A CASCADE IMPACTOR OPERATING AT LOW VOLUMETRIC FLOW RATES

by

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Albuquerque, New Mexico

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ABSTRACT

A five-stage cascade impactor, designed to operate at 50-150 cm$^3$/min, is described. The device comprises four impactor stages, in which round jets are used, and a filter stage. The method of calibration of the instrument is described and it is shown that the curves of impaction efficiency as a function of the $\sqrt{V}$ are similar to those of large impactors of similar design, with $\sqrt{V} = 0.29$ for a collection efficiency = 0.5. For deposit thicknesses of 0.05 to 55.7 mg/cm$^2$, the wall losses vary between 1.4 and 9.8 per cent. The significance of the collection efficiency and wall losses with respect to sampling for mass distributions is discussed.
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INTRODUCTION

The cascade impactor is a valuable tool for use in experiments designed to study the toxicity of airborne particulate material, because it provides a means for direct determination of the mass distribution of the aerosol under study. In the present case, highly radioactive aerosols are under investigation, and samples collected from large volumes of air cannot be tolerated. Since impactors described in the literature operate at flow rates of 10 to 30 liters/minute, while one was needed which operated at 50 to 150 cm$^3$/minute, it was necessary to design the instrument described below.

DESCRIPTION OF THE IMPACTOR

Design Considerations. Ideally, one would like to have an impactor in which the curve of efficiency versus particle size for each stage was a step function, with the particle diameter at which the step occurred differing by a factor of about two from one stage to the next. One would also like to have negligible wall losses in the impactor.

Davies and Aylward have shown on theoretical grounds that the efficiency of the impaction process for rectangular jets is a function of two dimensionless quantities; the inertial parameter, $\gamma$, of the particle, and the ratio of the jet-collector separation, $S$, to the jet width, $W$. The parameter $\gamma$ is given by

$$\gamma = \frac{\rho D^2 U_o c}{18 \eta W}$$
where \( p \) is the particle's density, \( D \) is its diameter, \( U_o \) is the velocity of the air stream as it emerges from the jet, \( \eta \) is the viscosity of the air, and \( C \) is the slip factor. For present purposes, the following expression for \( C \) is convenient:

\[
C = 1 + \frac{2}{D} \left[ 6.32 + 2.01 e^{-0.1095 \cdot 10^9 \cdot \rho \cdot D} \right]
\]

where \( \rho \) is the atmospheric pressure in cm of Hg, and \( D \) is the particle's diameter in microns. The quantity, \( \sqrt{\eta} \), which is proportional to \( D \), is more commonly used than \( \eta \). Davies and Aylward obtained theoretical curves of efficiency as a function of \( \sqrt{\eta} \) for a number of values of \( S/W \). These showed that as \( S/W \) decreased, there was a decrease in the value of \( \sqrt{\eta} \) for which the efficiency, \( E \), was 0.5, and an increase in the slope of the curve at that point. At low values of \( S/W \), the theoretical efficiency curve was almost a step function.

The original cascade impactor described by May \(^8\) employed rectangular jets, as did those described subsequently by Sonkin \(^{12}\), Laskin \(^5\), Wilcox \(^{13}\), and Lippman \(^7\). Ranz and Wong \(^{11}\) described a single stage impactor having a rectangular jet. In those cases in which the data can be interpreted in terms of the theory of Davies and Aylward, there is evidence that \( \sqrt{\eta} \) (\( E = 0.5 \)) decreases as predicted with decreasing \( S/W \) \(^9\); however, for a given value of \( S/W \), the experimental efficiency curves show a reduction in slope as \( E \) approaches 1.0.

Impactors using single round jets have been described by Ranz and Wong \(^{11}\), and Mitchell and Pilcher \(^{10}\), and one in which each stage included several hundred round jets was described by Andersen \(^1\). Ranz and Wong \(^{11}\) obtained a theoretical curve for the case in which, in effect, \( S/W = 0.5 \). While additional theoretical work is lacking, experimental work indicates that the effect of \( S/W \) for round jets is qualitatively similar to that for rectangular jets. Moreover, Mitchell and Pilcher \(^{10}\) found that for \( S/W = 0.375 \), the efficiency curve was very nearly a step function.

Because of the advantages to be expected with respect to collection efficiency, and because round jets are relatively more easy to machine, especially in the small sizes required in this case, it was decided to
design and construct a cascade impactor using a series of round jets.

The problem of wall losses is a serious matter with cascade impactors. They have been found to be quite high in rectangular jet impactors. Mitchell and Pilcher found it was necessary to provide quite large distances between the edge of the collector plate and the wall of the impactor in order to reduce wall losses to acceptable levels. Andersen, on the other hand, found wall losses to be negligible. Since in all impactors the linear velocity with which the air flows between jets is certainly much less than the linear velocity through the previous jet, it seems likely that wall losses are due to effects of turbulent flow between jets. In the impactors mentioned, except the Andersen, abrupt changes in the cross-sectional area of the air passage occur immediately after the air leaves the jet. For this reason, the present impactor was designed to minimize all such changes.

Operating Characteristics. The impactor is shown schematically in Fig. 1. The collector plates are 22-mm diameter glass cover slips. They are kept at the proper distance from the jet by three spacers of about 1-mm diameter set on a 5/8" circle about the jet and having lengths as shown in Table 1. Three stainless steel wire (11-mil) springs hold the collectors firmly in place. The use of the O-rings prevents any leakage of air around the stages. The two 1/16"-diameter pins, soldered into the first stage, fit through appropriate holes in each of the following stages to prevent lateral movement of the stages when assembling or disassembling the impactor. The overall dimensions of the impactor, not including the inlet and outlet tubes, are 2-1/8" diameter by 2" long. The jet diameters, spacer lengths, and linear air velocities through the jets are shown in Table 1.
SECTIONAL DIAGRAM OF CASCADE IMPACTOR

Aerosol Entry

Cover Plate

Jet-Collector Spacers

Cover Slips

Cover Slip Supports

Support Springs

Supports

Membrane Filter

Vacuum Applied

SECTION "A-A"

Fig. 1
TABLE 1. Operating Characteristics of the Small Impactor

<table>
<thead>
<tr>
<th>Stage</th>
<th>Jet diameter, W</th>
<th>Spacer length, S</th>
<th>S/W</th>
<th>Linear air velocity through jet*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.081 cm</td>
<td>0.030 cm</td>
<td>0.37</td>
<td>3.21 F cm/sec</td>
</tr>
<tr>
<td>2</td>
<td>0.053 &quot;</td>
<td>0.020 &quot;</td>
<td>0.38</td>
<td>7.44 F &quot;</td>
</tr>
<tr>
<td>3</td>
<td>0.033 &quot;</td>
<td>0.013 &quot;</td>
<td>0.39</td>
<td>19.49 F &quot;</td>
</tr>
<tr>
<td>4</td>
<td>0.016 &quot;</td>
<td>0.006 &quot;</td>
<td>0.38</td>
<td>82.80 F &quot;</td>
</tr>
</tbody>
</table>

*F = Total volumetric flow rate through the impactor in cm³/min

While the impactor referred to in Table 1 was the one of primary interest because of the low volumetric flow rate, a second was constructed which differed only in the jet diameters and spacer lengths. These were each 2.7 times the values shown in Table 1, so that at one liter/min the second impactor had linear velocities through the jets similar to the first impactor operated at 150 cm³/min. In the following, the first is identified as impactor 1, the second as impactor 2.

CALIBRATION METHODS

Experimental Set-up. The instrument was calibrated in terms of the collection efficiency as a function of \( \sqrt{v} \), since it was intended to use the effective cut-off method in the interpretation of sampling data. The experimental arrangement for collecting the samples for calibration is shown in Fig. 2.

Two types of aerosols were used. One was produced by atomization of liquid stearic acid, using an aerosol generator similar in principle to that described by Lauterbach et al. Upon mixing with the diluting air, the stearic acid particles solidified, giving an aerosol of essentially spherical particles of a wide range of sizes. The other aerosol was produced by means of a similar generator atomizing a suspension of polystyrene latex particles. In one case, particles of 0.365 micron diameter* were used in a dilution of 1:3000. Electron micrographs of these

*Obtained from the Dow Chemical Co., Midland, Mich.
Quick Disconnect Valve

Hood Exhaust

Rotameter

Vacuum

Filtered, Dry, Diluting Air

Compressed Air

Aerosol Solution

Aerosol Generator

Sampling Arrangement for Calibration of the Cascade Impactor

Fig. 2
particles indicated that the mean diameter was as stated. Particles, nominally of 0.81 micron diameter*, were also used, in a dilution of 1:2000. However, measurements made on electron micrographs of a sample collected by electrostatic precipitation gave an average diameter of 0.73 micron with a relative standard deviation of ± 5 per cent. Some of the particles had a slightly elliptical appearance so three measurements were made on each particle and averaged: two, mutually perpendicular, were made on the particle itself, and a third was made on the length of the shadow which had been cast at 30°. The aerosols obtained with polystyrene particles were made up predominantly of single spheres, although doublets, triplets, and occasionally particles of several unit spheres were observed. As will be seen below, however, these did not affect the determination of efficiency.

For a given set of conditions, the flow rate was set by means of the rotameter. The impactor inlet was then connected to a one-liter spirometer and the flow rate determined by measuring the time required to evacuate a given volume of air from the spirometer. Sampling was then begun and ended by the use of the quick-disconnect valve.

**Determination of Efficiency.** Two samples of the same aerosol, collected at the same flow rate, were necessary to make a determination of efficiency. Schematically, the samples were arranged in the following manner:

First Sample

\[
\begin{align*}
\text{Jet A} & \quad \text{Jet B} \\
N_o & \rightarrow (1 - E_{AW}) N_o & \rightarrow N_o \\
\text{Efficiency} &= E_{AW} & \text{Efficiency} &= E_B \\
N_A &= E_{AW} N_o & N_B &= E_B (1 - E_{AW}) N_o
\end{align*}
\]

*Obtained from the Difco Co., Detroit, Mich.
In collecting a sample, two jets were arranged in series in the impactor. Similar jets from two impactors were used in most cases; however, as the efficiency diminished it was necessary to use adjacent jets from the same impactor, with the jet designated as B having the smaller orifice. For the first sample, the collector behind jet A was coated with an adhesive; that behind jet B was left dry. (The adhesive used was Dow Aerosol Anti-Foam A, a silicone product. It was used initially because it was available; however, it was found to give a satisfactory adhesive that could be readily applied from the spray can in a uniform, viscous layer.) After the first sample was collected, the cover slips were replaced, the positions of the jets were reversed, and a second sample was collected in the same way.

The efficiency of jet A when operated with an adhesive coating on the collector could then be determined in the following way. Let $N_o$ be the number of particles of a given size entering the front jet during the sample. Let the efficiency of jet A, with adhesive, be $E_{AW}$ and of jet B, without adhesive, be $E_B$. For the first sample, the number of particles collected by jet A is

$$N_A = E_{AW} N_o$$

and the number collected by jet B is
\[ N_B = E_B (1 - E_{AW}) N_o. \]

For the second sample, the number collected by jet B is

\[ N_B' = E_B N_o. \]

The ratio \( N_B / N_B' = 1 - E_{AW} \), from which \( E_{AW} = 1 - \frac{N_B}{N_B'} \). For a given run, all the particles were counted within a rectangle having a width between 0.4 and 1.6 mm, depending on the jet diameter, and a length equal to the diameter of the cover slip, and having its center at the center of the deposit. This yielded numbers proportional to \( N_B \) and \( N_B' \). Actually, the numbers were very nearly equal to \( N_B \) and \( N_B' \), since the particles were very heavily concentrated under the jet.

This derivation assumes that no particles are lost between jets and that \( N_o \) and \( E_B \) do not vary between samples. That the first assumption is reasonable is shown by the low wall losses (see below). Changes in \( N_o \) would require changes in the aerosol output during the length of time needed to complete two samples. Since the time from the start of the first run to the end of the second was always less than five minutes, changes in \( N_o \) were unlikely. The consistency of the results indicate that changes in \( E_B \) are negligible.

All counting and measurements were made using an oil immersion objective (overall magnification \( \leq 900x \)). For the stearic acid samples, measurements were made using an eyepiece micrometer and only particles larger than 3 divisions (3.4 \( \mu \) under the conditions indicated) were included.

For stearic acid particles, the root inertial parameter is

\[ \sqrt{Y} = 2.33 \times 10^{-4} \frac{D}{W} \sqrt{\frac{F}{C}} \]

for \( F \) the volumetric flow rate in \( \text{cm}^3/\text{min} \), \( W \) the jet orifice diameter in \( \text{cm} \), \( D \) the particle diameter in microns, and \( C \) as defined above. For polystyrene particles the parameter is

\[ \sqrt{Y} = 2.62 \times 10^{-4} \frac{D}{W} \sqrt{\frac{F}{C}} \]
For a given jet and particle size, changes in $\sqrt{F}$ were brought about by varying $F$.

**Determination of Wall Losses.**

Wall losses were determined by using the impactor to sample an aerosol of sodium chloride containing the radioactive isotope Na$^{24}$. Two methods of measurement were used. In one, the impactor was prepared for sampling and then its gamma ray background was determined using a 2" x 2" NaI(Tl) crystal. A sample was then collected, after which the impactor was returned to the counter and its gamma ray emission measured again in the same geometry. The collecting cover slips and the filter were then removed, the impactor was reassembled, and counted a third time in the same geometry. The ratio of the difference between the first and third counts to the difference between the first and second counts represented the wall loss.

In the second method, the impactor was washed, dried, and used to collect a sample. Each collecting cover slip, the cover slip holder, and the stage itself, top and bottom, were counted for beta activity using a thin crystal [CsI(Tl)] counter. With the exception of the concave side of the jet stage, all counting was in essentially the same geometry. By counting a plane source at the minimum and maximum distances encountered with the jet stage it was found that the geometry could not affect a counting loss greater than 4 per cent. The wall loss for this method was calculated as the ratio of the beta counts not on collectors to the total beta counts.

**EXPERIMENTAL RESULTS**

Since the design of all jets was aerodynamically similar, the results for all four have been plotted on a single curve in Fig. 3. The value of $\sqrt{F}$ for which $E = 0.5$ appears to be 0.29.

The results of the measurements of wall loss are shown in Table 2. The total sample in micrograms was calculated from the observed activity of the sample and the activity and mass concentrations of the generator solution. The samples marked with an asterisk were taken with the diluting air inadvertently left off. In this case, the aerosol was collected in droplet form, causing unusually heavy deposits. The average deposit...
Fig. 3. Collection Efficiency as a Function of $\sqrt{\psi}$ for the Impactor Jets

\[ \sqrt{\psi} = \left( \frac{\rho D^2 U_0 C}{18 \eta W} \right)^{1/2} \]
thickness in mg/cm$^2$ was calculated by dividing the total deposit by the total cross-sectional area of all the jets.

In Fig. 4, the wall losses are plotted against the logarithm of the deposit thickness in mg/cm$^2$. Although no specific quantitative significance is attached to the straight line drawn through the points, it serves to bring out the existence of a relationship between wall losses and deposit thickness.

The wall losses occurred mainly around the orifices of jets 3 and 4, on the exhaust side, and with heavy deposits were visible as rings about the orifices. Losses to other surfaces amounted to only a fraction of a per cent.

**TABLE 2. Wall Losses for Various Sampling Conditions**

<table>
<thead>
<tr>
<th>Sampler</th>
<th>Flow rate $^3$ cm/min</th>
<th>Total sample, µg</th>
<th>Deposit mg/cm$^2$</th>
<th>Wall losses per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1050</td>
<td>11.8</td>
<td>0.20</td>
<td>2.5</td>
</tr>
<tr>
<td>1</td>
<td>53</td>
<td>0.5</td>
<td>0.06</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>1050</td>
<td>158</td>
<td>2.62</td>
<td>3.5</td>
</tr>
<tr>
<td>1</td>
<td>137</td>
<td>36.8</td>
<td>4.38</td>
<td>6.2</td>
</tr>
<tr>
<td>2</td>
<td>860</td>
<td>2160*</td>
<td>35.9</td>
<td>6.7</td>
</tr>
<tr>
<td>1</td>
<td>137</td>
<td>205*</td>
<td>24.5</td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>860</td>
<td>328</td>
<td>5.44</td>
<td>5.6</td>
</tr>
<tr>
<td>1</td>
<td>53</td>
<td>467*</td>
<td>55.7</td>
<td>9.8</td>
</tr>
<tr>
<td>2</td>
<td>860</td>
<td>28.3</td>
<td>3.37</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**DISCUSSION**

Although the values of S/W for the various jets (see Table 1) differed slightly from the value of 0.375 used by Mitchell and Pilcher $^{10}$, the curve shown in Fig. 3 is almost identical to the one they obtained for an impactor operating at 12 liters/min. Considering the marked difference between the two impactors with respect to physical dimensions and volumetric flow rates, this lends strong support to their statement that if round jets are properly machined with respect to W and S/W values, the calibration for one is adequate for all.

The curve of Fig. 3, of course, is the basis for interpreting sampling
Fig. 4. Wall Loss as a Function of the Deposit Thickness

- Log [Deposit Thickness in mg/cm²] vs. Wall Loss in Percent

○ = Impactor 1
□ = Impactor 2
data taken with the impactor. In the present case, the quantity $\sqrt{\frac{\rho}{C}} D$ is of most interest. For a given jet and flow rate, particles having equal values of $\sqrt{\frac{\rho}{C}} D$ will be collected with equal efficiencies. Such particles will also have equal settling velocities, provided laminar flow prevails. Hence, the quantity $\sqrt{\frac{\rho}{C}} D$ is of particular interest with respect to the deposition of inhaled particles in the respiratory tract. It will be referred to hereafter as the "aerodynamic diameter" of the particle, although the definition of that term has not always included $\sqrt{C}$. In using the impactor to determine the particle size distribution of an exposure aerosol, the cumulative per cent mass up to, and including, a given stage, is plotted against the value of $\sqrt{\frac{\rho}{C}} D$ for which $\sqrt{\gamma}$ for that stage equals 0.29, using logarithmic-probability paper. In this way a mass median aerodynamic diameter is obtained. Fig. 5 shows the values of these effective cut-off aerodynamic diameters for each stage of impactor 1 for values of $F$ between 50 and 150 cm$^3$/min.

Even if wall losses did not occur, the use of the effective cut-off method of interpreting impactor data would introduce errors due to the fact that the efficiency curve is not a true step function. The effect of these errors on the determination of the particle size distribution of an unknown aerosol has been discussed for an impactor having round jets exhibiting an efficiency curve such as that of Ranz and Wong. In the present case, the marked improvement in the efficiency curve reduces the magnitude of the error. The manner in which the mass of a sample from an aerosol having a mass median aerodynamic diameter of 1.0 and a geometric standard deviation of 2.0 would be distributed among the stages of impactor 1, when operated at 150 cm$^3$/min without wall losses, is shown in Fig. 6. The effective cut-off points are indicated. For each stage, the upper hatched area represents the mass assumed to be collected when it is not and the lower hatched area represents the mass assumed to escape when actually it is collected. The magnitude of the errors involved is shown in Table 3. While the total hatched area is in error, only the difference between the upper and lower areas contributes to the error in estimating the particle size distribution.
Fig. 5. Effective Cut-off "Aerodynamic" Diameters for Each Stage as Functions of the Volumetric Flow Rate Through the Impactor.
Fig. 6. Separation of Sample Aerosol in the Impactor
TABLE 3. Sampling Errors in the Use of the Effective Cut-off Method

<table>
<thead>
<tr>
<th>Stage</th>
<th>Cumulative mass fraction collected</th>
<th>Mass fraction in shaded areas</th>
<th>Relative mass error in per cent</th>
<th>Effective error in per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.133</td>
<td>0.0074</td>
<td>5.6</td>
<td>0.86</td>
</tr>
<tr>
<td>2</td>
<td>0.415</td>
<td>0.0162</td>
<td>3.9</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>0.796</td>
<td>0.0165</td>
<td>2.1</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>0.995</td>
<td>0.0029</td>
<td>0.3</td>
<td>0.007</td>
</tr>
</tbody>
</table>

In order for results such as those shown in Table 3 to apply in practice, it is necessary that the impactor be operated under conditions similar to those in effect when the efficiency curve of Fig. 3 was obtained. In particular, the thickness of the deposits in the various stages must be small enough not to alter the S/W values. This limits the deposit on stage 4 of impactor 1 to about 1 mg/cm\(^2\), which effectively restricts the use of that impactor to the sampling of aerosols which can be readily analyzed in small mass quantities, e.g., aerosols of radioactive substances of relatively high specific activity. This restriction becomes less stringent as the jet diameters increase.

The observed wall losses were considerably less than those reported for rectangular jet impactors\(^3,7\). They are comparable to the losses reported by Mitchell and Pilcher\(^10\). The fact that the losses occurred mainly around the third and fourth jets, where the jet-collector separation, S, is very small, suggests that impactors operating at higher volumetric flow rates, and thus having larger values of W and S, might show smaller losses of this type. However, it is not known to what extent higher flow rates might introduce more pronounced wall losses of the conventional type.

SUMMARY

A five-stage cascade impactor comprising four round jets and a filter stage and operating at volumetric flow rates of 50-150 cm\(^3\)/min has been described. The design provided aerodynamically similar conditions at each stage. The ratio of the jet-collector separation, S, to the jet orifice diameter, W, was maintained between 0.37 and 0.39. Abrupt changes in geometry, which could lead to turbulent flow between
jets with consequent high wall losses, were avoided.

The impactor was calibrated in terms of collection efficiency as a function of the root inertial parameter, \( \sqrt{\gamma} \). It was found that the results for all four jets fitted a single curve, which was almost identical to the curve reported by Mitchell and Pilcher\(^{10}\) for aerodynamically similar jets operating at 12 liters/min.

The value of \( \sqrt{\gamma} \) corresponding to a collection efficiency of 0.5 was found to be 0.29. The effective cut-off "aerodynamic" diameters for each stage were calculated for volumetric flow rates between 50 and 150 cm\(^3\)/min. The errors introduced when these diameters are used to determine the distribution parameters of an unknown aerosol have been discussed.

For a range of average deposit thicknesses between 0.06 and 55.7 mg/cm\(^2\), the total wall losses were found to vary between 1.4 and 9.8 per cent. The losses occurred mainly around the orifices of jets 3 and 4, on the exhaust side. The need for keeping sample masses low, effectively limits the use of the impactor to aerosols of materials for which highly sensitive analytical methods are available, e.g., radioactive materials of relatively high specific activity.
REFERENCES


