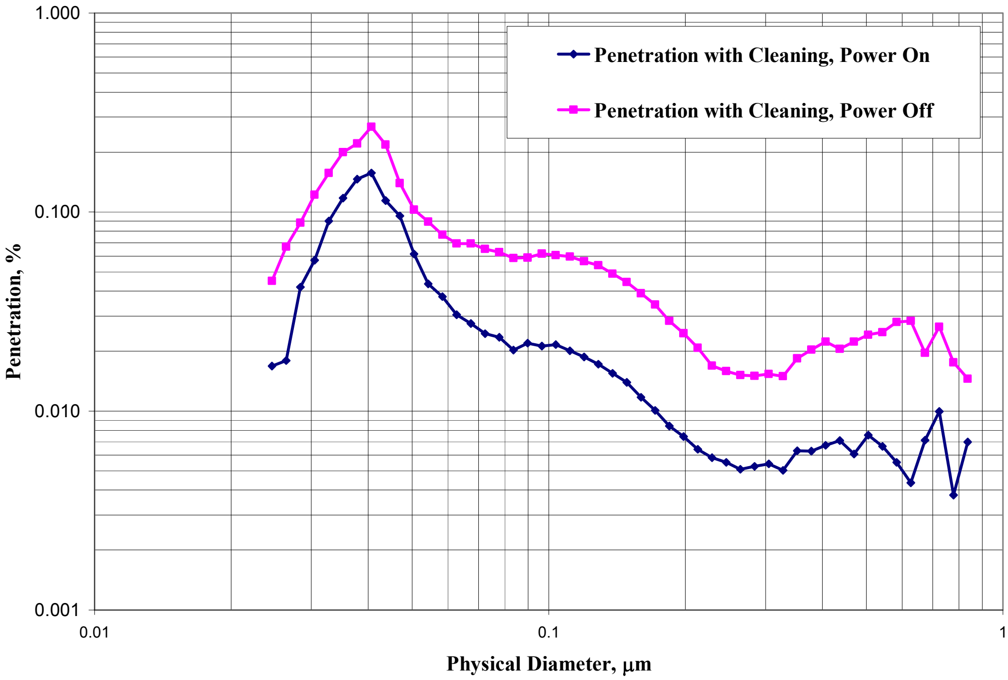


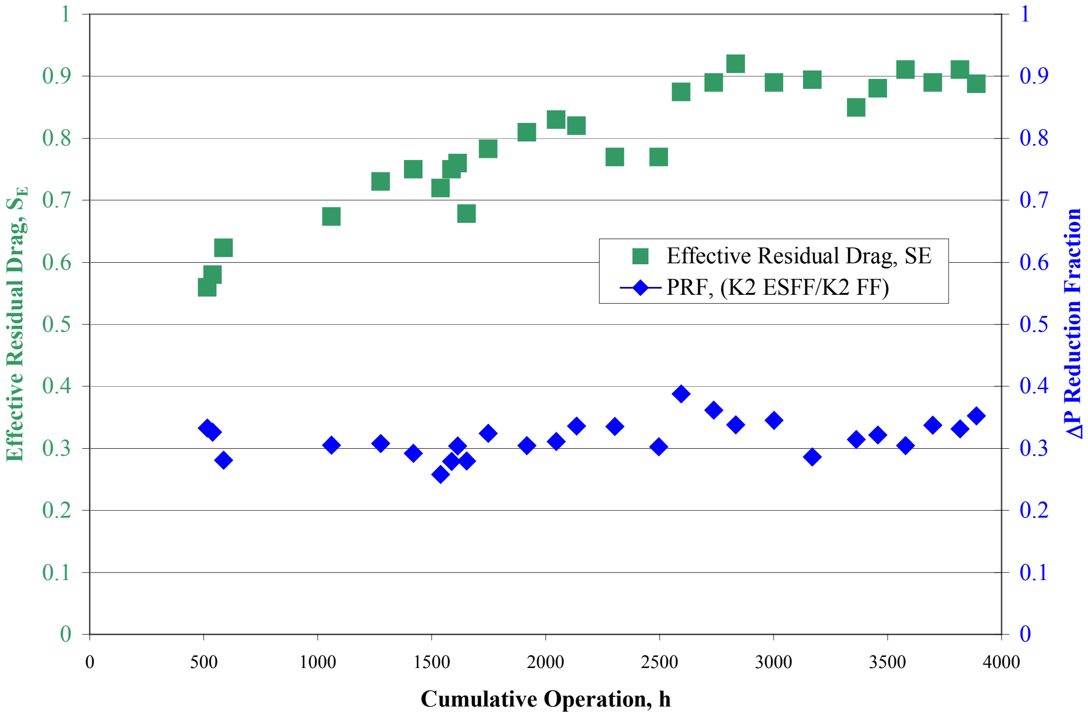
Figure 8. ESFF fine particle penetration measured with the SMPS.



Average values of K_2 and S_E were determined for several consecutive filtering cycles for stable full-load boiler operation. From these data a daily PRF was calculated. The PRF (Pressure Reduction Factor) is the ratio of K_2 for conventional filtration to K_2 for ESFF filtration. The results of this process are presented graphically in Figure 9.

Two characteristics of the data are significant. First, the PRF was stable throughout the testing, averaging 0.32 ± 0.03 (standard deviation). This performance indicates that the pressure drop reduction with ESFF is persistent. Secondly, S_E increased steadily from 0.56 to 0.89 in. H_2O/acfm/ft^2 over the first 2500 h of operation and stabilized at an average of 0.89 in. H_2O/acfm/ft^2 where it remained until testing ended. Slowly increasing and finally stabilizing values of S_E are expected following startup of a well-designed fabric filter. ESFF did not appear to affect S_E.

Figure 9. Effective residual drag and the pressure drop reduction factor throughout the long-term demonstration of ESFF performance at Plant Miller.



TWO-STAGE ESFF

Upon completion of the pilot-scale demonstration of ESFF, a chilled pipe precharger was inserted into the casing of the ESFF beneath the bags and the ESFF corona electrodes were replaced with 5/16 in. diameter rods to establish an electric field without corona. The array of collector electrodes was maintained at secondary voltages from 35 to 45 kV. The precharger was operated with secondary currents of 0.75 mA to 1.8 mA with secondary voltage values in the range of 37 to 41 kV. At these current levels the current density in the charging region ranged from 25 to 56 nA/cm^2.

The performance of the fabric filter was characterized for the four possible combinations of precharger and collector field operation. The values of K_2 for each mode of operation are shown in Figure 10. The fractional reduction in K_2 for each case was 0.35 for precharger alone, 0.41 for the collection field alone, and 0.55 for operation with both the precharger and collection field energized.

It is quite interesting that performance improvement was similar in magnitude for both the precharger in operation alone and with the collection field energized alone. This may indicate that there was enough natural charge on the fly ash particles to promote improved filtration properties in the presence of the collection field. The presence of some natural charge on the particles could account for the significant reduction in K_2 with no externally imposed charge on the particles. In that scenario the combined effects of particle charging and collection field energization would not be significantly better that either process alone.

HIGH PERMEABILITY BAGS

An extensive evaluation of ESFF performance with felted 7 denier (nine thousand meters of the fiber weighs 7 grams) PPS bags is planned as a part of the development of ESFF. Compared to standard 2.7 denier bags the pressure drop is reduced because the felt made with 7 denier fiber exhibits higher permeability. However increased emissions are typically seen with the 7 denier fabric. Nonetheless pressure drop and particulate collection performance of an ESFF fitted with 7 denier bags fabric offer intriguing possibilities.

Recently a three-week survey of mercury control technologies was conducted using the pilot scale ESFF baghouse. A set of 7 denier PPS bags was installed for this testing and the single-stage ESFF technology was utilized during the first week of operation. Figure 11 shows tubesheet pressure drop and A/C for parts of a day at the beginning of the test. The test plan called for ESFF operation at startup but equipment problems resulted in the baghouse operating for about a half-day without power on the ESFF high voltage array. The equipment was repaired at mid-day and the baghouse operated as an ESFF for the remainder of the day. The figure shows significant performance improvement in terms of the lower pressure drop with ESFF. The average value of K_2 dropped from 11.4 in. H_2O • min • ft/lb before the power was applied to the high-voltage array to 2.9 in. H_2O • min • ft/lb after the high voltage array was energized.

Figure 10. Values of the specific filtration coefficient (K_2) during the evaluation of two-stage ESFF.

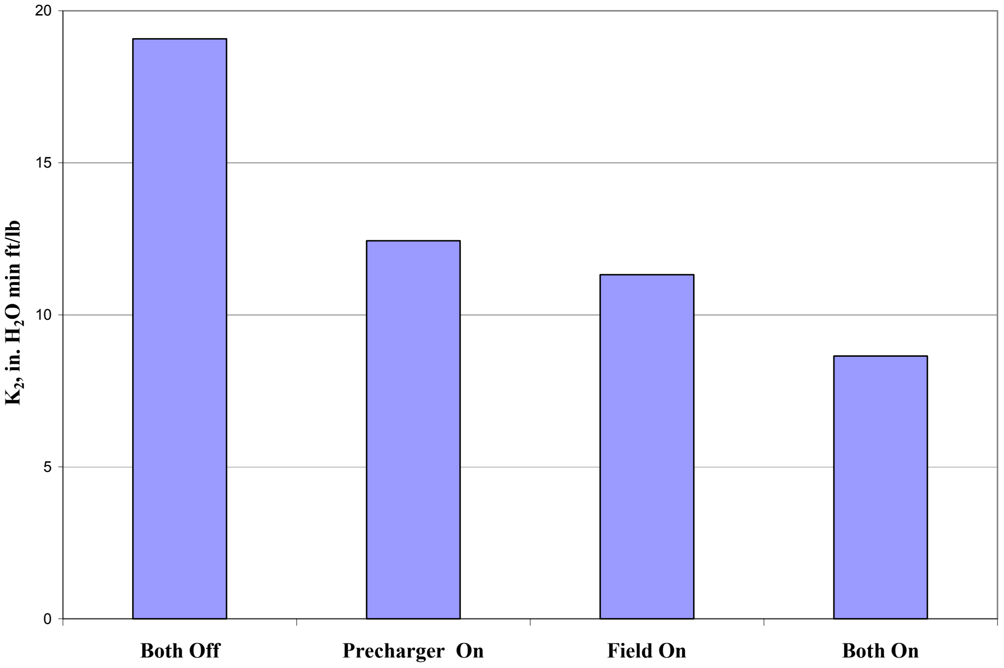
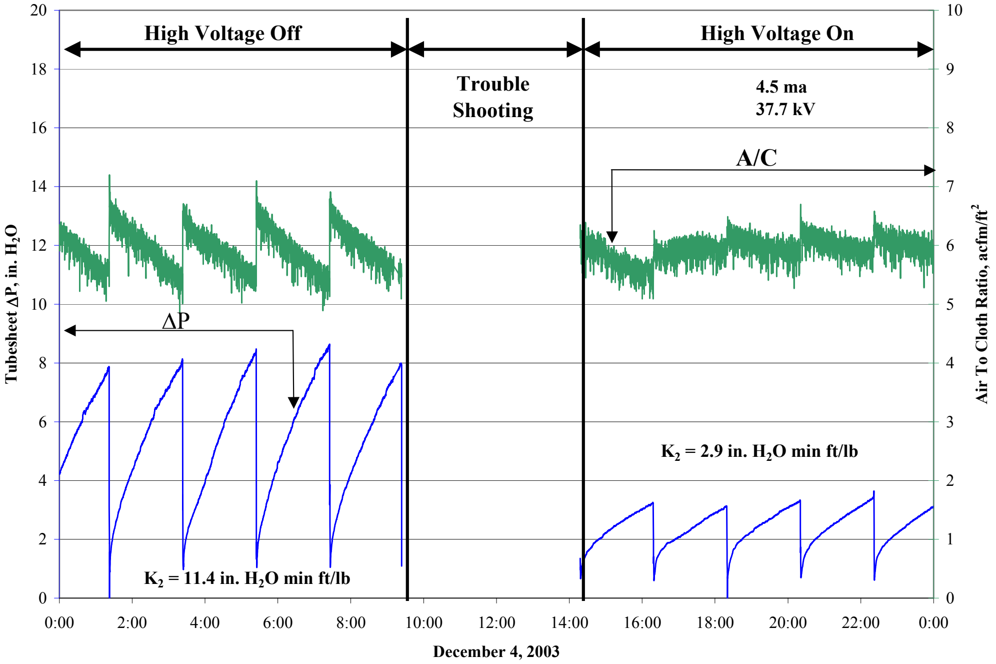


Figure 11. ESFF operation with high permeability (7 denier) bags.



The mass collection efficiency of the baghouse was measured on two occasions during the three-week test using USEPA Method 17, once while ESFF was used and again while the fabric filter was operated as a conventional baghouse. The tests consisted of three consecutive inlet method 17 runs of one hour each and a single outlet run spanning the entire time that the inlets were run. The mass collection efficiency while operating as a conventional pulsejet baghouse was 97.38%. and for the ESFF baghouse the mass collection efficiency was 99.99%. The baghouse was cleaned at two-hour intervals during all testing. Since these tests were conducted very early in the service life of these bags the results must be considered to be preliminary but are nonetheless very promising. The use of ESFF in conjunction with high permeability bags appears to offer the potential for low pressure drop with excellent mass collection efficiency. However, further testing of this combination is indicated.

COSTS

BHA Group, Inc., a licensee for this technology, has developed a preliminary design for a commercial offering of ESFF. The first estimate of installed cost for this technology is $6/cfm at a scale of 50,000 ft^3/min. Assuming a rate of 3333 ft^3/min of flue gas is generated to yield 1 MW of electric power from coal, 50,000 ft^3/min is equivalent to a 15 MW boiler. At that scale, the annual fan cost for one inch of water is approximately $2,000. Site-specific assumptions are needed to estimate the pressure drop reduction but it is reasonable, based on the results of this work, to expect up to 4 in. H_2O reduction. The annual cost of power for the ESFF electrode array would be $1,300. The net savings in operating cost would be $6,700/yr. These estimates assume an A/C of 6 acfm/ft^2, current density in the collector 9 $\mu A/ft^2$, collector voltage 35 kV, transformer-rectifier efficiency 70% and a cost for electricity of $.04 per kWh.

These cost estimates indicate that the return in operating costs for the investment in ESFF will be substantial. Further savings may be realized due to prolonged bag life because less-frequent cleaning is needed with ESFF.

CONCLUSIONS

Pulsejet fabric filter technology with electrostatic augmentation clearly offers performance in a particulate control device that is superior to either fabric filters or electrostatic precipitators alone. More flexibility in baghouse design is available since with ESFF, the casing can be smaller than a conventional baghouse or the pressure drop can be lower (and the cost for fan energy less) while particle capture is superior on both an overall mass basis and for submicron particles. Conventional pulsejet baghouses are economically competitive with ESP and rapidly gain an advantage if more demanding particle emissions standards must be met. With ESFF the advantage moves even more to filtration technology.

Although the performance data on the collection of primary fine particulate matter for the ESFF is promising, other performance issues may determine the ultimate usefulness of this technology. Specifically, the added complexity of electrifying a baghouse can only be justified if the overall costs of energy and bag replacement, as well as space reduction from a smaller retrofit footprint, produce net economic and operational savings. The added fine particle collection performance should be viewed as a “bonus” benefit.

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KEY WORDS

Current Density

Drag

Effective Residual Drag

Electrostatically Enhanced Fabric Filter (ESFF)

Fine Particulate

Particulate Penetration

$PM_{2.5}$

Pressure Drop
Secondary Current

Secondary Voltage

Specific Filtration Coefficient K_2

REFERENCES

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1 C. David Cooper and F. C. Alley, Air Pollution Control: A Design Approach, Prospect Heights, Illinois: Waveland Press, Inc., 1986, p. 161.

2 Heaphy, R. F., J. D. McCain, L. G. Felix. and J. P. Gooch, PILOT-SCALE TESTING OF AN ELECTROSTATICALLY STIMULATED PULSE-JET FABRIC FILTER: FINAL REPORT. Southern Research Institute. Submitted to: National Risk Management Research Laboratory U. S. Environmental Protection Agency, November 2000.

3 U. S. Department of Energy, Pittsburgh Energy Technology Center, FINAL REPORT: BAILLY STATION UNITS 7 AND 8 AND AFGD ICCT PROJECT, DOE CONTRACT NO. DE-AC22-93PC93254, Submitted by Southern Research Institute, October 20, 1994.

4 Felix, L. G., John P. Gooch and Robert F. Heaphy AN ELECTRIFYING NEW SOLUTION TO AN OLD PROBLEM?, Pollution Engineering, July 2000.