Indigenous development of an aerodynamic size separator for aerosol size distribution studies

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This article presents the indigenous design and development of the BARC aerodynamic size separator (BASS), which separates aerosol particles into seven size classes ranging from 0.53 to 10 μm based on impaction, and operates at a flow rate of 45 lpm. Unlike most commercially available impactors, BASS can be configured with the desired number of stages up to a maximum of seven. Inter-comparison studies between standard Andersen Mark-II cascade impactors and BASS, have shown consistently good performance by BASS in all respects. BASS has also been tested for its cut-off diameter characteristics and impaction stage response function, which have been found satisfactory. It is expected that this development will open up avenues for making size separators available at a relatively low cost, thereby giving an impetus for their wider use in the field of air pollution and aerosol research.

AEROSOLS are important from the point of view of air-pollution studies, material synthesis, occupational safety in industries and nuclear facilities. Their physical behaviour in outdoor and indoor environments, deposition characteristics in the lung and their technological manoeuvrability in material synthesis depend crucially on their size distributions¹. For this reason, several types of instruments have been built world over for obtaining the particle size distributions. From the point of view of air-pollution studies, it is important to understand the distribution of the various pollutant species with respect to the size of the inhaled particles in order to understand their deposition mechanisms in the lung². The sizes relevant to these studies are usually aerodynamic diameters of the particles. Particle sizes, such as the cascade impactors, based on impaction principle yield information on aerodynamic diameters directly¹. However, the lower limit on the sizes that can be measured using impaction principle is governed by the minimum nozzle sizes that can be machined with good precision. This puts a lower limit on the size at about 0.4 μm which can be extended down to about 0.05 μm by use of low-pressure stages. For particles lower than 0.05 μm, electrostatic classification techniques are generally employed.

Cascade impactors are widely used in air-pollution measurements as they are rugged, easy for field use and are relatively insensitive to the variabilities of the environmental conditions of temperature, pressure and relative humidity. Impactors are also often used in occupational safety in nuclear industry, powder-processing industries and in medical applications⁴.

Increasing concern about air pollution due to increased industrialization and urbanization has necessitated characterization of particulate pollution over wide regions and over long periods of time. This is further accentuated by the now well-recognized role played by aerosols in global warming. As these issues are of considerable concern in the Indian context, several national laboratories and universities in India are engaged in studies pertaining to particulate pollution in the atmosphere. These studies require use of relatively inexpensive impactor systems for particle size determinations and chemical identifications.

Although several types of impactors have been designed and operated over the past few decades, the most widely used commercially available instrument is the Andersen impactor from Andersen Graseby Inc, USA. This is considered a standard instrument and has been widely tested and used in aerosol studies. However, such instruments are relatively expensive, which has been a limiting factor in their wider use in the Indian context. This calls for an indigenous development of a cost-effective, particle-sizing system that would open up avenues of particle size measurements by various agencies and institutions across the country. This article reports the design and development of such a size separator operating at a flow rate of 45 lpm. This impactor, called BARC aerodynamic size separator (BASS), consists of seven impaction stages to collect particles in the size range of 0.53–10 μm. Particles smaller than 0.53 μm are collected in the back-up filter stage placed at the end of the seventh stage. This unit is easy to use and has a few advantages over the existing commercial systems. The optimal sampling time with this unit is highly dependent on the prevalent sizes in the environment to be monitored. However, typically about 4–5 days of sampling would be required in an environment having mass concentrations in the range of 200–300 μg/m³ for analysis by gravimetry. If the samples obtained are to be subjected to chemical characterization, then sampling time is governed by the concentration of the pollutant of interest and the sensitivity of the detection system.

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Description

In a single impaction stage of a cascade impactor, the sampled air stream is passed through a nozzle and directed onto the surface of an impaction plate, oriented perpendicular to the flow of sampled air stream. Aerosol particles having greater momentum than a threshold (determined by the geometrical and flow parameters) are collected on the plate by inertial impaction. Successive stages of the cascade impactor provide progressively higher velocities to the air stream to impart relatively greater momentum to the airborne particles, so as to collect the fractions corresponding to successively smaller particle sizes. The particulate mass deposited on each stage is determined using well-established techniques such as gravimetry or atomic absorption spectrometry (AAS). For associated radioactivity, the deposits are analysed for alpha or beta-gamma activity.

Good understanding of the design basis has been achieved on the subject of impactors since they were first introduced by May. Computer-based analysis for prediction of fluid flow and particle trajectories has enabled the development of design guidelines. These have helped in enabling the impactors to operate according to specific requirements with sharp cut-off characteristics.

Design considerations

An impactor is composed of a nozzle plate bearing N number of nozzles, each of diameter $W$, an impaction plate and a stage wall. Among these, the nozzle plate plays the most important role in determining the particle collection efficiency. Impactors that have a 'sharp cut-off' collection efficiency curve approach the ideal step-function in which all particles greater than a certain aerodynamic size are collected and all particles less than that size pass through. This size is called the cut-off diameter of the stage. The response of an impactor is characterized by the dimensionless parameter, the Stokes number $Stk$, defined as:

$$Stk = \frac{\rho_p VCD_p^2}{9\mu W},$$

where $\rho_p$ is the density of particles, $V$ the flow velocity through the nozzle, $D_p$ the diameter of particles, $\mu$ the dynamic viscosity of the fluid medium, $W$ the nozzle diameter and the Cunningham slip correction factor $C$, given by the following expression:

$$C = 1 + \frac{0.163}{PD_p} + \frac{0.05499}{PD_p} \exp(-6.66PD_p),$$

where $P$ is the absolute atmospheric pressure (atm) upstream of the nozzle and $D_p$ is specified in units of $\mu$m. The quantity of interest while designing an impactor is the $Stk_{50}$ which is the Stokes number that gives 50% collection efficiency. This is equivalent to assuming that the mass of particles larger than the cut-off size that get through equals that of the particles below the cut-off size that are collected. For a specified value of $Stk_{50}$, the constraint equations relating the flow rate $Q$, the jet Reynolds number $Re_j$ and the corresponding aerodynamic cut-off diameter $D_{p,50}$ are:

$$D_{p,50} = \frac{9\mu W}{\rho_p CV \sqrt{Stk_{50}}},$$

$$Q = \frac{\pi}{4} W^2 VN,$$

$$Re_j = \frac{\rho_a VW}{\mu},$$

where $N$ is the number of nozzles on the stage, $\mu$ the dynamic viscosity of the fluid medium and $\rho_a$ the density of the fluid medium.

From eqs (3)–(5), a size separator may be designed by appropriately computing the three unknowns, namely $W$, $V$ and $N$ for a specified set of $Re_j$, $D_{50}$ and $Q$. In the present case, the flow rate of the impactor was chosen to be 45 lpm. This is higher than that of the Andersen Mark II impactor (28 lpm). The higher flow rate will considerably reduce the sampling time required for an optimal sample. Further design specifications are achieved by optimizing the following parameters.

Stokes number

The standard value for $Stk_{50}$ calculated for a circular jet impactor is 0.25, while that for a rectangular jet is 0.59. As it is more convenient to make circular nozzles with precision, it was decided to develop the impactor with circular jets and hence all further design parameters were estimated using the value of 0.25 for $Stk_{50}$.

Cut-off diameter of impaction stages

The designed cut-off sizes were chosen to be in the range of particle sizes normally encountered in atmospheric and workplace environments. The lower limit of the designed particle size is constrained by the practical limitation of having a small-diameter nozzle operating at a high velocity. Conveniently machinable nozzles limit the range of the cut-off diameters between 0.5 and 10 $\mu$m. This range was suitably divided into seven stages and fairly evenly spaced cut-off diameters were chosen as 0.53, 0.98, 2.5, 3.5, 5.8, 7.7 and 10.0 $\mu$m.

Jet Reynolds number

The operation of the real impactor is complicated by viscous boundary layer effects due to the use of a jet of a finite
size. For a given flow rate, the jet velocity is quite uniform everywhere in the nozzle and across the exit plane of the jet, except in the region of the boundary near the wall\textsuperscript{11}. The thickness of this boundary layer is governed by the flow Reynolds number. As the Reynolds number is reduced, the boundary layer becomes thicker thus reducing the steepness of the collection efficiency curve and this results in poor cut-off characteristics. On the other hand, when the Reynolds number increases beyond 3000, the velocity profile at the jet exit is not greatly affected, but the efficiency curve is shifted to smaller Stokes number, due to reduced boundary layer thickness along the impaction plate. Related studies\textsuperscript{12} show that sharp cut-off characteristics can be obtained for the Reynolds number between 500 and 3000. The stage parameters were designed so as to limit the flow Reynolds number in the range 500–2000.

**Particle Reynolds number**

The impaction theory is valid only for particles in the Stokesian region and this sets a limit on the particle Reynolds number. As the jet velocity increases, the drag force on the particle which is related to the particle Reynolds number ($Re_p$) also increases as it attempts to leave the bending airstream to impact. As the drag force increases significantly, particles no longer behave in a manner predicted by Stokes law. This limits the value of $Re_p$ below about 3 so that the motion is in the Stokesian region\textsuperscript{13}.

**Geometrical parameters**

The collection efficiency of an impactor is dependent on its geometrical parameters such as the nozzle and collection plate inter-distance ($S$), the diameter of the nozzle ($W$) and the throat length ($T$). Several studies\textsuperscript{8,12} have shown that the $Stk_{50}$ value is sensitive to the $S/W$ ratio. For $S/W$ ratio lying between 1 and 5, the designed value of 0.49 for $Stk_{50}$ is achieved. The throat length of the nozzle does not greatly influence the cut-off characteristics of the impactor, although very long throat length, several times the nozzle diameter, should be avoided because the formation of the parabolic flow profile within the nozzle affects the collection efficiency. Detailed studies in the literature\textsuperscript{8,12} reveal that for sharp collection characteristics of an impactor, $T/W$ ratio in the range 1–2 is suitable.

**Cross-flow parameter**

The cross-flow parameter allows the prediction of jet deflection created by cross flow. This parameter is expressed as a function of geometric parameters of the multi nozzle impactor, and is given by $W/N/4D_c$, where $D_c$ is the nozzle cluster diameter. It is found that multi-nozzle impactors work satisfactorily, if the cross flow parameter is less than a critical value of 1.2.

The physical design parameters and the flow parameters of BASS to be operated at a flow rate of 45 lpm arrived at on the basis of the above design considerations are given in Tables 1 and 2. Figure 1a and b shows the schematic diagram and the photograph of the fully assembled unit respectively. Finer design details of the BASS are published elsewhere\textsuperscript{14}.

In addition to the above parameters, the inlet of the jet is tapered to minimize the formation of vena contracta\textsuperscript{15,17}. Also, the mechanical loading of the assembly is made simple by using stud-wing nut arrangement. An important feature of this seven-stage impactor assembly is that it can be operated with even lesser number of stages, if desired. This is particularly an advantage for carrying out studies on stage-wise response functions and determining the steepness parameter of the impactor.

**Performance evaluation: Theoretical methodology**

The most accurate method of evaluating the performance of the impactor involves generation of the response function curves for each stage as a function of Stokes number (or aerodynamic diameter). Monodisperse particles are generally used for such an evaluation. It is then tested for an integral response to a polydisperse aerosol of known size distribution\textsuperscript{18}. Generation of the response curves includes obtaining the $D_{50}$ as well as the steepness parameter. The steepness parameter of an impactor is a measure of the deviation of the response function from the ideal step function. The following section discusses the methodology

<table>
<thead>
<tr>
<th>Stage no.</th>
<th>$D_{50}$ (μm)</th>
<th>No. of nozzles $N$</th>
<th>Diameter of nozzles $D$ (mm)</th>
<th>$T/D$</th>
<th>$S/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.00</td>
<td>30</td>
<td>4.20</td>
<td>1.07</td>
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<td>7.70</td>
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<td>5</td>
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<td>90</td>
<td>1.15</td>
<td>1.30</td>
<td>3.69</td>
</tr>
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<td>0.60</td>
<td>1.66</td>
<td>6.20</td>
</tr>
<tr>
<td>7</td>
<td>0.53</td>
<td>100</td>
<td>0.40</td>
<td>1.75</td>
<td>4.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage no.</th>
<th>Stokes no. $S_h$</th>
<th>Jet velocity $V$ (cm/s)</th>
<th>Jet Reynolds no. $Re_j$</th>
<th>Particle Reynolds no. $Re_p$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.26296</td>
<td>179.3</td>
<td>503</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>0.26296</td>
<td>257.6</td>
<td>522</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>0.26296</td>
<td>333.5</td>
<td>486</td>
<td>1.2</td>
</tr>
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<td>4</td>
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<td>523.0</td>
<td>526</td>
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<td>5</td>
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<td>761.0</td>
<td>598</td>
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<td>6</td>
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<td>7</td>
<td>0.2577</td>
<td>5769.0</td>
<td>1561</td>
<td>2.1</td>
</tr>
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</table>

Using the values $\mu = 1.81 \times 10^{-4}$ g/cm/s, $\rho = 1.205 \times 10^{-1}$ g/cm$^3$, $\rho = 1$ g/cm$^3$.
used to determine the $D_{p,50}$ values and the steepness parameter using polydisperse test aerosols, characterized by the size distribution parameters, namely, the mass median aerodynamic diameter (MMAD) and the geometric standard deviation ($\sigma_g$).

**Estimation of stage cut-off diameter $D_{p,50}$**

Let $M$ be the total mass collected by the impactor in all the stages, i.e.

$$M = \sum_{i=1}^{n} m_i,$$

where $m_i$ denotes the mass collected on the $i$th stage and $n$ denotes the total number of stages ($i = 1$ corresponds to the top stage and $i = n$ corresponds to the back-up filter placed below the last stage of the impactor, which collects all the particles leaving the impactor). The fractional cumulative mass $M_k$ collected on all the stages lying above and inclusive of $k$th stage is

$$M_k = \frac{\sum_{i=k}^{n} m_i}{M}.$$  

(7)

Note that $M_n = 1$.

Assuming a log-normal distribution for the test aerosols, the fractional mass present in a given size range, $d$ to $d + \delta d$ is given by,

$$m(d)\delta d = \frac{1}{\sqrt{2\pi} s} \exp \left[\frac{-\ln(d/\text{MMAD})^2}{2s^2}\right] \delta d,$$  

(8)

where $s = \ln(\sigma_g)$, where $\sigma_g$ is the geometric standard deviation.

Assuming a step response, let $D_{p,50}$ for the $k$th stage be denoted by $D_k$. Then all particles above size $D_k$ will be collected in the stages between $i = 1$ to $k$. The cumulative mass fraction obtained up to the $k$th stage will correspond to the measured mass $M_k$, as given in eq. (7). For the given distribution in eq. (8), this mass $M_k$ may be related to the stage cut-off diameter ($D_k$) by integrating eq. (8) between $D_k$ and $\infty$ as given below:

$$M_k = \int_{D_k}^{\infty} \frac{1}{\sqrt{2\pi} s} \exp \left[\frac{-(\ln(d/\text{MMAD})^2)}{2s^2}\right] \frac{1}{d} \delta d.$$

(9)

Equation (9) may be expressed in terms of the standard error function

$$M_k = \frac{1}{2} - \frac{1}{2} \text{Erf} \left[\frac{1}{\sqrt{2} s} \ln \left(\frac{D_k}{\text{MMAD}}\right)\right].$$

(10)

A theoretical plot of $M_k$ vs $D_k$ generated using eq. (10) can be used for estimating $D_k$ for a particular value of $M_k$ for the $k$th stage.

**Estimation of steepness parameter**

For an ideal impactor, the collection efficiency should be a step function, wherein for any given stage of cut-off diameter $D_{p,50}$, the efficiency for collection of the particles is 100% for sizes greater than the specified cut-off and zero for sizes less than the specified cut-off. In real cases, the collection efficiency curve deviates from the step function
and is more of a sigmoid shape$^{19}$, represented by the formula

$$E_i = \frac{1}{1 + \left(\frac{D_i}{d}\right)^{s_i}},$$

where $E_i$ is the collection efficiency of the $i$th stage, having the cut-off ($D_i$) and steepness $s_i$. The shape of collection efficiency function can thus be obtained, and the steepness of this curve is indicative of the deviation of the impactor from ideal behaviour. This parameter can be assessed using the following technique. Configure the impactor using only two stages in such a way that if the steepness parameter for stage $i$ is to be determined, stage $i-1$ (with the next higher cut-off than $i$) is placed below stage $i$. This is in contrast to the normal configuration of the impactor, wherein stage $i-1$ is placed above stage $i$. Assuming a log-normal distribution for aerosols, we use a response function having the form$^{20}$

$$T_i = \frac{1}{1 + \left(\frac{d}{D_i}\right)^{\eta_i}},$$  \hspace{1cm} (11)

where $T_i$ denotes the transmission from the $i$th stage, $D_i$ is the $D_{50,50}$ for the $i$th stage, $d \ (0 < d < \infty)$ is the particle diameter of the test aerosols and $\eta_i$ is the steepness parameter of the $i$th stage. Let the total mass input to the impactor be

$$M_0 = \int_0^\infty m(d)\delta d = 1.$$  \hspace{1cm} (12)

The total mass collected on stage $i$ is

$$m_i = \int_0^\infty m(d)[1-T_i(d)]\delta d,$$  \hspace{1cm} (13)

and the total mass collected on stage $i-1$ placed below stage $i$ ($D_{i-1} > D_i$) will be

$$m_{i-1} = \int_0^\infty m(d)T_i(d)[1-T_{i-1}(d)]\delta d.$$  \hspace{1cm} (14)

From eqs (11)–(13), the fractional masses $f_i$ and $f_{i-1}$ collected on the stages $i$ and $i-1$ respectively, can be given as:

$$f_i = \int_0^\infty m(d)\left[1 - \left(1 + \left(\frac{d}{D_i}\right)^{\eta_i}\right)^{-1}\right]\delta d,$$  \hspace{1cm} (15)

$$f_{i-1} = \int_0^\infty m(d)\left[\frac{1}{1 + \left(\frac{d}{D_i}\right)^{\eta_i}}\right]\delta d.$$  \hspace{1cm} (16)

A comparison of the theoretically computed fractional masses using eqs (15) and (16) with the experimentally observed values, will yield the steepness parameter for stage $i$.

**Performance evaluation: Experimental methodology**

Initially, the size separator was assembled and tested for air leaks through the gaskets at different stages by comparing the flow rates at the inlet and the outlet ends through variation of the flow rate in the range from 5 to 100 lpm. The flow rates measured at both the ends were observed to be closely identical, thus ensuring leak tightness besides the adequacy of the gaskets and the tightening arrangements. Also, the total pressure drop at the end of the seventh stage was measured to be about 2 cm (Hg) at 45 lpm, which is less than 5% of the atmospheric pressure as required for validity of the design.

The integral performance of the BASS unit was evaluated by comparing the mass distribution of aerosols obtained with this unit and that obtained using the standard Andersen Mark-II impactor. This eight-stage impactor, manufactured by Graseby Andersen Inc., operates at a flow rate of 28.3 lpm and has stage cut-off diameters at 0.4, 0.7, 1.1, 2.2, 3.3, 4.8, 5.7 and 9.0 μm. For the evaluation of the impactor, deposited masses were collected on glass fibre filter paper substrates, as they are known to have minimal bounce-off losses and are amenable to chemical analysis. The standard procedure of evaluation involves use of monodisperse particles across a wide range of sizes, which may not always be feasible. Hence, alternative techniques using polydisperse aerosols were conceived for obtaining the cut-off diameters at each stage. For this, two types of measurements were carried out to assess the following:

(i) Radioactivity-size distribution of large-sized aerosols of magnesium fluoride (MgF$_2$) contaminated with uranium, which are generated during uranium slag treatment process and

(ii) Mass-size distribution of sodium chloride aerosols generated in the laboratory from a compressed air nebulizer.

Field measurements to assess the activity size distributions were carried out using aerosols of MgF$_2$ formed during the crushing and grinding of the MgF$_2$ slag. These were carried out by keeping the indigenous (BASS) and Andersen Mark–II cascade impactors close to each other,
and sampling the air simultaneously with the two impactors at their respective flow rates for a period of 30 min, as shown in Figure 2. The substrates on each stage of the impactors were counted for alpha activity due to uranium using ZnS(Ag) scintillation detector following standard radioactivity counting procedures and protocols.

To assess the mass-size distribution, several laboratory experiments were performed with polydisperse sodium chloride aerosols generated using the BARC nebulizer\(^1\), in which particle size distribution was varied by changing the concentration of the nebulising solution. Aerosols thus generated were fed to a 201 mixing chamber, having arrangements for drying, sampling and venting. Samples were taken from the mixing chamber simultaneously with the indigenous (BASS) and the standard impactor for the same aerosols. The deposited mass on each of the filter paper substrates was dissolved in distilled water and the ionic conductivity of the solution was measured using a conductivity meter. The concentration of NaCl particles in this solution was inferred from the measured conductivity by a proper calibration exercise.

For assessment of the steepness parameter, the impactor was configured with two successive stages mounted in a reverse order and exposed to nebulizer-generated NaCl aerosols. For example, to find the steepness parameter of stage 5, stage 4 was placed below it and the fractional masses collected on the two stages and the back-up filter were determined by measuring conductivity of the NaCl solution obtained by dissolving the substrates. Using eqs (15) and (16), the theoretical mass fractions were obtained for \(2 < s < 8\). The value of \(s\) for which the agreement between the theoretical mass fractions and the experimentally observed mass fractions is close, is assumed to be the steepness parameter of that stage.

The sharpness of the collection efficiency curve \(\sigma\), is estimated from the plot of the collection efficiency curves using

\[
\sigma = \frac{d_{85.1}}{d_{15.9}}
\]

where \(d_{85.1}\) and \(d_{15.9}\) are the sizes of particles having collection efficiencies of 84.1 and 15.9\% respectively\(^2\).

### Results and discussion

#### Studies with MgF\(_2\) aerosols

The data on stage-wise counts obtained by radioactivity counting of each stage were fitted to a log-normal distribution. The distribution parameters, namely, the activity median aerodynamic diameter (AMAD) and \(\sigma_g\) were evaluated from this. A set of four experiments was carried out and the results are given in Table 3. The AMADs as well as the \(\sigma_g\)s estimated using BASS agree closely with those obtained with the standard Andersen impactor. The variation in the AMADs as recorded by the two units was in the range of ± 8%.

#### Studies with sodium chloride aerosols

The mass concentrations obtained by both the impactors, inferred from the conductivity measurements of the deposits, were fitted to log-normal distribution to obtain the parameters of the size distribution, viz. MMAD and \(\sigma_g\). The results obtained are given in Table 4. It can be inferred that the overall agreement between the values obtained for the two impactors is good.

#### Estimation of stage cut-off diameters

As an illustration of estimating the stage cut-off diameters, a typical size distribution having the parameters MMAD = 2.09 \(\mu m\) and \(\sigma_g = 2.62\), obtained using aerosols of 20% NaCl solution was chosen. A theoretical log-normal plot was generated for this size distribution. From this plot, the cut-off diameters corresponding to the experimentally

### Table 3. Performance evaluation of BASS using radioactive aerosols

<table>
<thead>
<tr>
<th>AMAD ((\mu m))</th>
<th>(\sigma_g)</th>
<th>AMAD ((\mu m))</th>
<th>(\sigma_g)</th>
<th>Percentage variation in AMAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>2.2</td>
<td>9.2</td>
<td>2.1</td>
<td>7.6</td>
</tr>
<tr>
<td>7.6</td>
<td>2.0</td>
<td>8.0</td>
<td>2.0</td>
<td>5.0</td>
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<tr>
<td>7.8</td>
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<td>7.4</td>
<td>1.8</td>
<td>5.0</td>
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<td>7.2</td>
<td>2.2</td>
<td>7.4</td>
<td>2.0</td>
<td>2.7</td>
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</table>

### Table 4. Size distribution parameters obtained for different concentrations of NaCl solution

<table>
<thead>
<tr>
<th>Concentration of solution (%)</th>
<th>BASS MMAD ((\mu m))</th>
<th>(\sigma_g)</th>
<th>Andersen Mark-II impactor MMAD ((\mu m))</th>
<th>(\sigma_g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.80</td>
<td>2.56</td>
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<td>1.60</td>
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Table 5. Designed stage cut-off and estimated stage cut-off of BASS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed cut-off (μm)</td>
<td>0.53</td>
<td>0.98</td>
<td>2.5</td>
<td>3.5</td>
<td>5.8</td>
<td>7.7</td>
<td>10</td>
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<tr>
<td>Estimated cut-off (μm)</td>
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<td>1.03</td>
<td>2.94</td>
<td>4.14</td>
<td>6.09</td>
<td>7.91</td>
<td>8.95</td>
</tr>
<tr>
<td>Steepness parameter, s</td>
<td>2.0</td>
<td>2.8</td>
<td>5.3</td>
<td>7</td>
<td>4.8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sharpness of collection efficiency curve, σ</td>
<td>2.23</td>
<td>1.8</td>
<td>1.36</td>
<td>1.27</td>
<td>1.4</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 3. Log probability plots of NaCl (a, solute concentration 2.5% and b, solute concentration 10%) particle size distribution with designed (○) and experimentally determined (•) stage cut-off diameters using BASS.

Figure 4. Estimated collection efficiency curves for different stages of BASS.

observed mass fractions for each stage were estimated. These are compared with the designed values of the cut-off diameters in Table 5. It can be inferred from Table 5 that the experimentally measured cut-off diameters are quite close to the designed cut-offs (within 3–18%).

Figure 3 a and b shows the log-normal plots for size distributions obtained for nebulizer-generated NaCl aerosols at two different solution concentrations, viz. 2.5 and 10% respectively. In Figure 3, cumulative mass fractions have been plotted against experimentally estimated cut-off diameters and against designed cut-off values. As may be seen, the linearity of the plots is better with experimentally estimated cut-off diameters. Hence, it may be concluded that the characteristic cut-off diameters for BASS may be taken as experimentally determined cut-off diameters.

Estimation of steepness parameter

The estimated steepness parameters of different stages using the methodology described in the previous section are given in Table 5. The collection efficiency, $E_i (= 1 - T_i)$ of different stages is estimated using the derived steepness parameter and is plotted in Figure 4. The sharpness of the collection efficiency curves, $σ$, for different stages estimated using eq. (17) is also given in Table 5.

As seen from Table 5, the sharpness of the collection efficiency curves varies from 2.23 to 1.27. The last stage, having the finest nozzle diameter, shows a higher value of $σ$, which is indicative of a slightly poor response compared to the other stages. The values of $σ$ obtained for BASS
are comparable to those reported by Demokritou et al., wherein a higher value of \( \sigma \) has been reported for stages 7 and 8 (having fine nozzle sizes). This may be attributed to nozzle irregularities, mainly the extent of smoothness of its inner surface. This may be corrected for by improving the machining quality of the nozzles. However, this higher value for the sharpness of the collection efficiency curve has no significant bearing on the estimated size distributions for polydisperse aerosols. The steepness parameters have not been evaluated for the stages 1 and 2 in the present study as the mass loads collected on these stages were insignificant for a reliable analysis. This was due to the fact that the cut-off diameters for these stages are above 7 \( \mu \text{m} \), while the test particles used were in the range of 1–3 \( \mu \text{m} \). This analysis may be carried out by using test aerosols of sizes close to the cut-off diameters of these stages.

**Conclusion**

An indigenous BARC aerodynamic size separator has been designed and developed for particle size distribution measurements. Its performance has been evaluated vis-à-vis the standard Andersen Mark II impactor. The new unit differs from the latter in terms of several design parameters such as stage-cut off diameters, flow rate and stage assembling arrangement. The last aspect permits operation of the cascade impactor with any number of stages up to a maximum of seven. Performance evaluation shows that BASS reproduces quite accurately, the aerosol distribution parameters as obtained by the standard impactor. Experiments carried out indicated that the designed values of the cut-off diameters deviated slightly from experimentally determined values. In view of this, the stage cut-off diameters are re-specified from the latter values. Since BASS has a higher sampling rate, it can collect higher quantity of the sample and hence is better suited to both environmental and laboratory aerosol distribution studies, even when aerosol concentrations are low. In view of the cost-effectiveness and configuring advantages of the present impactor, it may be suitable for wider applications in pollution studies.


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