2
Fabric Filtration

Lawrence K. Wang, Clint Williford, and Wei-Yin Chen

CONTENTS

1. INTRODUCTION

Fabric filtration is a physical separation process in which a gas or liquid containing solids passes through a porous fabric medium, which retains the solids. This process may operate in a batch or semicontinuous mode, with periodic removal of the retained solids from the filter medium. Filtration systems may also be designed to operate in a continuous manner. As with other filtration techniques, an accumulating solid cake performs the bulk of the filtration. Importantly, an initial layer of filter cake must form at the beginning of the filtration operation (1,2).

Fabric filtration effectively controls environmental pollutants in gaseous or liquid streams. In air pollution control systems, it removes dry particles from gaseous emissions; in water pollution control, filtration removes suspended solids; in solid-waste disposal, filtration concentrates solids, reducing the landfill area required. Often, filtration processes simultaneously reduce air, water, and solid-waste disposal problems. An air pollution control system might, for example, remove particles and/or gases from an emission source and might consist of a scrubbing device that removes particulates by impaction and the gases by chemical absorption. The reaction products of gases and chemicals can produce a crystalline sludge. A fabric filter may also be used to remove solids from water so that the water can be recycled. As a result, effluent slurry does not present a water pollution problem. Effective use (optimization) of a fabric-filter system would minimize problems with waste disposal.

From: *Handbook of Environmental Engineering, Volume 1: Air Pollution Control Engineering*
Edited by: L. K. Wang, N. C. Pereira, and Y.-T. Hung © The Humana Press, Inc., Totowa, NJ

Although fabric filtration is suitable for removing solids from both gases and liquids, it is often important that the filter remain dry when gases are filtered, and likewise, it may be desirable to prevent the filter from drying out when liquids are filtered. In the gas system, many solids are deliquescent, and if moisture is present, these materials will have a tendency to pick up moisture and dissolve slightly, causing a bridging or blinding of the filter cloth. The result is a "mudded" filter fabric. In such cases, it is often impossible to remove this material from the cloth without washing or scraping the filter. If the cake on the cloth is allowed to dry during liquid filtration, a reduction in the porosity of the cake as well as a partial blinding of the filter could result, which could then reduce the rate of subsequent filtration.

2. PRINCIPLE AND THEORY

In section 1, it was stated that the fabric itself provides the support, and true filtering usually occurs through the retained solid cake that builds up on the fabric. This is especially true for woven fabrics; however, felts themselves actually can be considered as the filtering media. It has also been stated that the cake must be removed periodically for continued operation. The resistance to fluid flow through the fabric therefore consists of cloth resistance and cake resistance and is measured as a pressure drop across the filter. Cleaned cloth resistance is often reported, although this in itself is not the new or completely clean cloth resistance. Once the filter has been used and cleaned a few times, a constant minimum resistance is achieved, which consists of the clean cloth resistance and the residual resistance resulting from deposited material that remains trapped in the cloth pores. This resistance may remain constant for the life of the fabric. Changes in this resistance usually indicate either plugging of the pores or breaking of the filter. Clean cloth resistances may be obtained from suppliers. However, it is best to obtain the steady-state values by empirical measurements. An example of clean cloth resistance, expressed according to the American Standards of Testing and Materials (ASTM) permeability tests for air, ranges from 10 to 110 $ft^3/min\text{-}ft^2$ (3–33.5 $m^3/min\text{-}m^2$) with a pressure differential of 0.5 in. (1.27 cm) H_2O. In general, at low velocities, the gas flow through the fabric filter is viscous, and the pressure drop across the filter is directly proportional to flow:

$$\Delta P_1 = K_1 v \tag{1}$$

where ΔP_1 is the pressure drop across fabric (inches of water [cm H_2O]), K_1 is the resistance of the fabric [in. H_2O/ft/min (cm H_2O/m/min)], and v is gas flow velocity [ft/min (m/min)].

In practice, the fabric resistance K_1 is usually determined empirically. It is possible to estimate a theoretical value of this resistance coefficient from the properties of cloth media. Darcy's law states that

$$\Delta P_1 = -\left(vK/\mu\right) + \rho g \tag{2}$$

where K is the Kozeny permeability coefficient, μ is viscosity, ρ is density, and g is gravitational acceleration. Note that necessary constants need to be applied to make the equation dimensionally consistent. Values of the permeability coefficient K found in literature range between 10^{-14} and 10^{-6} ft^2 (10^{-15} and 10^{-8} m^2). Values of K may also be estimated using the relation

$$K = \varepsilon^3 / cS^2 \tag{3}$$

where ε is porosity or fraction void volume (dimensionless), c is a flow constant, K is the Kozeny coefficients, and S is the specific surface area per unit volume of porous media [ft^{-1} (m^{-1})]. Values of the Kozeny constant can be estimated using the free-surface model (2). Assuming a random orientation averaging two cross-flow fibers and one parallel fiber and assuming that a cloth medium behaves like a bed of randomly oriented cylinders, the constant for flow parallel to the cylinder is obtained by

$$c = 2\varepsilon^3 \Big/ \left\{ (1-\varepsilon)\left[2\ln\frac{1}{1-\varepsilon} - 3 + 4(1-\varepsilon) - (1-\varepsilon)^2 \right] \right\} \tag{4}$$

and when flow is at right angles to the cylinder,

$$c = 2\varepsilon^3 \Big/ \left\{ (1-\varepsilon)\left[\ln\left(\frac{1}{1-\varepsilon}\right) - \frac{1-(1-\varepsilon)^2}{1+(1-\varepsilon)^2} \right] \right\} \tag{5}$$

As the system is operated, cake deposits on the fabric, producing an additional flow resistance proportional to the properties of the granular cake layer. The resistance to fluid flow owing to cake build-up usually amounts to a significant portion of the total flow resistance. This resistance increases with time as the cake thickness increases. This additional resistance (ΔP_2) is typically of the same order of magnitude as the residual resistance (ΔP_1) and can be expressed as

$$\Delta P_2 = K_2 v^2 L t \tag{6}$$

where ΔP_2 is the change in pressure drop over time interval t [in. H_2O (cm H_2O)], K_2 is the cake-fabric filter resistance coefficient,

$$\left[\frac{\text{in. of water}}{(\text{lb}_\text{m}\text{dust}/\text{ft}^2)(\text{ft}/\text{min})} \right] \text{or} \left[\frac{\text{cm of water}}{(\text{kg dust}/\text{m}^2)(\text{m}/\text{min})} \right]$$

v is fluid velocity [ft/min (m/min)], L is inlet solids concentration [lb/ft^3 (kg/m^3)], and t is time (min). An expression for the cake–fabric filter resistance coefficient using the Kozeny–Carman procedure has been derived for determining flow through granular media (2):

$$K_2 = (3.2 \times 10^{-3}) \left(\frac{k}{g} \right) \left(\frac{\mu_f S^2}{\rho_p} \right) \left(\frac{1-\varepsilon}{\varepsilon^3} \right) \tag{7}$$

where k is the Kozeny–Carman coefficient, which equals approx 5 for a wide variety of fibrous and granular materials up to a porosity equal to about 0.8, ε is the porosity or fraction void volume in cake layer (dimensionless), μ_f is fluid viscosity [$lb_m/(s\ ft)$], ρ_P is the true density of solid material (lb_m/ft^3), and the S is the specific surface area/unit volume of solids in the cake layer (ft^{-1}). This equation shows that as the particles being filtered become smaller in diameter, the porosity of the cake decreases and consequently, K_2 increases. The net result of the larger cake–fabric filter resistance coefficient (K_2) is that the pressure drop increases as porosity decreases.

Table 1
Dust-Fabric Resistance Coefficients for Certain Industrial Dusts on Cloth-Type Air Filters

	K_2 (in. water per lb of dust per ft^2 per ft per m in of filtering velocity)[a] for particle size less than the following						
	Coarse		Medium[b]			Fine[b]	
Dust	~800 μm	~100 μm	~44 μm	<90 μm	<45 μm	<20 μm	<2 μm
Granite	1.58	2.20				19.80	
Foundry	0.62	1.58	3.78				
Gypsum			6.30			18.90	
Feldspar			6.30			27.30	
Stone	0.96			6.30			
Lamp black							47.20
Zinc oxide							15.70[c]
Wood				6.30		25.20	
Resin (cold)	0.62		11.00				
Oats	1.58		9.60	8.80			
Corn	0.62		1.58	3.78			

[a] $\dfrac{\text{in. water}}{(\text{lb/ft}^2)(\text{ft/min})} = \dfrac{1.75 \text{ cm water}}{(\text{kg/m}^2)(\text{m/min})}$

[b]Theoretical size of silica, no correction made for materials having other densities.
[c]Flocculated material, not dispersed; size actually larger.
Source: ref. 2.

The value of the dust–fabric filter resistance coefficient is necessary to predict the operating pressure drop in new fabric-filter installations. This information, with filter velocity and time between cleaning cycles, then may be used to estimate optimum operational procedures, which affect both installation and operating expenses. Some typical dust–fabric resistance coefficients for air–dust filter systems are given (2) in Table 1. The resistance coefficients calculated by Eq. (7) do not always agree with the values obtained from operating systems using Eq. (6). Some engineering data (2–4) are summarized in Table 2 for several particle sizes ranging from 0.1 to 100 μm for solids with a density of 2 g/cm^3. The specific area is estimated assuming spherical particles and standard conditions (SC) of 70°F (21.1°C) and 1 atm pressure. These data are taken from industrial cloth-type air filters.

The above equations and tables show that the various parameters of pressure drop, velocity inlet loading, and time are closely coupled with the physical properties of both the fluid and the solids being filtered. The value of K_2 also depends on the size distribution of the particles, which is often neglected when estimating porosity. Particles usually exhibit a log-normal (geometric) probability distribution. Two materials with the same mass mean size could be quite different in size distribution (geometric deviation), which would affect the porosity of the cake. The shape of the particles, which is not accounted for in the theoretical equations, is also significant and influences both cake porosity and fluid flow drag.

Table 2
Comparison of Calculated and Observed Dust-Fabric-Filter Resistance Coefficients (K_2) (4)

Particle size (μm)	S (ft^{-1})	Porosity ε	$\frac{1-\varepsilon}{\varepsilon^3}$	Resistance coefficient (K_2), in. $H_2O/(lb/ft^2)(ft/min)$	
				Calculated using Eqs. (6) and (7)	Observed
0.1	1.83×10^7	0.25	48.0	41,200	715
1	1.83×10^6	0.40	9.38	705	180
10	1.83×10^5	0.55	2.70	2.32	12
100	1.83×10^4	0.70	0.878	7.56×10^{-3}	0.2

When no data are available, it has been shown that it is possible to estimate values of the resistance coefficient; however, it is more desirable to obtain the coefficient by actual measurements [operating data and Eq. (6)] when this is possible. Once the coefficient is known, any one of the parameters in Eq. (6) can be determined by specifying the remaining variables.

Empirically derived values for the resistance coefficient also may differ for similar systems under different operating conditions. For example, if the cake is composed of hard, granular particles, it will be rigid and essentially incompressible. As the filtration process continues, there is no deformation of the particles and the porosity remains constant. On the other hand, if the cake is extremely soft, it can be deformed, resulting in a different effective porosity as filtration continues. The amount of cake buildup, which is a function of gas velocity, inlet solids concentration, and time, must be considered when attempting to obtain a meaningful value of K_2 for similar systems.

An equally perplexing problem is the fact that there is no standardized filtration rating test procedure. Ratings such as "nominal," "absolute," and "mean flow pore" serve largely to describe filter systems, but they do not provide a rational basis for filtration engineering and analysis.

Fabric filters consist of a porous filtration medium, in which the pores are not all uniform in size. Therefore, attempts are made in the rating procedures to take this into consideration; for example, the mean flow pore system exerts air pressure to one side of a porous filter, and the pressure is noted at which the first bubble appears on the wetted medium. This is called the bubble point and corresponds to the largest pore in the filter. The distribution of pores in the medium would be expected to be log-normal and obtaining the pressure corresponding to the smallest pore is quite a different story. Recently, Cole (5) suggested a "summation of flow" rating, in which an attempt is made to define the pore size at which about 16% of the flow goes through larger pores.

A common laboratory technique for obtaining empirical data for liquid fabric filters is to use a device called a filter leaf. In the test procedure, the filter fabric is secured over a backup screen and inserted in the test system. Unfortunately, this procedure is not standardized, although Purchas (6) has proposed a standardized test procedure for liquid filtration tests. This procedure consists of obtaining a 1-cm-thick cake when utilizing a

pressure differential of 1 atm. The result for a given fabric–solid combination would be a "standard cake formation time expressed in minutes." In gas filtration tests, the most common method for expressing new fabric resistance is to measure the gas volumetric flow rate at a 0.5-in. (1.27 cm) H_2O pressure drop.

3. APPLICATION

3.1. General

The use of fabrics as a porous filter medium in both liquid and gas cleaning systems has been stated, and the separation of solids from liquids will be discussed in detail in other chapters of this handbook series. The major emphasis of this section is on gas cleaning, and, in most applications, the gas considered is air.

3.2. Gas Cleaning

Filters used to clean gases are categorized in this section in five different ways according to the energy required, the fabric employed, the type of cycle, the service, and the application. The first category includes either *high-energy* or *low-energy* filters, depending on whether the filters are operated at high or low filter pressure drops. For any given application involving filters, a high-energy system is usually more efficient, but, ultimately, this depends on the size, size distribution, and type of material being filtered. Energy and efficiency are not always directly related and will be discussed below.

High-energy systems generally consist of pulse-jet devices, whereas low-energy cleaning systems utilize shaking and reverse flow. Note that this classification also describes the cleaning method used to remove dust from the bags. In the pulse-jet systems, blasts of air are blown through jet nozzles in pulses to free the dust from the fabric, as shown in Fig. 1. Note that the cleaning jet is introduced into the Venturi nozzle to expand and clean the bag.

The low-energy systems are split approx 50–50 between continuous and intermittent-type collectors. Shaking, as the word states, simply implies mechanically flexing the bag to clean it. Reverse-flow applications consist of introducing air into *sections* of the filter system in the opposite direction from normal gas flow to blow the dust off the bags. There is a third category, in which no cleaning energy is utilized. This applies to units designed for situations in which the media are disposable.

Fabric filters can be divided generally into two basic types, depending upon the fabric: felt (unwoven) and woven. Felt media are normally used in high-energy cleaning systems; woven media are used in low-energy devices. Felt fabrics are tighter in construction (i.e., less porous), and for this reason, they can be considered to be more of a true filter medium and should be kept as clean as possible to perform satisfactorily as a filter. In contrast, the woven fabric is, in general, only a site upon which the true filtering occurs as the dust layer builds up, through which the actual filtering takes place. In addition, a third type of fabric filter is nonwoven disposable configuration material, which is used as a vacuum cleaner with disposable bags.

Filter systems can also be categorized as either *continuous* or *intermittent collectors*. In a continuous collector, the cleaning is accomplished by sectionalizing the filter so that, while one part is being cleaned, the rest of the filter is still in operation. Under these conditions, the gas flow through the device and the overall pressure drop across the device are essentially constant with time. In contrast, there must be an interruption

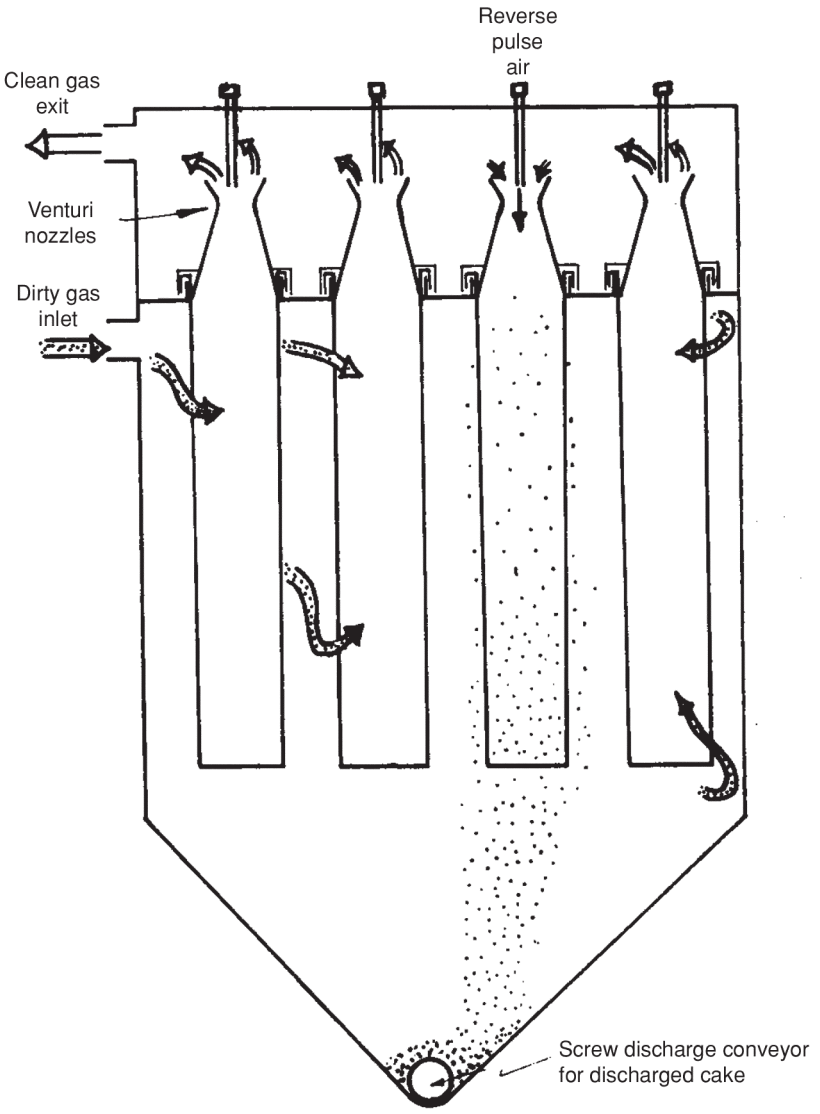

Fig. 1. Schematic diagram of a reverse-pulse baghouse.

in the gas flow while the cleaning process takes place in intermittent collectors. In these systems, gas flow is greatest immediately after the filter medium has been cleaned and decreases as the cake builds up. A typical cycle for an intermittent system is operating for 0.25–4 h and cleaning for 5 min.

A fourth major way in which fabric filters can be classified is by *service*. Particulate removal is the major service performed by fabric filters. However, they also can be used for gaseous control by adsorption and chemical adsorption (chemisorption), which are well-proven industrial techniques. For example, solid alumina can be used to adsorb chlorine; gaseous ammonia can be injected to react with sulfur oxides to form a solid particulate, which can be filtered; sodium and/or calcium compounds can be added as

precoats to react with and adsorb sulfur oxides; and activated carbon can be introduced to remove odors.

There is another basic service distinction between process and nonprocess work. Process functions may include the removal of material from air-conveying systems in which product collection is the primary function. A nonprocess application would be the removal of nuisance dust, where only a small amount of the product would actually encounter the filter. However, because of pollution control considerations, the same care and attention should be paid to nonprocess applications that have been given process collectors in the past.

The fifth and final classification of fabric filters is by *application*. These classes include temperature solids concentration type of pollution in the inlet gas moisture content suction, pressure applications size of filter and filter efficiency. The use of glass fiber media makes it possible to operate filters at temperatures up to about 550°F (288°C). A number of different fabric filter media and their characteristics are given in Table 3. Work is currently in progress to develop higher-temperature media, as indicated in the table.

Dust loading is defined as the concentration of solids in the inlet gas stream. Obviously, as dust loading increases, the amount of cake will increase for a given volumetric flow rate of gas. In order to maintain the necessary gas approach velocity and be able to operate an intermittent filter for a reasonable filter cycle time, it may be desirable to reduce the inlet dust loading. One method of doing this is to install mechanical collection devices in front of the fabric filter to remove large-diameter solid material. Gas conditioning, which can consist of introducing air as a diluent, could, in effect, reduce dust loading. However, this process is used more often to reduce inlet temperature and/or humidity.

It is a wise precaution to operate gas cleaning filter systems above the dew point temperature. It has been pointed out that if some dusts become wet, they will bridge and mud (plug) the filter. Methods of keeping the system above the dew point include insulating the filter, heating either the filter and/or the gas, and using warm, dry dilution gas.

Fabric filters can be used in systems that operate at either positive or negative pressures. Some systems are operated at pressures over 200 psi (1.38×10^6 N/m^2), and vacuum systems commonly operate at up to 15 in. (0.38 m) Hg. The most common operating range is ±20 in. (0.508 m) H_2O.

3.3. *Efficiency*

Fabric filters are extremely efficient solids removal devices and operate at nearly 100% efficiency. Efficiency depends on several factors (10,11):

1. Dust properties
   a. Size: particles between 0.1 and 1.0 μm in diameter may be more difficult to capture.
   b. Seepage characteristics: Small, spherical solid particles tend to escape.
   c. Inlet dust concentration: The deposit is likely to seal over sooner at high concentrations.
2. Fabric properties
   a. Surface depth: Shallow surfaces form a sealant dust cake sooner than napped surfaces.
   b. Weave thickness: Fabrics with high permeabilities, when clean, show lower efficiencies. Also, monofilament yarns, without fibrils protruding into the yarn interstices, show lower efficiencies than "fuzzier" staple yarns having similar interstitial spacing.

Table 3
Characteristics of Several Fibers Used in Fabric Filtration

Fiber type[a]	Max operating temp. (°F)	Resistance[b]				
		Abrasion	Mineral acids	Organic acids	Alkalis	Solvent
Cotton[c]	180	VG	P	G	P	E
Wool[d]	200	F/G	VG	VG	P/F	G
Modacrylic[d] (Dynel™)	160	F/G	E	E	E	E
Polypropylene[d]	200	E	E	E	E	G
Nylon polyamide[d] (Nylon 6 and 66)	200	E[e]	F	F	E	E
Acrylic[d] (Orlon™)	260	G	VG	G	F/G	E
Polyester[d] (Dacron[f])	275	VG	G	G	G	E
(Creslan™)	250	VG	G	G	G	E
Nylon aromatic[d] (Nomex™)	375	E	F	G	E	E
Fluorocarbon[d] (Teflon™, TFE)	450	F/G	E[g]	E[g]	E[g]	E[g]
Fiberglass[c]	500	F/G[h]	G	G	G	E
Ceramics[i] (Nextel 312™)	900+	—	—	—	—	—

[a]Fabric limited.
[b]P = poor resistance, F = fair resistance, G = good resistance, VG = very good resistance, E = excellent resistance.
[c]Woven fabrics only.
[d]Woven or felted fabrics.
[e]Considered to surpass all other fibers in abrasion resistance.
[f]Dacron dissolves partially in concentrated H_2SO_4.
[g]The most chemically resistant of all these fibers.
[h]After treatment with a lubricant coating.
[i]The ceramic fiber market is a very recent development. As a result, little information on long-term resistance and acid and alkali performance has been documented.
Source: Data from refs. 7–9.

   c. *Electrostatics*: Known to affect efficiency. (Particles, fabrics, and gas can all be influenced electrostatically and proper combination can significantly improve efficiency in both gas and liquid filtering systems.)

3. *Dust cake properties*
   a. Residual weight: The heavier the residual loading, the sooner the filter is apt to seal over.
   b. Residual particle size: The smaller the base particles, the smaller (and fewer) are the particles likely to escape.

4. *Air properties*. Humidity: with some dusts and fabrics, 60% relative humidity is much more effective than 20% relative humidity.
5. *Operational variables*
   a. Velocity: Increased velocity usually gives lower efficiency, but this can be reversed depending on the collection mechanisms, for example, impaction and infusion.

b. Pressure: Probably not a factor except that increase of pressure after part of the dust cake has formed can fracture it and greatly reduce efficiency until the cake reseals.
c. Cleaning: Relatively unstudied but discussed in the following sections.

It is important to stress that all of the considerations discussed thus far can be optimized only when the system is properly operated and maintained. Several of the factors mentioned earlier under operational variables are significant enough to merit further discussion in the following section.

4. ENGINEERING DESIGN

4.1. Pretreatment of an Emission Stream

The temperature of the emission stream should remain 50–100°F above the stream dew point. An emission stream too close to its dew point can experience moisture condensation, causing corrosion and bag rupture. Acid gases (e.g., SO_3) exacerbate this problem. Procedures for determining the dew point of an emission stream are provided in Chapter 1. If the emission stream temperature does not fall within the stated range, pretreatment (i.e., emission stream preheating or cooling) is necessary, as discussed in Chapter 1. Pretreatment alters emission stream characteristics, including those essential for baghouse design: emission stream temperature and flow rate. Therefore, after selecting an emission stream temperature, the new stream flow rate must be calculated. The calculation method depends on the type of pretreatment performed and should use appropriate standard industrial equations. Also, emission streams containing appreciable amounts of large particles (20–30 μm) typically undergo pretreatment with a mechanical dust collector. Chapter 1 also describes the use of mechanical dust collectors.

All fabric-filter systems share the same basic features and operate using the principle of aerodynamic capture of particles by fibers. Systems vary, however, in certain key details of construction and in the operating parameters. Successful design of a fabric filter depends on key design variables (7–26).

- Filter bag material
- Fabric cleaning method
- Air-to-cloth ratio
- Baghouse configuration (i.e., forced or induced draft)
- Materials of construction

4.2. Air-to-Cloth Ratio

The filtration velocity, or air-to-cloth (A/C) ratio, is defined as the ratio of actual volumetric air flow rate to the net cloth area. This superficial velocity can be expressed in units of feet per minute or as a ratio. A/C ratios of 1:1 to 10:1 are available in standard fabric-filter systems. Low-energy shaker and reverse-flow filters usually operate at A/C ratios of 1:1–3:1, whereas the high-energy reverse-pulse units operate at higher ratios.

Particulate collection on a filter fabric occurs by any or all mechanisms of inertial impaction, interception, and diffusion, as shown in Fig. 2. Inertial impaction occurs for particles above about 1 μm in diameter when the gas stream passes around the filter fiber, but the solid, with its high mass and inertia, collides with and is captured by the filter. Interception occurs when the particle moves with the gas stream around the filter fiber,

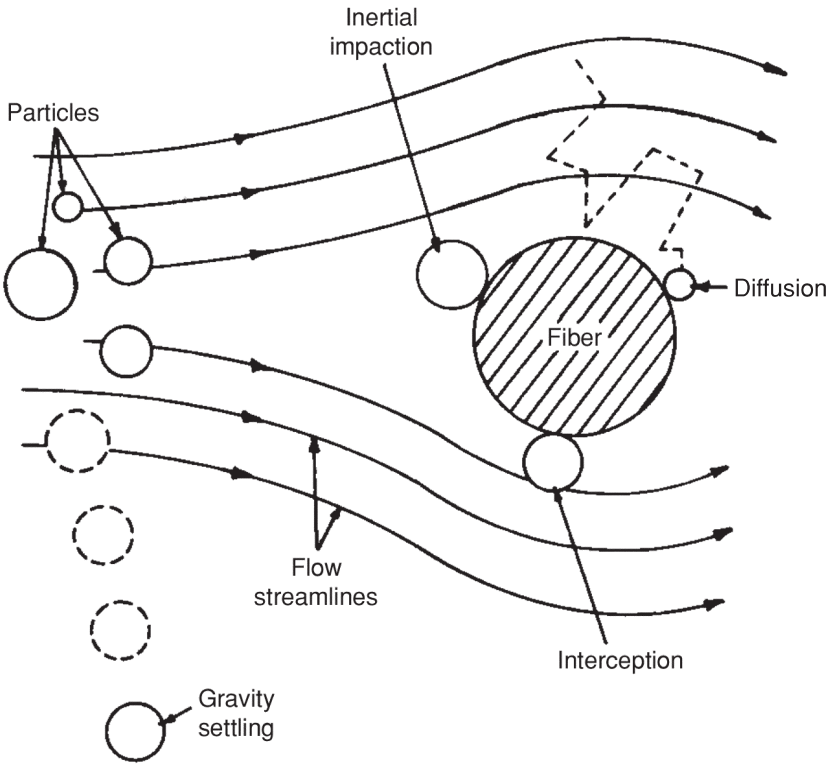

Fig. 2. Mechanisms for particle removal by a filter.

but touches and is captured by the filter. Diffusion consists of random particle motion in which the particles contact with and adhere to the fiber filters. Diffusion increases as particle size decreases and is only significant for submicron-diameter particles.

A high A/C ratio (filtering velocity) promotes particle capture by impaction. On the other hand, an excessive velocity will blow captured material off or through the fabric, in many cases the only support for the cake. This would reduce collection efficiency. As for filtering by diffusion, a higher air-to-cloth ratio reduces the residence time available for particle collection. "Normal" air-to-cloth ratios are about 3:1; "high" air-to-cloth ratios are 6:1 and above.

New filter fabrics having no buildup of solid material will often exhibit a pressure drop of 0.5 in. (1.27 cm) H_2O at normal air-to-cloth ratio ranges. This is called the fabric permeability and is often the same for woven and felted fabrics, although woven bags usually have a weight of 5–10 oz/yd^2 (170–340 g/m^2), and the much heavier and fuzzier felted bags have a weight of 10–20 oz/yd^2 (340–680 g/m^2). A/C ratios are not based on theoretical or empirical relationships, but on installation experience of industry and fabric-filter vendors. Recommended A/C ratios usually depend on a specific dust and a specific cleaning method.

Hand calculations using basic equations give only a general indication of the needed A/C ratio. In practice, tabulated values are frequently provided and are an approximation.

Table 4
Air-to-Cloth Ratios

Dust	Shaker/woven Reverse-air/woven	Pulse jet/felt
Alumina	2.5	8
Asbestos	3.0	10
Bauxite	2.5	8
Carbon black	1.5	5
Coal	2.5	8
Cocoa, chocolate	2.5	12
Clay	2.5	9
Cement	2.0	8
Cosmetics	1.5	10
Enamel frit	2.5	9
Feeds, grain	3.5	14
Feldspar	2.2	9
Fertilizer	3.0	8
Flour	3.0	12
Fly ash	2.5	5
Graphite	2.0	5
Gypsum	2.0	10
Iron ore	3.0	11
Iron oxide	2.5	7
Iron sulfate	2.0	6
Lead oxide	2.0	6
Leather dust	3.5	12
Lime	2.5	10
Limestone	2.7	8
Mica	2.7	9
Paint pigments	2.5	7
Paper	3.5	10
Plastics	2.5	7
Quartz	2.8	9
Rock dust	3.0	9
Sand	2.5	10
Sawdust (wood)	3.5	12
Silica	2.5	7
Slate	3.5	12
Soap detergents	2.0	5
Spices	2.7	10
Starch	3.0	8
Sugar	2.0	7
Talc	2.5	10
Tobacco	3.5	13
Zinc oxide	2.0	5

Note: Generally safe design values — application requires consideration of particle size and grain loading. A/C ratio units are $(ft^3/min)/(ft^2$ of cloth area).

Source: ref. 8.

Table 5
Factors to Obtain Gross Cloth Area from Net Cloth Area

Net cloth area, A_{nc} (ft^2)	Factor to obtain gross cloth area, A_{tc} (ft^2)
1–4,000	Multiply by 2
4,001–12,000	Multiply by 1.5
12,001–24,000	Multiply by 1.25
24,001–36,000	Multiply by 1.17
36,001–48,000	Multiply by 1.125
48,001–60,000	Multiply by 1.11
60,001–72,000	Multiply by 1.10
72,001–84,000	Multiply by 1.09
84,001–96,000	Multiply by 1.08
96,001–108,000	Multiply by 1.07
108,001–132,000	Multiply by 1.06
132,001–180,000	Multiply by 1.05

Source: ref. 8.

Computer software provides rigorous design. However, the purpose of this section is to provide the reader with some qualitative insight concerning the design and operation of fabric filters. Therefore, these programs are not discussed.

In addition to evaluating a particular fabric filter application, the A/C ratio and the emission stream flow rate ($Q_{e,a}$) are used to calculate net cloth area (A_{nc}):

$$\frac{Q_{e,a}}{\text{A/C ratio}} = A_{nc} \tag{8}$$

where $Q_{e,a}$ is the emission stream flow rate at actual conditions (acfm), A/C ratio is the air-to-cloth ratio, (acfm/ft^2 or ft/min) (from Table 4), and A_{nc} is the net cloth area (ft^2).

The net cloth area is the cloth area in active use at any point in time. Gross or total cloth area (A_{tc}), by comparison, is the total cloth area contained in a fabric filter, including that which is out of service at any point in time for cleaning or maintenance. In this text, costing of the fabric-filter structure and fabric filter bags uses gross cloth area. Table 5 presents factors to obtain gross cloth area from net cloth area:

$$A_{nc} \times \text{Factor} = A_{tc} \tag{9}$$

where Factor is the value from Table 5 (dimensionless) and, A_{tc} is the gross cloth area (ft^2). Fabric filters with higher A/C ratios require fewer bags and less space, and may be less expensive. However, the costs of more expensive (felted) bags, bag framework structure, increased power requirements, etc., may reduce the savings of high-A/C-ratio systems.

4.3. Fabric Cleaning Design

One removes the cake from the fabric by mechanically disturbing the system. This can be done by physically scraping the fabric, mechanically shaking it, or pneumatically or hydraulically reversing the flow of fluid through the fabric to clean the pores. For gas cleaning systems, the common cleaning methods include mechanical shaking, pulse cleaning, and reverse flow.

Fabric shaking combines stress in a normal direction to the dust–fabric interface (tension), stress directed parallel to the interface (shear), and stress developed during the warping, binding, or flexing of the fabric surfaces. Mechanical cleaning studies (10) indicate that dust removal efficiency is a function of the number of shakes, shaking frequency, shaking amplitude, and bag movement acceleration. In general, more dust is removed each time the bag is shaken. However, after about 100 shakes, very little extra dust can be removed, and 200 shakes are recommended as being optimum. At this point, often a maximum of only about 50% of the dust is removed. The shaking frequency is significant in that a resonance frequency can be set up when the fabric is mounted as a bag in a baghouse. More dust is removed at the resonance frequency, but, otherwise, it appears that the higher the frequency, the greater the amount of dust that is removed. In the shaker amplitude range 0–2 in. (0–5.08 cm), dust removal is increased with increased amplitude.

Filter capacity increases with bag shaking acceleration, up to 10 g. Beyond the acceleration range of 1.5–10 g, residual dust holding varies approximately with the inverse square root of the average bag acceleration. Other factors also affect fabric cleaning and filter capacity. These include initial bag tension, amount of cake deposited on the fabric, and cohesive forces binding dust to the fabric. The initial bag tension values should range between 0.5 and 5 lb_f (2–20 N).

Overcleaning requires additional energy and causes undue wear on the bag fabric. However, undercleaning a filter (e.g., by shaking less than the recommended 200 times), decreases system filtration capacity and adversely affects operating costs.

The amount of cleaning by pulsed-jet air varies directly with the rate of rise of the pressure differential across the bag. This should range from 1000 to 4000 in. (2500–10,000 cm) H_2O pressure drop per second. Residual resistance values after cleaning also depend on the dust–fabric combination. Mechanical shaking often augments the reversed-airflow cleaning of bags. This is especially applicable to woven fabric bags. Dust removal in woven bags during reverse flow is usually attributed to bag flexure. Reverse-flow cleaning is, in general, not a satisfactory cleaning technique. In fact, data indicate that in combined shaking–reverse-flow systems, mechanical shaking is responsible for essentially all of the cleaning. The main role played by the reverse air appears to be prevention of projection of dust into the clean air side of the system. Reverse-air cleaning velocities typically range from 4 to 11 ft/min with 0.3–3 ft^3 of gas required per square foot of bag area.

Selection of a cleaning method depends on the type of fabric used, the pollutant collected, and the experiences of manufacturers, vendors, and industry. A poor combination of filter-fabric and cleaning methods can cause premature failure of the fabric, incomplete cleaning, or blinding of the fabric. Blinding of a filter fabric occurs when the fabric pores are blocked and effective cleaning cannot occur. Blinding can result from moisture blocking the pores, increased dust adhesion, or high-velocity gas stream embedding of particles too deeply in the fabric. The selection of cleaning method may be based on cost, especially when more than one method is applicable. Cleaning methods are discussed individually below (13,14), with Table 6 containing a comparison of methods.

A summary of recommended A/C ratios by typical bag cleaning method for many dusts and fumes is found in Table 4. These ranges serve as a guide, but A/C ratios may

Table 6
Comparison of Fabric-Filter-Bag Cleaning Methods

Parameter	Mechanical shake	Reverse airflow	Pulse-jet individual bags	Pulse-jet compartmented bags
Cleaning on-line or off-line	Off-line	Off-line	On-line	Off-line
Cleaning time	High	High	Low	Low
Cleaning uniformity	Average	Good	Average	Good
Bag attrition	Average	Low	Average	Low
Equipment ruggedness	Average	Good	Good	Good
Fabric type[a]	Woven	Woven	Felt/woven[a]	Felt/woven[a]
Filter velocity	Average	Average	High	High
Power cost	Low	Low to medium	High to medium	Medium
Dust loading	Average	Average	Very high	High
Maximum temperature[b]	High	High	Medium	Medium
Collection efficiency	Good	Good	Good[c]	Good[c]

[a]With suitable backing, woven fabrics can perform similarly to felted.
[b]Fabric limited.
[c]For a properly operated system with moderate to low pressures, the collection efficiency may rival other methods.
Source: US EPA.

vary greatly from those reported. Fabric-filter size and cost will vary with A/C ratio. Lower A/C ratios, for example, require a larger and thus more expensive fabric filter.

4.4. Baghouse Configuration

Baghouses have two basic configurations, with gases either pushed through the system by a fan located on the upstream side (forced draft fan) or pulled through by a fan on the downstream side (induced draft fan). The former is called a positive-pressure baghouse; the latter, is called a negative-pressure or suction baghouse. Positive-pressure baghouses may be either open to the atmosphere or closed (sealed and pressure-isolated from the atmosphere). Negative-pressure baghouses can only be of the closed type. Only the closed suction design should be selected for a hazardous air pollutant application to prevent accidental release of captured pollutants. At temperatures near the gas stream dew point, greater care must be taken to prevent condensation, which can moisten the filter cake, plug the cloth, and promote corrosion of the housing and hoppers. In a suction-type fabric filter, infiltration of ambient air can occur, lowering the temperature below design levels (8).

4.5. Construction Materials

The most common material used in fabric-filter construction is carbon steel. In cases where the gas stream contains high concentrations of SO_3 or where liquid–gas contact areas are involved, stainless steel may be required. Stainless steel will increase the cost of the fabric filter significantly when compared to carbon steel. However, keeping the

emission stream temperature above the dew point and insulating the baghouse should eliminate the need for stainless steel.

4.6. Design Range of Effectiveness

A well-designed fabric filter can achieve collection efficiencies in excess of 99%, although optimal performance of the system may not occur for a number of cleaning cycles as the new filter material is "broken in." The fabric filter collection efficiency depends on the pressure drop across the system, component life, filter fabric, cleaning method and frequency, and the A/C ratio (13,14,26).

Performance can be improved by changing the A/C ratio, using a different fabric, or replacing worn or leaking filter bags. Collection efficiency can also be improved by decreasing the frequency of cleaning or allowing the system to operate over a greater pressure drop before cleaning is initiated. Section 5.2 will discuss the above filtration performance parameters in detail.

5. OPERATION

5.1. General Considerations

Many times, optimization of the fabric filter's collection efficiency occurs in the field after construction. The following discussion does not pertain to the preliminary design of the fabric filtration control system; however, the information presented should be helpful in achieving and maintaining the desired collection efficiency for the installed control system.

5.2. Collection Efficiency

To discuss fabric-filter "collection efficiency" is somewhat of a misnomer because a properly operated system yields very constant outlet concentrations over a broad range of inlet loadings. As such, the system really does not operate as an efficiency device—meaning that the performance of a fabric filter is not judged by the percent particulate matter (PM) reduction from initial PM concentration. Outlet concentrations are not a strong function of inlet loading. Typical outlet concentrations range between 0.001 and 0.01 g/dscf, averaging around 0.003–0.005 g/dscf. However, the term "collection efficiency" applies to a fabric-filter system when describing performance for a given application. The above given outlet concentration usually corresponds to very high collection efficiencies (17).

A well-designed fabric filter can achieve collection efficiencies in excess of 99%, although optimal performance of a fabric-filter system may not occur for a number of cleaning cycles, as the new filter material achieves a cake buildup. The fabric-filter collection efficiency is related to the pressure drop across the system, component life, filter fabric, cleaning method and frequency, and A/C ratio. These operating parameters should be modified to meet the required fabric filter performance. Modifications to improve performance include changing the A/C ratio, using a different fabric, replacing worn or leaking filter bags, and/or modifying the inlet plenum to ensure that the gas stream is evenly distributed within the baghouse. Collection efficiency can also be improved by decreasing the frequency of cleaning or allowing the system to operate over a greater pressure drop before cleaning.

5.3. System Pressure Drop

The pressure drop across the fabric-filter system depends on the resistance to the gas stream flow through the filter bags and accumulating dust cake, amount of dust deposit prior to bag cleaning, efficiency of cleaning, and plugging or blinding of the filter bags. Normally, the design pressure drop is set between 5 and 20 in. of water. In practice, variations in pressure drop outside the design range may indicate problems within the fabric-filter system. Excessive pressure differentials may indicate (1) an increase in gas stream volume, (2) blinding of the filter fabric, (3) hoppers full of dust, thus blocking the bags, and/or (4) inoperative cleaning mechanism. Subpar pressure differentials may indicate (1) fan or motor problems, (2) broken or unclamped bags, (3) plugged inlet ducting or closed damper; and/or (d) leakage between sections of the baghouse. For these reasons, continuous pressure-drop monitoring is recommended.

As the dust cake builds up during filtration, both the collection efficiency and system pressure drop increase. As the pressure drop increases toward a maximum, the filter bags (or at least a group of the bags contained in one isolated compartment) must be cleaned to reduce the dust cake resistance. This cleaning must be timed and performed to (1) maintain the pressure drop and thus operating costs within reasonable limits, (2) clean bags as gently and/or infrequently as possible to minimize bag wear and to maximize efficiency, and (3) leave a sufficient dust layer on the bags to maintain filter efficiency and to keep the instantaneous A/C ratio immediately after cleaning from reaching excessive levels, if woven fabric with no backing is used. In practice, these various considerations are balanced using engineering judgment and field trial experience to optimize the total system operation. Changes in the process or in fabric condition through fabric aging will shift in the cleaning requirements of the system. This shift may require more frequent manual adjustments to the automatic control to achieve the minimum cleaning requirements.

5.4. Power Requirements

The cost of electricity depends largely on the fan power requirement. Equation (10) can estimate this requirement, assuming a 65 % fan motor efficiency and a fluid specific gravity of 1.00:

$$F_p = 1.81 \times 10^{-4}\left(Q_{e,a}\right)(P)(\mathrm{HRS}) \tag{10}$$

where F_p is the fan power requirement (kWh/yr), $Q_{e,a}$ is the emission stream flow rate (acfm), P is the system pressure drop (in. H_2O), and HRS is the operating hours (h/yr). For mechanical shaking, Eq. (11) provides an estimate of the additional power:

$$P_{ms} = 6.05 \times 10^{-6}(\mathrm{HRS})\left(A_{tc}\right) \tag{11}$$

where P_{ms} is the mechanical shaking power requirement (kWh/yr) and A_{tc} is the gross cloth area (ft^2). The annual electricity cost is calculated as the sum of F_p and P_{ms}, multiplied by the cost of electricity given in Table 10.

A pulse-jet system uses about 2 scfm of compressed air per 1000 scfm of emission stream. Thus, a 100,000 scfm stream will consume about 200 scfm. Multiplying by both 60 and HRS gives the total yearly consumption. Multiplying this value by the cost of compressed air given in Table 10 gives annual costs. For other cleaning mechanisms, this consumption is assumed to be zero.

Table 7
Comparison of Calculated Values and Values Supplied by the Permit Applicant for Fabric Filters

Process variables	Calculated value (example case)[a]	Reported value
Continuous monitoring of system pressure drop and stack opacity	Yes	—
Emission stream temp. range[b]	365–415°F	—
Selected fabric material	Fiberglass or Teflon™	—
Baghouse cleaning method	Mechanical shaking, reverse-airflow, pulse jet	—
A/C ratio	2.5 ft/min for mechanical shaking or reverse air; 5 ft/min for pulse jet	—
Baghouse configuration	Negative pressure	—

[a]Based on the municipal incinerator emission stream.

5.5. Filter Bag Replacement

The cost of replacement bags is obtained from Eq. (12):

$$C_{RB} = \left[C_B + C_L\right]CRF_B \tag{12}$$

where C_{RB} is the bag replacement cost ($/yr), C_B is the initial bag cost ($), C_L is the bag replacement labor [$ (C_L = 0.14A_{nc}$)], and, CRF_B is the capital recovery factor, 0.5762 (indicates a 2-yr life, 10 % interest). Because the bag replacement labor cost is highly variable, a conservative high cost of $0.14/ft^2 of net bag area has been assumed (8).

6. MANAGEMENT

6.1. Evaluation of Permit Application

One can use Table 7 to compare the results from this section and the data supplied by the permit applicant (13). The calculated values are based on the typical case. As pointed out in the discussion on fabric filter design considerations, the basic design parameters are generally selected without the involved, analytical approach that characterizes many other control systems. Therefore, in evaluating the reasonableness of any system specifications on a permit application, the reviewer's main task will be to examine each parameter in terms of its compatibility with the gas stream and particulate conditions and with the other selected parameters. The following questions should be asked:

1. Is the temperature of the emission stream entering the baghouse within 50–100°F above the stream dew point?
2. Is the selected fabric material compatible with the conditions of the emission stream (i.e., temperature and composition) (*see* Table 3)?
3. Is the baghouse cleaning method compatible with the selected fabric material and its construction (i.e., material type and woven or felted construction) (*see* Section 4.3 and Table 6)?
4. Will the selected cleaning mechanism provide the desired control?
5. Is the A/C ratio appropriate for the application (i.e., type of dust and cleaning method used) (*see* Table 4)?

6. Are the values provided for the gas flow rate, A/C ratio, and net flow area consistent?

   The values can be checked with the following equation:

$$\text{A/C ratio} = \frac{Q_{e,a}}{A_{nc}} \tag{8}$$

   where the variables are as described earlier.
7. Is the baghouse configuration appropriate; that is, is it a negative-pressure baghouse?

6.2. Economics

Fabric filtration systems are attractive in that they are highly efficient collection devices that can be operated at low-energy requirements. In addition, they usually have no water requirements so that the solid-waste-disposal problem may be significantly less than that for wet systems. On the other hand, fabric filtration systems are expensive in that they require a large amount of space for installation [about 1 ft^2 (0.1 m^2) of floor space per each 5 ft^3/min (0.14 m^3/min)] and have a large capital investment.

The highest maintenance component of fabric-filter systems is the fabric itself. In baghouses, the bags have an average life of 18–36 mo and account for 20–40% of the equipment cost. If the system is expected to have a 10-yr life, this means that the bags must be replaced anywhere from three to seven times during this lifetime. Causes of bag failure include blinding (mudding), caking, burning, abrasion, chemical attack, and aging. Prior discussion in this chapter indicated how these problems can be reduced by proper operating and maintenance procedures.

The Industrial Gas Cleaning Institute (IGCI), representing about 90% of all fabric-filter gas cleaning device manufacturers, estimated that about half of the filter systems in the United States are low energy and half are high energy.

This chapter mentions factors affecting the economics of filter systems. These factors include the composition of both the solids and the gas, the type of filter system desired, requirements for gas conditioning, and proper operating and maintenance procedures. Other factors that also influence the cost of fabric filtration systems are, for example, *special* properties of the gas stream (toxic, explosive, corrosive, and/or abrasive), space restrictions in the installing facility, and the nature of ancillary equipment, such as hoods, ducts, fans, motors, material-handling conveyors, airlocks, stacks, controls, and valves.

These costs (Tables 8–10) are averages of all industries, and actual operating and relative costs would depend on the specific application. Abrasive, corrosive, hot applications may have greater total costs plus proportionally greater replacement and labor costs. Equipment costs for a fabric-filter system can be estimated by either obtaining quotations from vendors, or using generalized cost correlations from the literature. Total capital costs (*see* Table 9) include costs for the baghouse structure, the initial complement of the bags, auxiliary equipment, and the usual direct and indirect costs associated with installing or erecting new structures. The price per square foot of bags by type of fabric and cleaning system appears in Table 8 (3rd quarter 1986 dollars). The prices represent a 10 % range and should be escalated using the index provided in *Chemical Engineering* (27). The annual costs (*see* Table 11) for a fabric-filter system consist of the direct and indirect operating costs. Direct costs include utilities (electricity, replacement

Table 8
Bag Prices (3rd quarter 1986 $/ft^2)

Type of cleaning	Bag diameter (in.)	Type of material[a] PE	PP	NO	HA	FG	CO	TF
Pulse jet, TR[b]	4½ –5⅛	0.59	0.61	1.88	0.92	1.29	NA[c]	9.05
	6–8	0.43	0.44	1.56	0.71	1.08	NA	6.80
Pulse jet, BBR	4½–5⅛	0.37	0.40	1.37	0.66	1.24	NA	8.78
	6–8	0.32	0.33	1.18	0.58	0.95	NA	6.71
Shaker								
Strap top	5	0.45	0.48	1.28	0.75	NA	0.44	NA
Loop top	5	0.43	0.45	1.17	0.66	NA	0.39	NA
Reverse air with rings	8	0.46	NA	1.72	NA	0.99	NA	NA
Reverse air	8	0.32	NA	1.20	NA	0.69	NA	NA
w/o rings[d]	11½	0.32	NA	1.16	NA	0.53	NA	NA

Note: For pulse-jet baghouses, all bags are felts except for the fiberglass, which is woven. For bottom access pulse jets, the cage price for one cage can be calculated from the single-bag fabric area using the following:

In 50 cage lots:	$ = 4.941 + 0.163 ft^2	$ = 23.335 + 0.280 ft^2
In 100 cage lots:	$ = 4.441 + 0.163 ft^2	$ = 21.791 + 0.263 ft^2
In 500 cage lots:	$ = 3.941 + 0.163 ft^2	$ = 20.564 + 0.248 ft^2

[a]PE = 16-oz polyester; PP = 16-oz polypropylene; NO = 14-oz nomex; HA = 16-oz homopolymer acrylic; FG = 16-oz fiberglass with 10% TeflonTM; CO = 9-oz cotton; TF = 22-oz TeflonTM felt.

[b]Bag removal methods: TR = top bag removal (snap in); BBR = bottom bag removal

[c]NA = Not applicable

[d]Identified as reverse-air bags, but used in low-pressure pulse applications.

These costs apply to 4½-in.- or 5⅝-in.-diameter, 8-ft and 10-ft cages made of 11 gage mild steel and having 10 vertical wires and "Roll Band" tops. For flanged tops, add $1 per cage. If flow-control Venturis are used (as they are in about half of the pulse-jet manufacturers' designs), add $5 per cage.

For shakers and reverse air baghouses, all bags are woven. All prices are for finished bags and prices can vary from one supplier to another. For Gore-Tex^{TM} bag prices, multiply base fabric price by factors of 3–4.5.

Source: ref. 8.

bags, and compressed air), operating labor, and maintenance costs. Indirect costs consist of overhead, administrative costs, property taxes, insurance, and capital recovery. Table 10 provides the appropriate factors to estimate these costs.

The bag replacement labor cost depends on such factors as the number, size, and type of bags, the accessibility of the bags, how much they are connected to the tube sheet, and so forth. As such, these costs are highly variable. For simplicity, assume a conservatively high cost of $0.14/ft^2 net bag area, per EPA guidance (8). Dust disposal typically comprises a large cost component and varies widely with site. The reader should obtain accurate, localized costs. These fall between $20/ton and $30/ton for nonhazardous waste, and 10 times this amount for hazardous material (8).

The cost of operating labor assumes a requirement of 3 h per 8 h shift and the wage rate is provided in Table 10. Supervisory costs are taken as 15 % of operator labor costs. The cost of maintenance assumes a labor requirement of 1 h per 8 h shift, and the wage

Table 9
Capital Cost Factors for Fabric Filters

Direct costs	Factor
Purchased Equipment Costs (PEC)	
Fabric filter	As estimated
Bags	As estimated
Auxiliary equipment	As estimated
(EC = sum of as estimated)	
Instruments and controls	0.10 EC
Taxes	0.03 EC
Freight	0.05 EC
PEC = 1.18 EC	
Installation Direct Costs (IDC)	
Foundation and supports	0.04 PEC
Erection and handling	0.50 PEC
Electrical	0.08 PEC
Piping	0.01 PEC
Insulation for ductwork[a]	0.07 PEC
Painting[b]	0.02 PEC
Site preparation (SP)	As required
Buildings (Bldg.)	As required
IDC = 0.72 PEC + SP + Bldg.	
Total direct cost (DC) = PEC + IDC = 1.72 PEC + SP + Bldg.	
Indirect Costs	
Engineering and supervision	0.10 PEC
Construction and field expense	0.20 PEC
Construction fee	0.10 PEC
Start-up fee	0.01 PEC
Performance test	0.01 PEC
Contingencies	0.03 PEC
Total Indirect Cost, IC = 0.45 PEC	
Total capital cost (TCC) = DC + IC = 2.17 PEC + SP + Bldg.	

[a]If ductwork dimensions have been established, cost may be established based on \$10–\$12/ft^2 of surface for field application. Fan housings and stacks may also be insulated.
[b]The increased use of special coatings may increase this factor to 0.06 PEC or higher.
Source: ref. 8.

rate is provided in Table 10. The cost of maintenance materials is assumed to equal the maintenance labor costs.

6.3. New Technology Awareness

A sanitary bag filter has been developed to enhance clean-in-place (CIP) capability (28). The entire system can be cleaned between product changes without changing the filter bags. The system eliminates crosscontamination of products while still efficiently collecting powdered pollutants from an air emission stream. Another gas filter has been developed using the ceramic-element technology. The controlled filtration layers trap larger particles in the outer layer and catch smaller ones in the inner layer, resulting in

Table 10
Annual costs for Fabric Filters

Cost item	Factor
Direct Costs (DAC)	
Utilities	
Electricity	\$0.059/kWh
Compressed air	\$0.16/10^3 scfm
Replacement parts, bags	
Operating labor	
Operator	\$12.96/h
Supervisor	15% of operator labor
Maintenance	
Labor	\$14.26/h
Material	100% of maintenance labor
Waste disposal	Variable
Indirect costs (IAC)	
Overhead	0.60(operating labor + maintenance)
Administrative	2% of TCC (total capital cost)
Property tax	1% of TCC
Insurance	1% of TCC
Capital recovery[a]	$0.1175(TCC - 0.05C_L - 1.08\ C_B)$

[a]Capital recovery factor is estimated as $i(1+i)^n/[(1+i)^n - 1]$,
where i is the interest rate, (10%) and n is the equipment life, (20 yr).
Source: ref. 8.

a 99.999% removal rating for 0.003 μm at maximum flow rate. The ceramic medium is processed at temperatures above 2000°C, eliminating organic contaminants. It is capable of producing flow rates up to 2700 L/min (29).

The most recently developed filtration processes use membrane filtration media. Because substances that permeate nonporous membranes are reasonably volatile, application of a vacuum always causes the permeate to be desorbed from the membrane in the vapor state. Hence, the term "pervaporation" applies if the feed to the membrane filter is liquid, because the contaminant appears to evaporate through the membrane (30,31). If the feed is vapor, or a gas–vapor mixture, the process is called "vapor permeation" (30). More new technologies are reported elsewhere (32–36).

7. DESIGN EXAMPLES AND QUESTIONS

Example 1

The process flow diagram for a typical shaker fabric filter appears in Fig. 3. Give a general process description for the fabric filtration process.

Solution

Fabric filters are air pollution control devices designed for controlling particulate matter emissions from point sources. A typical fabric filter consists of one or more isolated compartments containing rows of fabric bags or tubes. Particle-laden gas passes up along the surface of the bags, then radially through the fabric. The upstream face of the bags retains particles while the clean gas stream vents to the atmosphere. The filter operates cyclically

to alternate between long filtering periods and short cleaning periods. During cleaning, accumulated dust on the bags is removed from the fabric surface and deposited in a hopper for subsequent disposal.

Fabric filters collect particles ranging from submicron to several hundred microns in diameter, at efficiencies generally in excess of 99% Routinely, gas temperatures can be accommodated up to about 500°F, with surges to approx 550°F. Most of the energy use in a fabric-filter system derives from the pressure drop across the bags and associated hardware and ducting. Typical values of pressure drop range from about 5 to 20 in. of water column.

Example 2

Fabric filters are often categorized by the cleaning method for removing the dust cake. Three common types include (1) shaker filters, (2) reverse-air filters, and (3) pulse-jet filters. Describe and discuss (1) general cleaning methods and (2) the three types of fabric filter.

Solution:

1. *General cleaning methods*: As dust accumulates on the filtering elements, the pressure drop across the bag compartment increases until cleaning of the bags occurs. Cleaning is usually controlled by a timer or a pressure switch set at the specified maximum pressure drop. At this point, the bags in the compartment are cleaned to remove the collected dust, and the cycle is then repeated. The two basic mechanisms for bag cleaning involve flexing the fabric to break up and dislodge the dust cake, and reverse airflow through the fabric to remove the dust. These may be used separately or together. The three principal methods used for fabric cleaning are mechanical shaking (manual or automatic), reverse airflow, and pulse-jet cleaning. The first method uses only the fabric flexing mechanism; the latter two methods use a combination of the reverse-airflow and fabric flexing mechanisms.
2. *Three types of fabric filters*:
   a. In a shaker filter (*see* Fig. 3), the bags are hung in a framework that is oscillated by a motor-controlled timer. In this type of system, the baghouse is usually divided into several compartments. The flow of gas to each compartment periodically is interrupted, and the bags are shaken to remove the collected dust. The shaking action produces more wear on the bags than other cleaning methods. For this reason, the bags used in this type of filter are usually heavier and made from durable fabrics (13,26).
   b. In a reverse-airflow filter, gas flow to the bag is stopped in the compartment being cleaned and a reverse flow of air is directed through the bags. This approach has the advantage of being "gentler" than shaking allowing the use of more fragile or lightweight bags (13).
   c. The third type of baghouse, pulse-jet fabric filter, is by far the most common type for Superfund applications. In this type of system, a blast of compressed air expands the bag and dislodges collected particles. One advantage of pulse-jet fabric filters is that bags can be cleaned on line, meaning fewer bags (less capacity) are required for a given application (26).

Example 3

Discuss (1) mechanical shaking cleaning methods, (2) reverse-airflow cleaning methods, and (3) pulse-jet cleaning methods in detail.

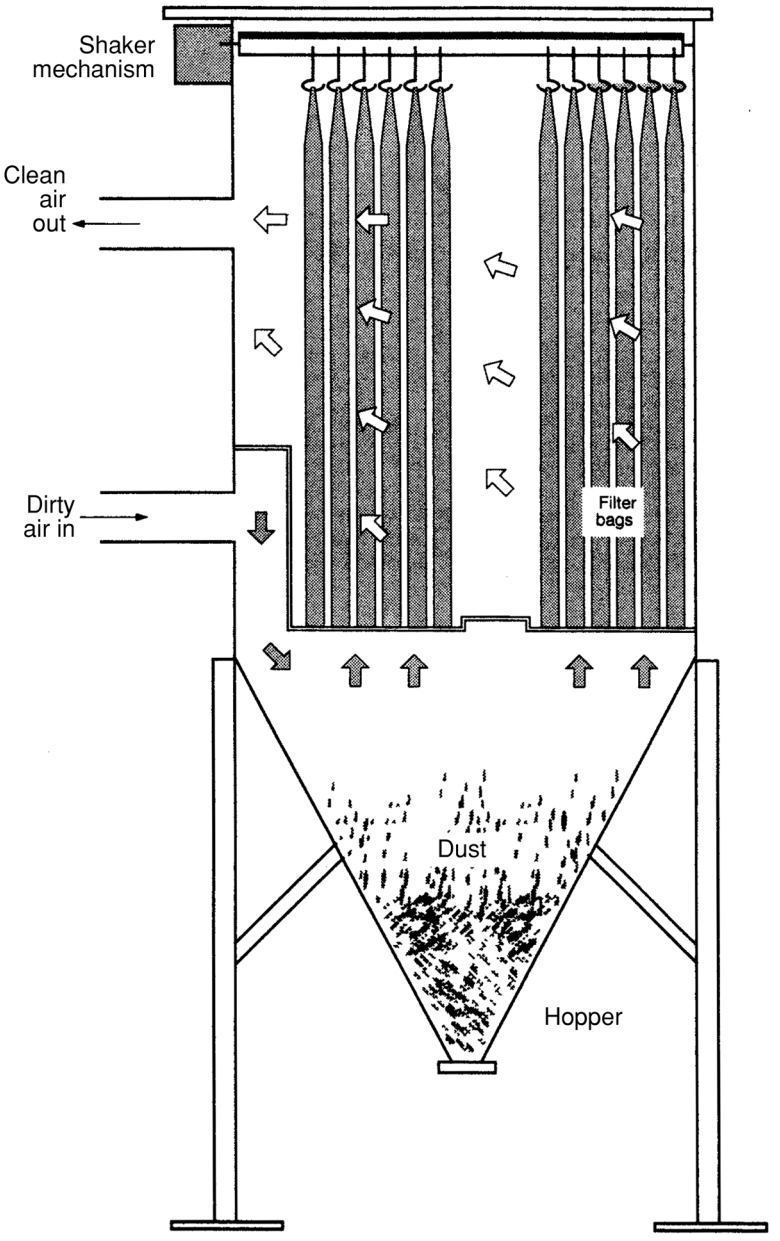

Fig. 3. Fabric-filter process flow diagram.

Solution

1. *Mechanical shaking cleaning method*: With mechanical shaking, bags hang on an oscillating framework that periodically shakes the bags at timed intervals or at a predefined pressure drop level (14,15,18). The shaker mechanisms produce violent action on the fabric-filter bags and, in general, produce more fabric wear than the other types of cleaning mechanism (16). For this reason, mechanical shaking is used in con-

junction with heavier more durable fabrics, such as most woven fabrics. Bags with fair to poor abrasion ratings in Table 3 (e.g., fiberglass) should not be chosen for fabric filters cleaned by mechanical shaking unless they are treated with a special coating (i.e., a backing) before use. Although shaking is abrasive to the fabric, it does allow a dust cake to remain on the fabric, thus maintaining high collection efficiency (15,22).

2. *Reverse-airflow cleaning method*: Reverse-airflow cleaning is used to flex or collapse the filter bags by allowing a large volume of low pressure air to pass countercurrent to the direction of normal gas stream flow during filtration (16,18). Reverse air is provided either by a separate fan or by a vent in the fan damper, which allows a backwash of air to clean the fabric filters. Reverse-airflow cleaning is usually performed off-line. It allows the use of fragile bags, such as fiberglass, or lightweight bags, and usually results in longer life for bags (16). As with mechanical shaking, woven fabrics are used. Because cleaning is less violent than with pulse-jet cleaning and is performed off-line, outlet concentrations are almost constant with varying inlet dust loading throughout the cleaning cycle. Reverse-airflow cleaning is, therefore, a good choice for fabric cleaning in hazardous air pollutant (HAP) control situations.
3. *Pulse-jet cleaning method*: In pulse-jet cleaning, a high-pressure air pulse enters the top of the bag through a compressed air jet. This rapidly expands the bag, vibrating it, dislodging particles, and thoroughly cleaning the fabric. The pulse of air cleans so effectively that no dust cake remains on the fabric to contribute to particulate collection. Because this cake is essential for effective collection on woven fabrics, felted fabrics are generally used in pulse-jet-cleaned fabric filters. Alternatively, woven fabrics with a suitable backing may be used. All fabric materials may be used with pulse-jet-cleaning, except cotton or fiberglass. Previously, mechanical shaking was considered superior to pulse-jet cleaning in terms of collection efficiency. Recent advances in pulse-jet cleaning have produced efficiencies rivaling those of mechanical shaking.

   Because the air pulse has such a high pressure (up to 100 psi) and short duration (≤0.1 s), cleaning may also be accomplished on-line, but off-line cleaning is also employed. Extra bags may not be necessary to compensate for bags off-line during cleaning. Cleaning occurs more frequently than with mechanical shaking or reverse-airflow cleaning, which permits higher air velocities (higher A/C ratios) than the other cleaning methods. Furthermore, because the bags move less during cleaning, they may be packed more closely together. In combination, these features allow pulse-jet-cleaned fabric filters to be installed in a smaller space, at a lower cost, than fabric filters cleaned by other methods. This cost savings may be somewhat counterbalanced by the greater expense and more frequent replacement required of bags, the higher power use that may occur, and the installation of fabric-filter framework that pulse-jet cleaning requires (14,16,18).

Example 4

A new 8000-ft^3/min shaker-type filter installation is being designed to remove iron oxide from an electric furnace emission. Consider the gas to be air at 110°F with an inlet dust concentration of 0.8 gr/ft^3 (grains per cubic foot). The A/C ratio is 3 ft/min and the mass mean particle size is approx 1 μm. Other design parameters include the following.

From Table 2 for a 1-μm spherical particle:

S = specific surface area per unit volume of solids = 1.83×10^6 ft^{-1}

e = porosity = 0.40

Assume that the Kozeny–Carman coefficient $k = 5$ and

ρ_p = particle density = (5.18)(62.4) = 323 lb/ft^3

μ_f = air viscosity = 1.21×10^{-5} $lb_m/(s\ ft)$
g = 32.174 ft/s^2

Determine the following design variables:

1. Cake fabric-filter resistance coefficient, K_2
2. Filtration cycle time, t
3. Blower horsepower
4. Fabric-filter area
5. Solids removal rate

Solution

1. Using Eq. (7),

$$K_2 = \left(3.2\times10^{-3}\right)\left(\frac{k}{g}\right)\left(\frac{\mu_f S^2}{\rho_p}\right)\left(\frac{1-\varepsilon}{\varepsilon^3}\right)$$
$$= \left(3.2\times10^{-3}\right)\left(\frac{5}{32.174}\right)\frac{\left(1.21\times10^{-5}\right)\left(1.83\times10^{6}\right)^2}{323}(9.38)$$
$$= 585 \text{ in. } H_2O/\left(lb_m/ft^2\right)(ft/min)$$

Operating data in the literature (3) show that for an installation of this type, using Orlon fabric filters, $K_2 = 45$. This is obtained via Eq. (6) for an inlet dust loading of 0.8 gr/ft^3.

2. Assume that the filtration should operate so that the pressure drop increases by up to about 3 in. H_2O. The filtration cycle time can then be estimated by rearranging Eq. (6) (use $K_2 = 45$):

$$t = \frac{\Delta P_2}{K_2 v^2 L}$$
$$= \frac{(3 \text{ in. } H_2O)(7000 \text{ grains/lb})}{\left[45 \text{ in. } H_2O/(lb/ft^2)(ft/min)\right](3 \text{ ft/min})^2(0.8 \text{ grains/ft}^3)}$$
$$= 65 \text{ min}$$

Therefore, it would be necessary to shake the system about once an hour.

3. Considering that the residual fabric-filter resistance is also about 3 in. H_2O and there are other gas flow pressure losses, assume an overall ΔP of 7 in. H_2O. The size of the blower can be estimated (7) using 60% blower efficiency:
   Blower horserpower(HP) = $(3 \times 10^{-4})(\Delta P)(Q)$
   ΔP = 7 in. H_2O
   Q = 8000 ft^3/min
   HP = $(3 \times 10^{-4})(7)(8000) = 17$

4. The size of the filter area required is

$$\text{air-to-cloth ratio} = 3 \text{ ft/min} = \frac{3 \text{ ft}^3/\text{min}}{\text{ft}^2}$$
$$\text{filter area} = \frac{8000 \text{ ft}^3/\text{min}}{3 \text{ ft/min}} = 2670 \text{ ft}^2$$

5. The material handling system to remove the solids must be able to handle a maximum of

$$\left(\frac{8000\ \text{ft}^3}{\text{min}}\right)\left(\frac{0.8\ \text{grains}}{\text{ft}^3}\right)\left(\frac{1\text{b}}{7000\ \text{grains}}\right)\left(\frac{60\ \text{min}}{\text{h}}\right) = 55\,\frac{1\text{b}}{\text{h}}$$

This assumes 100% filter efficiency (1320 lb/d for 24-h operation).

Example 5

What is the "HAP Emission Stream Data Form" recommended by the US Environmental Protection Agency (US EPA)?

Solution

The "HAP Emission Stream Data Form" recommended by the US EPA is presented in Appendix 1.

Example 6

Prepare a step-by-step calculation procedure for design of a fabric filtration system.

Solution

1. Engineering data gathering for the HAP emission stream characteristics:
   1) Flow rate: $Q_{e,a}$ = _____ acfm
   2) Moisture content: M_e = _____ % (vol)
   3) Temperature: T_e = _____ °F
   4) Particle mean diameter: D_p = _____ μm
   5) SO_3 content = _____ ppm (vol)
   6) Particulate content = _____ grains/scf
   7) HAP content = _____ % (mass)

2. Determine or decide the following engineering data for permit review and application:
   1) Filter fabric material _____
   2) Cleaning method (mechanical shaking, reverse air, pulse jet) _____
   3) Air-to-cloth ratio _____ ft/min
   4) Baghouse construction configuration (open pressure, closed pressure, closed suction)
   5) System pressure drop range _____ in. H_2O

3. Pretreatment Considerations:
   If the emission stream temperature is not from 50°F to 100°F above the dew point, pretreatment is necessary (see Chapter 1). Pretreatment will cause two of the pertinent emission stream characteristics to change; list the new values below.
   1) Maximum flow rate at actual conditions: $Q_{e,a}$ = _____ acfm
   2) Temperature: T_e = _____ °F

4. Fabric Filter System Design
   1) Fabric type(s) (use Table 3)
      a. _____
      b. _____
      c. _____
   2) Cleaning method(s)
      a. _____

b. _____

3) Air-to-cloth ratio (Table 4) _____ ft/min
4) Net cloth area, A_{nc}:

$$A_{nc} = Q_{e,a} / (\text{A/C ratio})$$

where A_{nc} is the net cloth area (ft^2), $Q_{e,a}$ = maximum flow rate at actual conditions (acfm) = $Q_e(T_e + 460)/537$ (which is to be used if given Q_e instead of $Q_{e,a}$), and A/C ratio = air-to-cloth ratio (ft/min)

A_{nc} = _____/_____

A_{nc} = _____ft^2

5) Gross cloth area, A_{tc}:

$$A_{tc} = A_{nc} \times \text{Factor}$$

where A_{tc} is the gross cloth area (ft^2) and Factor is the value from Table 5 (dimensionless).

A_{tc} = _____×_____

A_{tc} = _____ ft^2

6) Baghouse configuration _____
7) Materials of construction _____

5. Determination of baghouse operating parameters
   1) Collection efficiency (CE) = _____
   2) System pressure drop range _____ in. H_2O

Example 7

Fabric filtration is one of the selected control techniques for a municipal incinerator. Conduct a preliminary design for a fabric filtration system (select filter fabrics, decide cleaning method, and determine A/C ratio). The pertinent engineering data appear on the "HAP Emission Stream Data Form" (*see* Table 11).

Solution

1. Gather engineering data on HAP emission stream characteristics from Table 11:
   1) Flow rate, $Q_{e,a}$ = 110,000 acfm
   2) Moisture content, M_e = 5% vol
   3) Temperature, T_e = 400°F
   4) Particle mean diameter, D_p=1.0 μm
   5) SO_3 content = 200 ppm (vol)
   6) Particulate content = 3.2 gr/scf – flyash
   7) HAP content = 10% (mass) cadmium

2. Fabric-filter Preliminary Design. In this case, fabric selection depends on the emission stream temperature of 400°F, the SO_3 content of 200 ppmv, and the flyash particulate type. Table 3 indicates that filter fabrics capable of withstanding 400°F emission stream temperature are ceramics (Nextel 312^{TM}), nylon aromatic (Nomex), fluorocarbon (Teflon), and fiberglass. Because there is a high potential for acid damage (i.e., a high SO_3 content), however, Nomex bags should not be considered. To obtain an indication of the A/C ratio, use Table 4. This table shows that an A/C ratio of around 2.5 is

Table 11
Effluent Characteristics for a Municipal Incinerator Emission Stream

HAP EMISSION STREAM DATA FORM*

Company Incineration Inc.
Location (Street) 124 Main Stree
(City) Somewhere
(State, Zip)

Plant contact Mr. Phil Brothers
Telephone No. (999) 555-5024
Agency contact Mr. Ben. Hold
No. of Emission Streams Under Review 1

A.	Emission Stream Number/Plant Identification		#1/ Incineration		
B.	HAP Emission Source	(a) municipal incinerator	(b)	(c)	
C.	Source Classification	(a) process point	(b)	(c)	
D.	Emission Stream HAPs	(a) cadmium	(b)	(c)	
E.	HAP Class and Form	(a) inorganic particulate	(b)	(c)	
F.	HAP Content (1,2,3)**	(a) 10%	(b)	(c)	
G.	HAP Vapor Pressure (1,2)	(a)	(b)	(c)	
H.	HAP Solubility (1,2)	(a)	(b)	(c)	
I.	HAP Adsorptive Prop. (1,2)	(a	(b)	(c)	
J.	HAP Molecular Weight (1,2)	(a)	(b)	(c)	
K.	Moisture Content (1,2,3)	5% vol	P.	Organic Content (1)***	
L.	Temperature (1,2,3)	400°F	Q.	Heat/O_2 Content (1)	
M.	Flow Rate (1,2,3)	110,000 acfm	R.	Particulate Content (3) 3.2 gr/acf, flyash	
N.	Pressure (1,2)	atmospheric	S.	Particle Mean Diam. (3) 1.0 μm	
O.	Halogen/Metals (1,2)	none/none	T.	Drift Velocity/SO_3 (3) 0.31 ft/sec/ 200 ppmv	
U.	Applicable Regulation(s)				
V.	Required Control Level	assume 99.9% removal			
W.	Selected Control Methods	fabric filter, ESP, Venturi scrubber			

*The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

**The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:
1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

***Organic emission stream combustibles less HAP combustibles shown on lines D and F.

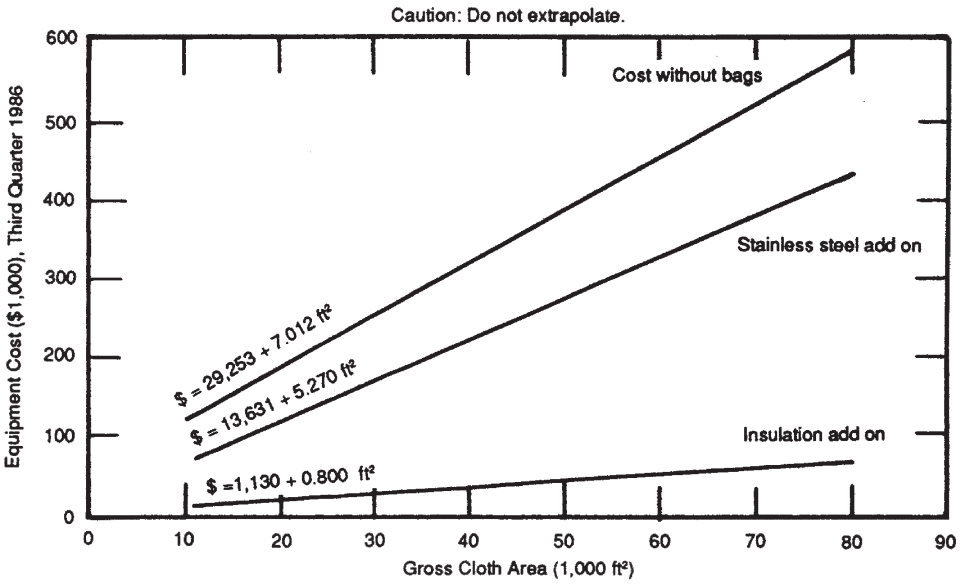

Fig. 4. Structure costs for reverse-air filters.

expected for mechanical shaking or reverse-air cleaning, and an A/C ratio of about 5.0 is expected for pulse-jet cleaning.

A fiberglass bag would provide the most protection during temperature surges (unless ceramics are used), and because fiberglass bags may be less expensive, it may be the fabric of choice for an installation with these emission characteristics. Fiberglass bags would require that reverse-air cleaning be used, unless a suitable backing allows pulse-jet cleaning. Teflon bags with mechanical shaking could also be a possibility (7,17). Limited information on the long-term effectiveness of ceramics has been documented. It is expected that ceramic fibers will have performance characteristics similar to the best synthetic fibers, but will cost significantly more.

Example 8

The HAP emission stream shown in Example 7 and Table 11 is to be treated by a reverse-air baghouse. Figure 4 is provided by the vendor for the cost of the baghouse structure. Determine the A/C ratio, net cloth area (A_{nc}), gross cloth area (A_{tc}), and the baghouse total capital cost (requiring stainless steel add-on and insulation).

Solution

1. From Table 4, flyash, the A/C ratio = 2.5.
2. Thus, A_{nc} = (110,000 acfm)/2.5 = 44,000 ft^2.
3. Obtain the total cloth area using Table 5. This table indicates that A_{nc} should be multiplied by 1.125 to obtain A_{tc}. Thus, A_{tc} = 44,000(1.125) = 49,500 ft^2. This value is used to obtain the structure cost.
4. Using Fig. 4, the structure cost equals $380,000 plus $270,000 for stainless-steel add-on, plus $40,000 for insulation. The total cost is then $380,000 + $270,000 + $40,000 = $690,000.

Table 12
Example Case Capital Costs

Direct costs		Cost ($)
Purchased Equipment Costs		
Fabric filter	$	690,000
Bags		49,000
Auxiliary equipment		10,000
	$	749,000
Instruments and controls	$	74,900
Taxes		22,500
Freight		37,500
Purchased equipment cost (PEC)	$	884,000
Installation Direct Costs		
Foundation and supports	$	35,400
Erection and handling		442,000
Electrical		70,700
Piping		8,840
Insulation for ductwork		61,900
Painting		17,700
Site preparation (SP)		—
Buildings (Bldg.)		—
	$	636,000
Total direct costs	$	1,520,000
Indirect Costs		
Engineering and supervision	$	88,400
Construction and field expense		177,000
Construction fee		88,400
Start-up fee		8,840
Performance test		8,840
Contingencies		26,500
Total indirect cost	$	398,000
Total direct and indirect cost = Total capital cost (TCC)	$	1,920,000

Table 8 is used to obtain the bag cost, C_B. From the previous example case, choose fiberglass bags with Teflon backing. Assume the bag diameter is 8 in. with rings. The bag cost is given as ($0.99/ft^2) × (49,500 ft^2) = $49,000.

Assume that auxiliary equipment costs obtained (see another chapter on cost estimation of air pollution control technologies) are $10,000. The equipment cost (EC) is then $690,000 + $49,000 + $10,000 = $749,000. Table 9 lists the purchased equipment cost (PEC):

Instrumentation = 0.10(EC) = $74,900
Taxes = 0.03(EC) = $22,500
Freight = 0.05(EC) = $37,500

The total PEC is then $749,000 + $74,900 + $22,500 + $37,500 = $884,000. Table 9 is then used to obtain the total capital cost (TCC) of the baghouse system. These costs are given in Table 12. Another Humana Press book (37) gives additional cost data.

Example 9

Assume that the waste generation ratio is 3.2 gr/ft^3 of HAP emission stream processed, the HAP emission stream flow is 110,000 ft^3/min, and the waste disposal cost is $200/ton-yr, determine the total annual waste disposal cost for a fabric filtration system.

Solution

1.

$$\text{Waste quantity generated} = 3.2\,\frac{\text{gr}}{\text{ft}^3} \times \frac{11\text{b}}{7000\ \text{gr}} \times \frac{110,000\ \text{ft}^3}{\text{min}} \times \frac{60\ \text{min}}{\text{h}} \times \frac{6000\ \text{h}}{\text{yr}}$$

$$= 1.81 \times 10^7 \times \frac{\text{lb}}{\text{yr}}$$

2.

$$\text{Annual waste disposal cost} = 1.81 \times 10^7\,\frac{\text{lb}}{\text{yr}} \times \frac{\text{ton}}{2000\ \text{lb}} \times \frac{200}{\text{ton/yr}}$$

$$= \$1,810,000$$

Example 10

The HAP emission stream shown in Example 7 and Table 11 is to be treated by a reverse-air baghouse. Assume the following are the given data:

1. Emission stream flow, Q_{acfm} = 110,000 acfm
2. System pressure drop = 10 in. H_2O
3. Annual operating hours, HRS = 6000 h/yr (assuming 8 h/shift)
4. Electricity cost = $0.059/kWh
5. Initial bag cost, C_B = $49,000 from Example 8
6. Net cloth area, A_{nc} = 44,000 ft^2 from Example 8
7. Operating labor and labor cost of baghouse at 3 h/shift and $12.96/h, respectively
8. Supervisory cost = 15% of total operating labor costs
9. Maintenance labor and cost of baghouse at 1 h/shift and $14.26/h, respectively
10. Maintenance cost = 100% maintenance labor cost
11. Waste generation rate = 3.2 gr/ft^3 of HAP emission stream processed. Waste generation cost = $1,810,600/yr from Example 9
12. Indirect annual cost = Table 10

Determine the following:

1. Total direct cost
2. Total indirect cost
3. Total annual cost

Solution

1. Total direct annual costs: Electricity usage is estimated using Eq. (10). Assume that the system pressure drop equals 10 in. H_2O.

$$F_p = 1.81 \times 10^{-4}(110,000)(10)(6,000)$$
$$= 1.19 \times 10^6$$

$$\text{Electricity cost} = \$0.059(1.19 \times 10^6) = \$70{,}200/\text{yr}$$

Because reverse air is used, $P_{ms} = 0$.
Bag replacement costs are obtained using Eq. (12):

$$C_{RB} = [49{,}000 + 0.14(44{,}000)]0.5762$$
$$= \$31{,}800/\text{yr}$$

Operating labor costs are estimated as

$$[(3\text{ h/shift})/(8\text{ h/shift})]6{,}000\text{ h/yr} = 2{,}250\text{ h/yr}$$
$$2{,}250\text{ h/yr}\ (\$12.96/\text{h}) = \$29{,}200/\text{yr}$$

Supervisory costs are taken as 15% of this total, or \$4370.
Maintenance labor costs are estimated as

$$[(1\text{ h/shift})/(8\text{ h/shift})]6{,}000\text{ h/yr} = 750\text{ h/yr}$$
$$750\text{ h/yr}\ (\$14.26/\text{h}) = \$10{,}700/\text{yr}$$

Maintenance materials are taken as 100% of this total, or \$10,700.
Waste disposal cost = \$1,810,600/yr from Example 9
Total direct annual costs = \$70,200 + \$31,800 + \$29,200 + \$4370 + \$10,700 + \$10,700 + \$1,810,000 = \$1,970,000

2. Total indirect annual costs: These costs are obtained from the factors presented in Table 10 and the example case presented above.
   Overhead = 0.60(\$29,200 + \$4370 + \$10,700 + \$10,700)
   = \$33,000
   Administrative = 0.02(\$1,920,000)
   = \$38,400
   Insurance = 0.01(\$1,920,000)
   = \$19,200
   Property taxes = 0.01(\$1,920,000)
   = \$19,200
   Capital recovery = 0.1175(\$1,920,000) − 1.08(\$49,000) − 0.05(\$0.14)(44,000)
   = \$219,000
   Total indirect costs = \$33,000 + \$38,400 + \$19,200 + \$19,200 + \$219,000
   = \$329,000
   Total annual costs = \$1,970,000 + \$329,000
   = \$2,200,000/yr

Example 11

The bag prices shown in Table 8 are for the third quarter 1986. Discuss how one can update the third quarter 1986 cost to the March 2002 cost, or any month in the future.

Solution
Using the following equation for equipment cost comparison:

$$\text{Cost}_b = \text{Cost}_a\ (\text{Index}_b)/(\text{Index}_a)$$

where Cost_b is the future cost (\$), Cost_a is the old cost (\$), Index_b is the future CE equipment cost index, and Index_a is the old CE equipment cost index. For instance, the CE (Chemical Engineering) equipment cost index for the third quarter 1986 can be obtained

from the literature (32) to be 336.6. The March 2002 CE equipment cost index can also be obtained from a different issue of the same source (27). In turn, the March 2002 equipment costs can be calculated using the known values of $Cost_{9\text{-}1986}$, $Index_{3\text{-}2002}$, and $Index_{9\text{-}1986}$:

$$Cost_{3\text{-}2002} = Cost_{9\text{-}1986}\ (Index_{3\text{-}2002})/Index_{9\text{-}1986,}$$

Readers are referred to ref. 37 for more detailed information on cost estimation.

NOMENCLATURE

A_{nc}	Net cloth area (ft^2)
A_{tc}	Gross cloth area (ft^2)
c	Flow constants
C_B	Initial bag cost ($)
C_{RB}	Bag replacement cost ($)
Cost	Equipment cost ($)
CRF_B	Capital recovery factor
D_P	Particle mean diameter (μm)
DAC	Direct annual costs ($)
ε	Porosity or fraction void volume (dimensionless)
F_P	Fan power requirement (kWh/yr)
g	Gravitational constant
HP	Horsepower
HRS	Operating hours (h/yr)
i	Interest rate
IAC	Indirect annual costs ($)
Index	*Chemical Engineering* equipment cost index (dimensionless)
k	Kozeny–Carman coefficient (approx 5 for $0.8 \geq \varepsilon$)
K	Kozeny permeability coefficient
K_1	Resistance of the fabric (in. H_2O/ft/min)
K_2	Cake–fabric–filter resistance coefficient
L	Inlet solids concentration (lb_m/ft^3)
M_e	Moisture content (vol %)
μ	Viscosity
μ_f	Fluid viscosity
n	Equipment life (yr)
P_{ms}	Mechanical shaking power requirement (kWh/yr)
ΔP	Pressure drop (in. H_2O)
ΔP_1	Pressure drop across fabric (in. H_2O)
ΔP_2	Change in pressure drop due to cake build–up over time interval t (in. H_2O)
ρ	Density
ρ_p	True density of solid material (lb_m/ft^3)
Q	Volumetric flow rate (ft^3/min)
S	Specific surface area per unit volume of either porous filter media or solids in cake layer (ft^2/ft^3)
t	Time (min)

T_e	Emission stream temperature (°F)
TCC	Total capital costs ($)
v	Gas flow velocity (ft/min)

REFERENCES

1. J. Happel, and H. Brenner, *Low Reynolds Number Hydrodynamics with Special Applications to Particulate Media*, Prentice-Hall, Englewood Cliffs, NJ, 1965.
2. C. E. Williams, T. Hatch, and L. Greenberg, *Heating Piping Air Condit*. 12, 259 (1965).
3. C. E. Billings and J. E. Wilder, *Proc. EPA Symp. Control Fine-Particulate Emissions from Industrial Sources,* 1974.
4. C. E. Billings, and J. E. Wilder, *Handbook of Fabric Filter Technology*, Vol. 1., NTIS No. PB 200 648, (1970).
5. F. W. Cole, *Filtrat. Sep*. 17–25 (1975).
6. D. B. Purchas, *Proc. Filtration in Process Plant Design and Development: Liquid–Solids Separation* (1971).
7. *The Fabric Filter Manual*, Chap. III, The McIlvaine Company, Northbrook, IL, 1975.
8. US EPA, *OAQPS Control Cost Manual*, 4th ed., EPA 450/3–90–006 (NTIS PB90–16954), US Environmental Protection Agency, Washington, DC, 1990.
9. G. Parkins, *Chem. Eng.* **96(4)** (1989).
10. R. Dennis, and J. E. Wilder, *Fabric Filter Cleaning Studies*, EPA/650/2–75–009, US Environmental Protection Agency, Washington, DC, 1975.
11. H. E. Hesketh, *Understanding and Controlling Air Pollution*, 2nd ed., Ann Arbor Science, publ., Ann Arbor, MI, 1974.
12. S. A. Reigel, R. P. Bundy, and C. D. Doyle, *Pollut. Eng.* **5(5)** (1973).
13. US EPA, *Control Technologies for Hazardous Air Pollutants*, EPA/625–91/014, US Environmental Protection Agency, Washington, DC, 1994.
14. P. C. Siebert, *Handbook on Fabric Filtration,* ITT Research Institute, Chicago, IL, 1977.
15. US EPA, *Handbook of Fabric Filter Technology, Volume 1: Fabric Filter Systems Study*, APTD 0690 (NTIS PB 200648), US Environmental Protection Agency, Washington, DC, 1970.
16. US EPA, *Capital and Operating Costs of Selected Air Pollution Control Systems*, EPA/450/5–80–002 (NTIS PB80–157282), US Environmental Protection Agency, Washington, DC, 1978.
17. US EPA *Control Techniques for Particulate Emissions from Stationary Sources—Volume 2,* EPA/450/3–81–005b (NTIS PB83–127480), US Environmental Protection Agency, Washington, DC, 1982.
18. US EPA, *Control Techniques for Particulate Emissions from Stationary Sources—Volume 1*, EPA/450/3–81–005a (NTIS PB83–127498), US Environmental Protection Agency, Washington, DC, 1982.
19. W. Strauss, *Industrial Gas Cleaning*, 2nd ed., Pergamon, Oxford (1975).
20. US EPA, *Procedures Manual for Fabric Filter Evaluation*, EPA/600/7–78–113 (NTIS PB 283289), U.S. Environmental Protection Agency, Washington, DC, 1978.
21. US EPA, *Air Pollution Engineering Manual,* AP-40 (NTIS PB 225132), US Environmental Protection Agency, Washington, DC, 1973.
22. US EPA, *Particulate Control Highlights: Research on Fabric Filtration Technology*, EPA/600/8–78/005d (NTIS PB 285393), US Environmental Protection Agency, Washington, DC, 1978.
23. US EPA, *Baghouse Efficiency on a Multiple Hearth Incinerator Burning Sewage Sludge*, EPA 600/2/89–016 (NTIS PB89–190318), US Environmental Protection Agency, Washington, DC, 1990.

24. US EPA, *Handbook: Guidance on Setting Permit Conditions and Reporting Trial Burn Results*, EPA625/6–89–019, US Environmental Protection Agency, Washington, DC, 1989.
25. N. C. Durham, Company data for the municipal waste combustion industry. PES, Inc., 1990.
26. US EPA, *Control of Air Emission from Superfund Sites*, EPA/625/R-92/012, US Environmental Protection Agency, Washington, DC, 1992.
27. Anon. Equipment indices, *Chemical Engineering,* McGraw-Hill, New York, March (2002).
28. N. Niro, *Chem. Eng. Prog.*, **97(10)**, 24 (2001).
29. N. Swagelok, SCF Series gas filter, *Chem. Eng. Prog.*, **97(10)**, 53 (2001).
30. N. Wynn, *Chem. Eng. Prog.*, **97(10)**, 66–72 (2001).
31. L. K. Wang, J. V. Krouzek, and U. Kounitson, *Case Studies of Cleaner Production and Site Remediation,* Training Manual No. DTT–5–4–95, United Nations Industrial Development Organization, Vienna, 1995.
32. Anon. Equipment indices. *Chemical Engineering*, McGraw-Hill, New York, Sept. (1986).
33. US EPA, *Control Techniques for Fugitive VOC Emissions from Chemical Process Facilities*, EPA/625/R–93/005. US Environmental Protection Agency, Cincinnati, OH (1994).
34. D. Corbin. *Environ. Protect*. **14(1)** 26–27 (2003).
35. H. E. Hesketh, Fabric filtration. *Handbook of Environmental Engineering, Volume 1, Air and Noise Pollution Control* (L. K., Wang, and N. C. Pereira, eds.), Humana, Totowa, NJ, 1979, pp. 41–60.
36. US EPA. Fabric Filtration Design and Baghouse Components. APTI Virtual Classroom, Lesson 1. http://yosemite.epa.gov. US Environmental Protection Agency, Washington DC. Jan. 23, 2004.
37. L. K. Wang, N. C. Pereira, and Y.-T. Hung (eds.). *Advanced Air and Noise Pollution Control*. Humana Press, Totowa, NJ, 2005.

APPENDIX 1

HAP EMISSION STREAM DATA FORM*

Company _____ Plant contact _____
Location (Street) _____ Telephone No _____
(City) _____ Agency contact _____
(State, Zip)_____ No. of Emission Streams Under Review _____

A.	Emission Stream Number/Plant Identification				
B.	HAP Emission Source	(a)_____	(b)_____	(c)_____	
C.	Source Classification	(a)_____	(b)_____	(c)_____	
D.	Emission Stream HAPs	(a)_____	(b)_____	(c)_____	
E.	HAP Class and Form	(a)_____	(b)_____	(c)_____	
F.	HAP Content (1,2,3)**	(a)_____	(b)_____	(c)_____	
G.	HAP Vapor Pressure (1,2)	(a)_____	(b)_____	(c)_____	
H.	HAP Solubility (1,2)	(a)_____	(b)_____	(c)_____	
I.	HAP Adsorptive Prop. (1,2)	(a)_____	(b)_____	(c)_____	
J.	HAP Molecular Weight (1,2)	(a)_____	(b)_____	(c)_____	
K.	Moisture Content (1,2,3)	_____	P. Organic Content (1)***	_____	
L.	Temperature (1,2,3)	_____	Q. Heat/O_2 Content (1)	_____	
M.	Flow Rate (1,2,3)	_____	R. Particulate Content (3)	_____	
N.	Pressure (1,2)	_____	S. Particle Mean Diam.(3)	_____	
O.	Halogen/Metals (1,2)	_____	T. Drift Velocity/SO_3 (3)	_____	
U.	Applicable Regulation(s)	_____			
V.	Required Control Level	_____			
W.	Selected Control Methods	_____			

*The data presented are for an emission stream (single or combined streams) prior to entry into the selected control method(s). Use extra forms if additional space is necessary (e.g., more than three HAPs) and note this need.

**The numbers in parentheses denote what data should be supplied depending on the data on lines C and E:

1 = organic vapor process emission
2 = inorganic vapor process emission
3 = particulate process emission

***Organic emission stream combustibles less HAP combustibles shown on lines D and F.

APPENDIX 2

METRIC CONVERSIONS

Nonmetric	Multiplied by	Yields metric
MMBtu/h	1054.35	MM J/h
°F	0.555556(°F-32)	°C
ft	0.3048	m.
acfm	0.028317	acmm
dscfm	0.028317	dscmm
gal	3.78541	L
hp	746	J/s
in.	2.54	cm
lb	0.453592	kg
mil	0.0254	mm
mile	1609.344	m.
ton	0.907185	Metric ton (1000 kg)
yd^3	0.76455	m^3