

containing a proportion of long asbestos fibres. The paper is folded into a rectangular panel and cemented into a wooden frame. The cells are manufactured from combustible material except for the small quantity of asbestos, so that complete destruction by incineration of the filter is possible after use if desired. In this case, the filters are manufactured to give a maximum penetration of 0.05% by the methylene blue test.

It has been possible to give here only a brief indication of the main types of air filters available which are suitable for the removal of micro-organisms from air. Many other types are currently on the market, but in general, where they differ markedly in design from the types mentioned, they are intended for general air cleaning and not specifically for spore removal.

In many cases, it has been found advantageous to employ two different types of filter in series for air sterilization. When this is done, the first filter is generally of the air cleaning type which removes virtually all of the coarse dust and a very high proportion of the spores present. The actual sterilizing filtration is then accomplished with a filter designed for the purpose, the active life of the filter being considerably lengthened by the pre-filtration cleaning.

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CHAPTER 4

Design and Testing of Fibrous Air Filters

As indicated in Chapter 3, filters constructed of fibrous materials are of very great importance in the removal of micro-organisms from air which is to be used for a wide variety of purposes. The kinetic considerations of Chapter 2 showed that, in theory at least, 100% removal of viable spores cannot be guaranteed, so that for any given application we must decide on an acceptable probability of an organism penetrating the filter and design the system accordingly. In practice it is possible to design filtration systems so that the chance of penetration is so small that it is quite acceptable. This chapter is concerned with the mechanism of air filtration and with the methods of testing and design which will enable us to produce a filter which is suitable for any given purpose.

THEORY OF FIBROUS FILTERS

Whenever air is passed through a bed of fibrous material there are a number of factors which may contribute to the removal of particulate matter from the air stream. The most important of these factors are:

- i. Direct interception by the fibres.
- ii. Inertial impaction.
- iii. Gravitational settling.
- iv. Brownian movement.
- v. Convection.
- vi. Electrical attraction arising from initial charge differences between particles and fibres.
- vii. Electrical attraction arising from induced charge differences.

The relative importance of these factors will, as might be expected, vary from case to case, depending on the nature of the particles and fibres, on the air velocity, humidity, temperature, etc. The way in which different mechanisms may assume different degrees of importance may be illustrated by the following example. The effect of inertial impaction will depend on the momentum of the particles and on the viscous drag, so that we might expect the collection effect from this cause to be directly proportional to the particle density, the square of the particle diameter and to the air

velocity and inversely proportional to the air viscosity. Gravitational settling, however, while being again directly proportional to particle density and the square of the diameter and inversely proportional to viscosity, will this time be inversely proportional to air velocity. Thus, an increase in air velocity will favour the impaction mechanism at the expense of a fall in efficiency of gravitational settling.

Similarly, while the above two effects increase rapidly with increasing particle diameter, electrostatic attraction resulting from initial charge difference will be inversely proportional to particle diameter so that this effect is more important for the smaller particles. Similar considerations apply to Brownian movement.

It is also worth noting that, in general, those effects which depend in any way on the diameter of the fibres indicate a reciprocal relationship so that the effect is enhanced by the use of fibres of small diameter. This is an important point, which will be mentioned again later.

The determination of expressions which adequately describe the nett effect of all of the collection mechanisms is clearly a very difficult task and it has not so far proved possible to obtain such an equation. Even if this were done, it is probable that the difficulty of determining values for all of the relevant factors in any single case would preclude its use in practical filter design.

Nevertheless, realistic attempts have been made to derive useful expressions for filter efficiency. These generally involve the concept of "single fibre efficiency". This is a somewhat nebulous idea, which concerns basically the ratio of the number of particles removed per unit length of fibre divided by the number of particles in the projected area of unit length of fibre. This single fibre efficiency, η_s , was related by Ranz and Wong to the ratio of the diameters of the particles (D_p) and the fibres (D_f) by the expression

$$\eta_s = \left(1 + \frac{D_p}{D_f} \right) - \frac{1}{\left(1 + \frac{D_p}{D_f} \right)} \quad (1)$$

This expression gives a reasonable result in some cases only. For example, if we consider particles of diameter 1μ and fibres of 10μ , the single fibre efficiency from this equation will be 0.2, i.e. 20%. If, however, we consider 1μ particles and 1μ fibres, η_s becomes 1.5 or 150%.

Several workers have used the single fibre efficiency in equations which they have found suitable for calculation of the efficiency of the filter as a whole. Davies proposed the equation

$$\eta_{\text{filter}} = 1 - \exp \left(\frac{-4\alpha\eta_s x}{\pi D_f (1 - \alpha)} \right) \quad (2)$$

where α = volume of fibres per unit volume of filter bed, i.e. the ratio of filter density over fibre density.

x = filter bed depth.
 D_f = fibre diameter.

Wong and Johnstone gave a very similar expression

$$\eta_{\text{filter}} = 1 - \exp \left(\frac{-4\alpha\eta_s x}{\pi D_f} \right) \quad (3)$$

Here, η_s is the effective fibre efficiency which is some function of η . Chen gave an expression which has similarities to those of Davies and Wong and Johnstone, but which relates the single fibre efficiency to the actual fractional penetration of the filter by the particles.

$$\eta = -\ln \left(\frac{N}{N_o} \right) \left(\frac{\pi(1-\alpha)(D_f)^2}{4\alpha \cdot x \cdot (D_f)_{\text{av}}} \right) \quad (4)$$

where N_o = concentration of particles entering filter.
 N = concentration of particles leaving filter.

$(D_f)_s$ = mean surface fibre diameter.
 $(D_f)_{\text{av}}$ = mean fibre diameter.

These and other similar equations can be of value in suggesting ways in which the collection efficiency of a filter bed may be improved. However, we require in general a simpler approach which can be used easily in the evaluation of filter materials and the design of filters.

If it is assumed that

- Particles which touch a fibre are held firmly by it, and
- Perfect mixing occurs at each level in the filter, so that the concentration of particles is the same at all points at the same depth in the filter,

then it follows that we might expect each layer of filter of unit thickness to reduce the concentration entering it by the same fraction.

Expressed mathematically, this gives

$$\frac{dN}{dx} = -KN \quad (5)$$

where K is a constant and where N is the concentration of particles in the air at a depth x in the filter. Thus

$$\frac{dN}{N} = -K dx \quad (6)$$

and integration between the limits of zero and x gives

$$\ln \left(\frac{N}{N_o} \right) = -K \cdot x \quad (7)$$

The constant K will depend on a variety of factors, such as the sizes of the particles and the fibres, etc. The equations (2), (3) and (4) above were, in fact, based in equation (7) and it is interesting to see the relationship between them. Equation (7) can be rewritten as

$$\frac{N}{N_0} = e^{-Kx} \quad (8)$$

Now if N/N_0 is the fractional reduction in particles through a depth x , then the efficiency of filtration will be $(N_0 - N)/N_0 = \eta_{\text{filter}}$. But

$$\frac{N_0 - N}{N_0} = 1 - \left(\frac{N}{N_0} \right) \quad (9)$$

so that

$$\eta_{\text{filter}} = 1 - e^{-Kx} \quad (10)$$

Equation 10 is of exactly the same form as those of Davies (equation (2)) and of Wong and Johnstone (equation 3).

If in equation (7) we make the substitution $\eta/k' = K$, where η = single fibre efficiency and k' is a constant, the expression

$$\eta = -\ln \left(\frac{N}{N_0} \right) \left(\frac{k'}{x} \right) \quad (11)$$

results, which is identical in form to that of Chen (equation (4)).

Equation (7) is generally known as the Log-Penetration Relation. It provides, as will be seen below, a rational basis for filter design and has been shown by many investigators to describe the behaviour of actual filters with fair accuracy. For ease of use, logarithms to the base 10 are normally employed, in which case a change of constant is required, where $k = K/2.303$

$$\log \left(\frac{N}{N_0} \right) = -k \cdot x \quad (12)$$

Humphrey and Gaden in particular have been concerned with the development and use of this method for filter design. They employ the concept of X_{90} , which they define as the filter bed thickness in inches which is needed to reduce the micro-organism concentration to 1/10 of that entering the filter. Reduction of the population to 1/10 signifies 90% filtration efficiency by that layer and the log-penetration relationship then indicates that each succeeding layer of the same thickness which we may add will again reduce the count to 1/10 of that entering the layer.

For a 90% reduction,

$$\log \left(\frac{N}{N_0} \right) = \log \left(\frac{1}{10} \right) = -1 = -k \cdot X_{90}$$

so that

$$X_{90} = 1/k$$

(13)

Thus, if we can determine X_{90} experimentally, the calculation of filter bed thickness to effect any required reduction in concentration becomes a simple matter.

In the next section the practical evaluation of air sterilizing filters will be described. The methods given are basically similar to those used by Humphrey and Gaden and Maxon and Gaden for bacterial filters and by Sadoff and Almlof for bacteriophage filters.

EVALUATION OF FILTER MEDIA

For many years most manufacturers of commercial air filters failed to recognize or accept the special requirements of the growing fermentation industry. This was perhaps partly due to the fact that the fermentation and finding that suitable filters were difficult to obtain, devised and built their own equipment on an empirical basis. The subsequent slow rate of progress in the rational design of sterilizing filters resulted from the high degree of success obtained with these empirical filters, many of which are still in use.

It is nevertheless possible by use of the log-penetration relationship coupled with relatively simple evaluation of filter media to design air filters which are more effective than the older types and which are also smaller, cheaper to construct and cheaper to maintain.

As discussed in Chapter 3, some fibrous filter media are available as a loose bulk material which must be packed into a container. Others are obtainable in the form of pre-formed slabs, sometimes bonded with synthetic resins, and some as sheets which can be made into filters by supporting them on wire mesh formers. However, the methods used for evaluating these filter media can be basically the same, differing only in the construction of the test filter itself.

Either physical or microbiological test methods can be used for testing air filters. The best known and most commonly employed physical method in the U.K. is the methylene blue test. Full details of this test are given in B.S.S. 2831/1957 which contains the recommendations of the British Standards Institution.

The principle of the methylene blue test is as follows. A solution of the dye in distilled water is atomized through a standard spray nozzle which is operated by compressed air at a standard pressure. The resultant spray is introduced into a duct of sufficient length to permit evaporation of the water from the droplets before reaching the filter. Not only is methylene blue solution atomized, but some evaporation results from the flow of air in the solution container and allowance must be made for this.

Evaporation of the water from the droplets dispersed in the air yields a

fine dispersion of the solid dye in the air stream which is then passed through the test filter.

The most frequently employed method of determining penetration involves taking upstream and downstream samples of air through white paper filters. A series of samples is taken at both points, the sampling being carried out to pass a range of volumes of air through the sample papers. In general, with high efficiency filters, the samples taken downstream of the test filter will need to be many times greater (e.g. several thousand times) than those on the inlet side.

The filter papers are then steamed gently to develop fully the colour of the dye and papers from upstream and downstream samples are compared to obtain stains of similar intensity. If, then, the stain obtained from an upstream sample of, say, 20 ml is similar to that obtained when 50 l of air is passed through a paper after the filter, the present penetration will be given by

$$\frac{0.020 \times 100}{50} = 0.04\%$$

The particles of dye produced under standard conditions by this method are generally in the range 0.1-1.0 μ , which is of the order of size of bacterial spores.

In the U.S.A. the methylene blue test is less widely used and is replaced by a similar test employing a smoke of diethyl-phthalate, of mean particle size about 0.3 μ . The principle of the test is similar.

A further alternative is the sodium flame test, the relevant standard in this case being B.S. 3928. This method shows advantages over the methylene blue method in that it gives an immediate figure for the penetration efficiency. In this case the test particles are produced by atomization of a 2% brine, giving crystalline particles in the range 0.01 to 1 μ . The air containing the salt spray is passed through a duct, which is heated if necessary, to allow the moisture to evaporate, and thence through the test filter. A sample of the effluent air is fed to a hydrogen flame photometer, where the brightness of the characteristic sodium yellow light is measured.

A sodium flame test rig is illustrated in Fig. 4.1.

The principle of microbiological testing of filter media is as follows. A water suspension of spores of a micro-organism is atomized in an air stream, the volume rate of flow of which can be measured. This infected air is then passed through a test filter containing a known quantity of the filter medium and after allowing time for steady conditions to be established, the air is sampled before and after the filter.

Microbiological determination of the concentration of organisms before and after the filter then permits calculation of $\log N/N_0$ for the particular

bed thickness and air flow rate. Repetition of this determination for a number of bed thicknesses enables the log-penetration constant to be obtained from a plot of $\log N/N_0$ against x .

Fig. 4.2 shows one suitable apparatus, based on that used by Maxon and Gadon. Here the spore suspension of the micro-organism being used is fed to an atomizer where it is dispersed by a primary air stream and passes to a mixing chamber. In the mixing chamber the infected air meets a secondary

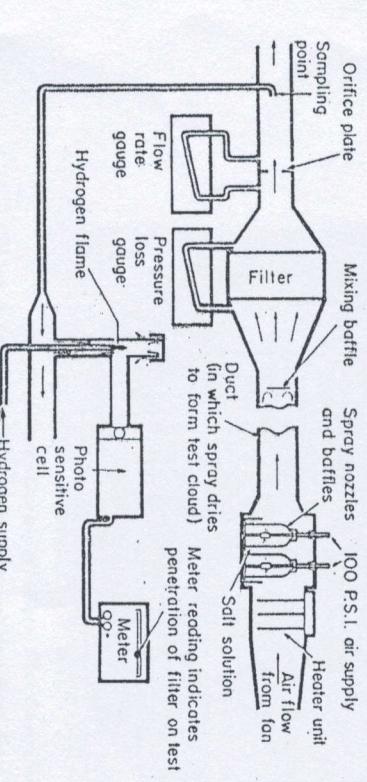


Fig. 4.1. Sodium flame test rig for evaluation of air filters. (Courtesy of Vokes, Ltd.)

air stream which mixes and dilutes it. The air then passes to the test filter and out to waste. A differential manometer is used to determine the pressure drop across the filter and samples of the air are withdrawn through bubble samplers before and after the filter. Serial dilution and plating of the suspensions collected in the samplers permits calculation of the concentrations of the samples. If the samplers have been filled with the same quantity of water and run for equal periods with the same air flows through them, then the ratio of downstream and upstream sampler concentrations can be used directly as the ratio N/N_0 .

Fig. 4.3 illustrates certain modifications which can be made to the above method. In the first place the spore suspension vessel and atomizer can be combined in one simple unit which operates on a scent-spray principle. The flow of air to the atomizer is taken from the main stream and can be readily adjusted by means of the valves A and B.

Secondly, membrane filters can be used for sampling the air before and after the test filter, air being drawn through them by a vacuum pump. These membrane filters are obtained ready-ruled with squares. After exposure, they are incubated on nutrient agar plates and colonies are counted directly. This method is essentially simple, but difficulties can be experienced in

counting when heavy membrane loadings occur, so that the liquid samplers and the serial dilution method are sometimes easier to handle.

Plate 1 shows the method of incubation of membrane filters, and Plate 2 shows colonies on the incubated disc.

Various micro-organisms have been used for testing filters. If a mixed culture is used, or if the colonies of the selected organism are not readily identifiable, it is necessary to heat-sterilize the whole apparatus before each test run is made and to employ careful aseptic techniques throughout. However, if a distinctive organism is employed the method becomes much simpler as only the colonies of the test organism are counted. Of such organisms, *Serratia marcescens* (*Chromobacterium prodigiosum*) is an obvious choice, partly on account of its red colonies which make it readily distinguishable and partly because, being readily killed by heat, the filter and samplers are easily sterilized with respect to it by heating in an air oven.

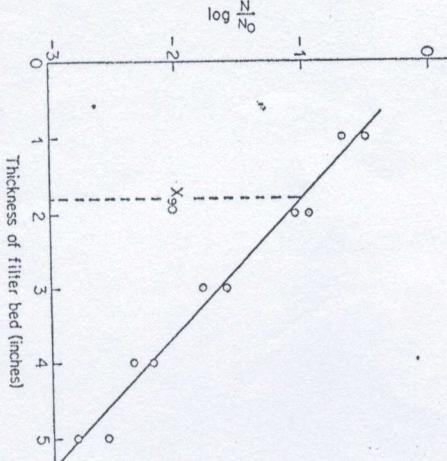


FIG. 4.4. Log-penetration graph for air filter medium.

In some cases, radio-activity has been used for identification and counting of the test organisms. For example, Sadoff and Almlöf used phosphorus-32 as a tracer for phage particles, counts being made with a Geiger tube.

Tests carefully carried out at one constant air velocity with equipment such as that shown in Figs. 4.2 and 4.3 will yield data suitable for plotting a log-penetration graph. One such graph is shown in Fig. 4.4. A line of best fit is drawn through the experimental points and the value of X_{90} can be read off directly as the bed thickness corresponding to $\log N/N_0 = -1$.

In this case $X_{90} = 1.8$ in. The value of k (equations 12 and 13) will be $1/X_{90}$, i.e. 0.56.

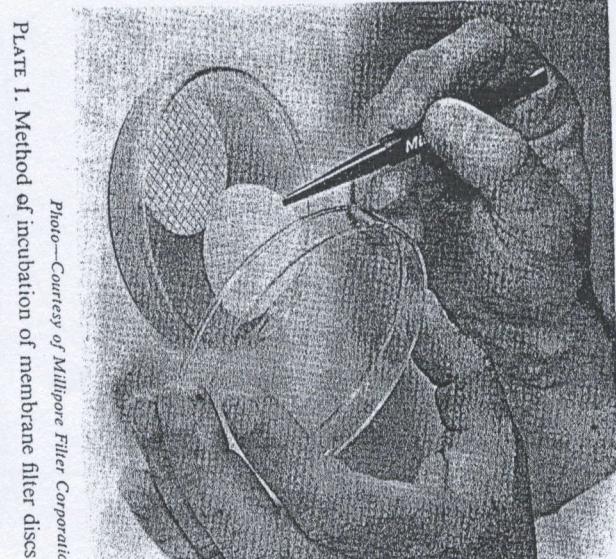


PLATE 1. Method of incubation of membrane filter discs.
Photo—Courtesy of Millipore Filter Corporation

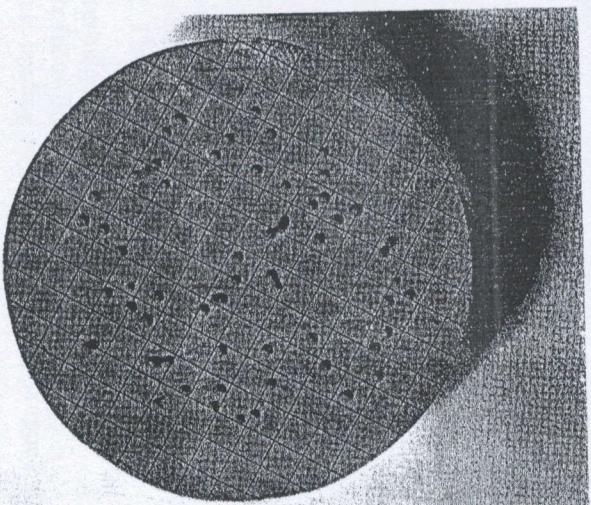


PLATE 2. Incubated membrane filter disc, showing the colonies which have developed from single organisms or organism-bearing particles.
Photo—Courtesy of Millipore Filter Corporation
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The value of k (or, of course, X_{90}) will vary from one filter medium to another and will, in general, be very dependent on the air velocity through the filter. It is therefore necessary in evaluating air filter media, not only to compare different filter media when tested under identical conditions, but also to investigate the variation of k with air velocity. As a result of the changes in collection mechanism arising from air velocity changes, as discussed earlier, a plot of k against the air velocity will be similar to that shown in Fig. 4.5. Here the air velocity is expressed as the volume/sec divided by the empty cross sectional area of the filter. The shape and position of this curve will vary considerably for different filter media.

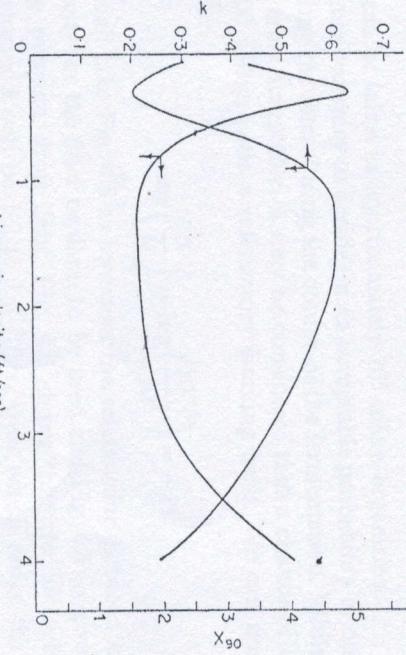


Fig. 4.5. Variation of k and X_{90} with linear air velocity.

Fig. 4.5 shows that as the air velocity is increased from a very low initial value, the efficiency of the filter falls to a minimum and then rises again with further increase in air velocity. The existence of this minimum was anticipated by Stairmand and Bosanquet from theoretical considerations of changing collection mechanism and was illustrated by Gaden and Humphrey when they obtained a maximum for X_{90} in a plot of this against air velocity. However, Fig. 4.5 also shows that above a certain air velocity the collection efficiency again falls off. This results from three causes:

- The onset of air turbulence within parts of the filter.
- Channeling of air following displacement of fibres.
- Vibration of fibres, tending to release previously trapped organisms.

It is clearly desirable to determine the variation of k with air velocity for any particular filter medium in order that the filter which is designed may be the smallest and most economical for the required job. Here, however,

another factor becomes very important, namely, pressure drop. The pressure loss through the filter will depend on the nature of the filter medium itself, the packing density of the filter, the density of the air and the linear velocity of the air passing through the filter. Various equations have been given for the pressure drop across a filter, such as that of Wong and Johnstone,

$$\Delta P = \frac{2\rho v^2 \alpha x C}{\pi D_f}$$

where ΔP is the pressure loss across the filter, v is the linear air velocity, ρ the air density, C is a drag coefficient depending on the bed characteristics and the other symbols have the meanings given earlier.

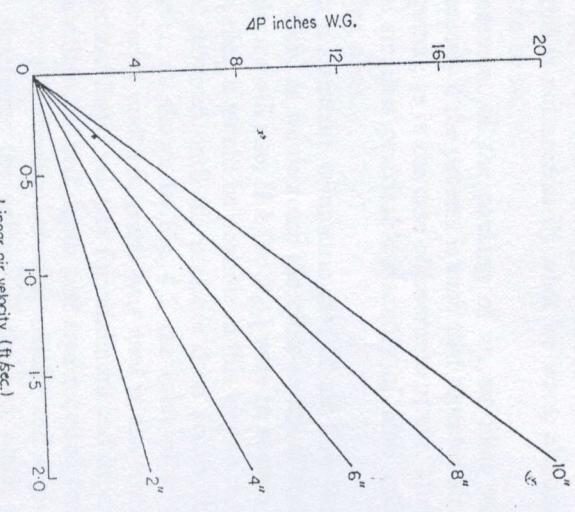


FIG. 4.6. Plot of pressure drop across air filter medium, against linear air velocity.

This equation indicates that the pressure loss will be proportional to the square of the air velocity, other things being equal. However, it is generally found that at low air velocities, at least up to 2 or 3 ft/sec, the dependence of pressure drop on velocity can be considered to be linear, without appreciable error.

The relationship between velocity and pressure drop for any test medium may be determined using basically the same equipment as that shown in Figs. 4.2 or 4.3. The pressure loss through the unpacked test filter can be first determined for a range of air flows, should this prove to be significant. Repetition of the same procedure with several thicknesses of filter medium

in the filter will permit plotting of a family of lines of nett pressure drop against air velocity. Such a graph is shown in Fig. 4.6.

BASIC FILTER DESIGN

Let us now consider the use of the test data described above in the design of sterilizing filters. This is best illustrated by means of an example.

Suppose we require a supply of sterile air at the rate of 500 C.F.M. for a fermentation, the duration of which is 100 hr. Let us also suppose that the air entering the filter has a bacterial count of 30/cu. ft. Then the total number of organisms to be removed will be given by

$$500 \times 60 \times 100 \times 30 = 9 \times 10^7$$

This can be taken as approximately 10^8 micro-organisms.

It is now necessary to decide on an acceptable probability of one organism penetrating the filter during the course of the fermentation. While no probability is truly acceptable, it may be considered that a chance of infection of 1 in 1000 will provide a satisfactory working basis. We can now calculate $\log N/N_0$.

$$\log \left(\frac{N}{N_0} \right) = \log \left(\frac{10^{-3}}{10^8} \right) = -11$$

We shall take Fig. 4.5 to represent the relationship between k and linear air velocity for the filter medium to be used and Fig. 4.6 to give the corresponding pressure drop data. Fig. 4.5 shows that the air velocity range for maximum k will be 1.2 to 1.8 ft/sec, over which range the value of k is 0.61. Assuming for the moment that this will be the best value of k to select, then from equation (12),

$$\log \left(\frac{N}{N_0} \right) = -k \cdot x$$

Thus

$$x = \frac{-11}{-0.61} = 18.03 \text{ in.}$$

i.e. approx. 18 in.

The linear velocity of choice will be midway between 1.2 and 1.8 ft/sec, i.e. 1.5 ft/sec. From Fig. 4.6 the pressure drop across 10 in. of filter at 1.5 ft/sec will be 15 in. W.G. and across 8 in. it will be 12 in. W.G., so that 18 in. of packing will produce a pressure drop of 27 in. W.G.

The filter diameter can now be calculated. With a flow of 500 C.F.M. at 1.5 ft/sec, the radius of the filter will be given by

$$\pi r^2 = \frac{500}{1.5 \times 60}$$

$$r = 1.33 \text{ ft}$$

Thus the required filter will have a diameter of 2 ft 8 in. and a packed height of 18 in.

Fig. 4.5 also shows the value of X_{90} for each air flow rate. If this is used, the calculation of filter bed depth required is as follows. $X_{90} = 1.64$ at a velocity of 1.5 ft/sec.

$$\text{Required depth} = X_{90}(-\log N/N_0) = 1.64(+11) = 18.04 \text{ in.}$$

QUANTITY OF FILTER MEDIUM REQUIRED

The above example illustrated the simplest way of calculating the dimensions of the filter bed to meet a given requirement. It will certainly provide a filter which is suitable for the job and, within the limits of accuracy of the experimental data, will operate to give the desired probability of penetration. However, this method of calculation gives the design of filter for minimum bed depth and this is not necessarily what we want, although at first sight it would appear to be so.

Periodic replacement of the packing of an air filter will normally be necessary, particularly if the process is such that repeated steam-sterilization of the bed is required, as in the case of intermittent use. Thus, design of the filter to use the smallest practicable quantity of filter medium assists in reducing operating costs.

If we consider a constant volumetric rate of air flow through a bed of constant depth, then, as we decrease the cross-sectional area of the bed so the linear air velocity will rise. If k (or X_{90}) were to remain constant under these conditions, then it would be possible in this way to reduce the volume of filter material required until the pressure drop across the filter became too high. However, as shown in Fig. 4.5, the value of k varies markedly with linear air velocity and this graph was used in the worked example to determine the optimal linear velocity for minimum bed depth.

Let us now calculate the bed depth and area required for a range of air velocities, using the relationship between velocity and k given in Fig. 4.5. In addition, we determine the volume of the bed which results and the pressure drop across it. These calculations are shown in Table IV.

It is apparent from the table that, while the original design gave the minimum bed depth, it did not result in the minimum pressure drop across the bed or in the minimum quantity of packing material. As might be anticipated, the lowest pressure drop is to be obtained by operating with a filter of large diameter at low air velocity.

However, when we consider bed volume, we see that in this instance we obtain a minimum volume of packing material at an air velocity of 3 ft/sec, at which rate the value of k is certainly not a maximum. At this air velocity and bed depth the pressure drop to be expected is almost double that for minimum bed depth.

TABLE IV

Air Velocity (ft/sec.)	k	Bed Depth (in.)	Bed Area (sq. ft)	Filter Diameter (ft)	Bed Volume (cu. ft)	Bed Drop (in. W.G.)
0.5	0.30	36.67	16.66	2.30	51.00	18.3
1.0	0.57	19.30	8.33	1.63	13.40	19.3
1.5	0.61	18.03	5.55	1.33	8.33	27.0
2.0	0.58	18.97	4.16	1.15	6.58	37.9
2.5	0.53	20.75	3.33	1.03	5.75	41.5
3.0	0.47	23.40	2.77	0.94	5.42	46.8
3.5	0.38	28.89	2.38	0.87	5.75	101.1
4.0	0.25	44.00	2.08	0.81	7.67	132.0

The filtration efficiency will be exactly the same for each of the filters represented by a line in Table IV, so that from that point of view, one design would be as good as another. Practical considerations will be the deciding factor in each particular application. If the pressure drop which can be tolerated is critical, then a large diameter filter may be necessary. If the filter is of too large a diameter, mechanical difficulties are encountered and the construction may have to be such that filter repacking becomes a slow job. When the filter medium itself is brittle, a filter of small diameter becomes very difficult to pack; when the medium is in the form of sheets or pads, problems of supporting the medium and sealing it in the filter body arise with large filters.

There is no single answer. In each practical case, the best compromise between all of the competing factors should be found and the corresponding filter design adopted.

PACKING DENSITY

Whenever the filter medium is supplied in the form of sheets or preformed pads, its packing density is fixed already. However, in the case of loose-packed glass or mineral slag wools (as in the above example), the packing density is a matter for selection and, as shown in equations (2), (3) and (4), will clearly have a considerable effect on both the efficiency and the pressure drop of the filter.

Any investigation aimed at determining the full potentialities of a loose filter medium will need to take packing density into account. In general, an increase in packing density will result in an increase in both efficiency and pressure drop, so that any gain in filter efficiency by increasing the packing density will be roughly equivalent to using a thicker bed of lower density. It will frequently be found that too close packing will lead to fibre

damage, while too loose packing results in channelling of air through the filter, so that in practice the available range of packing density is relatively narrow.

In practice, it is found that over the normal range of air velocities through the filter bed the pressure drop is approximately proportional to the square of the packing density. Equations (2), (3) and (4) suggest that the collection efficiency will bear an exponential relationship to some function of the packing density. It must, however, be borne in mind that an increase in packing density can affect the various particle collection mechanisms in different ways, so that for any given filter medium the only safe way is to determine the relationship between efficiency and density experimentally.

The example given above referred to a loose-packed filter medium. When the material involved is in the form of preformed pads or sheets, the method to be adopted is essentially the same. In this case, however, the single pad or sheet is taken as the unit of thickness, so that in Fig. 4.4 the abscissa shows number of pad thicknesses used instead of the bed thickness in inches.

Great care is necessary in making sure that the pads or sheets of filter medium are homogeneous. A good indication of whether or not this is so can be obtained by carrying out the pressure drop against air velocity test.

In Fig. 4.6, which showed such results for a loose packed material, the bed depth would again be replaced by numbers of pads used. Repetition of the test with a new set of pads will usually show readily if reproducible results can be obtained.

The effect, if any, of sterilization on the filtration efficiency of a filter medium must be determined. This is best done by using a test bed for collection efficiency trials and pressure drop tests as shown earlier and then repeating both tests after repeated steaming of the filter. In some cases, where resin-bonded mats are used, a small increase in pressure drop and a slight fall in collection efficiency may be expected after repeated sterilization of the bed.

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CHAPTER 5

Thermal Sterilization of Liquids

The kinetic groundwork for the more detailed consideration of thermal sterilization of liquids has been laid in Chapter 2. It is now necessary to investigate more fully how kinetic methods can be applied to increase understanding of the sterilization process and how they can be used to determine the mechanics of the sterilization method which will best suit our purpose.

There is a considerable literature on various aspects of thermal sterilization and therefore, as one might expect, a variety of approaches has been employed resulting in the use of a rather confusing array of terms and parameters. It is appropriate to consider the chief of these and to see how they are related.

THERMAL DEATH RATE CONSTANT *k*

This has already been discussed in Chapter 2. If, in the rate equation,

$$\ln \left(\frac{N}{N_0} \right) = -kt \quad (1)$$

N/N_0 is the fraction of viable organisms which survive after heat treatment for time *t*, *k* is the thermal death rate constant.

THERMAL DEATH TIME, *t_D*

The effect of temperature on thermal death rates is often shown for a particular micro-organism in the form of a thermal death time graph, such as that shown in Fig. 5.1. This graph shows the time needed, by experiment, for complete kill of all spores of the organism for a range of temperatures. Let us examine what this means a little more closely. Suppose we have a litre of liquid which contains 10^6 viable spores/ml. Thus the litre will contain 10^9 spores. If we were to conduct a series of experiments in which a litre of the liquid was held at a temperature *T₁* for varying periods, we should find one time *t₁* which was just sufficient to kill all spores. Then we can say that the spore count has been reduced from 10^9 to less than 1.

If the reduction in count were to one organism, which, for an initial