Atmospheric Environment Vol. 10, pp. 891–896. Pergamon Press 1976. Printed in Great Britain.

IMPACTOR DESIGN

Virgil A. Marple and Klaus Willeke*
Mechanical Engineering Department, University of Minnesota, Minneapolis, MN 55455, U.S.A.

(*First received* 28 *October* 1975 *and in final form* 6 *April* 1976)

Abstract—The performance of an impactor can be accurately predicted, if design criteria which were numerically developed and experimentally proven, are adhered to. Based on these criteria, charts have been developed to aid in the design of round or rectangular impaction stages. In the case of round impactors, the desired cutoff size is related to the number and size of nozzles and to the total volumetric flow rate through the stage. In the case of rectangular impactors, the volumetric flow rate is expressed per unit length of the slot.

INTRODUCTION

Cascade Impactors have been used for many years for the classification of particles by aerodynamic size. Since the original study of the cascade impactor by May (1945), numerous impactors have been designed, used and reported in the literature. (See, e.g. Ranz and Wong, 1952; Mercer and Chow, 1968; Mercer and Stafford, 1969; Andersen, 1966; Lundgren, 1967; and Cohen and Montan, 1967).

Typically, a cascade impactor is made up of a number of classification stages consisting of a nozzle and an impaction plate arranged as shown in Fig. 1. In each stage an aerosol stream passes through the nozzle and impinges upon the plate. Particles in the aerosol stream having a large enough inertia will impact upon the plate, and smaller particles will pass as an aerosol onto the next stage. By designing each successive stage with higher aerosol velocities in the nozzle, smaller diameter particles will be collected at each stage. Particles too small to be collected in the last stage are generally collected on an after-filter.

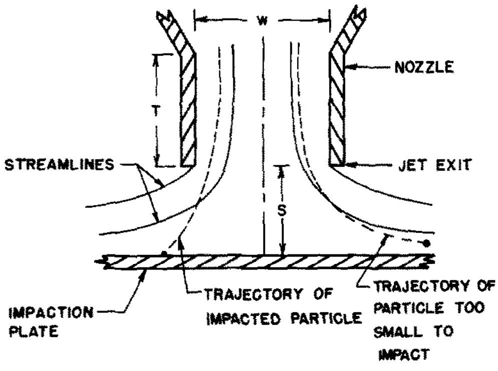


Fig. 1. Streamlines and particle trajectories for a typical impactor.

The popularity of impactors is evidenced by the large number of cascade impactors commercially available. Figure 2 lists some of these impactors and the approximate cutoff size for unit density spheres (equivalent aerodynamic diameter) of the various stages at the given flow rate. Most impactors, however, are not confined to the indicated flow rate and may be operated over a range of flow rates which would shift the cut points to larger or smaller diameters. Particles with a density different from unity would also shift the cut points. The classification of single or multiple nozzles in Fig. 2 refers to the number of nozzles in each individual stage.

Studies of impactors enable us theoretically to predict with good accuracy the cutoff size of an impactor (Marple and Liu, 1974; Schott, 1973). It has been found that experimentally determined cutoff sizes agree well with those predicted theoretically (Jaenicke and Blifford, 1974; Willeke and McFeters, 1975; Rao, 1975; Willeke, 1975).

DESIGN CRITERIA

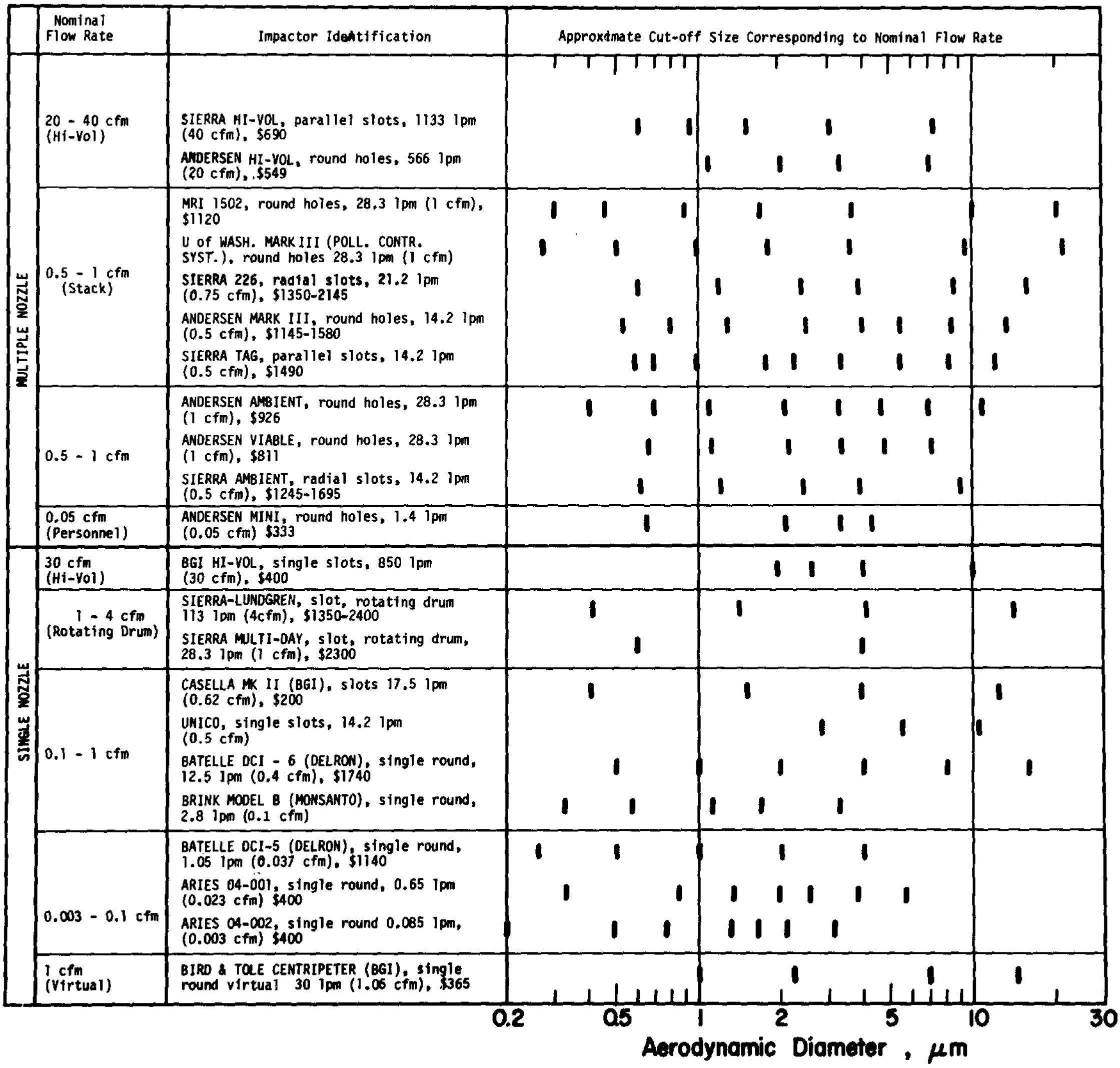
The most important characteristic of an impactor stage is the collection efficiency curve, which indicates the percent of particles of any size which are collected on the impaction plate as a function of the particle size. It is desirable for this efficiency curve to have a sharp division between the particles collected and those which are not.

By the application of finite difference methods, it is possible to make an accurate theoretical prediction of the efficiency curves for impactor stages of specific designs. In a recent study (Marple and Liu, 1974), this method was used to determine the influence of the Reynolds number, *Re*, dimensionless jet-to-plate distance, S/W (where S is the jet-to-plate distance and W is the jet width or diameter), and the dimensionless nozzle throat length, T/W (where T is the nozzle throat length).

The theoretical influence of the Reynolds number on the efficiency curves is shown in Fig. 3 for both

---

* Present address: Kettering Laboratory, University of Cincinnati Medical Center, Cincinnati, OH 45267, U.S.A.



	Nominal Flow Rate	Impactor Identification
MULTIPLE NOZZLE	20 - 40 cfm (Hi-Vol)	SIERRA HI-VOL, parallel slots, 1133 lpm (40 cfm), $690
		ANDERSEN HI-VOL, round holes, 566 lpm (20 cfm), $549
	0.5 - 1 cfm (Stack)	MRI 1502, round holes, 28.3 lpm (1 cfm), $1120
		U of WASH. MARK III (POLL. CONTR. SYST.), round holes 28.3 lpm (1 cfm)
		SIERRA 226, radial slots, 21.2 lpm (0.75 cfm), $1350-2145
		ANDERSEN MARK III, round holes, 14.2 lpm (0.5 cfm), $1145-1580
		SIERRA TAG, parallel slots, 14.2 lpm (0.5 cfm), $1490
	0.5 - 1 cfm	ANDERSEN AMBIENT, round holes, 28.3 lpm (1 cfm), $926
		ANDERSEN VIABLE, round holes, 28.3 lpm (1 cfm), $811
		SIERRA AMBIENT, radial slots, 14.2 lpm (0.5 cfm), $1245-1695
	0.05 cfm (Personnel)	ANDERSEN MINI, round holes, 1.4 lpm (0.05 cfm) $333
SINGLE NOZZLE	30 cfm (Hi-Vol)	BGI HI-VOL, single slots, 850 lpm (30 cfm), $400
	1 - 4 cfm (Rotating Drum)	SIERRA-LUNDGREN, slot, rotating drum 113 lpm (4cfm), $1350-2400
		SIERRA MULTI-DAY, slot, rotating drum, 28.3 lpm (1 cfm), $2300
	0.1 - 1 cfm	CASELLA MK II (BGI), slots 17.5 lpm (0.62 cfm), $200
		UNICO, single slots, 14.2 lpm (0.5 cfm)
		BATELLE DCI - 6 (DELRON), single round, 12.5 lpm (0.4 cfm), $1740
		BRINK MODEL B (MONSANTO), single round, 2.8 lpm (0.1 cfm)
	0.003 - 0.1 cfm	BATELLE DCI-5 (DELRON), single round, 1.05 lpm (0.037 cfm), $1140
		ARIES 04-001, single round, 0.65 lpm (0.023 cfm) $400
		ARIES 04-002, single round 0.085 lpm, (0.003 cfm) $400
	1 cfm (Virtual)	BIRD & TOLE CENTRIPETER (BGI), single round virtual 30 lpm (1.06 cfm), $365

Fig. 2. Some commercially available cascade impactors. Operation at other than nominal flow rates will affect the cutoff sizes.

the round and the rectangular impactor. The Reynolds number is based on the hydraulic diameter of the nozzle throat. The particle size is a dimensionless particle diameter expressed in units of the square root of the Stokes number, $\sqrt{Stk}$. The Stokes number, defined as the ratio of the particle stopping distance to the halfwidth or the radius of the impactor throat (Fuchs, 1964), is expressed as:

$$Stk = \frac{\rho_p V_0 C D_p^2 / 18\mu}{W/2}, \tag{1}$$

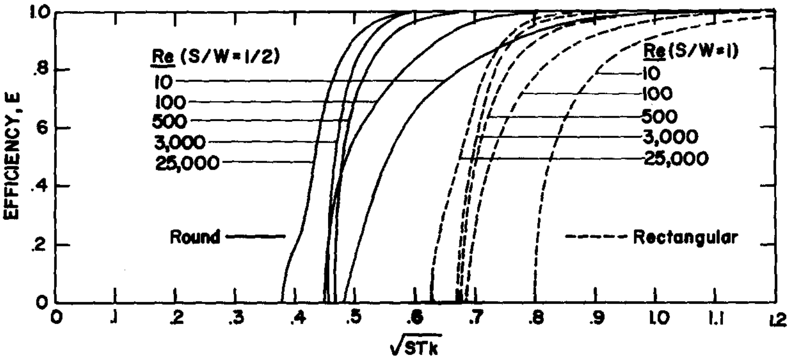


Fig. 3. Theoretical impactor efficiency curves for retangular and round impactors, both at $T/W = 1$.

where ρ_p is the particle density, C is the Cunningham slip correction factor, V_0 is the mean velocity at the throat, D_p is the particle diameter, and μ is the fluid viscosity.

In examining the curves of Fig. 3 it can be seen that the sharpness of cut is best for $Re = 500$ and 3000. The poorer cutoff characteristic at lower Reynolds numbers is caused by a thick viscous boundary layer in the jet of the impactor. For the high Reynolds number case ($Re = 25000$) the knee in the efficiency curve at the low values of efficiency appears to be caused by a very thin boundary layer over portions of the impaction plate adjacent to the stagnation point (Marple and Liu, 1975). This thin boundary layer, having a thickness about equal to the particle diameter, allows smaller particles to impact than in areas where the boundary layer is thicker.

The study of the effect of the S/W ratio on the efficiency curve (Marple and Liu, 1974) showed that the 50% cutoff size $\sqrt{Stk_{50}}$ (the value of $\sqrt{Stk}$ where the collection efficiency $E = 50\%$) was strongly dependent upon S/W for $S/W < 1$ for rectangular impactors and for $S/W < 1/2$ for round impactors. For S/W ratios larger than these values, $\sqrt{Stk_{50}}$ and the shape of the efficiency curves are relatively constant. As a design criteria, the values of

$$\begin{aligned} & S/W = 1.0 \text{ (round impactors)} \\ \text{and} \quad & S/W = 1.5 \text{ (rectanglular impactor)} \end{aligned} \tag{2}$$

should be the minimum jet-to-plate distance used. Under this condition, small variations of jet-to-plate distance will not effect the value of $\sqrt{Stk_{50}}$.

It was also found that the ratio T/W does not greatly influence the cutoff characteristics; especially for impactors with a tapered or conical inlet section as shown in Fig. 1. In the absence of the tapered or conical entrance, a short throat may not allow sufficient time for the particle to accelerate to the fluid velocity in the throat and will thus alter the efficiency curve. Also, particle losses (discussed later) may be found at a sharp entrance. Thus, if possible, the entrance of an impactor nozzle should be tapered or conical and the throat of the nozzle should be of constant width or dia. for $T/W \geqslant 1.0$.

Thus, if the design criteria of equation (2) is observed and T/W is greater than one, the Reynolds number is the only parameter of the three parameters Re, S/W and T/W which requires special consideration in an impactor design. As can be seen in Fig. 3, the Reynolds number should be between 500 and several thousand for the efficiency curve to have a sharp cutoff characteristic and for $\sqrt{Stk_{50}}$ to be insensitive to small changes in Re.

For round impactors the Reynolds number through the nozzle can be controlled by using more than one identical nozzle per stage. The relationship between the number of round jets, n, and the Reynolds number is found by expressing the average velocity within the round jets, V_0, as

$$V_0 = \frac{4Q}{\pi n W^2}, \tag{3}$$

where Q = total volumetric flow rate through the stage. In a cascade impactor, Q will increase as the air density decreases. This velocity expression is now substituted into the expressions for Reynolds number and Stokes number:

$$Re = \frac{\rho V_0 W}{\mu} = \frac{4\rho Q}{\pi n \mu W} \tag{4}$$

$$Stk_{50} = \frac{4\rho_p Q C D_{50}^2}{9\pi n \mu W^3}, \tag{5}$$

where D_{50} and Stk_{50} are, respectively, particle dia. and Stokes number at 50% collection efficiency, and ρ is the fluid density. If W is eliminated from equations (4 and 5), we obtain the expression

$$Q = \frac{\pi}{12}\left(\frac{\rho_p}{Stk_{50}}\right)^{1/2}\left(\frac{Re}{\rho}\right)^{3/2} n\mu\sqrt{C}\,D_{50}. \tag{6}$$

By assuming unit density particles ($\rho_p = 1\,\mathrm{g\,cm^{-3}}$) and air flow at normal temperatures and pressures ($\rho = 1.205 \times 10^{-3}\,\mathrm{g\,cm^{-3}}$, $\mu = 1.81 \times 10^{-4}$ P) and noting that Stk_{50} is a function of Re and the specific design, equation (6) can be expressed graphically as shown in Fig. 4. If the conditions of temperature and pressure differ from these assumptions, the curves in Fig. 4 should be used only as a first approximation. The design procedures described below should then be used for exact calculations. Figure 4 is for $S/W = 1$, $T/W = 1$, and $Re = 500$, 3000 and 10000. With these values of S and T, small variations in S and T will have a negligible effect on the impaction efficiency.

Also note in Fig. 4 that the parameter $\sqrt{C}\,D_{50}$ corresponds to a specific value of W. This relationship is found by eliminating Q/n from equations (4 and 5).

$$W = \sqrt{\frac{\rho_p Re}{9\rho Stk_{50}}}\sqrt{C}\,D_{50}. \tag{7}$$

As an example of the use of these curves, assume it is desired to have a cutoff size of $\sqrt{C}\,D_{50} = 2\,\mu$m, a total flow rate of $40\,\mathrm{l\,min^{-1}}$, and $Re = 500$. From Fig. 4 it is found that this stage must have about 125 holes of 0.0894 cm dia. This number can be reduced to about eight 0.226 cm dia. holes if $Re = 3000$ or further reduced to about one 0.426 cm dia. hole at $Re = 10000$.

A similar analysis can be made of rectangular impactors. However, instead of defining the number of jets, it is more convenient to define the total length, L, of the jets, irrespective of how this total length is divided into individual jets. Now the mean fluid velocity at the throat, V_0, is defined as

$$V_0 = \frac{Q}{LW} \tag{8}$$

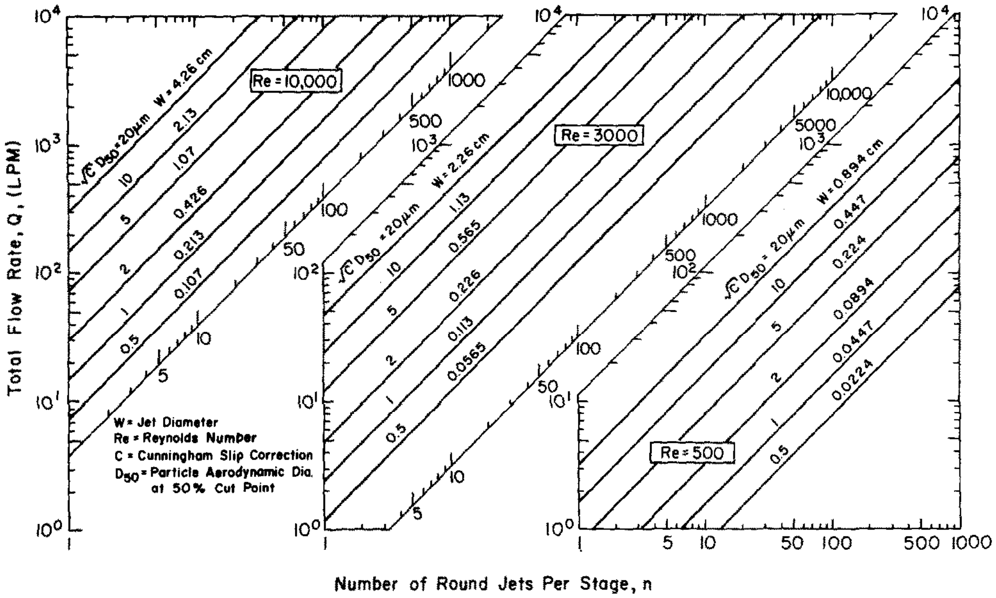


Fig. 4. Design chart for round impactors. (D_{50} = aerodynamic dia. at 50% cut point).

and the Reynolds number (defined in terms of the hydraulic dia.) and Stokes number become

$$Re = \frac{2\rho V_0 W}{\mu} = \frac{2\rho Q}{\mu L} \tag{9}$$

$$Stk_{50} = \frac{\rho_p Q C D_{50}^2}{9\mu L W^2}. \tag{10}$$

Since W does not appear in the expression for Re, we cannot eliminate it from equations (9 and 10) as we did for the round impactor. However, if the volumetric flow rate in a rectangular impactor of width W is expressed per unit length of the jet, the parameter Q/L vs W can be plotted from equation (10) by allowing $\sqrt{C}\,D_{50}$ to be a parameter as shown in Fig. 5. The value of Stk_{50} in this equation is a function of Re (Fig. 3) and, thus, a function of Q/L as defined by equation (9). The corresponding value of Re is also shown in Fig. 5. In this case $S/W = 1.5$ and $T/W = 1$.

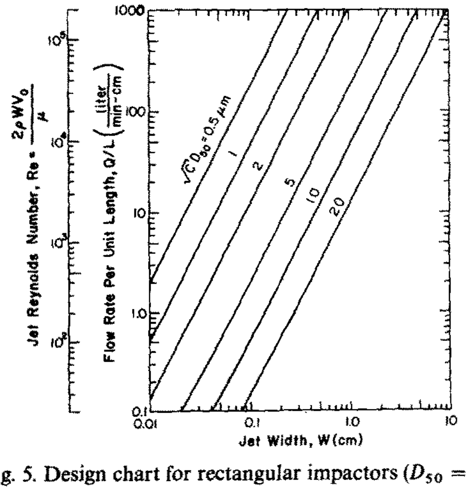


Fig. 5. Design chart for rectangular impactors (D_{50} = aerodynamic dia. at 50% cut point).

DESIGN PROCEDURE

It is possible to design an impactor for a specific flow rate and be fairly certain of the particle cutoff size by making use of the results from the theoretical analysis. The procedure for designing an impactor is essentially the same for either the round or the rectangular configuration. For a cascade impactor operating at a specific flow rate, a suggested procedure is as follows:

1. Choose a desired cutoff dia. D_p. If the density, ρ_p is different from unity, calculate the value $\sqrt{C}\,D_{50}$ (where D_{50} is the equivalent aerodynamic dia. of a unit density sphere) from:

$$\sqrt{C}\,D_{50} = \sqrt{\rho_p}\sqrt{C}\,D_p. \tag{11}$$

The variation in the Cunningham slip correction is usually negligible for small diameter differences. Thus, the values of C on both sides of equation (11) are approximately equal to each other in most cases.

2(a) (*Round*)—Use Fig. 4 and determine the number and size of jets required for the desired operating Reynolds number, Re, and aerodynamic cutoff size, $\sqrt{C}\,D_{50}$. Since the cutoff characteristics are fairly constant and sharp over a Reynolds number range from 500 to several thousand, a Reynolds number of 3000 may be assumed for the calculations.

2(b) (*Rectangular*)—Use Fig. 5 and choose a desirable Reynolds number (again $Re = 3000$ is satisfactory) and determine the Q/L value and jet width, W, for the desired aerodynamic cutoff size $\sqrt{C}\,D_{50}$. Special note must be made of the resulting value of the jet aspect ratio, L/W, since end effects can become detrimental to the sharpness of cut for nozzles with small L/W values.

3. Select a convenient size of jet dia. or jet width which is close to the value found in step 1. For a round impactor this would be a standard reamer size.

4. For this value of jet dia. or jet width, check the Reynolds number using equation (4 or 9).

5 Determine the value of $\sqrt{Stk_{50}}$ from Fig. 3 and calculate the cutoff size, $\sqrt{C}D_p$, by using equation (5 or 10).

6. Determine the pressure in the impaction region, P_2, by assuming that the pressure drop in the stage is equal to the dynamic pressure of the jet. Thus

$$P_2 = P_1 - 1/2\,\rho V_0^2 \qquad (12)$$

where P_1 = static pressure at the impactor stage inlet
P_2 = static pressure at the impaction plate
ρ = fluid density
V_0 = average velocity in the jet.

7. Determine the cutoff particle size, by calculating the Cunningham slip correction (Wahi and Liu, 1971) from the equation:

$$C = 1 + \frac{0.163}{D_p P_2} + \frac{0.0549}{D_p P_2}\exp(-6.66\,D_p P_2), \qquad (13)$$

where P_2 = static pressure (atm)
D_p = particle dia. (μm).

Besides determining the impactor jet diameter at each stage, it is also important to design the impactor such that the jet-to-plate distance criteria of equation (2) are satisified. This will insure that small variations in the jet-to-plate distance from manufacturing tolerances, assembly or deposit buildup will not greatly shift the cutoff size of the impactor.

The throat length of the nozzle does not have a strong influence on the cutoff size or sharpness of cut of the impactor. However, the throat must be of sufficient length to accurately establish the nozzle throat diameter or width, since equation (5) shows that W influences the value of $\sqrt{Stk_{50}}$ by the power of 1.5. Thus, the required throat length will depend somewhat upon the nozzle entrance design. If the entrance is tapered or conical as shown in Fig. 1, the throat does not have to be as long as it may have to be when the entrance is abrupt. In most cases a value of $T/W \geqslant 1$ should be sufficient.

Design of the impactor between stages is also important since this is where interstage losses of the aerosol occur. In general, the fluid velocity must be kept large enough so that particles are not lost from settling and yet not so large as to lose particles from impaction in the interstage space. Also, obstructions and sharp corners should be kept at a minimum, since particles are deposited in the resulting turbulent areas behind these obstructions.

It should be noted, that by using Fig. 3 to determine the cutoff size in the design procedure, the design will be based on the assumption that the nozzle entrance is as shown in Fig. 1. However, Fig. 3 should also be valid for sharp entrances, if the nozzle is of sufficient length. But it has been shown that, if the flow approaches a sharp entrance laterally and the throat is not of sufficient length, efficiency curves different from Fig. 3 can be obtained (Willeke and McFeters, 1975). In these cases, the correct $\sqrt{Stk_{50}}$ values for that design must be used in the design procedure. At present no theoretical values of $\sqrt{Stk_{50}}$ for different inlet designs are available.

OPERATIONAL PRECAUTIONS

It has been shown that an impactor has the ability to sharply classify particles into distinct ranges of aerodynamic size. In some applications, forces other than those due to inertia, such as gravity and electrostatics, may affect the collection characteristics. There may also be some effects from surface roughness in the nozzle and the wall thickness at the nozzle exit. These effects are generally small. However, the effects of inlet losses, interstage losses, and particle reentrainment from the impaction plate may be considerable and should be minimized.

Inlet losses

As is the case with any size analyzing instrument, the efficiency with which the impactor inlet is sampling the aerosol particles must be known before accurate size distribution and particle concentration data can be obtained (Fuchs, 1975). Although the efficiency for sampling from calm air environments may be high (Agarwal, 1975), one should determine the sampling for typical cross-wind velocities. If the impactor is to sample from a moving air stream such as in ducts and stacks, isokinetic conditions at the inlet will aid in efficient sampling of particles.

Interstage losses

Particle losses in an impactor, generally referred to as wall losses or interstage losses, is the deposition of particles on surfaces other than the impaction plate. Currently, no theory exists to predict these losses, and thus, they must be determined experimentally.

Experimental studies have shown that total interstage losses in a cascade impactor are a function of particle size and are generally about 5–10% (Willeke, 1975; Rao, 1975). However, in some cases much higher losses have been found.

Particle reentrainment (bounce-off and blow-off)

The limitations of impactors due to particles bouncing off the impaction plate or being blown off the impaction plate after collection are essentially the same; in both cases, particles which should have been collected are reentrained into the airstream. For single stage impactors, this means that the concentration of particles collected on the impaction plate will be too small. For cascade impactors, the resulting size distribution will be shifted to smaller sizes, since reentrained particles will be collected on stages intended to collect smaller particle sizes.

The degree of particle reentrainment is a function of the type of particle and the nature of the impaction surface (Rao, 1975). Liquid particles will impact on any type of surface with very little reentrainment. The reentrainment of solid particles, however, is a strong function of the type of impaction surface used. The maximum amount of reentrainment is experienced with a dry, smooth surface and the least with a very sticky surface. Thus, if dry particles are to be collected, a sticky coating should be applied to the collection surface and precautions taken not to overload the impaction plate with the particulate deposit, since subsequent impacting particles will impact upon the deposit and not upon the sticky surface.

Fibrous filter media are frequently used as the impaction surface. In this case the fibers provide a large surface area to which the particles may adhere and the voids in the filter media aid in reducing particle reentrainment. The resulting collection efficiency curve, however, has a decreased sharpness of cut relative to the one obtained by impaction onto a smooth surface (Willeke, 1975; Rao, 1975).

SUMMARY AND CONCLUSIONS

Inertial impactors have become a popular tool for the analysis of the size distribution and concentration of aerosols.

The performance of impactors can be accurately predicted by the use of modern numerical methods which solve the equations governing the fluid flow and particle motion in this flow. This theory shows that impactor stages which are properly designed and operated will provide sharp classification between the particles collected and those which are not. Also, the theory can be successfully used to aid in the design of multiple hole impactors. These results, presented in the form of design charts, indicate the number and size of holes needed, for a specific flow rate, to keep the flow conditions (Reynolds number) near optimum.

Although impactors are capable of making a sharply defined cut between particle sizes, special precautions must be taken to insure reliable and accurate data. Such problems as particle losses at the inlet, particle reentrainment from the impaction surface, and particle losses between stages of a cascade impactor can result in the indicated particle size distribution being considerably different from the one sampled. However, by the use of proper design and impaction surface coatings, these problems can be minimized.

REFERENCES

Agarwal J. K. (1975) Aerosol sampling and transport. Ph.D. Thesis, Particle Technology Laboratory, Mech. Eng. Dept., University of Minnesota.

Andersen A. A. (1966) A sampler for respiratory health hazard assessment. *Am. Ind. Hyg. Assoc. J.* **27**, 160.

Cohen J. J. and Montan D. N. (1967) Theoretical considerations, design, and evaluation of a cascade impactor. *Am. Ind. Hyg. Assoc. J.* **28**, 95–104.

Fuchs N. A. (1964) *The Mechanics of Aerosols*, p. 154. Pergamon Press, New York.

Fuchs N. A. (1975) Sampling of aerosols. *Atmospheric Enviroment* **9**, 697–707.

Jaenicke R. and Blifford I. H. (1974) The influence of aerosol characteristics on the calibration of impactors. *J. Aerosol Sci.* **5**, 457–464.

Lundgren D. A. (1967) An aerosol sampler for determination of particle concentration as a function of size and time. *J. Air Pollut. Control Ass.* **17**, 225.

May K. R. (1945) The cascade impactor: an instrument for sampling coarse aerosols. *J. Sci. Instrm.* **22**, 187–195.

Marple V. A. and Liu B. Y. H. (1974) Characteristics of laminar jet impactors. *Environ. Sci. Technol.* **8**, 648–654.

Marple V. A. and Liu B. Y. H. (1975) On fluid flow and aerosol impaction in inertial impactors. *J. Colloid Interface Sci.* **53**, 31–34.

Mercer T. T. and Chow H. Y. (1968) Impaction from rectangular jets. *J. Colloid Interface Sci.* **27**, 75.

Mercer T. T. and Stafford R. G. (1969) Impaction from round jets. *Ann. Occup. Hyg.* **12**, 41.

Ranz W. E. and Wong J. B. (1952) Impaction of dust and smoke particles. *Ind. Engng Chem.* **44**, 1371.

Rao A. K. (1975) An experimental study of inertial impactors. Ph.D. Thesis, Particle Technology Laboratory, Mech. Eng. Dept., University of Minnesota.

Schott J. H. (1973) Jet-cone impactors as aerosol particle separators. M.S. Thesis, Chemical Eng. Dept., University of Minnesota.

Wahi B. N. and Liu B. Y. H. (1971) The mobility of polystyrene latex particles in the transition and the free molecular regimes. *J. Colloid Interface Sci.* **37**, 374–381.

Willeke K. (1975) Performance of the slotted impactor. *Am. Ind. Hyg. Assoc. J.* **36**, 683–691.

Willeke K. and McFeters J. J. (1975) The influence of flow entry and collecting surface on the impaction efficiency of inertial impactors. *J. Colloid Interface Sci.* **53**, 121–127.