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COLORADO SPRINGS UTILITIES IMPROVES FABRIC FILTER PERFORMANCE BY INSTALLING EXPANDED PTFE MEMBRANE FILTER BAGS

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ABSTRACT

Actual operating results have been used to empirically determine the relationship between fabric filter (baghouse) differential pressure and stack gas flow in a reverse gas cleaned fabric filter. Assumptions are made that the tubesheet pressure drop is the sum of the pressure loss across the filter media and the dust cake. The dust cake is comprised of a component that remains on the bag after cleaning and a removable component that accumulates between cleaning cycles. The component that accumulates between cleaning is proportionate to the inlet dust concentration, the filter velocity and the time between cleaning. This relationship was examined with conventional fiberglass filter bags and with filter bags that have an ePTFE membrane laminated to the woven fiberglass. On average, the results show a 41% decrease in fabric filter drag that allowed actual stack gas flow to increase by 5% and baghouse pressure differential to decrease by 39%. Results suggest the lower drag is attributable to improved ash removal from the bag during cleaning and not due to lower resistance through the filter media itself. Maximum electric power generation increased by 2.8% during the peak summer demand period due to the higher gas flow achieved with the ePTFE membrane bags.

NOMENCLATURE

$DP_{t/s}$ = tubesheet differential pressure, in w.g.
$DP_{(mech)}$ = differential pressure across baghouse dampers and plenums, in. w.g.
$DP_{(baghouse)}$ = flange to flange fabric filter pressure differential, in. w.g.
K_f = fabric resistance coefficient
V = filter velocity (air to cloth ratio), fpm
Vol = actual stack gas flow, thousand actual cubic feet per minute (kacfm)
K_2 = specific dust cake resistance
Wr = residual dust cake
C = the fly ash (dust) loading in the gas stream
t = filtration time between cleanings
K_3 = constant (specific to the size and shape of the plenums and dampers)
$Drag_{(tubesheet)}$ = resistance to flow across the tubesheet. in. w.g./fpm
$Drag_{(mech)}$ = resistance to flow through the baghouse plenums and dampers, in. w.g./fpm
$Drag_{(baghouse)}$ = Resistance to flow across the entire fabric filter, in w.g./fpm
MW = Electrical power generation, megawatts

INTRODUCTION

An Electrostatic Precipitator (ESP) exhibits no gas flow constriction caused by high pressure differential from the inlet flange to the outlet flange of the casing. However, particulate emissions vary based on such factors as Specific Collecting Area (SCA) and the inlet fly ash load. Higher inlet fly ash loading does not cause increased pressure loss, but may create higher particulate emissions from the control device.

In the case where a fabric filter (also referred to as a baghouse) is utilized to filter the flue gas, particulate emissions are much less dependent on the inlet ash load as compared to ESP's. However, increased fly ash loading can result in increased pressure loss. With a baghouse increased ash load does require more frequent or vigorous cleaning. This, generally, leads to slightly higher emissions just after bag cleaning. So the inlet loading does affect the outlet emission level.

Regardless, baghouses can comply with the strictest particulate emission standards encountered. This is especially true of bags that use an ePTFE membrane laminated onto a backing material. With respect to baghouses, the tradeoff of low emissions with higher ash loading is a higher pressure drop across the baghouse, which leads to lower stack gas flow and possibly less electrical power generation.

Baghouses can use the following methods to remove the fly ash from the bags:

- Shaking the bags – ash collects on the inside of the bags (Shaker)
- Shaking in combination with a relatively low flow of gas in the reverse direction through the bags – ash collects on the inside of the bags (Shake and deflate)
- Compressed air pulsed into the bags – ash collects on the outside of the bags (Pulse)
- Gas flow in the reverse direction and sometimes assisted by a sonic horn – ash collects on the inside of the bags. (Reverse gas).

This paper investigates the relationship between the baghouse differential pressure and gas flow using conventional woven fiberglass filter media bags and the same relationship using filter bags that have an ePTFE membrane laminated to the fiberglass media. Additionally, the relationship between gas flow and electric power generation will be discussed. In particular, the paper documents the performance of a coal fired boiler at the Drake Station, a power plant operated by Colorado Springs Utilities (CSU), a publicly owned utility in the Western United States

ORIGINAL DESIGN

Originally CSU installed an ESP to control emissions from their #6 boiler at Drake Station. Due to concerns about increased opacity the utility replaced the ESP with a baghouse filter in 1977. The No. 6 baghouse uses the reverse gas cleaning method. Sonics horns are available to assist the cleaning, if needed. The baghouse was designed to handle the flue gas from a Babcock and Wilcox pulverized coal boiler. The furnace operates under positive pressure.

The boiler used subituminous coal mined in the Western USA. The relatively low heat value and the extremely low sulfur content of the fuel made compliance with existing opacity requirements problematic for an ESP. Table 1 shows the original design conditions used in sizing the baghouse.

Table 1: Original design conditions

Elevation	ft (amsl)	5957
Total flue gas flue rate	Acfm	400,000
Dust in flue gas entering baghouse	grs/acf	5.55
Coal fired	lb/hr	93,400
Coal Analysis		
Moisture	%	13.4
Ash (maximum0	%	15.6
Sulfur (minimum)	%	0.3
Volatile matter	%	29.5
Fixed Carbon	%	40.9
Heating value	Btu/lb	9300
Power Generation	MW	85

Based on these design conditions the utility decided to use a twelve compartment baghouse with reverse gas cleaning. Table 2 shows the sizing for the baghouse:

The first set of filter bags were woven fiberglass (10 oz/sq yd) with a Teflon B finish cleaned with reverse gas. Glass provides excellent resistance to acid attack, can easily withstand the maximum inlet gas temperature, and is dimensionally stable.

Table 2: Original Baghouse Sizing

Baghouse Cleaning		Reverse Gas
Filter Media		Woven Fiberglass
Baghouse inlet gas volume	Acfm	400,000
Baghouse inlet temperature	F	315
Compartments		12
Bags/compartment		198
Nominal bag diameter	Inches	12.0
Nominal bag length	Ft	30.0
Compartments off line for cleaning		1
Gross air/cloth ratio	Fpm	1.79
Net air/cloth ratio (with rev air)	Fpm	2.12
Reverse gas flow	Acfm	29,000 to 36,000
Max. expected baghouse DP	in. w.g.	6.0
Removal Efficiency	%	99.9
Outlet Emissions	grs/acf	0.008
Expected Bag Life	Yr	3

PRESSURE DIFFERENTIAL AND FILTER VELOCITY RELATIONSHIP

The relationship between the baghouse pressure drop and the flue gas volume is directly proportionate to the filter velocity (sometimes referred to as the air to cloth ratio). The baghouse pressure drop is the combination of the pressure drop across the individual compartments (tubesheet differential pressure) and the frictional losses through the plenums and dampers. Earlier authors (1) have found laminar flow through the filter bag. The relationship between the tubesheet differential and the filter velocity has been expressed as follows: (2)

$$DP_{t/s} = K_f V + K_2 WrV + K_2 CtV^2$$

Equation 1

Assuming turbulent flow through the plenums and dampers the pressure loss across the plenums can be written as follows:

$$DP_{(mech)} = K_3 V^2$$

Equation 2

The baghouse differential is the sum of the tubesheet differential and the frictional losses through the plenums and dampers.

$$DP_{(baghouse)} = DP_{t/s} + DP_{mech}$$

Equation 3

Equation 3 is equivalent to the following expanded form:

$$DP_{(baghouse)} = K_f V + K_2 WrV + K_2 CtV^2 + K_3 V^2$$

Equation 3a

The first term in Equation 3a represents the pressured drop across the fabric itself. This is generally negligible, but can be substantial in cases where the dust or ash plugs into the interstitial spaces of the fabric.

For conventional fiberglass filter media the permeability starts at a very high level, with – 30 to 40 cfm/sq ft @ ½ inch w.g. differential common. In service this value quickly drops to 2 to 3 cfm. For membrane bags the permeability starts at a much lower level (typically 6 to 8 cfm) and drops over a longer period to the 2 to 3 cfm level. Since the filter velocity is very low (about 2 fpm) the flow through the fabric is in the laminar range where the pressure differential is proportionate to the first power of the velocity (1).

The second term in Equation 3a represents the pressure differential caused by the dust cake that remains on the inside of the surface of the bag after cleaning. This can be referred to as the residual dust cake. The most effective reverse gas cleaning systems even with sonic horn assist will leave some dust within the bag. Conventional bags rely on this dust cake for filtration. The velocity through the dust cake is again very low and it reasonable to assume that the velocity is in the laminar range where the pressure drop is proportionate to the first power of the filter velocity.

The third term in Equation 3a represents the dust accumulation in the bag since the last cleaning. Again this is at low velocity and can be assumed to be in the laminar range. Both the time between cleanings and the amount of dust accumulated in the bag between cleaning are proportionate to the dust loading and the filter velocity. Hence, the accumulated dust can be expressed as K_2CtV. So, the differential pressure attributable to the accumulated dust is $K_2CtV * V$ or K_2CtV^2. This introduces a velocity square term to the tubesheet pressure drop equation.

K_2 is primarily a function of the porosity of the dust cake and is influenced by the dust particle size distribution. K_2 is expected to be lower where the particles are large and agglomerate easily. Liquid water carry over to the bags (as may occur during tube leaks) can significantly lower the dust porosity resulting in higher tubesheet and baghouse differential pressure.

The fourth term in Equation 3a represents the pressure drop across the baghouse dampers and plenums. This component of the pressure is proportionate to the velocity squared.

EVALUATION OF BAGHOUSE PERFORMANCE

In order to evaluate the operation of the baghouse the utility furnished the following data with each point marked with the date and time of the reading.

- Power generation (MW)
- Stack gas flow (scfm)
- Baghouse DP (in. w.g.)
- Baghouse inlet temperature (degrees F)

With this data and adjusting for the plant elevation, the actual stack gas volume was calculated. The filter area was calculated and the estimated reverse gas flow was taken from the data sheets supplied by the original equipment manufacturer (Buell).

In analyzing the field data the following assumptions were applied:

1) The fly ash concentration in the gas stream is the same at all times. This does not mean the amount of fly ash is the same. The fly ash quantity varies with the gas volume. This is reasonable since the fuel and operating practice was similar during the analyzed periods.
2) All data samples are taken at the same time after cleaning, so the t in Equation 3a is a constant. This is not actually the case, but does not introduce a significant error since the time between cleanings is very short (about 5 minutes) and the cleaning cycle did not change in the evaluation periods.

Based on these assumptions Equation 3a can be rewritten as follows where the A and B coefficients can be determined empirically from the operating data.

$$DP_{(baghouse)} = AV^2 + BV$$

Equation 4

Since the actual gas volume is proportionate to the filter velocity Equation 4a follows:

$$DP_{(baghouse)} = A'(Vol)^2 + B'(Vol)$$

Equation 4a

Calculation of Filter Drag

The tubesheet filter drag is defined as the tubesheet differential divided by the filter velocity:

$$Drag_{(tubesheet)} = DP_{t/s}/V$$

Equation 5

The drag associated with the baghouse mechanical losses can be written as follows:

$$Drag_{(mech)} = DP_{(mech)}/V$$

Equation 6

In this case we do not have the individual compartment differential pressures, so the drag is extended to cover the entire baghouse.

$$Drag_{(baghouse)} = Drag_{(tubesheet)} + Drag_{(mechanical)}$$

$$= DP_{(baghouse)}/V$$

Equation 7

The drag equation is the first derivative of the pressure equation:

$$Drag_{(baghouse)} = AV + B$$

Equation 8

Reduced drag allows more gas flow through the baghouse or lower pressure drop across the baghouse or some combination of both.

In Equation 3a the constants K_2 (porosity constant of the dust cake), C (dust concentration in the gas stream), and K_3 (constant specific to the size and shape of the plenums and dampers) and t (time between cleaning) all influence the pressure loss related to the velocity to the second power. Changing the filter media cannot change these values. So, the change to membrane bags is not expected to reduce (A') coefficient associated with the velocity square term of Equation 3a.

Examining Equation 3a again finds that K_2, Wr (ash retained within the bag after cleaning), and K_f (fabric resistance coefficient) influence the pressure loss arising from the filter velocity to the first power. As stated before changing the filter media is not expected to change K_2 and the K_f constants. However, a filter media that cleans better would allow a lower value for Wr leading to a lower coefficient (B') preceding the velocity to the first power is expected upon conversion to membrane bags.

Membrane bags have an ePTFE membrane laminated to the backing material -- in this case woven fiberglass. The membrane deters fine ash particles from entering the interstitial spaces of the fabric and can make the fabric easier to clean.

For conventional fiberglass media the original permeability is very high (30 to 40 cfm/sq ft at ½ in. w.g.) across the fabric itself, but quickly drops in service to as low as 2 cfm/sq ft in a few months.

Membrane filter bags start with a lower permeability (6 to 8 cfm/sq ft) than conventional glass, but may drop to 3 to 4 cfm/sq ft in a few months. While the permeability is important to measure when assessing the filter bag performance, unless the bag is blinded (permeability less than 1 cfm/sq ft) the loss through the fabric itself does not account for a substantial amount of differential pressure across a filter bag.

With respect to reverse gas baghouses used in coal fired boiler applications the filter velocity is usually about 2 fpm. So, if the clean bag permeability is as low as 2 fpm the K_f term in Equation 3a only contributes ½ inch w.g. to the differential pressure across the bag.

Membrane bags offer the benefit of keeping the permeability in the acceptable range for a longer period of time. However, in the short term the difference in pressure loss through the clean fabric between membrane and conventional bags is negligible. The biggest advantage membrane bags can offer over conventional media results from better cleaning. Better cleaning means less residual dust in the bag reflected in a lower Wr term in the overall baghouse pressure drop equation (Equation 3a).

Actual Operations

Colorado Springs Utilities Drake Station Unit No. 6 now burns 20 to 25% Powder River Basin Coal at 8100 to 8300 Btu/lb and 75 to 80 % Foidel Creek Coal at 8600 to 8900 Btu/lb. Operating experience showed that the baghouse pressure drop increased as a result of the addition of Powder River Basin Coal to the fuel mix.

In order to reduce the higher than expected baghouse pressure differential and related gas flow restrictions, the CSU decided to replace the existing conventional woven fiberglass bags with ePTFE membrane filter bags during the October 2004 maintenance shut down.

Baghouse Performance Comparison

July 1 to October 4 2004 (conventional glass bag operation)

To evaluate the baghouse performance the utility furnished operating data taken twice daily from July 1 until the unit shut down on October 4 2004. The empirical data during this period is used to find the coefficients in general Equation 4a above. The following is the relationship between baghouse pressure loss and the stack gas flow;

$$DP_{(baghouse)} = 5.7488732 * 10^{-6} * (Vol)^2 + 1.23180890692 * 10^{-2} * (Vol)$$

$$R^2 = .71$$

Equation 9

The investigation of power generation and acfm yielded the following result;

$$MW = 3.251577633 * 10^{-5} * (Vol)^2 + 1.9866180880952 * 10^{-1} * (Vol)$$

$$R^2 = .91$$

Equation 10

Figures 1 and 2 and the following Table 4 summarizes the baghouse performance with conventional fiberglass bags during January 2004:

November 25 2005 to January 24 2006 (ePTFE membrane bag operation)

CSU shut down the No. #6 Boiler on October 4 2004 for a scheduled maintenance outage. During this time the existing bags were replaced with ePTFE membrane filter bags. As would be expected after the start up on November 25 2004 the bags showed a much lower differential pressure. In order to allow the membrane bags to reach equilibrium their performance was examined commencing one year after start up. The data during this period is used to determine the coefficients for general Equation 4a above.

$$DP_{(baghouse)} = 9.692337 * 10^{-6} * (Vol)^2 + 4.965477160 * 10^{-3} * (Vol)$$

$$R^2 = .56$$

Equation 11

The investigation of power generation and acfm during the membrane bags operating period yields the following result;

$$MW = 2.363497172 * 10^{-5} * (Vol)^2 + 2.2049881796487 * 10^{-1} (Vol)$$

$$R^2 = .89$$

Equation 12

Figures 1 and 2 and the following Table 4 summarize the baghouse performance with ePTFE membrane filter bags during both periods.

DISCUSSION OF RESULTS

It is significant to note that the results show that the pressure loss component that is proportionate to the velocity square term actually increased with membrane bags. It is not clear why this occurred. Perhaps there were some subtle changes in the ash loading. However, the velocity square component of the pressure is the smaller part of the overall baghouse pressure differential. Much of this is the loss through the inlet dampers and is not influenced by the filter media.

The important improvement is the much lower coefficient associated with flow through the bags in the laminar range where the pressure loss is proportionate to the first power of the velocity. In the laminar flow range the pressure drop was 60% lower with ePTFE bags at the average stack gas flow. This is a likely indication that the membrane bag cleans much more effectively resulting in less residual dust in the bag after cleaning, so the Wr term in Equation 3a is lower.

Table 4: Baghouse performance (conventional glass filter bags)

Unit 6 -- Operation with Conventional Fiberglass Bags		Begin	End
Data Period		1-Jul-2004	4-Oct-2004
		Average	Maximum
Stack Gas Flow	acfm	327,287	386,655
Stack Gas Flow	scfm	180,493	206,061
Baghouse Inlet temperature	F	309	339
Baghouse DP	In. w.g.	4.66	6.80
Gross Air to Cloth ratio	fpm	1.50	1.77
Net air to Cloth ratio	fpm	1.77	2.07
Drag $_{\text{(baghouse)}}$	in w.g./fpm	3.11	3.84
Generated Power	MW	68.6	82.7

Unit 6 -- Operation with ePTFE Membrane Bags		Begin	End
Data Period		25-Nov-2005	24-Jan-2006
		Average	Maximum
Stack Gas Flow	acfm	344,135	374,677
Stack Gas Flow	scfm	193,408	210,060
Baghouse Inlet temperature	F	297	321
Baghouse DP	In. w.g.	2.86	3.97
Gross Air to Cloth ratio	fpm	1.58	1.72
Net air to Cloth ratio	fpm	1.86	2.01
Drag $_{\text{(baghouse)}}$	in w.g./fpm	1.82	2.31
Generated Power	MW	78.7	85.0

Increased power generation was CSU’s expected goal when they decided to use the membrane bags. Actual results show that CSU was able to increase the maximum power generation to 85.0 MW with the membrane bags vs. 82.7 MW with conventional fiberglass bags. When using the conventional fiberglass bags, CSU had to decrease generation in the summer to maintain $NO_{(x)}$ and CO at the appropriate levels. Because of the decreased generation in the summer months CSU’s only option was purchase power on the open market at a premium price. The true benefit of the membrane bags is the 2.3 MW (2.8%) power increase that was not achievable with the conventional fiberglass bags.

Using a conservative figure of $ 50/MWhr for purchase power cost, the cost savings in the first year of operation during the summer period (April 15 to September 15) approached $345,000.

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Figure 1: Baghouse Differential Pressure vs. Stack Flow

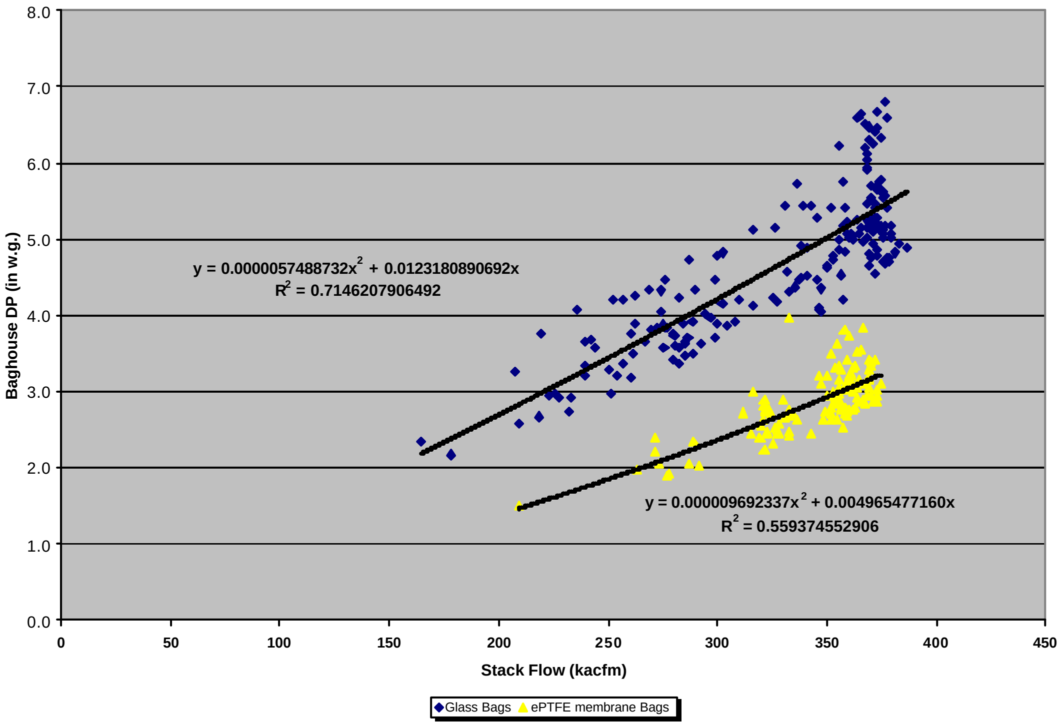

Figure 2: Power Generation vs. Stack Gas Flow