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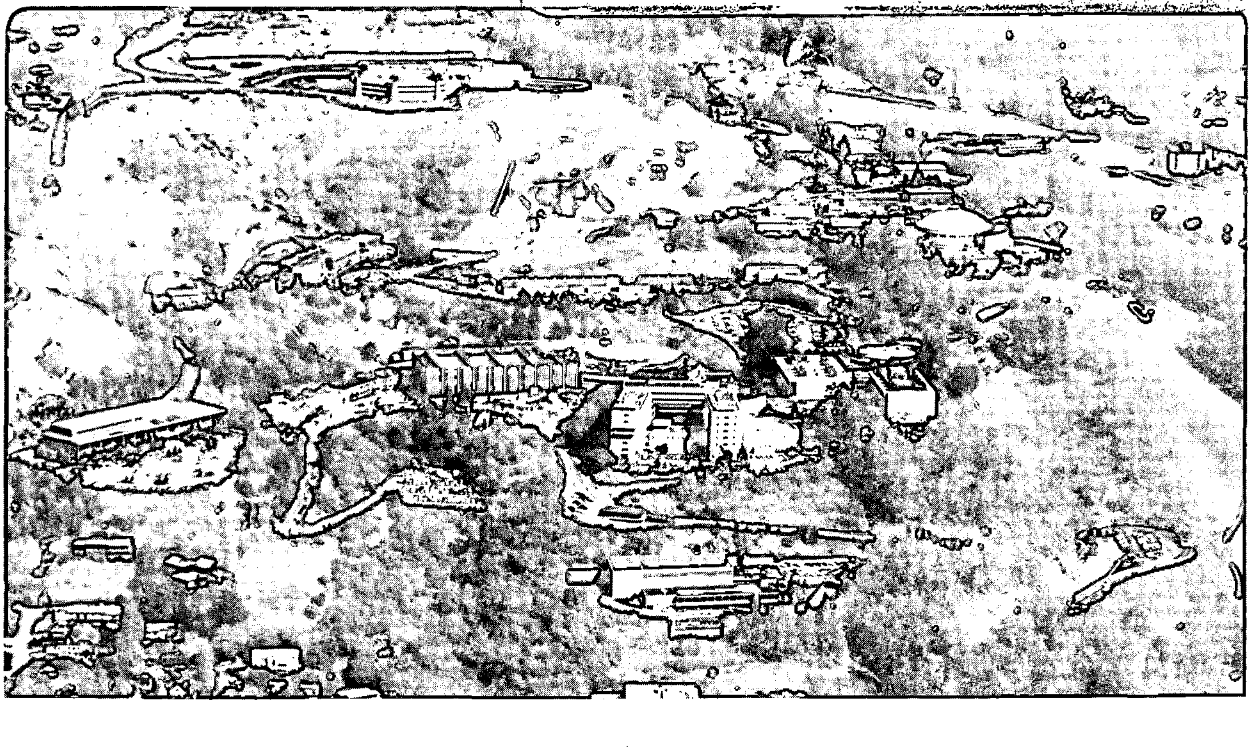

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THE DEVELOPMENT OF HIGH EFFICIENCY VIRTUAL IMPACTORS

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ABSTRACT

We have briefly reviewed the development of the virtual impactor which, as an inertial particle separator according to aerodynamic sizes, has played a unique role in particle sampling, concentration, classification and generation. Its performance characteristics in size separation are predictable by theoretical model calculations. However, its behavior in terms of internal wall losses has thus far defied quantitative analysis, and its ultimate control has eluded most practitioners in virtual impactor design. Through experimentation, we have identified the relevant parameters in a virtual impactor and have indicated their relative sensitivity and acceptable ranges of variability. With the detailed illustration of a specific high efficiency virtual impactor design, we have demonstrated the underlying principles that are crucial to minimizing losses and which may be generally applicable to future developments.

BACKGROUND

Common means of classifying particles according to their aerodynamic sizes include elutriators, cyclones, centrifuges and impactors. Among these devices, the laminar jet impactor has enjoyed the widest application mainly because it is simple in construction and is well understood theoretically (Marple and Liu, 1974, Marple and Willeke, 1976) so that its performance characteristics can be predicted. The problem with inertial impactors, has been the interaction of the particles with the impaction surface, resulting in particle fragmentation, bounce, overload and re-entrainment. These problems have been avoided since the idea of impacting particles on a virtual collection surface or a slowly pumped void was introduced (Hounam and Sherwood, 1965, Conner , 1966). The development of practical virtual impactors, however, was prompted by the need for large-scale sampling of atmospheric aerosols.

The bimodal nature of the size distribution of ambient aerosol is well known. Differences between fine and coarse airborne particles with respect to their origins, chemical properties and environmental impacts call for their separate collection and analysis. A first generation of virtual impactors, utilizing two stages of separation, has been developed to meet these needs (Loo and Jaklevic, 1974, Loo et al. 1976). These dichotomous samplers have been used in many field studies and have contributed substantially to the existing body of data on ambient aerosols (e.g. Dzubay and Stevens 1975, Loo et al. 1978, Lewis and Macias, 1980, Jaklevic et al. 1980).

Theoretical studies of virtual impactors are entirely similar to those of real inertial impactors. The usual approach is to simulate the impactor geometry and flow conditions on a computer, and solve the Navier Stokes equations and particle trajectories in the flow fields by finite element analysis. Both theoretical and experimental work has been done on the two-dimensional slit virtual impactor (Ravenhall et al. 1978 and 1982, Forney 1982). Analytical studies on round virtual impactors have been conducted by Hassan et al. (1979) and more thoroughly by Marple and Chien (1980).

In a virtual impactor, the intake air is typically divided into two streams with the major flow carrying most of the fine particles smaller than some distinct cutpoint and the minor flow carrying all of the coarse particles above the cutpoint together with a small fraction of the fine particles. Both particle fractions are then collected on separate filters or redirected into other downstream instruments. Thus, a virtual impactor can serve one of many functions in particle concentration and classification. In cases where the presence of some fine particles in the coarse particle stream is objectionable, modifications have been made to eliminate the cross contamination. These include the opposing jets design (Willeke and Pavlik, 1978) and the introduction of a clean air core and envelope around the particle-laden stream (Masuda et al. 1979, Chen et al. 1986).

These developments have demonstrated that the virtual impactor has the main advantages of a conventional inertial impactor which include sharp separation characteristics, simplicity, and predictable performance. Furthermore, because the particle collection is external to the apparatus, it is free of problems with the collection surface. It is also more versatile in terms of adaptability to other instruments and lends itself readily to automation. On the other hand, as a flow-through device, the internal losses of particles is a problem that must be critically addressed in order to achieve a high efficiency device.

DEVELOPMENT OF HIGH EFFICIENCY VIRTUAL IMPACTORS

Our effort to develop a second generation of dichotomous samplers was prompted again by the need for studying and monitoring atmospheric aerosols (Stevens and Dzubay, 1978). The objectives were quite specific: (1) It should be a simple single-stage-single-jet virtual impactor designed to serve as the model for commercial production. (2) The 50% cutpoint was to be either 2.5µm or 3.5µm at the sampling rate of 1 m^3/hr. (3) Internal wall losses must be minimized in the particle size range of interest (0-20µm). (4) Particle depositions had to be uniform on both collection filters so that their masses and elemental compositions would be suitable to be analyzed by beta-gauge and x-ray fluorescence spectrometry (Jaklevic et al. 1981 and 1977) respectively.

In this paper we describe in detail the design considerations and testing result of a single-stage virtual impactor which met these criteria. This work was undertaken in 1978-79 and has resulted in a successful design which has been exploited in a number of commercial instruments offered by companies such as Anderson Samplers, Beckman Instruments and Sierra Instruments. These samplers have been utilized in many field studies (e.g., Spengler and Thurston, 1983). Although we have previously reported the fabrication of fully automated dichotomous samplers (Loo et al. 1979) and described the features leading to the high efficiency virtual impactor design in a U.S. patent document (Loo, 1980), we feel that there is a need to recount our research in greater detail because most investigators who design virtual impactors are still reporting very high (10-50%) internal wall losses. Our purpose here is to describe the method and approach that we have used, and to identify and comment on the relative importance of various parameters in achieving a high efficiency design.

Approach

We learned from our previous work that wall losses in a virtual impactor consist of two basic components. The particle loss spectrum tends to exhibit a pronounced peak near the cutpoint and a sharp increase in losses beyond some large particle sizes. The large particle losses are readily understandable from gravitation settling and impaction theory. The loss peak near the cutpoint did emerge in model calculations, but quantitatively, the theoretical predictions were very high in the tens of percents (Marple and Chien, 1980). Guided by the inertial impaction theory and a qualitative understanding of the flow field that exists in the virtual impactor, we have taken an empirical approach.

Consider a very crude virtual impactor as shown in Fig. 1. The inlet air is drawn through the acceleration nozzle of diameter D_1. The coarse particles are concentrated into the minor flow Q_1 through the collection probe of diameter D_2 and the fine particles are carried by the major flow Q_2. One would find that, by and large, the cutpoint of this device would agree well with theoretical prediction. However, particle losses are likely to be found on the wall of cavity D_c because it may not be sufficiently large, and on the back side of the acceleration nozzle because streamlines tend to re-attach to these surfaces (Marple and Chien, 1980). Much of the losses will be found on the inner lip of the collection probe. Closer examination would reveal that the depositions here are skewed because Q_2 has seriously broken the axial symmetry of the flow. Changes must then be implemented to correct these defects. By making measurements on the particle loss and separation characteristics of a prototype instrument, various controlling parameters were identified. We thus aimed at converging on an optimum design through successive modifications and refinements. Our basic premise was that as we maneuver particles within an instrument, impaction losses should be minimized when particle trajectories were nearly **tangent** to the physical surfaces which shaped the streamlines.

Methods of Measurements

We have used liquid particles to evaluate the performance of the virtual impactor because they can be generated with ease and consistency. They also provide the most severe test for wall losses. Test particles of dioctyl phthalate (DOP) in the size range of 1-20µm were generated in a Berglund-Liu monodisperse aerosol generator with uranine (fluorescein sodium) used as a tracer for quantitative measurements. The details of particle generation and measurement have been previously reported (Loo and Jaklevic, 1974). The advantage of using DOP is that, unlike oleic acid, uranine is not soluble in it; therefore deposits can be extracted instantly and completely from impactor parts and collection filters with water. Practically all deposits were removed from impactor parts with a squirt bottle of water or a wet cotton swab because a second rinse or even wash by immersion usually yields less than detectable amounts (< 0.2%). Uranine from the filters were extracted by immersing in a dish containing approximately 20ml of deionized water. The uranine from the fine particles entered the solution very readily. For measuring coarse particles over 10µm, the dish was usually placed in an ultrasonic bath for up to one minute for complete extraction. A UV fluorescence analyzer of our own design was used for convenience; because of the unique optical setup, it was unnecessary to transfer fluid from the extraction dish or to measure the volume of the fluid actually used (Loo and Jaklevic, 1974). The detector output remained constant even if 100% more water was added to the sample.

A flow controller was used to maintain constant sampling conditions. Details of the flow system have been previously described (Loo et al. 1979). Flow calibrations were performed using a wet test meter (GCA/Precision Scientific, Chicago, IL 60647). The accuracy of the system was better than 3% with a precision of about 1%.

In a typical test run, the sampling time usually ranged from a few minutes up to 15 minutes depending on the size of the particles used. The minimum detectable limit of the analyzer for uranine was 1 ng/cm^2 or about 10 ng in the sample. Since losses and separation characteristics were all relative measurements in terms of ratios, no absolute calibration was needed. We found that uranine had a tendency to agglomerate at the tip of the collection probe, sometimes even protrude above the smooth impactor surface, if the deposits were very heavy. Thus, excessively long test runs tended to exaggerate losses. We usually aimed at collecting a total of about 10μg of uranine so that losses in the amount of 0.2% could be readily detected.

Results and Discussion

The realization of an optimum design involves a large number of controlling factors acting in concert. Arriving at such a design is analogous to searching for a "saddle point" in a multi-dimensional space. We have reported some of the test data in an earlier design study (Loo et al. 1976). It would be impractical to collect the very large data set in order to illustrate in a general way the dependency of system performance on the variation of parameters under various combinations. Our hope is that by discussing the sensitivity of the parameters identified, some general insight might be gained towards designing future systems and understanding the performances of past developments (e.g., McFarland et al. 1978, Solomon and Moyers, 1983, Chen et al. 1985).

Fig. 2 shows a cross-sectional view of a dichotomous sampler with a single-stage virtual impactor. This design was the result of our effort to fulfill the list of objectives stated earlier. Since the minor flow fraction Q_1/Q_0 was chosen to be 0.10, the cutpoint of the device was then the particle size at which C/(C+F) = 0.55, where C and F were the particle depositions on the coarse and fine filters respectively.

We summarize our finding in terms of the following 27 parameters which are labeled in Fig. 3. The specific values used in our design are given in parentheses.

(1) Q_0 Total inlet flow rate (1 m^3/hr). At a given cutpoint (2.5µm), the jet Reynold's number (7700) is primarily determined by this sampling rate.

(2) Q_1 The minor flow to carry and disperse the coarse particles. The ratio Q_1/Q_0 (10%) is chosen as a compromise between higher losses at lower values of Q_1/Q_0 (< 5%) and higher contamination of fine particles in the coarse particle stream at higher values of that ratio. The cutpoint is sensitive to this ratio but is predictable by theory (Marple and Chien, 1980).

(3) Q_2 The major flow to transport the fine particles. This is not an independent parameter, with (Q_1+Q_2) being equal to Q_0.

(4) D_0 Inlet diameter (2.86 cm). Should be large enough to ease the 20µm particles into the acceleration nozzle without impaction loss while small enough to minimize gravitational settling loss.

(5) D_1 Diameter of acceleration nozzle (0.305 cm). Critical in determining the particle velocity, hence the cutpoint, as expressed by the critical Stoke's number.

(6) D_1^* (0.635 cm) Proper size required to shape streamlines to eliminate

impaction on the back side of the acceleration nozzle. A ratio between 2-2.5 is recommended for D_1^*/D_1.

(7) D_2 Diameter of collection probe (0.422 cm). A critical ratio of D_2/D_1 in the range of 1.3-1.4 must be used to minimize the loss peak near the cutpoint. There will be further discussion on this later.

(8) D_2^* The O.D. at the tip of the collection probe (0.64 cm). Should be small enough to allow the dispersion of the radial air streams.

(9) D_3 (0.95 cm). An abrupt enlargement in the I.D. of the collection probe designed to deliver an impulse to the coarse particles to distribute them more uniformly across the drift tube.

(10) D_3^* The I.D. of the drift tube (3.18 cm) designed to match the effective area of the filter below.

(11) D_4 Eight holes (0.32 cm) evenly spaced to provide sufficient flow impedance to ensure azimuthal flow symmetry in the separation region.

(12) D_5 (2.54 cm). Provides a 0.32 cm step near the wall of the drift tube to avoid impaction loss.

(13) D_c I.D. of the separation cavity (7.6 cm) should be large enough to avoid impaction while small enough to minimize gravitational settling.

(14) l_0 Length of the inlet pipe (>30 cm). Long enough to establish parallel streamlines and to allow for some damping of any axial angular momentum that exists in the intake air.

(15) l_1 Acceleration and focusing region (0.32 cm). A range of 0.8-1.2 is recommended for the ratio l_1/D_1.

(16) l_1^* (0.95 cm). To provide sufficient relief to eliminate back-impaction

loss.

(17) l_2 Region of size separation (0.79 cm). Should be slightly deeper than D_2 but short enough to allow for the dispersion of the very large particles. A range of 1.5-2.5 is recommended for the ratio l_2/D_2.

(18) l_2^* (0.80 cm). Use l_2^* to be about twice D_2 for proper dispersion of coarse particles.

(19) l_3 Length of drift tube (11.4 cm) should be long enough to allow uniform distribution of coarse particles on the filter below.

(20) l_c Depth of the separation cavity (3.97 cm) in which Q_2 is symmetrically distributed.

(21) θ_0 Intake angle (45^o) to effect particle focusing and reducing coarse particle loss. A range of 40^o-50^o is recommended.

(22) θ_1 (30^o). Surface shaped to eliminate back-impaction loss.

(23) θ_2 (15^o). Allowing the dispersion of Q_2.

(24) θ_3 (7^o). An angle in the range of 5^o-9^o was found to be helpful to control the dispersion of large particles while avoiding impaction on the drift tube.

(25) R Polished radius (0.089 cm) on the inner lip of the collection probe is essential in minimizing the loss peak near the cutpoint. There will be further discussion on this later.

(26) S The spacing between the acceleration nozzle and the collection probe (0.48 cm). This gap does not affect the cutpoint appreciably but is coupled to other parameters in defining the flow geometry. The ratio of S/D_1 should be kept within the range of 1.2-1.8.

(27) δ The axial misalignment between the acceleration nozzle and the

collection probe should be kept to a minimum (<0.005 cm) to avoid increased losses due to flow asymmetry in the critical size separation region.

Among these 27 parameters, 26 are independently adjustable; but only an optimum combination would produce the desired performance. The three flow parameters are assumed to be held constant. Five of the geometrical parameters (D_1*, l_1, l_2, θ_0, and θ_3) are moderately sensitive, and the recommended ranges of variability have been indicated. The most critical parameters are D_1, D_2, R and δ.

Once Q_0 and Q_1 are specified, the cutpoint is essentially determined by D_1. Within reasonable limits, D_2 and S have relatively minor but measurable effects on the cutpoint. In view of the close agreement between our measured cut characteristics with theory, a calculated value of D_1 may be used as a good starting point for any new design. Experimentally, D_1 can be determined to within 2% when other parameters are fixed.

Particle losses near the cutpoint are strongly dependent on the ratio D_2/D_1. When this ratio is close to or even less than unity, one expects to find impaction losses at the tip of the collection probe. As the ratio is increased, those streamlines which have penetrated somewhat into the collection probe become less crowded radially and can make smoother exits. Thus impaction losses for those particles near the cutpoint tend toward a minimum. As D_2 is increased further, the penetration of the streamlines also becomes deeper. When D_2/D_1 approaches 1.5 and beyond, there is room for many streamlines to make almost complete U-turns and result in very high losses on both the collection probe and the backside of the acceleration nozzle over quite a wide particle size range. We found that the optimum ratio lies between 1.35 and 1.40, allowing a sufficient safety margin.

Impaction efficiency depends on the angle of approach between the particle trajectory and the physical surface. The inner lip of the collection probe should therefore be curved to better parallel the streamlines that are making an exit from this critical size separation region. The radius of curvature R cannot be too large without significantly altering the pre-existing size separation geometry. We found a R/D_2 ratio between 0.18-0.24 to be effective in minimizing losses.

Finally, the axial misalignment δ between the acceleration nozzle and the collection probe must be kept to a minimum. We found that losses increase initially at a rate of about 1% per 0.005 cm of misalignment, and presumably will increase at higher values of δ.

The performance characteristics of a dichotomous sampler with those design parameters specified above are shown in Fig. 4. The cutpoint was 2.5 µm and liquid particle losses were under 1% throughout the size range (1-20 µm) tested. No detectable (<5%) non-uniformities of particle depositions on the filters were observed for particles up to 20µm. The validity of our measurement was demonstrated in part by the good agreement between our experimental cutpoint with theory (Marple and Chien, 1980), and significantly by the excellent agreement with the comparison of performance results obtained on several commercial copies by quite independent procedures (John and Wall, 1983). The average peak loss of those samplers tested was about 2% at the cutpoint. We should point out that the higher losses at 20µm observed in that study were due to slight departures of those commercial adaptations from the LBL design. In view of the fact that most ambient aerosol samplers are now equipped with inlets with a 10 µm cutoff, this performance deficiency at very large particle sizes is of little practical consequence.

This virtual impactor design permits a different particle size cutpoint to be realized by a simple replacement of the acceleration nozzle and the collection probe. Fig. 5 shows the similar performance results obtained for a 3.5 µm cutpoint version in which only the jet diameter D_1 was changed to 0.391 cm with other sensitive dimensions, such as D_2, R and D_1*, scaled accordingly. The error bars shown in both Fig. 4 and 5 represent the standard deviations of repeated loss measurements taken at the cutpoints of the instruments.

CONCLUSION

With all of its inherent advantages, the dichotomous sampler equipped with a high efficiency virtual impactor has proven to be an invaluable tool in ambient aerosol sampling in particular and particle sizing in general.

The performance of virtual impactors used in aerosol research applications has traditionally relied largely on the intuition and the perceived importance of various design features of the practitioner. The size separation characteristics have now been shown to follow quite closely with theoretical analysis. Through specific examples, we have demonstrated that very low internal wall losses are achievable despite theoretical predictions to the contrary. This discrepancy was probably due to the insufficiently fine definition of details for calculations conducted at the critical regions of particle separation.

We would like to reiterate two seemingly obvious principles which have contributed to the success of our design but have eluded the consistent application in most other developments. The first is that impaction efficiency should decrease with the angle at which a particle strikes a surface. Armed with the theoretical description of the flow field and the knowledge of impaction theory, one should be able to match the internal physical surfaces to the streamlines accordingly. The second is the matter of symmetry. There is an inevitable distribution of flow conditions among all the streamlines. If an optimum condition is realized for one streamline, it will be simultaneously realized for others that are similar. Thus a high degree of flow symmetry should not only lead to sharper cuts but also lower losses. For this reason, round impactors should outperform rectangular impactors. In our design, the degree of symmetry is enhanced by the straightening and reducing the angular momentum of the flow in the inlet pipe, the slight focusing of the particles in the acceleration region, the even distribution of the radial flow in the separation cavity, and the strict adherence to maintaining the alignment between the acceleration nozzle and the collection probe. We note with interest that according to the theoretical model (Marple and Chien, 1980), the penetration, hence the distribution, of the streamlines into the collection probe are highest for the intermediate range of jet Reynold's numbers (100-1000). But the results of calculation indicated a monotonic increase of losses for Reynolds numbers in the range of 10-15000. From the standpoint of symmetry, we would predict higher losses for those virtual impactors operating at intermediate Reynold's number. We expect that the efficiency of a virtual impactor should ultimately be higher at Reynold's numbers beyond 1000 where the velocity profile of the streamlines are flatter, and the penetration into the collection probe shallower when other parameters are properly optimized.

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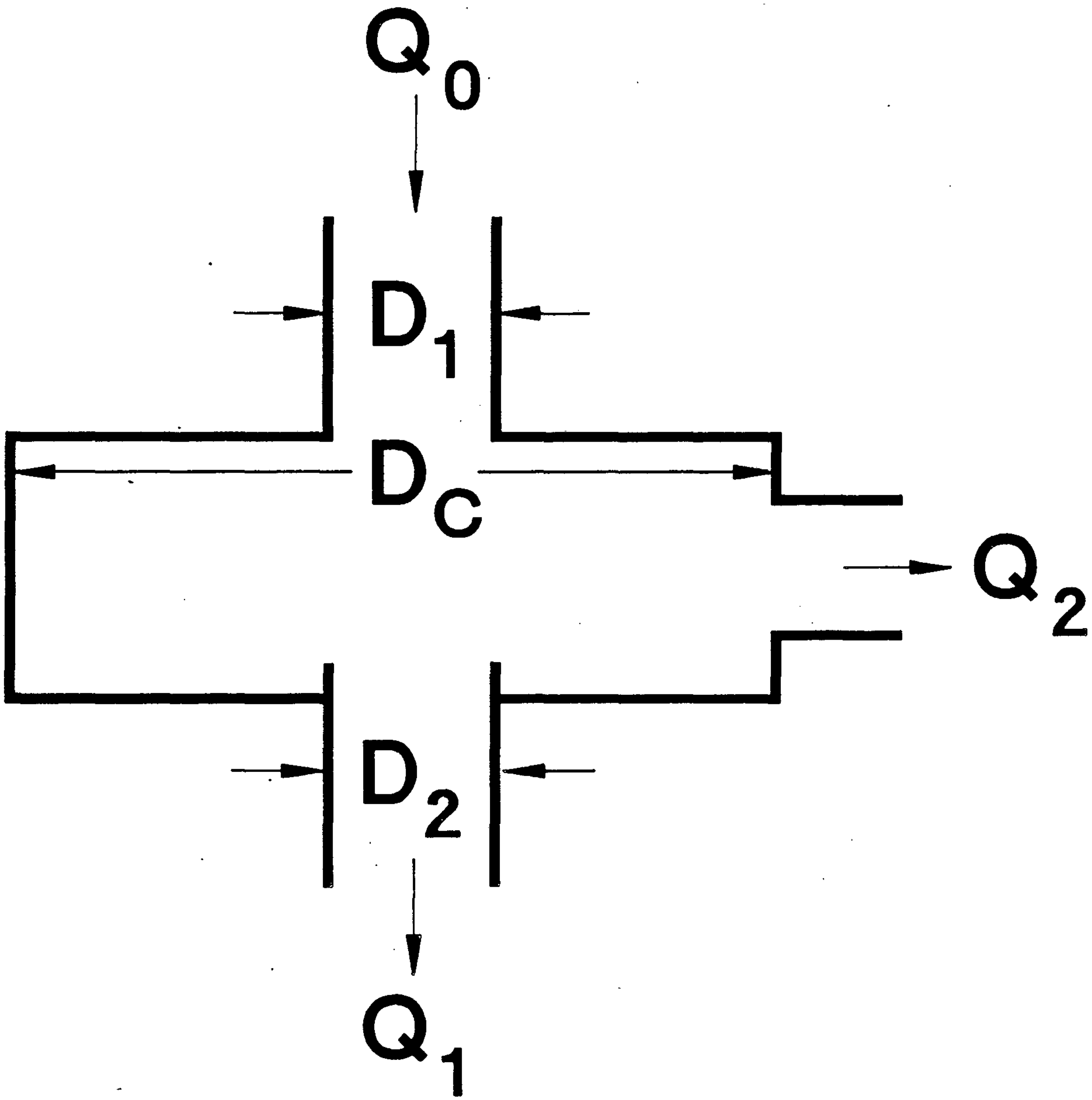

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Fig. 1. A crude virtual impactor.

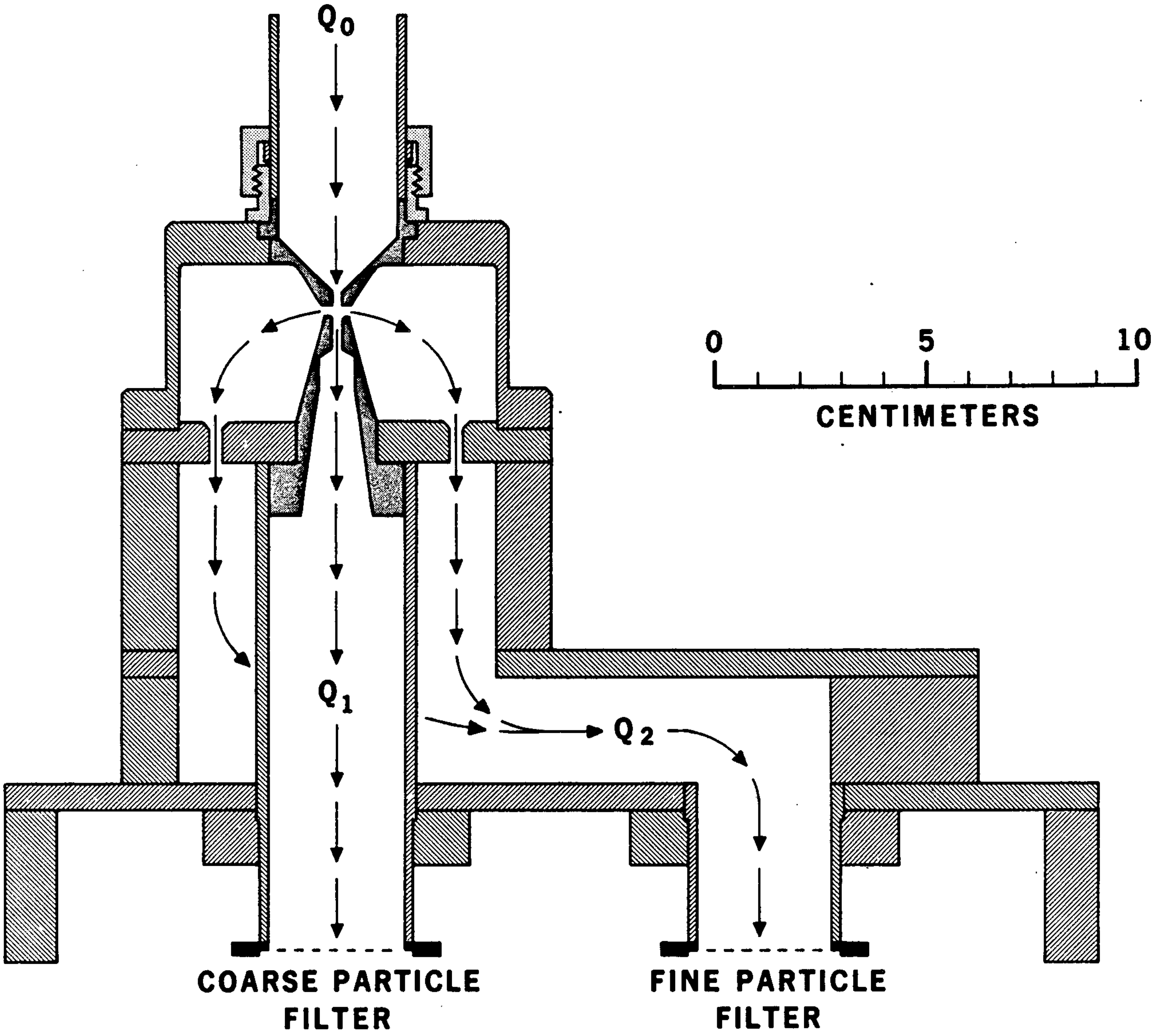

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Fig. 2. A cross-sectional view of a dichotomous sampler equipped with a high efficiency virtual impactor.

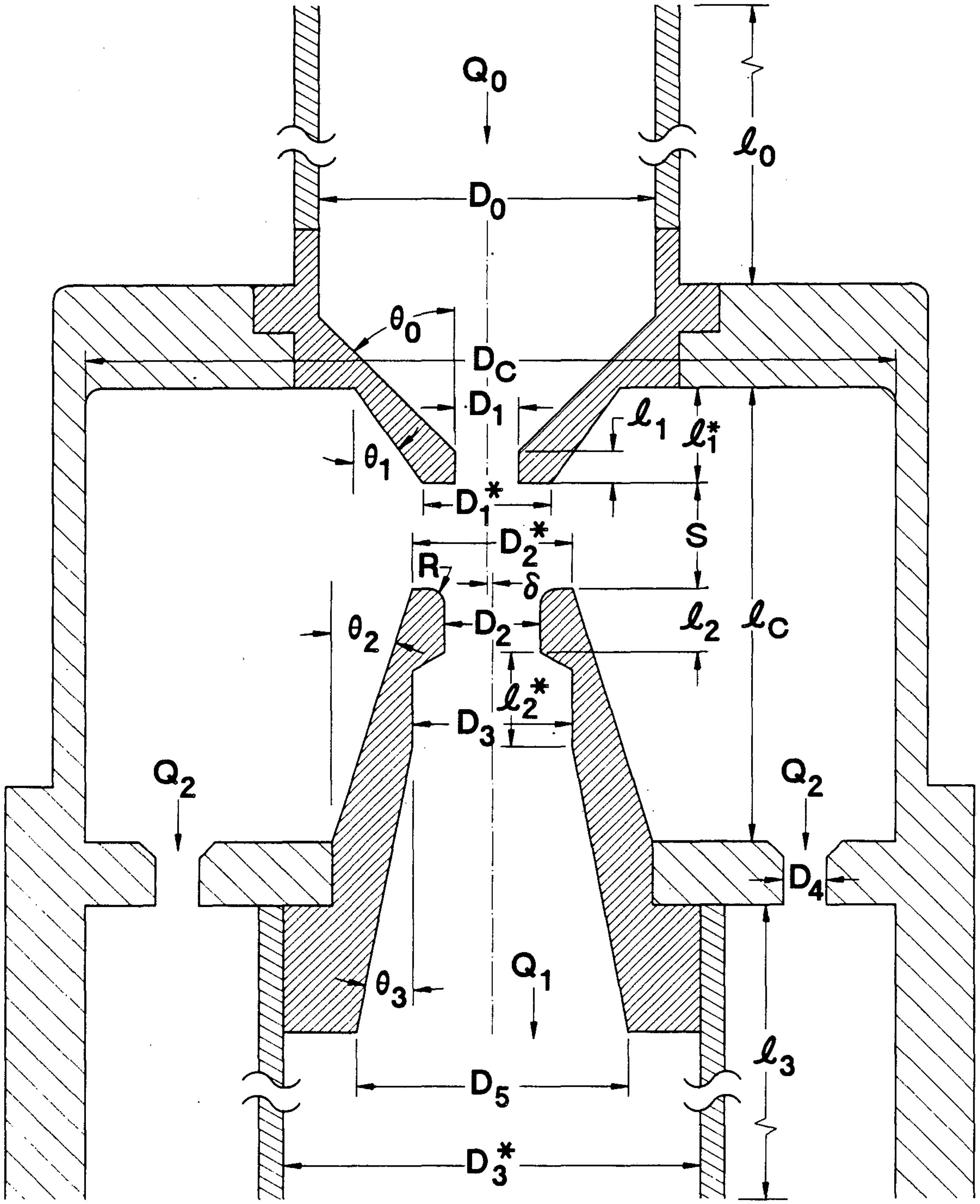

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Fig. 3. Relevant parameters in a virtual impactor design.

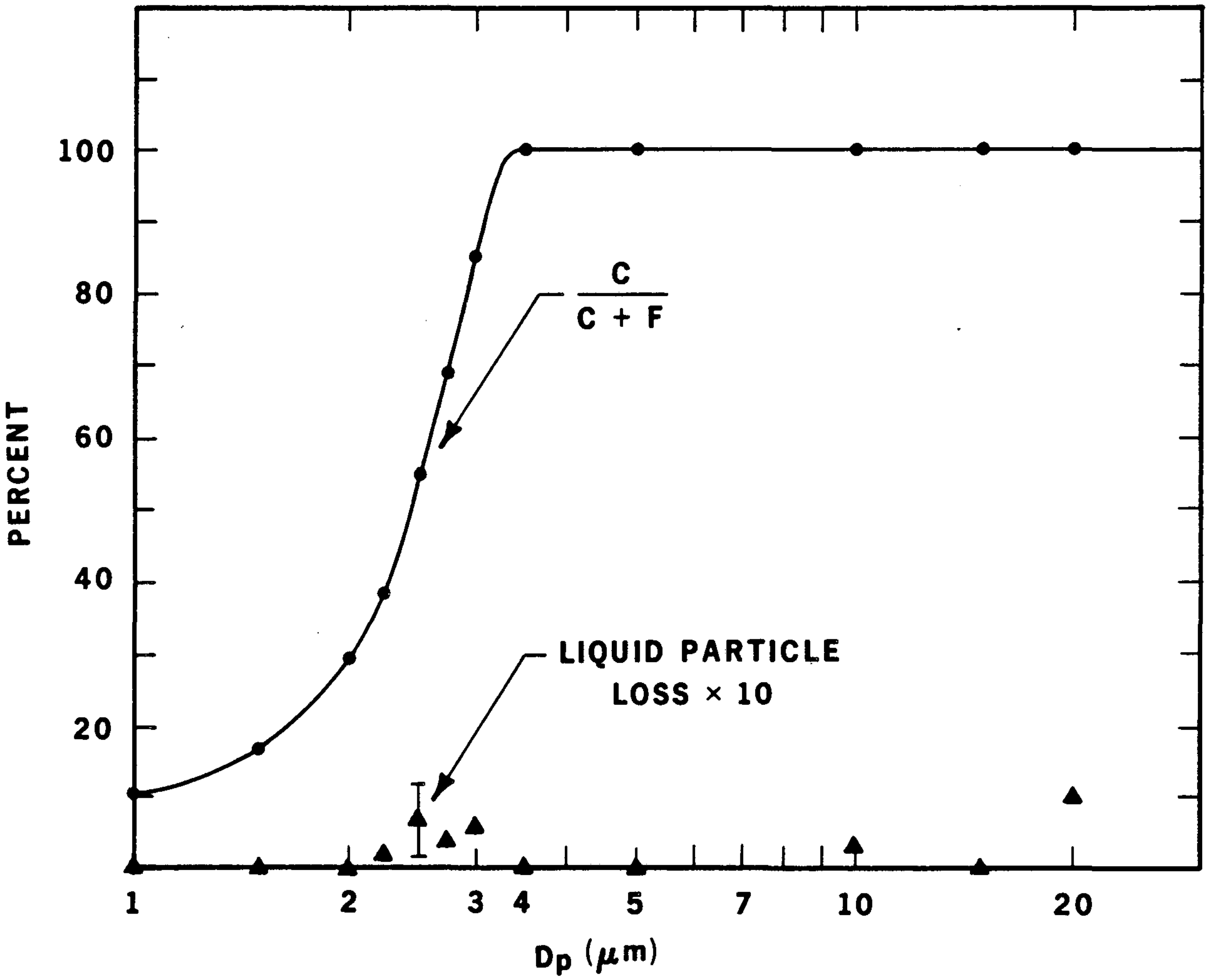

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Fig. 4. The size separation characteristics and wall loss measurement of a 2.5 μm cutpoint virtual impactor as a function of particle size Dp. C and F represent particle collections on the coarse and fine filters respectively.

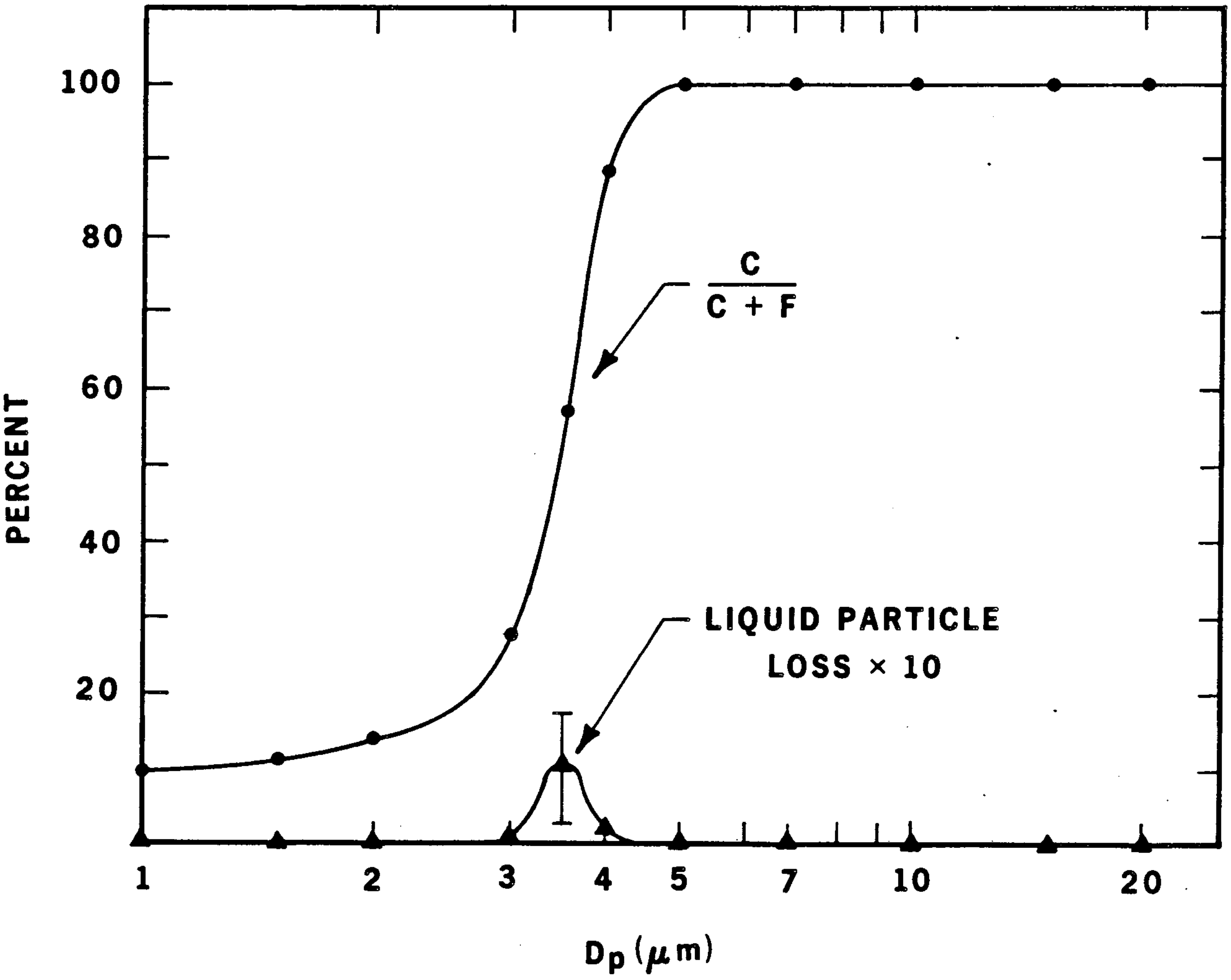

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Fig. 5. The size separation characteristics and wall loss measurement of a 3.5 μm cutpoint virtual impactor.

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