The Determination of the "True" Filtration Characteristics of Diatomaceous Earth[1]

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ABSTRACT

The flow through any filter bed is directly related to the permeability of the bed, which may be calculated from the size of particles comprising the bed and the void volume (or voidage) between the particles. Conventional measurement by Coulter Counter of the particle size of diatomaceous earth and void volume by displacement of volume leads to unrealistically high values of permeability. This is because the influence of the porosity (internal void volume) of the diatomaceous earth particles is not accounted for in the straight application of conventional measurements to the calculation of permeability. A method was developed whereby the particle size and bed void volume relevant to filtration may be determined by the analysis of data on the volumes of beds comprising mixtures of diatomaceous earths and particles of known filtration characteristics. The diatomaceous earths Celite 578, Standard Supercel, and Hyflo Supercel have total void volumes of 83, 86, and 86%, respectively; the effective bed void volumes for filtration, however, are only 27, 33, and 58%. These results imply that true sizes of diatomaceous earth particles are some 1.7 times greater than indicated by the Coulter Counter. The method also gives an indication of the size of the voids in a bed of filter aid. Effective bed void volume and true particle size give reasonable predictions of permeability.

Key words: Diatomaceous earth, Filtration, Filter-bed permeability, Void volume, Particle size, Particle shape

It seems remarkable that information on diatomaceous earths is insufficient to allow a brewery filter room manager to select the type and quantity of filter aid for any given task from data sheets alone, without recourse to laboratory experiments and experience on full-scale plant. Although suppliers' data for diatomaceous earth are available, most of the information is not that required by the filter room manager and may even be misleading for filtration decisions. To assist in the selection of the type and quantity of filter aid, the manager needs to know the permeability of the filter aid, the proportion of the filter cake that is available for the entrapment of beer solids, and the sizes of the voids and other pores that determine the particle cutoff size in the filter.

Filtration of beer using diatomaceous earth as bodyfeed follows the laws of filtration as defined by the Darcy or pressure equation (1).

$$\Delta P = \frac{\mu u L}{\beta} \quad (1)$$

and

$$\beta = \frac{\epsilon^3}{Ks^2(1-\epsilon)^2} \quad (2)$$

where ΔP = pressure drop across the filter; μ = viscosity of beer; u = nominal velocity or flow rate per unit area; L = depth of the filter; β = permeability of the filter cake; and ϵ = void volume or voidage of the filter cake; s = specific surface area of particles, i.e., the surface area of particles per unit volume of particles; and K = constant (Table I).

These equations can be derived from basic principles and have been shown to hold true in practice (7). The permeability frequently quoted by suppliers is derived via equation 1 from the measurement of pressure drop across a bed of filter aid. As such it is a true experimental result that, allowing for variability in the material, is not open to question.

Permeability depends on the void volume, ϵ, of the filter cake and the specific surface area of the particles making up the bed. The specific surface area, s, is primarily related to the size of the particles and to some extent the shape of the particles. For spheres it is equal to six divided by the diameter. The constant K in equation 2 also depends on the shape of the particles, and is generally between two and eight but is commonly five (1).

For a bed comprised of particles of known shape and size, it is a simple matter to calculate the specific surface area and to measure the void volume. Unfortunately, the materials used for beer filtration are not so easily characterized. They are rarely spherical. Diatomaceous earths in particular have complex structures that incorporate part of the void volume into individual particles. In fact, as can be seen in Table II, conventional measurements of void volume and particle size (assuming spherical character for calculation of specific surface area) result in calculated permeabilities (from ϵ_t and d_{CC}, Table II) far greater than the true value calculated from pressure drop data and equation 1.

Whereas an estimate of specific surface area of filter aid particles can be calculated from conventional particle sizing techniques such as Coulter counting, it is essential that the physical characteristics of the filter aid are allowed for in this calculation. Where materials that have a distribution of sizes are concerned, it is important that any mean particle diameter should reflect the specific surface area of the material. That is to say, smaller particles have a greater specific surface area than larger particles on a volume to volume basis. Accordingly, in this paper the mean diameters are calculated from the specific surface area of particles derived from Coulter Counter data. Any direct measure of specific surface area using Brunauer-Emmett-Teller (BET) adsorption techniques does not correspond to the overall size and shape of complex structures such as diatoms, but rather to surface roughness and convoluted internal structure. Thus the specific surface area available for the adsorption of gases has little relevance to filtration other than giving an indication of the permeability of the diatoms' walls.

The calculation of permeability from equation 2 is particularly sensitive to void volume, or perhaps more accurately, the effective bed void volume, i.e., the volume of the voids in the bed *between* the particles of filter aid. It is also the effective bed void volume that gives an indication of the space available in the filter aid for the

TABLE I
Definitions of Terms and Symbols

Symbol	Definition
ΔP	Pressure drop ($N \cdot m^{-2}$)
μ	Viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
u	Nominal velocity ($m \cdot s^{-1}$)
L	Depth (m)
d	Particle diameter (m)
d_{CC}	Particle diameter, measured by Coulter Counter (μm)
d_{eff}	Effective particle diameter (μm)
s	Surface area of particles per unit volume of particles (m^{-1})
ϵ	Void volume
ϵ_t	Total void volume (%)
ϵ_b	Effective bed void volume (%)
β	Permeability ($m^2 = 10^{12}\ \mu m^2$)
K	Permeability equation constant
ρ_s	Density of solid fraction of filter aid ($g \cdot ml^{-1}$)
ρ_b	Dry bulk density of bed of filter aid ($g \cdot ml^{-1}$)

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entrapment of beer particles. It is the measurement of this effective bed void volume, and its influence on effective particle size, which is described in this paper.

EXPERIMENTAL

Measurements of Effective Bed Void Volume—Principles

The simplest method, both in concept and operation, to assess the effective bed void volume with respect to filtration, is to determine experimentally the volume of very fine material (compared to diatomaceous earth particles) that can be introduced into the bed of diatomaceous earth without increasing the volume of the bed. Providing the particle size of the added material (filler) is very much smaller than the size of the voids in the bed, small additions should not increase bed volume. The addition of further filler will only increase the volume of the bed, as shown by line 1 in Figure 1, when the voids between the filter aid particles are full. At this point the volume of the bed will increase by the volume of filler added, that is to say, the gradient of the line will be unity. It should be noted that the volume of the filler is the total bed volume of the filler material, i.e., the wetted bulk volume.

Thus, for a diatomaceous earth with an effective bed void volume of 50%, the point of intersection of the line of unit slope and the x-axis should be equivalent to 50 ml of filler per 100 ml of earth.

Line 1 (Fig. 1) is a somewhat idealized case, although it can be approached, as will be shown later. When the particle size of the filler is not sufficiently small, there will be a tendency for the overall volume of the bed to increase prematurely (line 2) even though not all of the bed void volume between the diatomaceous earth particles is filled. Preferably, the filler comprises particles with a wide range of sizes, so that the smaller filler particles will fill in between the larger filler particles and diatomaceous earth.

There is, of course, the choice of size of the filler particles. On the one hand, they should be as small as possible in order to approximate to line 1; on the other, they should not be so small as to enter the porous structure of diatomaceous particles. There is good reason to select particles with a size distribution similar to particles of haze that are filtered from rough beer, i.e., with a range of 0.5–4 μm (6). This will ensure that only those parts of a bed of diatomaceous earth that can accommodate beer particles will register as voidage in the test. The material used as filler in this work was Gasil 23D, supplied by Crosfield Chemicals. Figure 2 compares the particle size range of Gasil 23D with the particles in unfiltered beer. The Gasil covers the range of particles in rough beer just out of the cold conditioning tank, which are generally composed of proteinaceous material. The peak in unfiltered beer solids between 0.4 and 0.5 μm was not reflected in the Gasil, but only a small portion of these solids is removed in beer filtration.

When establishing the effective bed void volume of diatomaceous earth available for entrapment of particles, the object must be to simulate as closely as possible the packing conditions that occur when filter cake is continuously building up on a support, as during the filtration of beer. Under these conditions, filter aid is constantly supplied to the filter and a uniform bed develops with an even distribution of particle sizes throughout. This consideration becomes even more important when a fine filler is added, for if sedimentation occurs during the formation of the cake, there will be a tendency for the filler not to be trapped in the bed of diatomaceous earth but to settle out separately, and low estimates of bed void volume would result. Provided that correct packing is

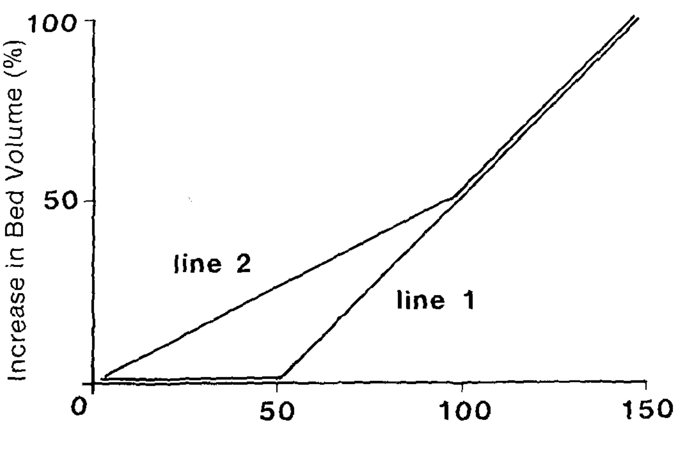

Fig. 1. Schematic representation of the increase in bed volume of filter aid on addition of filler.

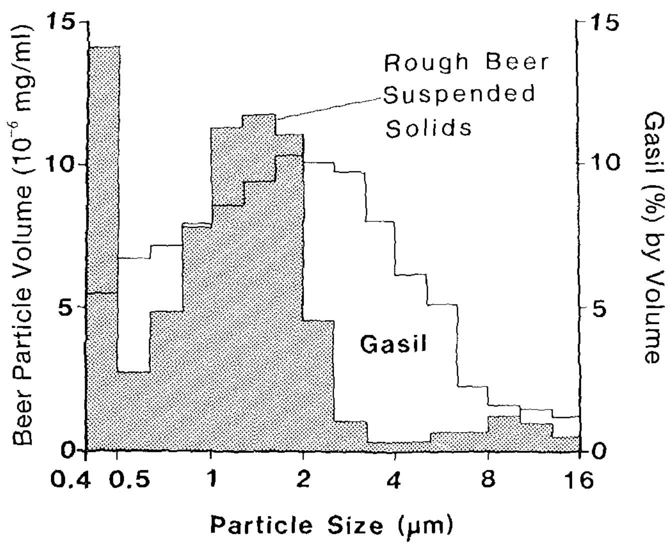

Fig. 2. Comparison of particle size profiles by Coulter Counter of Gasil 23D and suspended solids in rough beer (shown as shaded histogram).

TABLE II
Summary of Results and Comparison of True and Calculated Permeabilities

Diatomaceous Earths	Total Void Volume[a] ϵ_t (%)	Effective Bed Void Volume[b] ϵ_b (%)	Coulter Counter Particle Size[c] d_{CC} (μm)	Effective Particle Size[d] d_{eff} (μm)	Permeabilities: "True"[e] (μm²)	Permeabilities: Calculated from ϵ_t, d_{CC} (μm²)	Permeabilities: Calculated from ϵ_b, d_{eff} (μm²)
Celite 578	83	27	7.1	11.5	0.07	6	0.025
Standard Supercel	86	35	6.8	11.5	0.20	8	0.058
Hyflo Supercel	86	58	10.7	15.4	1.62	21	1.46

[a] Measured by displacement of liquid.
[b] Measured by bed volume technique described in text.
[c] Apparent surface area weighted mean, assuming spherical particles.
[d] Calculated using equation 6.
[e] From pressure drop data.

achieved, any fluid can be used to form the bed, consequently both water and air were tested. Air has the potential to give results more rapidly, but unfortunately caused irregular packing and resulted in bed volumes larger than those obtained with water.

Measurements of Effective Bed Void Volume—Procedure

The apparatus used for these experiments was the EBC filter (2). This device was designed originally for measuring the permeability of filter sheets and filter aids in connection with equation 1.

The EBC filter comprises a pressurized glass cylinder with internal diameter 50.5 mm into which filter aid may be loaded from the top. Filter aid collects on a Whatman No. 1 filter paper that is fixed at the base of the filter and is firmly sealed onto a perforated support plate. Any liquid is extracted via a syphon connected to the apparatus beneath the support plate. In order to achieve accuracy in the bed depth measurement within 1%, a bed depth of at least 50 mm is required to accommodate the error of ±0.5 mm in depth measurement. This is equivalent to roughly 40 g of combined diatomaceous earth and filler.

The diatomaceous earth and filler cannot be added to the filter as a dilute slurry, because the rate of filtration is too slow to prevent differential sedimentation of particles of different size. The material must be made up into as thick a slurry as possible commensurate with pouring it into the filter; typically 200 ml of water per 50 g of filter aid and filler was used. As much of the filter aid and filler was scraped into the filter as possible, but no attempt was made to wash in the residual quantities, although on occasion it was necessary to agitate the slurry to remove air pockets. The filter was then sealed and top pressurized with air to between 2 to 3 atmospheres. As the materials used form a noncompressible cake, the exact pressure is of no importance. Following this procedure, no sedimentation occurred, and the water was simply squeezed from the bed. Once the filter cake formed and air had blown through, the depth of the bed was measured using a broad-ended dipstick, subtracting the distance between the top of the bed to the top of the filter from the overall depth of the filter. The residual quantity of solids not poured into the filter was dried and weighed, and the recorded depth of the cake was corrected to account for this material.

The procedure was used with 50 g of diatomaceous earth and with increasing proportions of filler. The volume of the filler per unit weight was assessed using the above procedure for 50 g of filler alone; 50 g of Gasil 23D has a bed volume of 181 ml. The volumes of filler and the bed volumes of the mixtures were expressed as a percentage of the bed volume of 50 g of the diatomaceous earth under test. A graph of percentage volume of filler versus percentage increase in bed volume was then established. The bed void volume of the diatomaceous earth was read directly off the x-axis, by back interpolation if necessary.

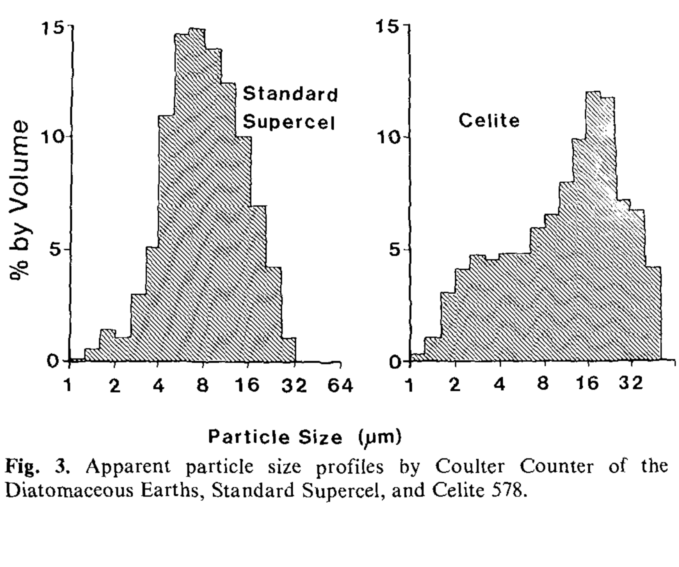

Fig. 3. Apparent particle size profiles by Coulter Counter of the Diatomaceous Earths, Standard Supercel, and Celite 578.

Miscellaneous Analyses

Coulter counting. The procedure and conditions used to count and size the suspended solids in beer (Fig. 2) were those recommended by Morris (5).

Particle sizes of filter aids and Gasil 23D. Measurements (Figs. 2 and 3) were made using suspensions of 0.1 g/L in 2.5% w/w sodium chloride electrolyte.

Bed volume. The bed volume of the filter aid was assessed following the procedure outlined in Experimental but without filler.

Density of the solid fraction of the filter aid ρ_s. A 100-ml volumetric flask was dried and weighed. Roughly 15 g of perlite or 20 g of diatomaceous earth was added as a dried powder to the flask. The flask was weighed and the exact weight of filter aid calculated. Water was added carefully to the flask until the 100 ml mark was reached. The flask was then reweighed, and the weight and volume of water were calculated. The density of the filter aid was then calculated by

$$\rho_2 = \frac{\text{Wt filter aid (g)}}{\text{100 ml} - \text{volume water added (ml)}} \quad (3)$$

Total void volume. The total void volume is the ratio of bed volume not occupied by solid material to the bed volume. It is frequently expressed as a percentage.

$$\epsilon_t = \left\{ \frac{\left[\text{bed volume} - \frac{\text{weight}}{\rho_s}\right]}{\text{bed volume}} \right\} 100\% \quad (4)$$

$$= \left\{ 1 - \frac{\rho_b}{\rho_s} \right\} 100\% \quad (5)$$

where ρ_b is the dry bulk density of the bed.

RESULTS AND DISCUSSION

The total void volume, i.e., the proportion of a bed of filter aid not occupied by *solid* material, is 86% for Standard Supercel and 83% for Celite, which are supplied by Johns Manville and are commonly used in the U.K. brewing industry. Total void volume was measured by the technique outlined in the Experimental section, and these figures were typical of those quoted by suppliers. A common method of measuring the size of diatomaceous earth particles is Coulter counting, frequently used by suppliers of filter aid. Figure 3 shows the particle size distribution for Standard Supercel and Celite 578. The mean diameters are 6.8 μm for the Standard Supercel and 7.1 μm for the Celite. Placing these figures for total void volume and particle size into equation 2 yields a value for β of 8 μm^2 for Standard Supercel and 6 μm^2 for Celite. It is assumed for the purposes of these calculations that the constant K is equal to five and that the particles are spherical. The true permeabilities derived from pressure measurements and equation 1, on the other had, are 0.2 μm^2 and 0.07 μm^2, respectively, as given in Table II. Not only are the values of β calculated using total void volume many times higher than found in practice, but the difference in permeability between the two filter aids, as calculated from equation 2, is greatly diminished. Furthermore, if total void volume is available for entrapping beer particles, it is hard to understand why so much diatomaceous earth has to be used as bodyfeed in practice.

The reason for these discrepancies is not that the well established filtration equations do not apply to brewing material but is found in the structure of diatomaceous earth. Each particle is the siliceous exoskeleton of a microscopic marine organism. While a proportion are fragments of broken skeletons, the bulk are whole units. Each unit has a hollow center connected to the outside by minute pores. In Figure 4 a whole unit is attached to a broken unit revealing both the external and the internal structure. In most cases, the internal pores are very small and accordingly have high specific surface areas. The pores offer high resistance to the flow of liquid through them, and consequently reduce the importance of the porosity, i.e., internal void volume of the particles, in filtration. The diatom fragments also tend to be porous, and consequently behave much like complete diatoms. Thus, the effective bed void volume is equal to the total void volume of the filter aid minus the porosity of the particles. The particle porosity also means that care must be taken when interpreting Coulter Counter results.

The Coulter Counter monitors the change in electrical resistance of liquid caused by the presence of particles with a conductivity different from that of the liquid (4). It measures the number of particles and the volume of solid material in the particles. The particle diameters are calculated on the assumption that the particles are spherical and have zero porosity. Thus, with a porous structure, such as diatomaceous earth, the Counter registers only the solid fraction of the particles and consequently underestimates the true volume. It therefore follows that for the true size of a porous particle, the Coulter Counter size must be increased by an amount equivalent to the porosity of the particle.

It is these over-estimates of void volume and under-estimates of particle size and specific surface area that are responsible for the excessively high values of permeability that result from calculations based on total void volume and mean Coulter Counter size in equation 2.

Effective Bed Void Volume of Diatomaceous Earths

The results of the bed volume experiments for three diatomaceous earths are summarized in Figure 5. As stated earlier, Celite has the lowest true permeability, 0.07 μm^2, but has effectively the same mean Coulter Counter particle size of 7 μm as Standard Supercel, which has a permeability of 0.2 μm^2, i.e., three times greater. Hyflo Supercel, which is used as a first precoat, has a mean Coulter Counter particle size of 10.7 μm and high true permeability, 1.62 μm^2.

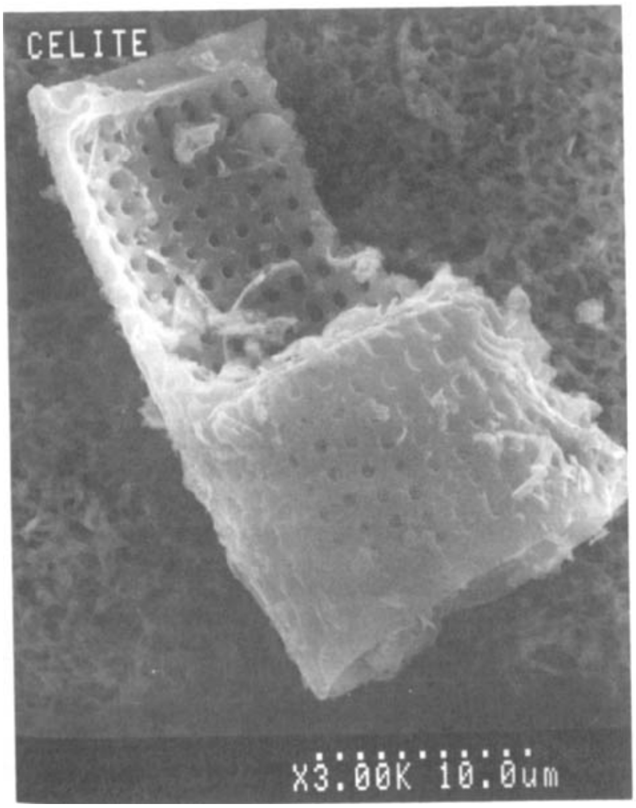

Fig. 4. Electronmicrograph of a diatom in Celite 578. Magnification × 3,000, scale length 10 μm as indicated.

The results in Figure 5 indicate effective bed void volumes of 27% for Celite, 33% for Standard Supercel, and 58% for Hyflo Supercel.

The initial gradients on Figure 5 are easily accounted for by the reasoning given earlier. The voids in the precoat filter aid, Hyflo Supercel, are sufficiently large to encompass the filler particles without any separation of the Hyflo Supercel particles. This was not true for Standard Supercel and especially for Celite, where there was considerable overlap in the particle sizes with those of the filler (Figs. 2 and 3). Some 20% of the Celite particles were similar in size to those of the filler, resulting in a marked premature bed expansion. This also indicates that the average size of the voids is smaller in Celite than in the Standard Supercel, in keeping with the generally held view of Celite's superior removal of haze material from beer. This is confirmed by the fact that Celite had 1.6 times more particles per unit weight than Standard Supercel (based on Coulter Counter figures, or calculated from the data in Fig. 3). It follows that the greater the rate of premature bed expansion for any given filler, the smaller the size of the voids.

An interesting point with Standard Supercel and Hyflo Supercel is that the rate of normal bed expansion is not unity but 0.9, indicating that some 10% of the filler was finding its way into the internal voidage of the filter aids. Considering the pore sizes in the diatomaceous skeletons and the small sizes of some of the finer filler particles, this is hardly surprising. With larger addition rates the bed expands normally.

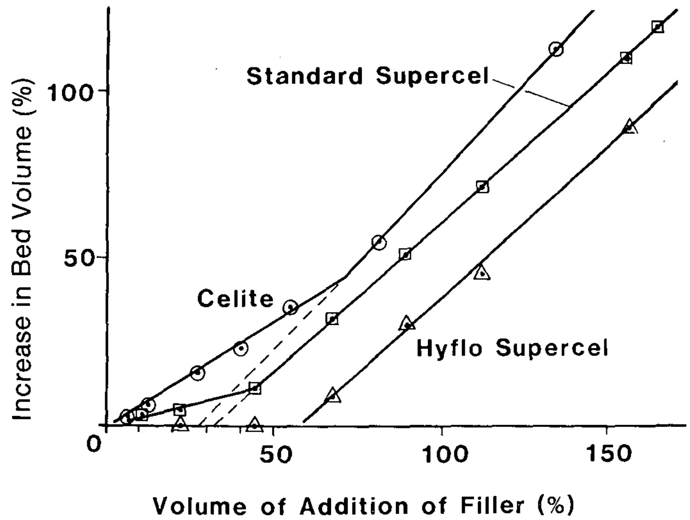

Fig. 5. Effect of increase in bed volume of diatomaceous earths on addition of filler.

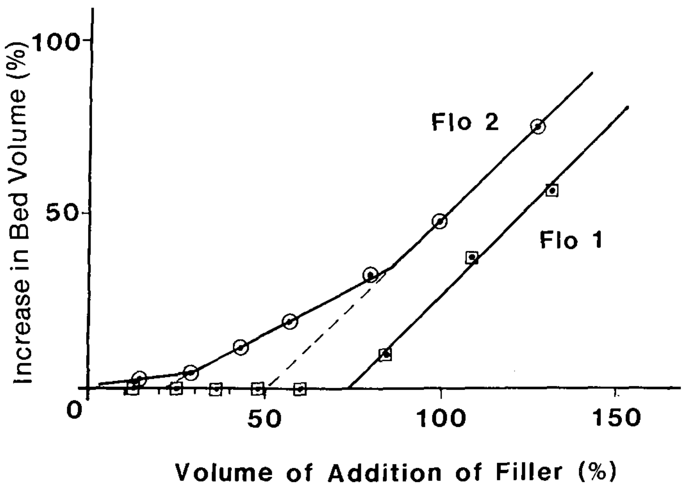

Fig. 6. Effect of increase in bed volume of perlites on addition of filler.

Effective Bed Void Volumes of Perlites

In order to demonstrate that the effective bed void volume measurement technique can be applied to filter aids other than diatomaceous earth, the results for two perlite filter aids, Flo 1 and Flo 2 supplied by British Ceca, are given in Figure 6. Flo 1, which registers an effective bed void volume of 73%, is a first precoat grade, and Flo 2, which registers an effective bed void volume of 50%, is a bodyfeed grade with a true permeability of 0.33 μm^2, similar to that of Standard Supercel.

Flo 1 registers an effective bed void volume of 73% for the entrapment of particles. This high void volume is a direct consequence of the manner in which the filter aid is produced, having a partially crushed honeycomb structure.

The data on Flo 2 (Fig. 6) suggest that there are two void volumes relevant to filtration. Flo 2 is composed essentially of platelike particles, produced by crushing the material used to manufacture Flo 1. Despite the large size of the plates, only a limited effective bed void volume of 22% has spaces sufficiently large to encompass most of the filler particles. The gradient of this section of the premature bed expansion line is less than that for Standard Supercel, indicating that these voids in the Flo 2 are larger. This was confirmed by laboratory filtration that demonstrated the Flo 2 to be less effective at removing beer haze material than the Standard Supercel. The remainder of the 50% overall effective bed void volume of Flo 2 is probably composed of space sandwiched between the plates; this void volume of 28% is considerable but appears from the gradient to be composed of very narrow spaces that are only capable of containing very fine particles.

These results on perlite further indicate that the technique developed for determining effective bed void volume has potential for the determination of size of the voids in beds of filter aid and the assessment of particle cutoff size in filtration.

Solids Loading

Because the effective bed void volume of diatomaceous earth, as measured by this bed volume technique, is so much smaller than is commonly accepted, it is worthwhile using a commonly held rule of thumb in the filtration of beer to support the results.

It is frequently claimed that 10 times more filter aid should be used than the suspended matter being removed from the beer, on a dry weight basis (3). The reason for this claim is that at higher loadings of suspended solids the bed of filter aid is progressively choked with solids, and filtration is adversely affected. If the effective bed void volume equals total voidage, e.g., 83%, the ratio of solid material to voids in the diatomaceous earth would be 17:83 or 1:5. Therefore, if one part of filter aid is used per five parts suspended matter, the bed of diatomaceous earth would just be choked. Clearly, operating with a blocked bed is impracticable and substantially more filter aid must be used. It would seem resonable to assume that increasing the dose of filter aid five times to give a ratio of 1:1 would maintain an open bed. In contrast, if the effective bed voidage is only 33%, then the ratio of porous particles to voids in the filter aid would be 2:1. If, again, it is assumed that this ratio must be increased five times to maintain an open bed when filtering suspended solids, the result would be a filter aid-to-suspended solids ratio of 10:1.

The 10:1 ratio on a weight basis also happens to coincide with a ratio of 10:1 on a volume basis for both the diatomaceous earth and filler, and diatomaceous earth and beer solids, when including the volume of water bound in the beer solids.

Experiments on a laboratory scale candle filter supported the 10:1 optimum ratio for both Celite and Standard Supercel (in terms of minimum pressure drop), despite differences in the true permeabilities of the two materials. Minimum pressures are actually obtained after a range of filter aid additions between 5:1 and 10:1 for both filter aids. The difference in effective bed void volume between Celite, 27%, and Standard Supercel, 33%, is small and had little effect on the capacity of the filter aids to entrap matter.

True Size of Diatomaceous Earth Particles

Coulter Counter sizes only correspond to the volume of the solid in the particles being measured. As diatomaceous earth comprises hollow porous particles, the size of these particles must be increased to encompass the particle porosity. The effective volume of the particles is therefore equal to the Coulter Counter volume multiplied by the cubed root of one minus the effective bed void volume divided by one minus the the total void volume, as shown in equation 6. The effective bed void volumes, indicated on Figure 5, of Celite and Standard Supercel result in this factor being approximately 5. Thus, the effective diameter of the particles is the cube root of 5, i.e., 1.7 times the measured Coulter Counter size. It is this larger measure that should be used for the purposes of estimating the size of interparticular voids and associated permeabilities in equation 2.

$$\begin{matrix}\text{Effective} \\ \text{particle size}\end{matrix} = \left\{\begin{matrix}\text{Coulter Counter} \\ \text{particle size}\end{matrix}\right\} \left\{\frac{1-\epsilon_{bed}}{1-\epsilon_{total}}\right\}^{1/3} \tag{6}$$

Mechanism of Beer Filtration with Diatomaceous Earth

Using the effective bed void volumes and the effective particle diameters derived from Coulter Counter results and particle porosity, the calculated permeabilities are 1.46 μm^2 for Hyflo Supercel, 0.058 μm^2 for Standard Supercel, and 0.025 μm^2 for Celite, as shown in Table II. These values compare with true permeabilities derived from pressure drop data of 1.62, 0.2, and 0.07 μm^2, respectively. The permeabilities calculated using the effective bed void volume for Celite and Standard Supercel are too low by a factor of about three. However, this should be compared to the calculated permeabilities using total void volume, which are between one and two orders of magnitude too large.

Permeability is critically dependent on void volume, as illustrated by the fact that small differences lead to Standard Supercel having twice the permeability of Celite, as calculated from the effective bed void volume and effective particle size. The difference between the true permeability and the permeability calculated from the effective bed void volume may be explained in two ways. Firstly, the bed void volumes measured by the bed volume measurement technique may be too small. If the permeability equation is used to calculate void volume from the true permeability, the void volumes appear to be 45% for Standard Supercel and 35% for Celite. Secondly, the void volume between particles is responsible for only part of the total permeability of diatomaceous earth, and the porosity of the particles is responsible for the remainder. Whereas the first possibility may well be partially true, the second possibility is likely to be the most important, since the data show that fine material can be washed into the internal pores of diatomaceous earth particles, indicating flow through them. In the case of Hyflo Supercel, even if the flow through the particle porosity is the same as that through the Standard Supercel particles, it is unlikely to contribute to the overall permeability of this highly permeable first precoat filter aid.

CONCLUSIONS

The effective bed void volumes of diatomaceous earth for the entrapment of suspended material in beer or other liquids may be assessed by measuring the increase in bed volume of the earth after addition of a fine filler material.

The effective bed void volume is much smaller than the total void volume measured by volumetric techniques and is approximately 30% for bodyfeed-grade diatomaceous earths.

The effective particle size of diatomaceous earths is that measured by the Coulter Counter multiplied by a factor that allows for the internal porosity of the particles.

It appears that the relative sizes of the voids in different filter aids can be estimated by comparing the rates of premature bed expansion when using filler.

Using the effective bed void volume and the effective particle size, a much more resonable estimate of true permeability, derived from pressure drop data, can be achieved than by use of total void volume and Coulter Counter size. Further improvements in prediction await a method of accounting for flow through the porosity, i.e., the internal void volume of filter aid particles.

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LITERATURE CITED

1. Coulson, J. M., and Richardson, J. F. Pages 125 and 134 in: Chemical Engineering, Vol. 2. 3rd ed. Pergamon Press: London, 1978.
2. European Brewery Convention. Page E101 in: Analytica, 3rd ed. Zoeterwoude, The Netherlands, 1975.
3. Hertjes, P. M., and Zuideveld, P. L. *Powder Technol.* 19:45, 1978.
4. Leedham, P. A., and Carpenter, P. M. *Eur. Brew. Conv. Proc. Cong., 16th, Amsterdam, 1977,* p. 729.
5. Morris, T. M. *J. Inst. Brew.* 90:162, 1984.
6. Morris, T. M. *J. Inst. Brew.* 92:93, 1986.
7. Reed, R. J. R., Grimmett, C. M., and Leeder, G. I. *Eur. Brew. Conv. Proc. Congr. 19th, London, 1983,* p. 225.

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