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Determination of Large Aerosol Particle Size by Elutriation

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Inhalable dust fraction determination requires aerodynamic size information for large aerosol particles. Operation of cascade impactors at flows that collect these particles leads to jet Reynolds numbers outside the range of established impactor performance. Horizontal elutriators, designed to match earlier respirable dust curves at a single flow rate, may be used to provide aerodynamic size information for particles larger than 50 μm. Operation of these elutriators at higher than design flow rates and angles other than horizontal provides for particle penetration over the size range of the inhalable dust curve. Equations are provided that relate penetration, flow rate, and angle to aerodynamic diameter to allow for bracketing the desired size and distribution. The use of impactor data reduction methods to determine size distributions with the MRE horizontal elutriator is examined with a spreadsheet model. Comparison of elutriator size determination with an impactor in the 10 to 15 μm range, where both methods could be used, resulted in reasonable agreement. This method provides for determination of aerodynamic characteristics of large aerosols in field sampling conditions.

Keywords Inhalable Dust, Elutriation, Large Aerosols

The latest sampling convention for inhalable aerosol particles requires size distribution information for particles of 10 to 100 μm aerodynamic diameter. Cascade impactors, often used for field determination of aerosol particle size, can be operated at reduced flow to size some of these aerosols. However, to size aerosols with aerodynamic diameters above 15 μm, the impactor jet Reynolds number falls below the values for established impactor performance.(1) Horizontal elutriators developed to match earlier respirable deposition curves, when operated at a single flow rate, provide a means to characterize larger particle aerosols with operation at higher flow rates and at angles other than horizontal. The MRE gravimetric dust sampler(2) and the Hexlet(3) are examples of these types of instruments.

METHOD

The utilization of an elutriator to determine size distributions requires adjustment of performance to provide penetration fractions bracketing the median size of the aerosol of interest. This can be done with equations, curves, or tables for the available elutriators.

Equations describing horizontal elutriator performance are given in texts on aerosols.(4,5,7) These equations describe horizontal elutriator channels to provide maximum sedimentation time. To simplify the equations and illustrate the operating principles, these equations solve for centerline flow or infinitely wide deposition ducts. Modification of these equations to account for other than horizontal orientation and channels of finite width is straightforward using the elutriation channel shown in Figure 1. The axes are placed at the half height of the channel with sample flow in the x direction. The height of the channel is in the y direction from $-H/2$ to $+H/2$. The width of the channel is in the z direction from $-W/2$ to $+W/2$. Particle velocity in the x direction is the combination of the sample flow velocity and the x component of the sedimentation or terminal settling velocity (V_{ts}).

$$V_{xp} = \frac{dx}{dt} = U_x(y, z) + V_{ts} \sin\theta \quad [1]$$

Particle velocity in the y direction is the y component of the sedimentation velocity

$$V_{yp} = -\frac{dy}{dt} = -V_{ts} \cos\theta \quad [2]$$

Where

$$U_x(y, z) = U_{xo}\left[1 - \left(\frac{2y}{H}\right)^2 - \left(\frac{2z}{W}\right)^2\right] \quad [3]$$

Where U_{xo} is the centerline velocity at $y = z = 0$ in the x direction and assuming a parabolic velocity profile across the channel height and width. This expression may be divided by the cross-sectional area of the channel (WH) and integrated

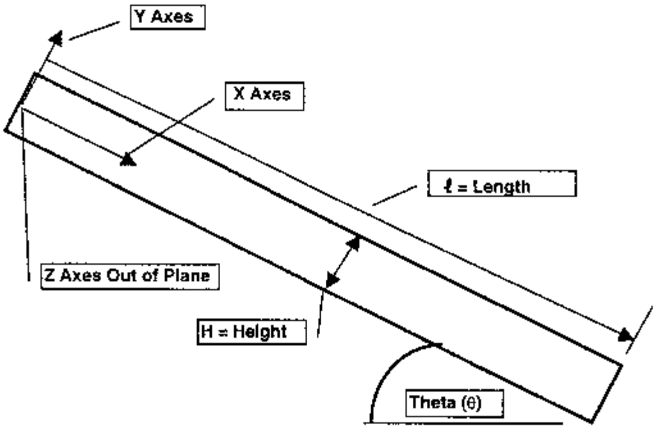

FIGURE 1
Diagram of elutriation flow channel.

across the height and width to determine the average velocity.

$$\bar{U} = \frac{U_{xo}}{WH} \int_{-\frac{W}{2}}^{+\frac{W}{2}} \int_{-\frac{H}{2}}^{+\frac{H}{2}} \left[1 - \left(\frac{2y}{H}\right)^2 - \left(\frac{2z}{W}\right)^2\right] dydz = \frac{U_{xo}}{3} \quad [4]$$

The average velocity is also given by the channel volumetric flow divided by the cross-sectional area (WH).

$$\bar{U} = \frac{Q}{WH}, \quad \text{so} \quad U_{xo} = \frac{3\,Q}{WH} \quad [5]$$

Penetration curves are determined by eliminating time in the x and y velocity component expressions to determine particle path length (ℓ) in the x direction.

$$\ell = \int_0^{\ell} dx = \frac{U_{xo}}{-V_{ts}\cos\theta} \int_{-\frac{W}{2}}^{+\frac{W}{2}} \int_{A}^{-\frac{H}{2}} \left[1 - \left(\frac{2y}{H}\right)^2 - \left(\frac{2z}{W}\right)^2\right] dydz + \int_{-\frac{W}{2}}^{+\frac{W}{2}} \int_{A}^{-\frac{H}{2}} \tan\theta \; dydz \quad [6]$$

Setting A = 0 results in the average ℓ value for a given V_{ts}, representing particles that enter at the centerline. A = +H/2 results in the maximum value of ℓ for particles entering at the top of the channel. The constant sedimentation velocity and mixing at the inlet allows one to determine penetration fraction by setting ℓ to multiples of the actual channel length. Solutions of this equation for the MRE gravimetric dust sampler uses a channel length of 17 cm, a width of 4 cm, and a height of 0.14 cm. The channel flow Q is equal to the total flow Q_t divided by 8 (the MRE unit has 8 parallel channels). This results in

$$V_{ts} = \frac{Q_t}{8\cos\theta(2\ell + HW\tan\theta)} \quad [7]$$

For midline (y = 0) entry and

$$V_{ts} = \frac{Q_t}{8\cos\theta(\ell + HW\tan\theta)} \quad [8]$$

For entry at the top of the channel (y = H/2). Modification of these equations for the Hexlet or other instrument would require an adjustment for deposition duct number and the appropriate values of ℓ, H, and W.

The assumptions used to derive these expressions require laminar flow. Using the hydraulic radius (4 times the cross-sectional area divided by the wetted perimeter) to represent length in the Reynolds number expression, results in a Reynolds number of 2000 at a total flow of just over 300 Lpm for the MRE unit. Flows of up to 200 Lpm should safely provide laminar flow of the sample air in this elutriator.

FLOW DETERMINATION CURVES

Penetration curves for flows of 2.5, 50, and 200 Lpm and theta (θ) values of 0, 30, 60, and 80 degrees are shown in Figures 2, 3, and 4. These curves represent average penetration for midline entry. The theta (θ) equals 0 (horizontal operation) curve for 2.5 Lpm flow should match the British Medical Research Council (BMRC)[6] respirable dust curve. The curve intercepts zero penetration for 7.13 μm aerodynamic diameter particles and 50 percent penetration for 5.04 μm diameter particles. The BMRC curve has a 50 percent penetration value of 5.0 μm aerodynamic diameter and a zero penetration at 7.1 μm.[6] Agreement with this established and documented curve supports the use of the equations to determine penetration curves for adjustment of the operating parameters of this elutriator to match the aerosol of interest.

The 50 percent penetration value would be about 63 μm for operation at 200 Lpm with theta (θ) equal to 60 degrees. The 50 percent penetration particle size for flow rates up to 200 Lpm is shown in Figure 5 for theta (θ) values of 0, 30, and 60 degrees. The curves indicate that existing elutriators may be used to determine aerodynamic-sized distributions over the 20 to 80 ìm median size range.

METHOD

Particle size distributions may be estimated by collecting sequential samples at different flow rates or angles to determine mass fraction for particles smaller than the zero penetration size. A simultaneous filter sample may be collected to determine total mass concentration. The equations given above may be used to determine a set of operating parameters that bracket the median value of the aerosol of interest.

The penetration curves for the elutriator are not as steep as the curves for an impactor. However, elutriator penetration curves are fairly symmetrical about the 50 percent penetration particle size and steep relative to size distributions in the 20 to

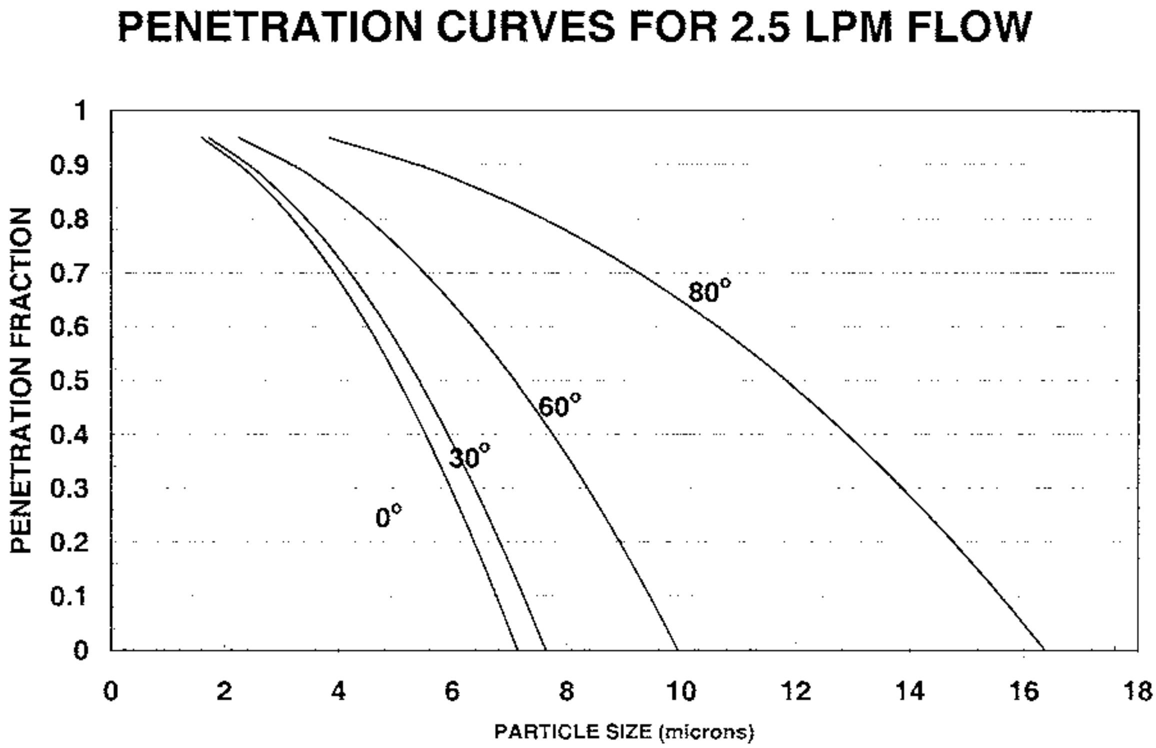

FIGURE 2
Penetration curves for 2.5 liters per minute total flow.

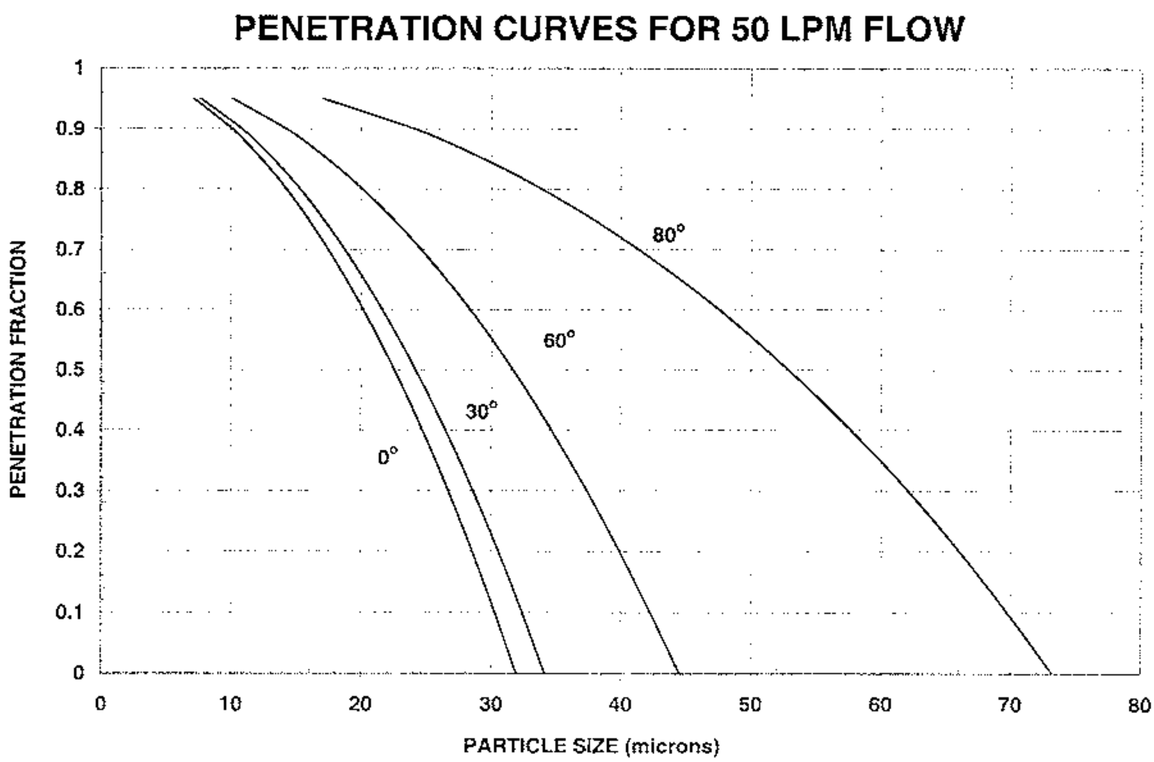

FIGURE 3
Penetration curves for 50.0 liters per minute total flow.

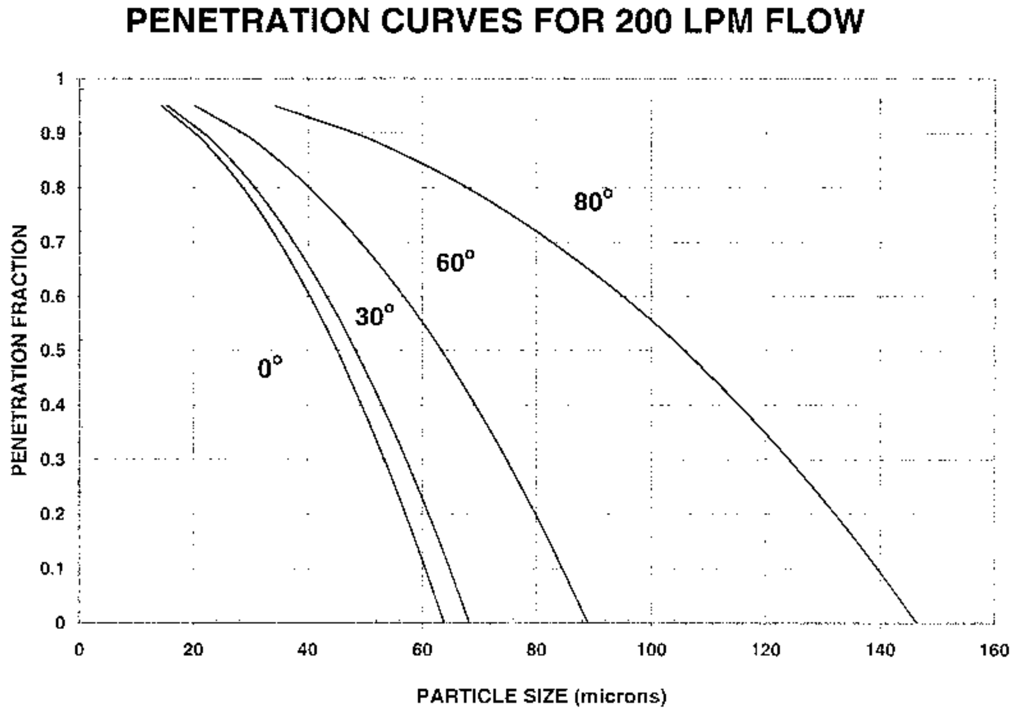

FIGURE 4
Penetration curves for 200.0 liters per minute total flow.

100 μm range. The impactor data treatment method of assuming a sharp cutoff at the 50 percent penetration particle size provides a method to determine size distributions using the elutriator data from the selected set of operating parameters.[1]

A theoretical evaluation was carried out to evaluate the impactor approach. Size distributions were created on an Excel spreadsheet. These distributions were clipped by the penetration curves to determine penetrating mass at four or five sets

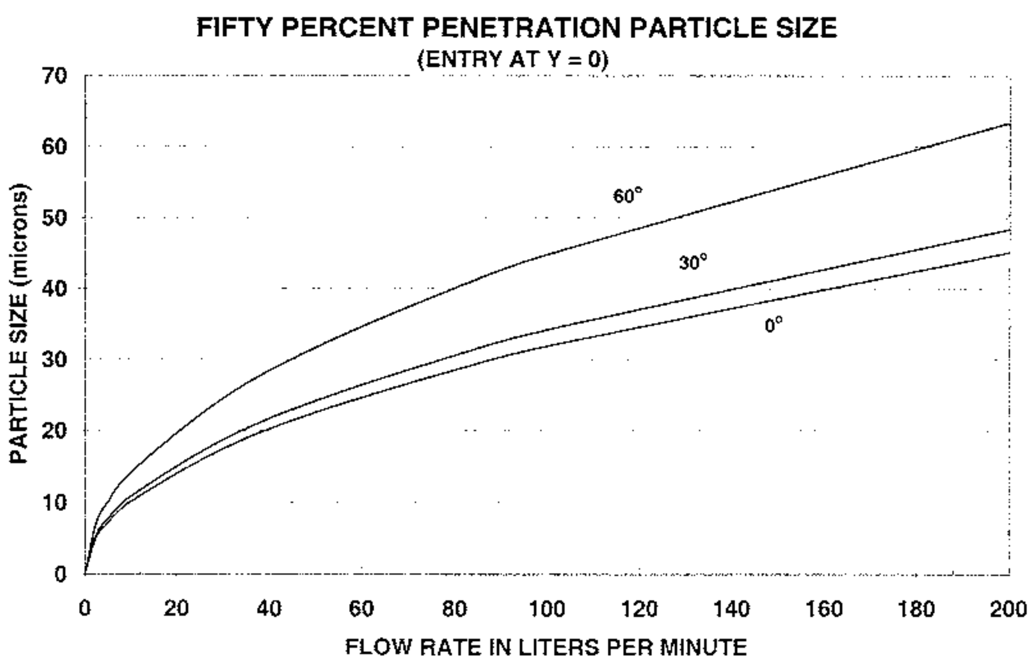

FIGURE 5
Fifty percent penetration particle size curves as function of total flow.

TABLE I
Results of numerical analysis of size distribution determination from elutriator data

Test aerosol		Regression fit results		Ratio of fit to test	
MMAD[A] (Microns)	σ_g^B	MMAD[A] (Microns)	σ_g^B	MMAD[A] (Microns)	σ_g^B
30	2.0	33.5	2.19	1.117	1.095
40	2.0	44.6	2.24	1.115	1.120
50	2.0	55.8	2.24	1.116	1.120
30	2.5	34.0	2.74	1.133	1.088
40	2.5	45.3	2.72	1.132	1.104
50	2.5	56.6	2.76	1.132	1.104
30	3.0	34.0	3.25	1.133	1.083
40	3.0	45.7	3.29	1.142	1.083
50	3.0	57.1	2.39	1.142	1.083

[A]MMAD = mass median aerodynamic diameter.
[B]σ_g = geometric standard deviation.

of operating conditions (different flow rates and/or theta (θ) values). This data was evaluated using the 50 percent penetration size as a sharp cutoff to determine the mass associated with particles smaller than the cutoff size. Assuming the size distribution would be represented by a log normal distribution, an Excel spreadsheet was used to determine the probit and the regression fit for the probit against the log of the cutoff size.

RESULTS

Nine aerosols with mass median diameters of 20, 30, and 50 μm and geometric standard deviations of 2.0, 2.5, and 3.0 were used. The results of this evaluation are shown in Table I. In all cases the final results were larger than the input data. Geometric standard deviations were overestimated in this range (2.0 to 3.0) by 10.1 percent on the average, with a standard deviation of 0.012. The mass median diameter in this range (20 to 50 microns) was over estimated by 12.9 percent on the average with a standard deviation of 0.011.

These determinations were made with either 4 or 5 penetration curves. The total dust concentration sampler would result in 5 or 6 samples. The results indicate there would be little advantage to collecting more size fractions.

Comparison of size estimates between instruments is limited by the established operating parameters for impactors, and the equipment requirements for other methods (sedimentation, optical microscopy, and the Aerodynamic Particle Sizer). A few comparisons were carried out with an Andersen impactor modified by removal of three impaction stages and operation at reduced flow rates. These studies were limited to the 10 to 15 μm size range and provided little data in the range of greatest interest (20–80 μm) for elutriator use. In the 10 to 15 μm range, the two methods agreed within 10 percent in both size and geometric standard deviation estimates.

DISCUSSION

The standard method of determining aerodynamic particle size distributions with cascade impactors is to assume the size distribution is lognormal and that each stage's size collection efficiency is a steep curve with respect to particle size. The stage's 50 percent collection efficiency value is used as the effective cutoff diameter representing the stage's performance. The mass penetrating each stage is plotted as the mass fraction of particles smaller than the effective cutoff diameter on log probit paper. The plot indicates the mass median aerodynamic diameter and the geometric standard deviation.[1] A more rigorous plot with goodness of fit and other statistics can be obtained with an Excel spreadsheet. The step function at the effective cutoff diameter provides a good representation of the impactor stage efficiency curve as the mass associated with the particles bigger than the ECD and not collected on the stage is matched by the mass of particles smaller than the ECD collected on the stage.

The collection efficiency curves for elutriators are not as steep as for impactors. The slope is less on the small particle size side of the 50 percent collection point than on the large particle size side. The wide distributions normally associated with large particle aerosols results in the same type of compensation with respect to collected mass and mass passed to the exit filter. The bias to oversize may be related to failure to exactly compensate for penetrating and nonpenetrating mass across the 50 percent collection size.

CONCLUSIONS

The errors encountered with the impactor data treatment method are small relative to errors normally encountered in field sampling. The results suggest the method will be adequate for field data when the corrections are applied. More accurate results could be obtained by use of the actual penetration curves and inversion techniques to determine size distributions. The gain in data reduction accuracy would often be small relative to normal errors in field determination of size distributions.

There are several potential problems to consider in using this sizing method. When sampling large aerosols, aspiration efficiency must be carefully controlled. The inlet to the elutriator and the total mass sampler must be designed to provide isokinetic sampling if there is an air flow and minimal bias when the sample is from still air.[4–6] The samplers must also be located to collect a sample representative of the conditions of interest.

Resuspension from the collection surface may be a problem at high values of theta (θ). No difficulty was encountered at 60 degrees if the collection surfaces were carefully cleaned between sample runs. Higher angles might require a sticky coating on the collection surface.

Operation of the MRE at the higher flow rates required bypassing the internal pump with an external unit. The bulk of the

MRE presents some difficulties with the design of an appropriate inlet system. This can be reduced as the internal pump and power system can be removed.

This sampling and size separation method provides for the field measurement of particles important to the current definition of inhalable aerosol using existing equipment.

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