Lesson 3

Fabric Filter Design Variables

Goal

To familiarize you with the variables used by vendors to design fabric filter systems.

Objectives

At the end of this lesson, you will be able to do the following:

1. Define pressure drop and recognize the equations used to calculate pressure drop
2. Define the term *filter drag*
3. Define the terms *air-to-cloth ratio* and *filtration velocity*
4. Identify the typical air-to-cloth ratios for shaker, reverse-air, and pulse-jet baghouses

Video Presentation (optional): If you have acquired the video titled, *Pulse-Jet and Reverse-Air Fabric Filters: Operating Principles and Components,* please view it at the end of this lesson.

Introduction

Baghouses are designed by considering a number of variables: **pressure drop, filter drag, air-to-cloth ratio,** and **collection efficiency**. Although rarely done because it may not be possible or practical, it is a good idea to use a pilot-scale baghouse during the initial stages of the baghouse design. However, previous vendor experience with the same or similar process to be controlled will generally be adequate for design purposes. Careful design will reduce the number of operating problems and possible air pollution violations.

Pressure Drop

Pressure drop (Δp), a very important baghouse design variable, describes the resistance to air flow across the baghouse: the higher the pressure drop, the higher the resistance to air flow. Pressure drop is usually expressed in millimeters of mercury or inches of water. The pressure drop of a system (fabric filter) is determined by measuring the difference in total pressure at two points, usually the inlet and outlet. The total system pressure drop can be related to the size of the fan that would be necessary to either push or pull the exhaust gas through the baghouse. A baghouse with a high pressure drop would need more energy or possibly a larger fan to move the exhaust gas through the baghouse.

Many different relationships have been used to estimate the pressure drop across a fabric filter. In a baghouse, the total pressure drop is a function of the pressure drop across both the filter and the deposited dust cake. Some pressure losses due to friction also occur as the gas stream moves through the baghouse.

The simplest equation used to predict pressure drop across a filter is derived from Darcy's law governing the flow of fluids through porous materials and given as:

$$\Delta p_f = k_1 v_f \qquad (3\text{-}1)$$

Where: Δp_f = pressure drop across the clean fabric, in. H_2O (cm H_2O)
k_1 = fabric resistance, in. H_2O/(ft/min) [cm H_2O/(cm/sec)]
v_f = filtration velocity, ft/min (cm/sec)

The term k_1 is the fabric resistance (also called drag) and is a function of exhaust gas viscosity and filter characteristics such as thickness and porosity. Porosity describes the amount of void volume in the filter.

The pressure drop across the deposited dust cake can be estimated by using Equation 3-2 (Billings and Wilder 1970). This formula is also derived from Darcy's law and the simplified form is given as:

$$\Delta p_c = k_2 c_i v_f^2 t \qquad (3\text{-}2)$$

Where: Δp_c = pressure drop across the cake, in. H_2O (cm H_2O)
k_2 = resistance of the cake, in. H_2O/(lb/ft^2-ft/min$^)$
[cm H_2O/(g/cm2-cm/sec)]
c_i = dust concentration loading, lb/ft^3 (g/cm^3)
v_f = filtration velocity, ft/min (cm/sec)
t = filtration time, min (sec)

The term k_2 is the dust-fabric filter resistance coefficient and is determined experimentally. This coefficient depends on gas viscosity, particle density and dust porosity. The dust porosity is the amount of void volume in the dust cake. The porosity is related to the permeability. Permeability for the fabric only is defined in American Society of Testing and Materials (ASTM) standard D737-69 as the volume of air which can be passed through one square foot of filter medium with a pressure drop of no more than 0.5 inches of water. The term k_2 is dependent on the size of the particles in the gas stream. If the particles are very small (< 2μm) k_2 is high. If k_2 is high, then the pressure drop will tend to increase and the bags will have to be cleaned more frequently.

Filtration velocity also has an effect on k_2. In more recent tests, conducted in the late 1980's under controlled conditions, the relationships of k_2, particle size, and velocity have been shown more clearly. Researchers including Dennis, Cass, and Cooper (1977) and Davis and Kurzyske (1979) showed that both particle size and velocity have an effect on k_2.

The total pressure drop equals the pressure drop across the filter plus the pressure drop across the cake and is given as:

$$\Delta p_t = \Delta p_f + \Delta p_c \qquad (3\text{-}3)$$

$$\Delta p_t = k_1 v_f + k_2\, c_i\, v_f^2\, t \qquad (3\text{-}4)$$

Use equations 3-3 and 3-4 only as an estimate of pressure drop across shaker and reverse-air cleaning baghouses. In the industrial filtration process, complicated particle-fabric interactions are occurring just after the filtration cycle begins. In addition, the filter resistance factor k_1 can take on two values; one value for the filter before it is brought on-line and another after the filter has been cleaned. When the dust cake builds up to a significant thickness, the pressure drop will become exceedingly high (> 10 in. H_2O or 25 cm H_2O). At this time the filter must be cleaned. Some dust will remain on the cloth even after cleaning; therefore, the filter resistance level will be higher than during original conditions. A baghouse is normally operated with a pressure drop across the unit of 4 to 10 in. H_2O. But many units operate at less than 6 in. of H_2O. Bag cleaning is usually initiated when the pressure drop approaches this point.

Filter Drag

Filter drag is the filter resistance across the fabric-dust layer. The equation for filter drag essentially gives the pressure drop occurring per unit velocity. It is a function of the quantity of dust accumulated on the fabric and is given as:

$$S = \frac{\Delta p}{v_f} \qquad (3\text{-}5)$$

Where: S = filter drag, in. H_2O/(ft/min) [cm H_2O/(cm/sec)]
Δp = pressure drop across the fabric and dust cake, in. H_2O (cm H_2O)
v_f = filtration velocity, ft/min (cm/sec)

The true filtering surface of a woven filter is not the bag itself, but the dust layer. Dust bridges the pores or openings in the weave, plugging the openings with particles, increasing the drag rapidly.

Single Bag

A filter performance curve of a single bag of a fabric is shown in Figure 3-1. The drag is plotted versus the dust mass, or cake, deposited on the filter.

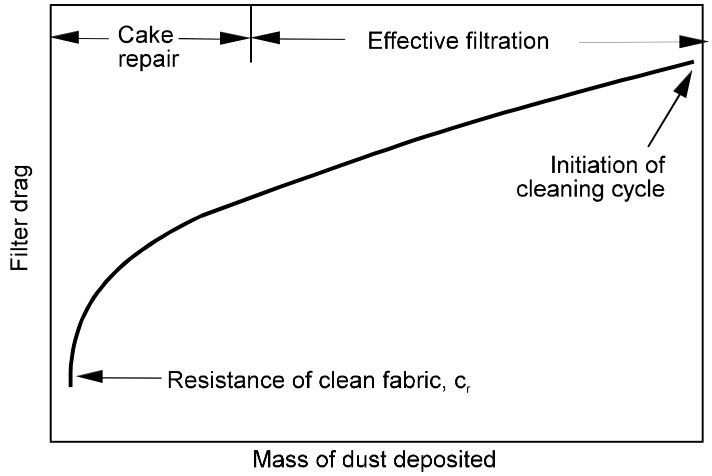

Figure 3-1. Performance curve for a single woven bag

The point c_r on the graph is the residual drag of the clean filter medium. The filter drag increases exponentially up to a constant rate of increase. This is the period of cake repair and initial cake buildup. Effective filtration takes place while the filter drag increases at a constant rate. When the total pressure drop reaches a value set by the system design, bag cleaning is initiated. At this point, the pressure drop decreases (almost vertically on the performance curve) to the initial point. Cake repair begins when the cleaning cycle stops and the cycle repeats. Baghouses are designed to remove most of the dust cake during the cleaning process. However, shaking or reverse-air baghouses are designed so that during the cleaning cycle some dust will remain on the bags. Therefore, a dust layer will *not* have to be built up again on the openings in the weave of the fabric. If the fabric is cleaned too efficiently, the cake repair cycle would be as long as the initial cake buildup, lessening the overall effective filtration time of the baghouse.

Multicompartment Baghouse

In multicompartment baghouses where the various compartments are cleaned one at a time, the performance curve takes on a different shape. In this case the change in the curve is less pronounced than in Figure 3-1. The performance curve has a slight saw tooth shape for the net pressure drop across the entire baghouse (Figure 3-2). Each of the minimum points on the curve represents the cleaning of an entire compartment. The average pressure drop would be represented by the dotted line. For optimum filtration rate and collection efficiency, the baghouse should be designed to operate at a pressure drop that approaches a constant value. This involves careful selection of fabrics and cleaning mechanisms for the baghouse. The weave, and any pretreatment of the fabric can affect the cake repair time. Poor cleaning will increase the filter drag; therefore, the bags must be thoroughly cleaned to reduce the filter drag effect. If cake repair time can be minimized, the pressure drop will be lower. Consequently, the effective filtration rate will be longer for optimum filtering use.

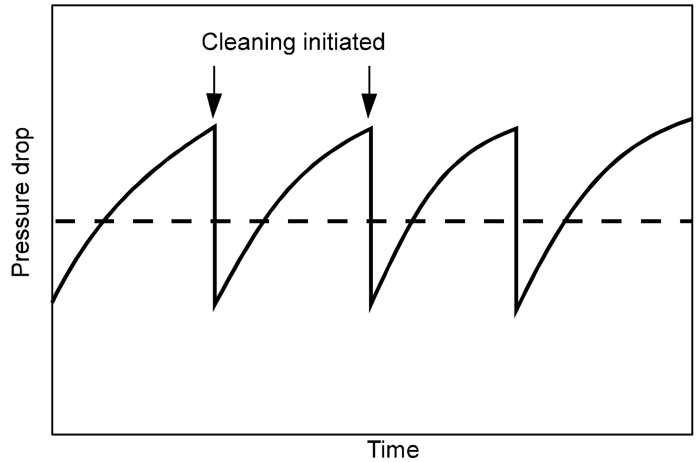

Figure 3-2. Overall pressure drop of a multi-compartment baghouse

Pulse-Jet Baghouse

In a pulse-jet baghouse, felted filters are typically used as bag material (although woven fabrics can also be used). Since there are no openings in the fabric material, there is no initial cake buildup period. Effective filtration begins immediately as the dust is filtered by the bag. The performance curve of a pulse-jet bag (or row of bags) is given in Figure 3-3. The pressure drop across the bags is slightly higher than with woven filters. The baghouse is usually operated with pressure drops of 4 to 6 in. of H_2O and occasionally as high as 10 in. of H_2O. In a pulse-jet baghouse one row of bags is cleaned at a time. Some of the dust is knocked off the bags being cleaned while adjacent rows are still filtering. Bag cleaning cycles are initiated to keep the overall pressure drop across the baghouse within the designed range. If off-line cleaning is used, a compartment is taken out of service and bag cleaning is initiated in that compartment (module).

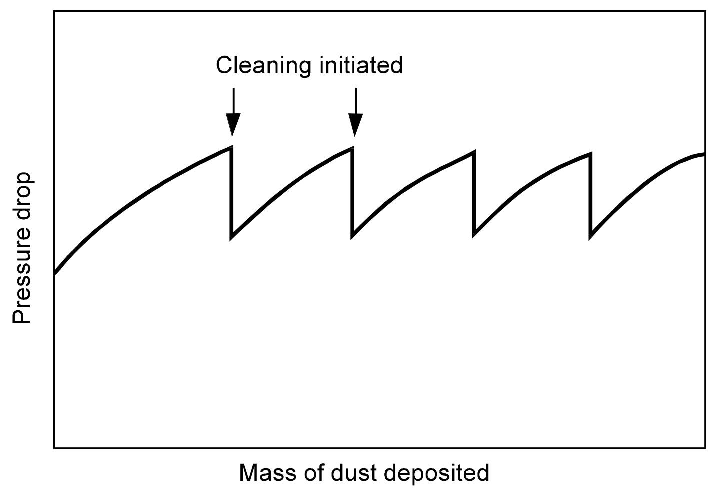

Figure 3-3. Performance curve of a pulse-jet bag or a row of bags

To test your knowledge of the preceding section, answer the questions in Part 1 of the Review Exercise.

Filtration Velocity: Air-To-Cloth Ratio

The terms *filtration velocity* and *air-to-cloth (A/C) ratio* can be used interchangeably. The formula used to express filtration velocity is:

$$v_f = \frac{Q}{A_c} \tag{3-6}$$

Where: v_f = filtration velocity, ft/min (cm/sec)
Q = volumetric air flow rate, ft^3/min (cm^3/sec)
A_c = area of cloth filter, ft^2 (cm^2)

The **air-to-cloth ratio** (also called the *gas-to-cloth ratio*) is defined as the ratio of gas filtered in cubic feet per minute (cfm) to the area of filtering media in square feet. Typical units used to express the A/C ratio are:

$(ft^3/min)/ft^2$ or $(cm^3/sec)/cm^2$

These A/C ratio units reduce to velocity units. The units for filtration velocity are ft/min or cm/sec.

The term **gross air-to-cloth ratio** refers to the total amount of cloth area used to filter the entire flue gas stream. The term **net air-to-cloth ratio** is used to describe the net amount of cloth available for filtering when one baghouse compartment is taken off-line for maintenance or bag cleaning. The term **net, net air-to-cloth ratio** describes the amount of cloth available when 2 compartments are taken off-line. In Lesson 5, you will learn how to calculate these ratios.

Bag Cleaning Comparisons

Air-to-cloth ratios describe how much dirty gas passes through a given surface area of filter in a given time. A high air-to-cloth ratio means a large volume of air passes through the fabric area. A low air-to-cloth ratio means a small volume of air passes through the fabric. When using the A/C ratios for comparison purposes the units are $(ft^3/min)/ft^2$ or $(cm^3/sec)/cm^2$. Likewise, when using filtration velocities the units are ft/min or cm/sec.

Reverse-air cleaning baghouses generally have very low air-to-cloth ratios. For reverse-air baghouses, the filtering velocity (filtration velocity) range is usually between 1 and 4 ft/min (0.51 and 2.04 cm/sec).

For shaker baghouses, the filtering velocity ranges between 2 and 6 ft/min (1.02 and 3.05 cm/sec). More cloth is generally needed for a given flow rate in a reverse-air baghouse than in a shaker baghouse. Hence, reverse-air baghouses tend to be larger in size.

Occasionally, baghouse cleaning is accomplished by two methods in combination. Many baghouses have been designed with both reverse-air and gentle shaking to remove the dust cake from the bag. This cleaning is called shake and deflate.

Pulse-jet baghouses are designed with filtering velocities between 2 and 15 ft/min (1 to 7.5 cm/sec), with many velocities falling in the 2.0 to 2.5 ft/min range. Therefore, these units typically use felted fabrics as bag material. Felted material holds up very well under the high filtering rate and vigorous pulse-jet cleaning. Due to their typically higher A/C ratios, pulse-jet baghouses are generally smaller in size than reverse-air and shaker baghouses. Pulse-jet cleaning methods have the advantage of having no moving parts within the compartments. In addition, pulse-jet units can clean bags on a continuous basis without isolating a compartment from service. The duration of the cleaning time is short (< 1.0 sec) when compared to the length of time between cleaning intervals (approximately 20 min to several hours). The major disadvantage of high pressure cleaning methods is that the bags are subjected to more mechanical stress. Fabrics with higher dimensional stability and high tensile strength are required for these units. Air-to-cloth ratios for the various cleaning methods are given in Table 3-1. Comparisons of the cleaning methods are given in Table 3-2.

Table 3-1. Typical air-to-cloth ratio (filtration velocity) comparisons for three cleaning mechanisms

Cleaning mechanisms	Air-to-cloth ratio		Filtration velocity	
	$(cm^3/sec)/cm^2$	$(ft^3/min)/ft^2$	cm/sec	ft/min
Shaking	1 to 3:1	2 to 6:1	1 to 3:1	2 to 6:1
Reverse-air	0.5 to 2:1	1 to 4:1	0.5 to 2:1	1 to 4:1
Pulse-jet	1 to 7.5:1	2 to 15:1	1 to 7.5:1	2 to 15:1

Note: These may vary for specific applications.

The A/C ratio (filtering velocity) is a very important factor used in the design and operation of a baghouse. Improper ratios can contribute to inefficient operation of the baghouse. Operating at an A/C ratio that is too high may lead to a number of problems. Very high ratios can cause compaction of dust on the bag resulting in excessive pressure drops. In addition, breakdown of the dust cake could also occur, which in turn results in reduced collection efficiency. The major problem of a baghouse using a very low A/C ratio is that the baghouse will be larger in size, and therefore have a higher capital cost.

Collection Efficiency

Extremely small particles (less than 1 μm in diameter) can be efficiently collected in a baghouse. Emission regulations for various industries including municipal waste combustors and hazardous waste incinerators require emission limits of 0.010 gr/dscf. Baghouse units designed with overall collection efficiencies of 99.9% (varying particle sizes) are common. Exhaust air from many baghouses can even be recirculated back into the plant for heating purposes, as long as the gas stream is not toxic.

Baghouses are not normally designed with the use of fractional efficiency curves as are some of the other particulate emission control devices. Vendors design and size the units strictly on experience. The baghouse units are designed to meet particulate emission outlet loading and opacity regulations. There is no one formula that can determine the collection efficiency of a baghouse. Some theoretical formulas for determining collection efficiency have been suggested, but these formulas contain numerous (3 to 4) experimentally determined coefficients in the equations. Therefore, these efficiency equations give at best only an estimate of baghouse performance.

Table 3-2. Comparison of bag cleaning parameters

Parameter	Shake cleaning	Reverse-air cleaning	Pulse-jet cleaning
Frequency	Usually several cycles/ second; adjustable	Cleaned one compartment at a time, sequencing one compartment after another; can be continuous or initiated by a maximum-pressure-drop switch	Usually, a row of bags at a time, sequenced one row after another; can sequence such that no adjacent rows clean one after another; initiation of cleaning can be triggered by maximum-pressure-drop switch or may be continuous
Motion	Simple harmonic or sinusoidal	Gentle collapse of bag (concave inward) upon deflation: slowly repressurize a compartment after completion of a backflush	Shock wave passes down bag; bag distends from cage momentarily
Peak acceleration	4 to 8 g	1 - 2 g	30 - 60 g
Amplitude	Fraction of an inch to few inches	NA	NA
Mode	Off-stream	Off-stream	On-stream: in difficult-to-clean applications such as coal-fired boilers, off-stream compartment cleaning being studied
Duration	10 to 100 cycles, 30 sec to few minutes	1 to 2 min. including valve opening and closing and dust settling periods: reverse-air flow itself normally 10-30 sec	Compressed-air (40 - 100 psi) pulse duration 0.1 sec: bag row effectively off-line
Common bag dimensions	5, 8, 12 in. diam; 8 to 10, 22, 30 ft length	8, 12 in. diam; 22, 30, 40 ft length	5 to 6 in. diam; 8 to 20 ft length
Bag tension	NA	50 to 120 lbs typical, optimum varies; adjusted after on-stream	NA

Sources: McKenna and Greiner 1982.
Dennis and Klemm 1980.
Morris 1984.

If you have acquired the video titled, *Pulse-Jet and Reverse-Air Fabric Filters: Operating Principles and Components*, please view it before proceeding to the next lesson.

To test your knowledge of the preceding section, answer the questions in Part 2 of the Review Exercise.

Review Exercise

Part 1

1. The ____________________ ____________________ of a system is determined by measuring the difference in total pressure at two points.

2. True or False? Compared to a baghouse with a high pressure drop, a baghouse with a low pressure drop would need a large fan and require more energy to move the gas through the baghouse.

3. What is the formula used to estimate the pressure drop across the clean fabric?

   a. $\Delta p_f = k_1 v_f$
   b. $\Delta p_c = k_2 v_f$
   c. $\Delta p_f = v_c^2 c_i t$

4. In the formula, $p_c = k_2 c_i v_f^2 t$, used to estimate the pressure drop across the dust cake, the term k_2 is the dust-fabric filter resistance coefficient. If the dust particles are very small (< 2 μm), k_2 is large. In this case, the pressure drop will:

   a. Generally decrease
   b. Generally increase
   c. Stay the same

5. Many baghouses operate with a pressure drop:

   a. Between 15 and 20 in. H_2O
   b. Greater than 20 in. H_2O
   c. Of approximately 4 to 6 in. H_2O

6. The filter resistance across a fabric-dust layer is called ____________________ ____________________.

7. In a reverse-air or shaker baghouse, bags are cleaned:

   a. To remove all dust completely
   b. To leave a small amount of dust on the bag
   c. To leave approximately 60% of the dust cake on the bag

8. True or False? The pressure drop across a pulse-jet baghouse is generally higher than across a reverse-air baghouse.

Part 2

9. True or False? The terms *filtration velocity,* (v_f), and *air-to-cloth ratio* (A/C) can be used interchangeably.

10. Air-to-cloth ratios:

    a. Describe how much dirty gas passes through a given surface area of filter in a given time
    b. Describe how efficiently bags are cleaned by a pulse of reverse air
    c. Indicate how fast the dirty air passes through a square foot of cloth material

11. Air-to-cloth ratios are usually expressed in units of:

    a. ft^2/min.
    b. $(ft^3/min)/ft^2$
    c. $(ft/min)/ft^2$

12. A high air-to-cloth ratio means that a ____________________ volume of air passes through the fabric.

13. The air-to-cloth ratios for shaker baghouses are typically less than ____________________ $(cm^3/sec)/cm^2$.

14. What are the usual air-to-cloth ratios for reverse-air baghouses?

    a. Less than 4:1 $(ft^3/min)/ft^2$
    b. Greater than 5:1 $(ft^3/min)/ft^2$
    c. Between 3:1 and 8:1 $(ft^3/min)/ft^2$

15. The baghouses that usually have the highest air-to-cloth ratios are:

    a. Pulse-jet
    b. Reverse-air
    c. Shaker

16. True or False? For a given exhaust flow rate, pulse-jet baghouses are usually smaller than reverse-air baghouses.

17. Operating the baghouse at air-to-cloth ratios ____________________ than the designed values can cause problems in the baghouse.

    a. Greater
    b. Less

Review Answers

Part 1

1. **Pressure drop**
The pressure drop of a system is determined by measuring the difference in total pressure at two points.

2. **False**
Baghouses with low pressure drops need *less* energy to move the exhaust gas than baghouses with high pressure drops.

3. **a. $\Delta p_f = k_1 v_f$**
The formula for estimating the pressure drop across the clean fabric is: $\Delta p_f = k_1 v_f$.

4. **b. Generally increase**
In the formula, $p_c = k_2 c_i v_f^2 t$, used to estimate the pressure drop across the dust cake, the term k_2 is the dust-fabric filter resistance coefficient. If the dust particles are very small (< 2 μm), k_2 is large. In this case, the pressure drop will generally increase.

5. **c. Of approximately 4 to 6 in. H_2O**
Many baghouses operate with a pressure drop of approximately 4 to 6 in. H_2O, but the pressure drop in some baghouses can sometimes be as high as 10 in. of H_2O.

6. **Filter drag**
The filter resistance across a fabric-dust layer is called filter drag.

7. **b. To leave a small amount of dust on the bag**
In a reverse-air or shaker baghouse, bags are cleaned to the point where a small amount of dust is left on the bag.

8. **True**
The pressure drop across a pulse-jet baghouse is generally higher than across a reverse-air baghouse.

Part 2

9. **True**
The terms *filtration velocity,* (v_f), and *air-to-cloth ratio* (A/C) can be used interchangeably.

10. **a. Describe how much dirty gas passes through a given surface area of filter in a given time.**
Air-to-cloth ratios describe how much dirty gas passes through a given surface area of filter in a given time.

11. **b. $(ft^3/min)/ft^2$**
Air-to-cloth ratios are usually expressed in units of $(ft^3/min)/ft^2$.

12. **Large**
    A high air-to-cloth ratio means that a large volume of air passes through the fabric.

13. **3:1 (cm^3/sec)/cm^2 [6:1 (ft^3/min)/ft^2]**
    The air-to-cloth ratios for shaker baghouses are typically less than 3:1 (cm^3/sec)/cm^2 [6:1 (ft^3/min)/ft^2].

14. **a. Less than 4:1 (ft^3/min)/ft^2**
    Air-to-cloth ratios for reverse-air baghouses are usually less than 4:1 (ft^3/min)/ft^2.

15. **a. Pulse-jet**
    Pulse-jet baghouses usually have the highest air-to-cloth ratios.

16. **True**
    For a given exhaust flow rate, pulse-jet baghouses are usually smaller than reverse-air baghouses.

17. **a. Greater**
    Operating the baghouse at air-to-cloth ratios greater than the designed values can cause problems in the baghouse.

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