6 Fabric Filters

6.1 Collection Mechanisms

Introduction

Particles from an industrial source generally float along the gas stream. If we put something in their path, they would bump into it and under the right circumstances, stay there. As a filter is having tiny pores in it, it allows the gas molecules to flow through it. These molecules create a continuous stream around the fiber in the filter.

Bag filter uses filter media made of cotton, wool, and man-made fibers for filtration. Consider a brand-new woven filter cloth, as depicted in Figure 6.1. The fibers are about 100-150 microns in diameter, and the open spaces between the fibers can be as large as 50-75 microns. The spaces are occupied by tiny, randomly oriented fibrils. The particle size is often much smaller than these pores, so, when this clean cloth is put into service, the collection efficiency will be low because a large portion of the dust will pass directly through (penetrate) the cloth. However, coarse dust particles are first retained and a "bridge" phenomenon occurs between the pores, and a so-called dust primary layer is quickly formed on the surface of the filter cloth. Relying on this dust primary layer, the subsequent particles are captured by the dust primary layer and gradually accumulate on it to form a dust layer under the effects of screening, inertial collision, direct interception, diffusion. As the dust layer thickens, fine particles can also be captured. The reason why the bag filter has a high dust filtration efficiency: it mainly relies on the filtration effect of the dust layer attached to the filter material, and the filter cloth only plays the role of forming the dust layer and supporting its skeleton.

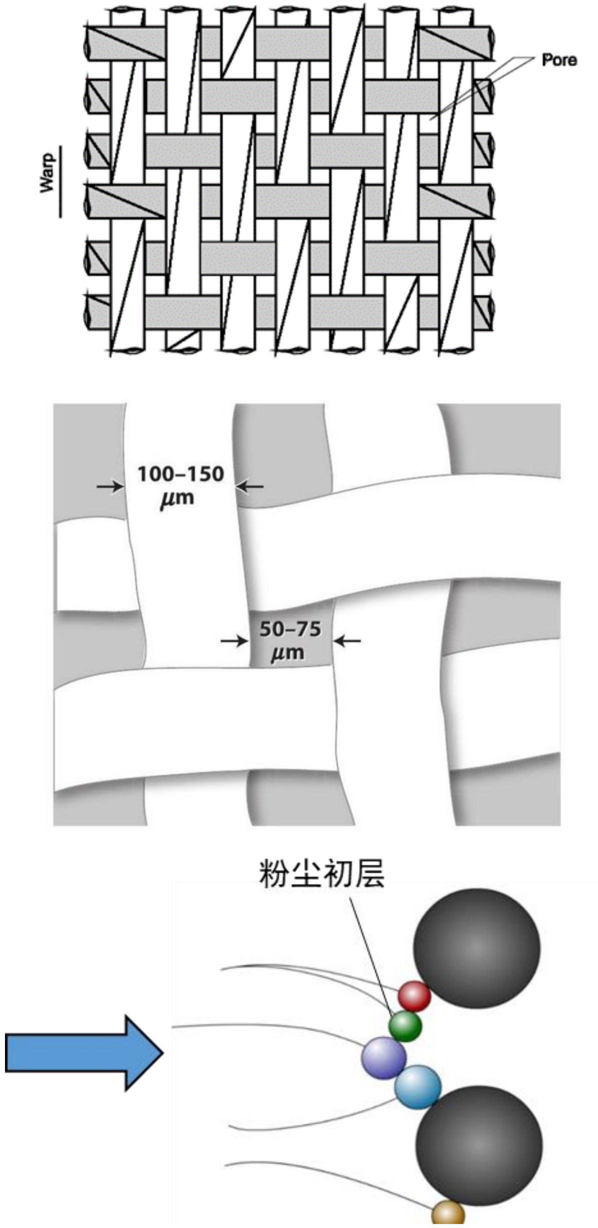


Fig6.1 Schematic diagram of fiber-bed

Mechanisms

Impaction In case of large particles, because of their too much inertia, they can't make turn around the fiber and keep going straight ahead until they impact on the fiber's surface and stay there as shown in above figure. This behavior is called impaction.

Interception Medium sized particles have less inertia. Actually they tend to start going around the fiber with the gas stream, but they can't quite make it. So, instead of hitting the fiber head on, as shown in above figure (if the distance between the center of the particle and the outside of the fiber is less than the particle radius), they end up grazing it on the side or being "intercepted". This behavior is called direct interception.

Impaction and direct interception account for almost 99% collection of the particles greater than 1 μm in aerodynamic diameter in fabric filter system.

Diffusion Fabric filters can also collect very small particles, less than 1 μm in aerodynamic diameter. One would think that this size particle would be carried right along with the gas stream. In fact, these particles are so small, they just sort of bounce around and deflect slightly when they are stuck by gas molecules. This individual or random motion causes them to be distributed throughout the gas as shown in above figure and is known as Brownian Motion or Brownian Diffusion. The particle may have a different velocity than the gas stream and at some point could come in contact with the fiber and be collected. This behavior is called diffusion.

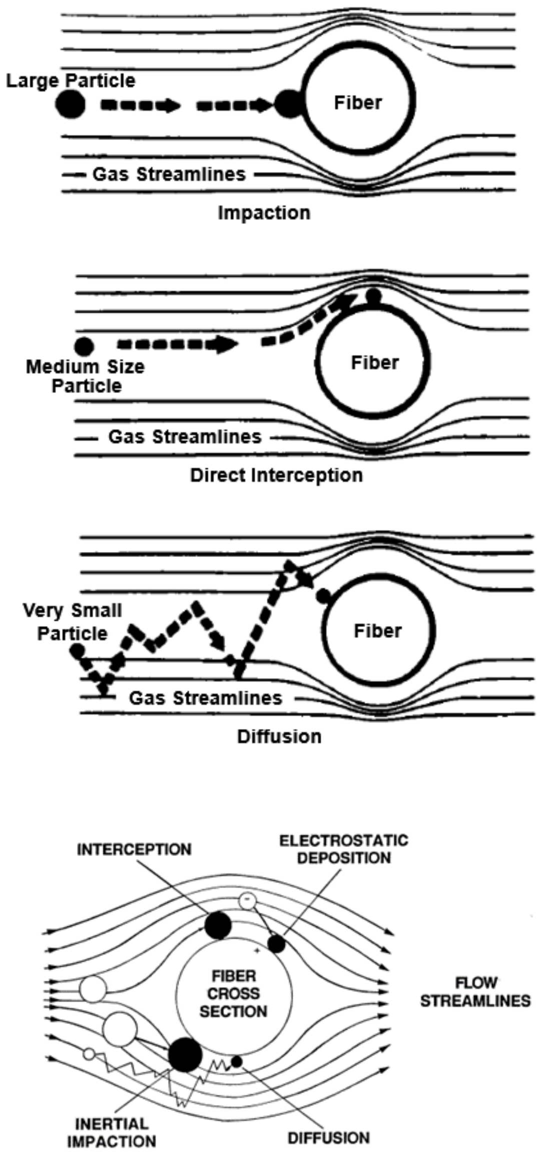


Fig6.2 Schematic diagram of collecting mechanism

6.2 Collection Efficiency

To analyze the overall collection efficiency of the fiber filter bed, we must first analyze the collection mechanism of a single fibers.

Deposition of Particles on a Cylindrical Collector by Inertial Impaction

As we described earlier, inertial impaction results because sufficiently massive particles are unable to follow curvilinear fluid motion and tend to continue along a straight path as the fluid curves around the collector. This capture mechanism is especially dominant in the case of micronic particles ($dp > 1\ \mu m$), which have a high inertia. It depends on two factors:

- The distribution of gas velocity around the fibers

$$Re_f = \frac{\rho u_0 d_f}{\mu} \qquad (6.1)$$

where Re_f =the fiber Reynolds number; ρ =density of the gas, kg/m^3; u_0 =gas velocity of undisturbed upstream gas,m/s; d_f =The diameter of a fiber, m; μ = gas viscosity, $kg/m \cdot s$.

At high Re_f (potential flow), the sudden expansion of streamlines increases the inertia of the particles, which in turn results in higher capture efficiency.

- The trajectory of particles

The dimensionless parameter associated with inertia is Stokes number, defined as the relationship between the stopping distance of the particle and the fiber diameter d_f

$$St = \frac{d_p^2 \rho_p u_0 C}{18 \mu d_f} \qquad (6.2)$$

where St = Inertial parameters (Stokes number); ρ_p =density of the particle, kg/m^3; d_p = diameter of the particle, m; C =Cunningham's correction factor.

$$\eta_I = f(st, Re_f) \qquad (6.3)$$

Viscous flow ($R_{ef} \leq 1$): $\eta_I = 1 - \frac{1.2}{R_e^{0.2} s_{tk}^{0.54}} + \frac{0.36}{R_e^{0.4} s_{tk}^{1.08}}$ (6.4)

Potential flow ($R_{ef} \to \infty$) : $\eta_I = \frac{s_{tk}}{s_{tk}+1.5}$ (6.5)

transition zone($R_{ef} = 10$): $\eta_I = \frac{s_{tk}^3}{s_{tk}^3+0.77 s_{tk}^2+0.22}$ (6.6)

Deposition of Particles on a single fiber by interception

This mode of capture involves particles that are larger than 0.1 μm. It is assumed that a particle with a diameter, dp, is intercepted by a fiber when it approaches this fiber at a distance smaller than its radius.

The mechanism, independent of the filtration velocity, is a function of the interception parameter R.

$$R = \frac{d_p}{d_f} \quad (6.7)$$

Viscous flow(Re_f<1): $\eta_R = \frac{1}{2.002 - lnRe_D}\left[(1+R)ln(1+R) - \frac{R(2+R)}{2(1+R)}\right]$ (6.8)

Potential flow ($R_{ef} \to \infty$): $\eta_R = 1 + R - \frac{1}{1+R}$ (6.9)

Deposition of Particles on a single fiber by diffusion

This type of capture is significant for particles with a small diameter (dp <0.1 μm) that come into contact with fibers by Brownian agitation and adhere to them.

The characteristic parameter of this mechanism is Peclet's dimensionless number (Pe) that compares the convectional transport rate to the diffusional transport rate:

$$P_e = u_0 d_f / \mathcal{D} \quad (6.10)$$

P_e =Peclet number;$\mathcal{D}$=Diffusion coefficient for the particle ($m^2.s^{-1}$).

Viscous flow ($R_{ef} \leq 1$): $\eta_D = \frac{1.71 Pe^{-2/3}}{(2-\ln Re_D)^{1/3}}$ (6.11)

Potential flow ($R_{ef} \to \infty$) : $\eta_D = \frac{3.19}{Pe^{1/2}}$ (6.12) diameter of the particle(dp)> Mean free path of the gas(λ), According to Einstein's equation

$$\mathcal{D}=\frac{CkT}{3\pi\mu d_p}$$

diameter of the particle(dp) < Mean free path of the gas(λ), According to Langmuir's equation

$$\mathcal{D}=\frac{4kT}{3\pi d_p^2 p}\sqrt{\frac{8RT}{\pi M}}$$

where k=Boltzmann's constant, 1.381×10^{-23} J · K^{-1}; T=Gas temperature，K； R=8.314J · mol^{-1} · K^{-1};
Combined efficiency

$$\eta_T=\eta_I+\eta_R+\eta_D \tag{6.13}$$

In actual filters, the fibers are arranged and combined into a group in a certain way. The situation of gas flowing around isolated fibers is obviously different from the situation of gas flowing around single fibers in composite fibers. Therefore, the capture efficiency of single fibers in composite fibers will be different from that of isolated fibers, and certain corrections must be made. In addition, the gas containing particles will continuously collide with many fibers, which is different from a single collision with an isolated fiber, and its impact must also be considered separately. Therefore, the problem is very complicated, and it is often necessary to obtain some empirical methods through experiments.

Inertia, interception, and diffusion capture efficiency of a single fiber considering the influence of neighboring fibers.

$$\eta_I=\frac{J}{K_u}S_{tk} \tag{6.14}$$

$$\eta_R=\frac{1}{2K_u}\left[2(1+R)\ln(1+R)-(1+R)+\frac{1}{(1+R)}+\alpha\left(-2R^2-\frac{R^4}{2}+\frac{R^5}{2}+\cdots\right)\right] \tag{6.15}$$

$$\eta_D=\frac{2.9}{K_u^{1/3}P_e^{2/3}}+\frac{0.62}{P_e}+\frac{1.24R^{2/3}}{K_u^{1/2}P_e^{1/2}} \tag{6.16}$$

式中：$J=(29.6-28\alpha^{0.62})R^2-27.5R^{2.8}$；$K_u=-\frac{1}{2}\ln\alpha-\frac{3}{4}+\alpha-\frac{\alpha^2}{4}$； $\alpha=1-\varepsilon$； ε—复合捕集物的空隙率。

Example 6.1

For air with a flow velocity of u = 10 cm/s at T = 293 K and normal pressure , containing particles with a density of 1000 kg/m^3. cylinders fibers-bed are arranged in the filter, the porosity of bed ε = 0.95, diameter of fiber d_f = 10 μm. Calculate the efficiency when d_p = 0.01, 0.1, 1, 2 μm.

Solution

$\alpha = 1-\varepsilon = 0.05$， $K_u = -\frac{1}{2}\ln\alpha - \frac{3}{4} + \alpha - \frac{\alpha^2}{4} = 0.797, R_e = \frac{\rho u_0 d_f}{\mu} = \frac{1.205\times0.1\times10\times10^{-6}}{1.81\times10^{-5}} = 0.0664$

the efficiency of a single fiber

d_p	η_I	η_R	η_D	$\eta_T = \eta_I + \eta_R + \eta_D$
0.01	—	—	0.1438	0.144
0.1	—	0.002	0.0079	0.008
1	0.01	0.002	0.0009	0.0013
2	0.02	0.0075	—	0.0028

the efficiency of a single fiber considering the influence of neighboring fibers.

dp（μm)	C_u	S_{tk}	R	D_{mp}(cm^2/s)	Pe	η_I	η_R	η_D	η_T
0.01			0.001	5.3×10^{-4}	18.9	–	–	0.476	0.476
0.1	2.89	0.000887	0.01	6.8×10^{-6}	1470	–	0.0002	0.0324	0.0326
1	1.166	0.0357	0.1	2.76×10^{-7}	3.6×10^{4}	0.0096	0.0105	0.0045	0.0245
2	1.083	0.1326	0.2	1.3×10^{-7}	7.7×10^{4}	0.117	0.0419	–	0.159

Overall Collection Efficiency

$$\eta_i = 1 - \exp[-\frac{4(1-\varepsilon)L\eta_{\mathrm{Ti}}}{\pi\varepsilon d_{\mathrm{f}}}] \qquad (6.17)$$

Where η_i = collection efficiency for the i th particle size range;L= thickness of the fiber bed, m.

Example 6.2

For Example 4.1 , Calculate the collecting efficiency of different bed thickness L = 0.1, 0.2 cm

(1) $L = 0.1cm$

$$d_p = 0.01\mu m$$

$$\eta_{0.01} = 1 - \exp[-\frac{4(1-\varepsilon)L\eta_{\mathrm{T}}}{\pi\varepsilon d_{\mathrm{f}}}] = 1 - \exp(-\frac{4\times(1-0.95)\times 0.1\times 10^{-2}}{3.1416\times 0.95\times 10\times 10^{-6}}\times\eta_T)$$

$$= 1 - \exp(-6.7\eta_T) = 1 - \exp(-6.7\times 0.476) = 0.959$$

$$d_p = 0.1\mu m$$

$$\eta_{0.1} = 1 - \exp(-6.7\eta_T) = 1 - \exp(-6.7\times 0.0326) = 0.196$$

$$d_p = 1.0\mu m$$

$$\eta_1 = 1 - \exp(-6.7\eta_T) = 1 - \exp(-6.7\times 0.0245) = 0.151$$

$$d_p = 2.0\mu m$$

$$\eta_2 = 1 - \exp(-6.7\eta_T) = 1 - \exp(-6.7\times 0.159) = 0.655$$

(2) $L = 0.2cm$

$$d_p = 0.01\mu m$$

$$\eta_{0.01} = 1 - \exp[-\frac{4(1-\varepsilon)L\eta_{\mathrm{T}}}{\pi\varepsilon d_{\mathrm{f}}}] = 1 - \exp(-\frac{4\times(1-0.95)\times 0.2\times 10^{-2}}{3.1416\times 0.95\times 10\times 10^{-6}}\times\eta_T)$$

$$= 1 - \exp(-13.4\eta_T) = 1 - \exp(-13.4\times 0.476) = 0.998$$

$$d_p = 0.1\mu m$$

$$\eta_{0.1} = 1 - \exp(-13.4\eta_T) = 1 - \exp(-13.4\times 0.0326) = 0.354$$

$$d_p = 1.0\mu m$$

$$\eta_1 = 1 - \exp(-13.4\eta_T) = 1 - \exp(-13.4\times 0.0245) = 0.280$$

$$d_p = 2.0\mu m$$

$$\eta_2 = 1 - \exp(-13.4\eta_T) = 1 - \exp(-13.4\times 0.159) = 0.881$$

The results are summarized in the table below

d_p (μm)	η_T	η		d_p (μm)	η_T	η	
		$L = 0.1$ cm	$L = 0.2$cm			$L = 0.1$ cm	$L = 0.1$ cm
0.01	0.476	0.959	0.9983	1	0.0245	0.151	0.28
0.1	0.0326	0.196	0.354	2	0.159	0.655	0.881

6.3 Pressure Drop

The pressure drop through a baghouse at a given gas flow rate is given by

$$\Delta P = \Delta P_f + \Delta P_p + \Delta P_s \tag{6.18}$$

where ΔP = total pressure drop,Pa; ΔP_f =pressure drop due to the fabric,Pa; ΔP_p =pressure drop due to the particulate layer, Pa; ΔP_s = pressure drop due to the baghouse structure, Pa.

The pressure drop due to the structure usually is low, and it will be ignored in the following discussion.

From Darcy's equation for fluid flow through porous media, equations can be written individually for the fabric and the particulate layer; that is,

$$\Delta P_f = \frac{D_f \mu V}{K_f} \tag{6.19}$$

$$\Delta P_p = \frac{D_p \mu V}{K_p} \tag{6.20}$$

where D_f, D_p =depth (in the direction of flow) of the filter and the particulate layer, respectively,m; μ=gas viscosity,kg/m · s ; V=superficial filtering velocity,m/s.

$$V = \frac{Q}{A} \tag{6.21}$$

where Q =volumetric gas flow rate, m^3/s;A = cloth area, m^2.

As the filter operates, the depth of the dust layer, D_p, increases. In fact, for a constant filtering velocity and a constant mass concentration of dust (often referred to as dust loading), D_p should increase linearly with time; that is,

$$D_p = \frac{cVt}{\rho_c} \tag{6.22}$$

where c = dust loading, g/m^3;t = time of operation, s;ρ_c = bulk density of the particulate layer, g/m^3.

Let $K_1 = \frac{D_f \mu}{K_f}$ $K_2 = \frac{\mu}{K_p \rho_L}$ $W = cVt$

$$\Delta P = \left(\frac{D_f \mu}{K_f}\right) V + \left(\frac{\mu}{K_p \rho_L}\right) (cVt) V = (K_1 + K_2 W) V \qquad (6.23)$$

Let $S = K_1 + K_2 W$ (6.24)

$\Delta P = SV$

$$S = \frac{\Delta P}{V} \qquad (6.25)$$

Where S = filter drag, $N - min/m^3$ or $Pa - min/m$; W = areal dust density, g/m^2 of fabric.

Example 6.3

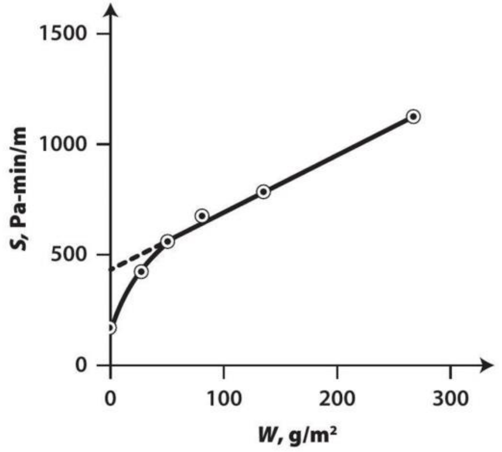
Based on the following test data for a clean fabric, predict the design pressure drop in a baghouse after 70 minutes of operation with $c = 5.0\ g/m^3$ and $V = 0.9\ m/min$.

Test Data		
Time, min	$\Delta P, Pa$	Constants
0	150	$V = 0.9\ m/min$
5	380	$L = 5.0\ g/m^3$
10	505	
20	610	
30	690	
60	990	

Solution

First, we use the test data to generate a plot of filter drag versus areal dust density. The data to be plotted are

$S = \Delta P/V$, Pa − min/m	$W = LVt$, g/m^2
167	0
422	22.5
561	45
678	90
767	135
1100	270



A plot of these data (see the figure) shows an initial characteristic curvature, which should be ignored in obtaining the slope and intercept.

From a linear least-squares fit of the last four data points, the values of the constants K_1 and K_2 are 329 Pa − min/m and 3.058 Pa − min − m/g, respectively.

Knowing the coefficients of the filter drag model, we can predict the design pressure drop.

$$W = 5.0\frac{\text{g}}{\text{m}^3} \times 0.9\frac{\text{m}}{\text{min}} \times 70\text{min} = 315\frac{\text{g}}{\text{m}^2}$$

$$S = 329\frac{\text{Pa–min}}{\text{m}} + \left(3.058\frac{\text{Pa–min} - \text{m}}{\text{g}}\right)\left(315\frac{\text{g}}{\text{m}^2}\right) = 1292\frac{\text{Pa–min}}{\text{m}}$$

$$\Delta P = 0.9\frac{\text{m}}{\text{min}} \times 1292\frac{\text{Pa–min}}{\text{m}} = 1163\text{Pa}$$

6.4 Design

Designing a baghouse is somewhat unusual in that the collection efficiency is generally not a concern of the designer! The reason is that a well-designed, well-maintained fabric filter that is operated properly generally collects particles ranging from submicron sizes to those several hundred microns in diameter at efficiencies of greater than 99% (Turner et al. 1987a). With a high collection efficiency as a "given," baghouse design involves optimizing the filtering velocity V to balance capital costs (baghouse size) versus operating costs (pressure drop). Major factors that affect the selection of the design V include prior experience with similar dusts, fabric characteristics, particle characteristics, and gas stream characteristics.

(1)Cleaning Methods

Reverse-Air Baghouses

In reverse - air cleaning, a combination of bag deflection (inward collapse) and reverse flow is used to remove dust from the fabric. This process, which results in very low stresses on the fabric, was developed specifically for easily damaged fabrics, such as fiberglass.

Pulse-Jet Baghouses

Pulse - cleaned baghouses use outside – in flow, where the fabric collapses against a wire cage during filtration. During cleaning, a pulse of high - pressure air is directed into the bag (the reverse - flow direction), inflating the bag and causing fabric/cake deflection and high inertial forces that separate the dust from the bag. Although reverse - airflow is involved, it is thought to have a minor effect on cleaning.

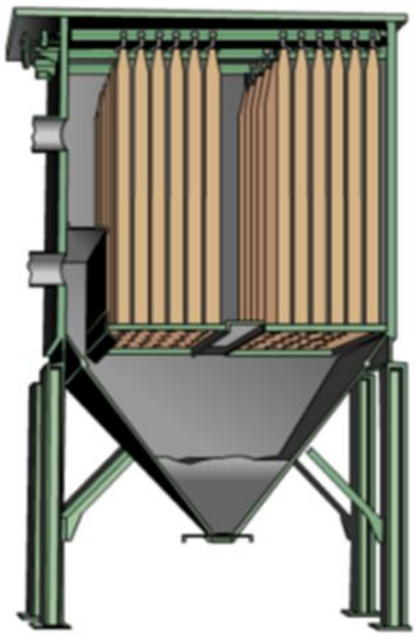


Fig6.3 Schematic diagram of Reverse-Air Baghouses

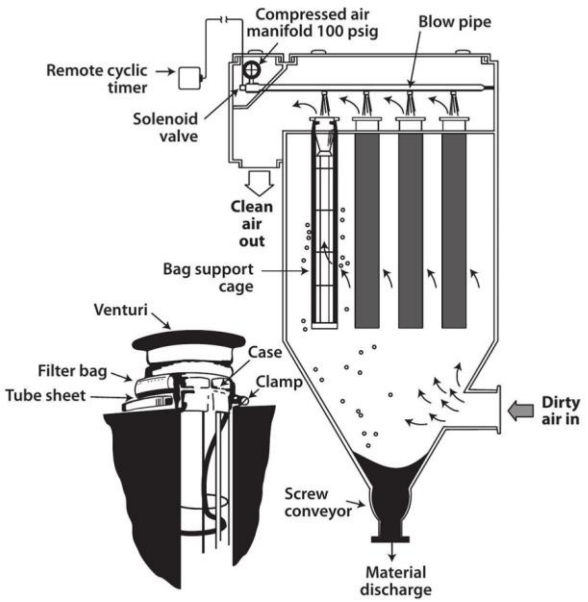


Fig6.4 Schematic diagram of Pulse-Jet Baghouses

(2)filtering velocity and Fabric

Table 6.1 Maximum Filtering Velocities for Various Dusts in Reverse-Air Baghouses

Dusts	Maximum Filtering Velocity,ft/min
Activated Charcoal, Carbon Black, Detergents, Metal Fumes	1.50
Aluminum Oxide, Carbon, Fertilizer, Graphite, Iron Ore, Lime, Paint Pigments,	2.0
Fly Ash, Dyes	2.25
Lluminum, Clay, Coke, Charcoal, Cocoa, Bauxite, Ceramics, Chrome Ore, Feldspar, Flour, Flint, Glass, Gypsum, Plastics, Cement	2.50
Asbestos, Limestone, Quartz, Silica Cork, Feeds and Grain, Marble, Oyster Shell, Salt	2.75
Leather, Paper, Tobacco, Wood	3.0 – 3.25

Table 6.2 Maximum Filtering Velocities for Various Dusts or Fumes in Pulse-Jet Baghouses

Dusts or Fumes	Maximum Filtering Velocity,ft/min
Carbon, Graphite, Metallurgical Fumes,	5 – 6
Soap, Detergents, Zinc Oxide	7 – 8
Paint (Rigments, Starch, Sugar, Wood,	
Gypsum, Zinc (Metallic)	9 – 11
Aluminum Oxide, Cement (Finished),	
Clay (Vitrified), Lime, Limestone, Mica, Quartz, Soybean, Talc	12 – 14
Cocoa, Chocolate, Flour, Grains, Leather Dust, Sawdust, Tobacco	

Table 6.3 Temperature and Chemical Resistance of Some Common Industrial Fabrics

	Recommended Maximum Temperature, °F	Acid	Chemical Resistance
Fabric	160	Good	Base
Dynel	180	Poor	Good
Cotton	200	Good	Good
Wool	200	Poor	Poor
Nylon	200	Excellent	Good
Polypropylene	260	Good	Excellent
Orlon	275	Good	Fair
Dacron	400	Fair	Fair
Nomex ®	400	Excellent	Good
Teflon ®	550	Good	Excellent
Glass			Good

(3) The number of compartments

The number of compartments chosen during the design depends on the total flow to be filtered, the available (or desired) maximum pressure drop ΔP_m, the filtration time t_f desired between two cleanings of the same compartment, and the time required to clean one compartment t_c. The time interval between cleanings of any two compartments is the run time t_r, (portrayed schematically with t_c in Fig-ure 6.5). The filtration time t_f is the elapsed time from the moment one compartment is returned to service until that same compartment is removed for cleaning again (after all the other compartments have been cleaned in rotation).

Table 6.4 Number of Compartments as a Function of Net Cloth Area

Net Cloth Area, ft ^{2}	Number of Compartments
$1-4000$	2
$4000-12{,}000$	3
$12{,}000-25{,}000$	$4-5$
$25{,}000-40{,}000$	$6-7$
$40{,}000-60{,}000$	$8-10$
$60{,}000-80{,}000$	$11-13$
$80{,}000-110{,}000$	$14-16$
$110{,}000-150{,}000$	$17-20$
$> 150{,}000$	> 20

(4) Pressure Drop and Cleaning cycle

$$T_c = \frac{\Delta P - K_1 V}{K_2 c V^2}$$

Example 6.4

You are in the process of designing a pulse-jet baghouse to filter coal fly ash from the flue gas of a large power plant boiler. The gas flow is 1.4 million acfm (at 1 atm pressure and 360°F). The bags are 5 inches in diameter and 26 feet long. Assume that your company guidelines require that bags be positioned in rows and columns with two inches of space between bag edges and 6 inches between the outer rows of bags and the walls of the compartment. Furthermore, the guidelines say that there can be no more than 1296(36 × 36) bags per compartment. In your design, specify the number of compartments, the filtering velocity, the can velocity, and estimate the overall dimensions of the baghouse.

Solution

Each bag has a filtering area of $\pi\left(\frac{5}{12}\right)\text{ft} \times 26\text{ft} = 34.0\text{ft}^2$

Initially, choose a design filtering velocity of 4ft/min; the area of fabric needed is $\frac{1.4(10)^6\text{cfm}}{4\text{ft/min}} = 3.5(10)^5\text{ft}^2$

And the number of bags is $\frac{3.5(10)^5\text{ft}^2}{34\text{ft}^2/\text{bag}} = 10{,}294\text{bags}$

At 1296 bags per compartment, this gives $\frac{10{,}294\text{ bags}}{1296\text{ bags/comp}} = 8\text{ compartments}$

The length of one side of the square compartment is $36\text{ bags } \times \frac{5}{12} + 35\text{ spaces } \times \frac{2}{12} + 2\text{ spaces } \times \frac{6}{12} = 21.8\text{ft}$

Thus, the floor area of the compartment is $21.8 \times 21.8 = 476\text{ft}^2$

and the total area of the bag openings is $1296\text{ bags } \times \frac{\pi(5/12)^2\text{ft}^2}{4} = 177\text{ft}^2$

The net open area between bags is $476 - 177 = 299\text{ft}^2$; thus the can velocity is $\frac{1.4(10)^6\text{cfm}}{8\text{comp}} \times \frac{1}{299\text{ft}^2} = 585\text{ft/min}$

This is above the limit. The solution is to add more compartments and bags and reduce the filtering velocity. We do this iteratively, and we might end up with a final design that calls for 14 compartments, and gives a filtering velocity of 2.4ft/min and a can velocity of 5.6ft/sec. The overall dimensions of this baghouse will be about 90 feet wide, 180 feet long, and 75 feet tall.