Passive Sampler Used for Simultaneous Measurement of Breathing Zone Size Distribution, Inhalable Dust Concentration and Other Size Fractions Involving Large Particles

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Received 26 March 2001; in final form 13 August 2001

The particle size-dependent sampling velocity of the passive dust sampler developed by Vinzents (1996) is investigated under field conditions. Microscopical determination of the projected area equivalent diameter is used to quantify particles deposited on the sampler foils. Parameters for a semi-empirical model for particle deposition velocities on upward and forward facing foils are fitted to the data and it is shown that deposition mechanisms other than gravitational settling on the upward facing foil can be neglected. For calculation of airborne mass concentration no information on particle density is needed and only the ratio between the dynamic and volume shape factors needs to be known. Given the sampling velocity, the airborne mass per diameter interval is calculated from samples obtained in the wood industry, from which inhalable dust concentrations are calculated. The results are in line with parallel samples obtained with an inhalable dust sampler. A ‘total’ dust sampling characteristic can be fitted which reproduces measured ‘total’ dust with a closed face monitor. The results of this study demonstrate the validity of the passive dust sampling principle in environments involving even large (>100 µm) particles and the potential to predict the concentration of several size fractions.

Keywords: personal passive dust sampler; size distribution; sampling efficiency; inhalable dust; total dust

INTRODUCTION

Passive personal samplers for airborne contaminants offer many advantages over active samplers. They have no moving parts, are robust, simple, lightweight and noiseless. They are particularly suited to large-scale exposure studies since they are simple to distribute and collect and can be deployed in large numbers due to low capital costs. Even if a given passive sampler does not equal an active sampler in accuracy and precision, the possibility of taking a larger number of samples at the same total cost can increase the power to detect associations between exposure and health outcomes (Armstrong, 1996). While many passive samplers are available for gases and vapours, only three passive dust samplers appear to have been described (Brown et al., 1995; Vinzents, 1996; Wagner and Leith, 2001a).

In the present study the properties of the passive sampler developed by Vinzents (1996) are further explored. This sampler collects particles deposited on sticky, transparent foils mounted at right angles (facing up, forward and down) (Fig. 1). The collected particles are quantified by their total projected area. The projector area is measured as the increase in extinction of an expanded laser beam passing through the dust-covered part of the foil. The sampler has been calibrated in a series of wind tunnel tests to determine the diameter-dependent sampling velocities on the three foils.

For personal sampling the sampler is mounted on the chest and thus the upward facing foil is oriented approximately horizontal and the forward approximately vertical. A calibration function has been developed by which the measured area percentages on the foils facing up, forward and down and a field...
blank are combined to give what will be termed the equivalent inhalable mass concentration. This calibration function has been developed from parallel samples taken with the IOM inhalable dust filter cassette (e.g. Vincent, 1989) and includes measurements in the wood industry (Schlünssen et al., 2001).

The present paper further explores the sampling characteristics of the passive sampler, in particular for large (>100 µm) particles, and the feasibility of calculating the inhalable and other size fraction mass concentrations from microscopical analysis of the projected area equivalent diameter of particles deposited on the sampler foil facing upward.

MATERIALS AND METHODS

As part of a study of exposure to dust in the wood industry, equivalent inhalable dust concentrations were measured using a passive dust sampler (Schlünssen et al., 2001). Parallel samples were taken with an IOM inhalable dust sampler and with a closed face filter cassette for 'total' dust. This was a 37 mm diameter cassette with an entry hole diameter of 5.6 mm and entry velocity of 1.25 m/s. Foils facing forward and upward that were suitable for optical microscopy analysis using automatic image analysis were selected for the present study. When selecting samples for image processing two problems had to be considered. If the dust concentration on the filter was very low automatic focusing under the microscope did not work, as there would be images without any particles to focus on. On the other hand, if the dust concentration was very high there would be too much particle–particle overlap, thereby distorting the size distribution. Based on a number of tests it was found that the total projected particle area on the foils had to be in the range 1.0–25% of the total area in order to perform a reliable analysis. This resulted in a total of 27 sets with parallel samples. These sets did not include all types of samples and subsets had to be formed for certain combinations. The resulting number is given in the results.

The microscope was an Olympus Vanox-T (Olympus Optical Co., Japan) equipped with a 10× S-plan lens, a motorized stage and focusing controlled by the software. A Optronics TEC-470 CCD camera (Optronics Engineering, Goleta, USA) was used and the image analysis software was KS 400 rel. 2 (Carl Zeiss, Germany). A description of the method can be found elsewhere (Kildesø and Nielsen, 1997). For each foil, 64 fields of view were counted. In total ~65000 particles were counted and sized. They were grouped into size bins with diameter boundaries that followed a geometric progression with a factor of 1.2.

All foils were exposed for approximately the same duration and the same number of fields (64) were counted. One meta sample of all foils facing forward and one for all samples facing upward was thus formed by simple addition of the counts.
THEORY

The determination of airborne mass concentration from the projected area diameter of deposited particles involves the following key steps.

Correction for edge effects in image analysis

The projected area diameter \( D_p \) was determined by optical microscopy. The counting field used for image analysis was rectangular with height 871 µm and width 869 µm. Particles crossing the upper and right edge were not included. Particles crossing the left and lower edge were included. Some of these particles will extend beyond the active screen area. Therefore, an active area is defined by a line 180 µm to the left and a line 93 µm below the left and bottom edge of the counting field. The image analysis program determines only the area of that part of a countable particle that is within the active area. This introduces an underestimation of the area of very large particles and the software did not identify which particles crossed the active area. A correction procedure was developed using a simulation program written in Mathcad (MathSoft Inc., 2000). In principle, the program did the following. First, all particles sized were pooled to give a population of \( \sim 65000 \) particles. They were assumed to be circular with a diameter equal to the particle area equivalent diameter. Secondly, a random particle was sampled from the population and dropped at random on that part of the area to make them countable, i.e. no crossing of the upper or right border of the field of view. Thirdly, for each particle the area was determined. The procedure treated crossing the lower and left border of the active area as independent events for simplicity, thereby neglecting that particles could cross both the lower and left border.

A total of 500000 particles were sampled (sampling with replacement from the population of 65000 particles) and dropped and sorted into the same size bins (number in size bin \( i \) is \( S_i \)) as the original population (number in size bin \( i \) is \( O_i \)). \( O_i \) is thus the seed distribution and \( S_i \) the first iteration of the true size distribution. Then, for size bin \( i \) the correction factor was estimated as \( O_i/S_i \). The correction factors are only valid for that particular particle population or, rather, size distribution.

**Determination of volume equivalent diameter**

The volume equivalent diameter \( D_v \) is obtained from \( D_p \) assuming a constant relation

\[
D_v = \kappa D_p
\]  

where \( \kappa \) is a volume shape factor including the effect of preferred orientation of particles on the foil. Wagner and Leith (2001a) have listed values of \( \kappa \) for several common dusts, which were in the range 1.2–1.6. The mid-point value of \( \kappa = 1.4 \) was selected for the present study.

**Sampling velocity**

The aerodynamic diameter \( D_{ae} \) is calculated from the volume equivalent diameter as

\[
D_{ae} = \sqrt{\frac{\rho_p \text{Cun}(D_v)}{\mu \text{Cun}(D_{ae})}} D_v
\]

where \( \rho_p \) and \( \rho_0 \) are the particle and unit densities, \( \chi \) is the dynamic shape factor and \( \text{Cun}(D) \) is Cunningham's slip correction. Wagner and Leith (2001a) have listed values of \( \chi \) in the range 1.05–2.04. The mid-point value of \( \chi = 1.5 \) was selected for the present study. For wood, a representative value \( \rho_p = 0.7 \) (CRC Press, 1981) was chosen. The gravitational settling velocity \( v_{sed} \) is given by

\[
v_{sed} = \frac{g \rho_0 \text{Cun}(D_{ae}) D_v^2}{18 \mu}
\]

where \( g \) is the gravity constant and \( \mu \) is the dynamic viscosity of air.

Equations (2) and (3) hold only for drag following Stokes law. Gravitational settling of particles exceeding 50 µm occurs in an ultra-Stokesian regime and the approximation of drag used by Brockmann and Rader (1990) was used to calculate the settling velocity \( v_{sed} \) for non-spherical particles extending into the ultra-Stokes region (see Appendix).

The airborne particle concentration \( C \) by number is calculated in two ways. The first, the *simple method*, applies only to the upward facing foil, assuming that it was horizontal and that the deposition velocity equals the gravitational settling velocity \( v_{sed} \)

\[
C = J/v_{sed}
\]

where \( J \) is the particle flux to the upward facing foil.

The airborne mass concentration in size bin \( i \) (\( M_i \)) was calculated from the number in size bin \( i \) (\( C_i \)) as

\[
M_i = \frac{\pi}{6} \rho_p D_{ae,i}^3 C_i
\]

where \( D_{ae,i} \) is the class mid-point volume equivalent diameter. By combining equations (1)–(5):

\[
M_i = \frac{3 \pi}{g} \frac{\mu \chi}{\kappa \text{Cun}(D_{ae,i})} D_p, i J_i
\]

Equation (6) shows that to the approximation to which equations (1)–(5) hold, information on particle density is not needed and that only the ratio of the dynamic to volume shape factors needs to be known, neglecting the (small) effect of variation in Cunningham’s correction. There will be covariance...
between \( \chi \) and \( \kappa \), which will reduce the range of the ratio. Thus, measurement of projected area diameter and flux of particles to an upward facing foil has the potential to predict the airborne mass concentration without a knowledge of particle density and with only a general knowledge of particle shape.

The second method, the extended method, includes the combined Brownian and turbulent diffusion velocity \( (v_{\text{diff}}) \) in the total deposition velocity \( (v_{\text{dep}}) \) (Sehmel, 1970; Schneider et al., 1994):

\[
v_{\text{dep}} = \frac{v_{\text{sed}} \cos \theta}{1 - \exp\left(\frac{-v_{\text{sed}} \cos \theta}{v_{\text{diff}}} \right)} \quad (7)
\]

where \( \theta \) is the angle between the direction of gravity and normal to the surface. During sampling, the passive sampler is not always in a horizontal/vertical position and \( v_{\text{dep}} \) has to be averaged over an interval assumed to be symmetrical, i.e. \( \theta \in [-\Theta, \Theta] \). A uniform distribution of values in this interval will be assumed.

There are several approaches to calculating \( v_{\text{diff}} \). In the original documentation of the passive sampler (Vincent, 1996), a semi-empirical model for sampling velocity was fitted to data obtained in a wind tunnel, using a model developed by Schneider et al. (1994), to which the reader is referred for details (see also Appendix). In this model, particles were assumed to be transported towards the surface by gravity, turbulent diffusion and Brownian diffusion. When they have reached within one stopping distance (+ one particle radius) of the surface they are assumed to escape from turbulent eddies and continue in free flight to the surface. The stopping distance \( (\sigma) \) is determined by the friction velocity \( (u^*) \) and particle relaxation time \( (\tau) \) using a relation given by Sehmel (1970):

\[
\frac{u^* \sigma}{\nu} = 1.49 \left( \frac{\left( \frac{u^*}{\nu} \right)^2 \tau}{\nu} \right)^{1/2} \quad (8)
\]

where \( \nu \) is the kinematic viscosity of air and \( s = 0.51 \).

It was assumed that equation (8) would hold for any particle size.

There are only two parameters in the model, the friction velocity \( (u^*) \) and \( \kappa \). The parameter \( \kappa \) characterizes turbulent diffusion as a function of distance from the surface (see Appendix). The value \( \kappa = 0.0034 \left( \frac{u^*}{\nu} \right)^2 \) determined by fitting expressions like equation (7) to wind tunnel data (Vincent, 1996), was used in the present model.

There was no a priori information on \( \Theta \) or \( u^* \). Thus, they had to be determined by a fitting procedure. This was done by first calculating the airborne number distribution, \( C_i^{ae} \), from the upward and \( C_f \) from the forward facing foil, using the orientation averaged deposition velocities. Then \( \sum (C_i^{ae} - C_f) \) was minimized by varying \( u^* \) and \( \Theta \).

It turned out that this model (equations 7 and 8) could not collapse \( C_i^{ae} \) and \( C_f \). Thus, \( s \) (equation 8) was gradually increased and an excellent fit (Fig. 2) was obtained when \( s = 1.0 \). Thus, this value was used in the final model. The forward facing foil data were only used to determine the model parameters. Only upward facing foil data were used to calculate the airborne concentration.

Having determined the deposition velocity \( v_{\text{dep}} \), the airborne mass in each size bin could then be calculated. A (non-normalized) log-normal distribution was fitted to the mass-weighted size distribution.

Using the same procedure, and with the fitted values of \( \Theta \) and \( u^* \), the inhalable (European Committee for Standardization, 1993) mass concentration was calculated for each of the 25 individual samples. In the following this will be termed the calculated inhalable dust concentration to distinguish it from the equivalent inhalable dust concentration as determined by the calibration function given by Schlünsen et al. (2001). The geometric mean and standard deviation of the mass-weighted volume equivalent diameter distribution for the fitted log-normal distribution were also calculated.

In order to calculate a ‘total’ mass concentration a curve was fitted to the sampling efficiency \( (E_{\text{tot}}) \) of the closed face 37 mm sampling cassette placed on a manikin as determined by Kenny et al. (1999). A simple curve with only two parameters, \( \alpha \) and \( \beta \), and having the same shape as the inhalable convention was used for fitting:

\[
E_{\text{tot}} = \frac{\exp(-D_{ae}/\beta)}{\alpha} \quad D_{ae} \leq -\beta \ln(\alpha) \quad D_{ae} \geq -\beta \ln(\alpha) \quad (9)
\]

The fitting criteria was that the geometric mean of the ratio of measured to calculated ‘total’ mass should equal 1 and that the resulting efficiency curve should be a reasonable fit to the experimental data of Kenny et al. (1999). A strict minimization was not conducted and some judgement was made in selecting the final values.

**STATISTICAL METHODS**

Fitting was performed using the Minerr procedure (MathSoft Inc., 2000).

The number of particles in each size bin has variance, which is at least the Poisson variance. The minimal variance in the estimate of the inhalable mass was thus estimated by generating 100 samples where the number of particles in each size bin was a random number from a Poisson distribution with expectation equal to the measured number. If there were no particles in a size bin, it was assigned the number 1.
In comparing the calculated inhalable mass and the mass measured with the IOM sampler it cannot be assumed that one is approximately error free, which has to be the case if conventional regression analysis is performed. Rather, it is assumed that there is an error $\sigma_x$ in the $x$ variable and $\sigma_y$ in the $y$ variable. The comparison is made using the method of Mandel (1984). The method requires that $\lambda = \sigma_x^2/\sigma_y^2$ and the correlation $\rho$ between $\sigma_x$ and $\sigma_y$ are known a priori. It was assumed that $\lambda = 1$ and $\rho = 0$.

**RESULTS**

The correction factors for the edge effects induced by image analysis are given in Table 1.

The calculated and fitted airborne number distributions calculated from the upward ($C_u$) and forward ($C_f$) facing meta samples for the best fit parameter values $u^* = 0.18$ m/s and $\Theta = 10^\circ$ (given $s = 1$) are shown in Fig. 2.

Given $u^* = 0.18$ m/s it was found that $v_{sed}$ was in the range 0.96–0.99 $\times v_{tot}$ for all diameter classes and thus other deposition mechanisms than gravitational settling can be neglected for the upward facing foil. Therefore, and also since the average of $\cos(\alpha)$ over the interval $-30^\circ$ to $30^\circ$ is 0.955, any reasonable deviation from a horizontal position can be neglected. Thus, the simple method was used in all further calculations.

The distribution calculated from the upward facing meta sample using the simple method with the best fit parameter values and fitted log-normal distribution with mass-weighted geometric mean volume equivalent diameter (MGMD$_v$) = 36 $\mu$m and geometric standard deviation (GSD) = 3.2 is shown in Fig. 3.

The Poisson error for the calculated mass for the 25 individual samples had relative standard deviations ranging from 1.5 to 7.5%.

The results of the comparison of the IOM sampler with the calculated and with the equivalent inhalable mass concentration are given in Table 2 and Fig. 4.

The fitted values of $\alpha$ and $\beta$ (equation 9) were $\alpha = 0.15$ and $\beta = 26$ $\mu$m. The ‘total’ dust concentrations calculated using these values are shown in Fig. 5, together with the measured concentrations. The corresponding efficiency curve $E_{tot}$ is plotted in Fig. 6, together with the experimental data of Kenny et al. (1999).
The fitted values of MGMD_e and GSD for the 25 individual samples are plotted in Fig. 7.

**DISCUSSION**

Table 1 shows that a correction is needed for particles with \(D_p > 150\ \mu m\) to correct for the bias introduced by image analysis edge effects.

The finding that \(v_{sed}\) was close to \(v_{tot}\) for all diameter classes is in line with the assumptions of Wagner and Leith (2001a), who studied particles up to 10 \(\mu m\). Also, since the deviation from horizontal up to 30° at most results in a deviation of 5%, the simple method gives a good estimate of the airborne concentration.

The validity of the passive sampler for dust sampling and the model for characterizing the total sampling velocity is supported by the following results. First, an excellent fit between the airborne number concentration based on the upward and forward facing foil data can be obtained by adjusting only a few parameters (\(s\), \(\Theta\) and \(u^*\)) and the fitting procedure leads to the plausible value \(\Theta = 10°\). Also, the value of \(u^* = 0.18\ \text{m/s}\) is in line with the results obtained by others. In the wind tunnel experiments of Vinzents (1996) it was found that \(u^* = 0.29\ \text{m/s}\) for the experimental conditions wind speed 0.5 m/s, grid generated turbulence intensity 1.3% and torso facing the wind. Wind speeds in industry are lower, \(\sim 0.2\ \text{m/s}\), with turbulence intensity 30% (Baldwin and Maynard, 1998). Using the relation \(u^* = (\text{average velocity} \times \text{turbulent intensity})/0.63\) [see equation (A7)], this would give a friction velocity \(u^*\) of 0.1 m/s. Wagner and Leith (2001b) measured \(u^*\) in industrial settings, finding \(u^* = 0.2\ \text{m/s}\) (open doors) and \(u^* = 0.1\ \text{m/s}\) (reduced ventilation).

The finding that the best fit of the exponent \(s\) in equation (8) is \(s = 1\) gives the following relation of the stopping distance

\[
\sigma = 1.49 u^* \tau = v_\sigma \tau
\]  

(10)

where \(v_\sigma = 0.27\ \text{m/s}\) using the fitted value of \(u^* = 0.18\ \text{m/s}\). This finding strongly suggests that impac-
The validity of the simple method under field conditions is supported by the good agreement with the inhalable dust concentration as measured with the IOM sampler (Table 2 and Fig. 4). The slope is close to 1 and the intercept ± SD includes 0. Notice that the method was developed without any consideration of the results of the measurements with the IOM sampler. Table 2 and Fig. 4 suggest that the present method is a real improvement compared with the original passive sampler approach of Vinzents (1996) using the most recent calibration given by Schlünssen et al. (2001).

Notice that particle diameter $D_p$ is to the power of one only, because sedimentation from air has weighted the airborne number concentration with diameter to the second power. Thus, calculation of mass from the foil data is more reliable than conversion of airborne number to airborne mass concentrations, which involves diameter to the third power.

It is also encouraging that a reasonable agreement could be obtained for the calculated and measured 'total' dust concentration, using a sampling efficiency that is in reasonable agreement with experimental data. It is not claimed that the fitted efficiency curve reflects the true efficiency as obtained during field sampling. The calculations merely intend to demonstrate the feasibility to calculate a hypothetical 'total' mass fraction.

The true size distribution of the airborne dust is not known, but it is reasonable to assume that it is log-normal. Given this assumption, the good fit of the mass distribution to a log-normal distribution (Fig. 3) also provides support that the method can provide an unbiased estimate of airborne concentration for large particles (>100 μm). This is an advantage over active samplers because there is only limited understanding of their sampling efficiencies for large particles. Furthermore, there is only limited information on biologically relevant size fractions for particles >100 μm, and even if there was, samplers would have to be developed to sample according to such criteria. The present method provides the possibility to numerically calculate the mass of any hypothetically relevant size fraction.

To further characterize the sampler and model, a sensitivity analysis was performed. The procedure was as follows. Given the upward facing meta sample, the nominal inhalable mass concentration ($M_N$) is calculated. Parameters are varied one at a time and the resulting change in inhalable mass is calculated. Sensitivity $S_e$ is calculated as

$$S_e = \frac{(\Delta M \cdot \alpha_N)}{(M_N \cdot \Delta \alpha)}$$

Table 3. Calculated inhalable concentration $M$ for a given change in the model parameter and parameter sensitivity $S_e$ [equation (11)]

<table>
<thead>
<tr>
<th>Model</th>
<th>$\delta$</th>
<th>$u^*$ (m/s)</th>
<th>$\Theta^*$</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$\kappa$</th>
<th>$\chi$</th>
<th>$M$ (mg/m$^3$)</th>
<th>$S_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended</td>
<td>1</td>
<td>18</td>
<td>10</td>
<td>0.7</td>
<td>1.4</td>
<td>1.5</td>
<td>1.161</td>
<td>Nominal values</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.161</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>19</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.149</td>
<td>–0.17</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>–</td>
<td>20</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.178</td>
<td>+0.017</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.5</td>
<td>–</td>
<td>–</td>
<td>1.137</td>
<td>–0.021</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
<td>–</td>
<td>1.349</td>
<td>–1.32</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.3</td>
<td>0.996</td>
<td>+1.24</td>
</tr>
<tr>
<td>Simple</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.7</td>
<td>1.4</td>
<td>1.5</td>
<td>1.169</td>
<td>Model sensitivity</td>
</tr>
</tbody>
</table>

NA, not applicable; –, unchanged relative to nominal value.
SEM could also be applied for the present foils, and there is potential for IR microscopy (Spurny, 1986) in characterizing organic compounds, given a suitable collecting substrate can be found.

Wagner and Leith (2001a) used a stainless steel mesh to prevent deposition of very large particles, such as sand, hair, etc. However, such particles can be easily recognized by microscopy and deleted from the results. The design of the passive dust sampler prevents inadvertent contact with fingers and other objects (Vinzents, 1996).

**CONCLUSIONS**

- An internally consistent relation between the sampling velocity onto the forward and upward facing foils was found, indicating that the model reflects the relative contribution of the various deposition mechanisms.
- For calculating airborne mass, particle density information is not needed, and only a broad knowledge of the volume and dynamic shape factors, in particular their covariance, is needed.
- Good agreement was found between the calculated inhalable dust concentration and the concentration measured with the IOM inhalable dust sampler.
- Agreement with the IOM sampler results was improved compared with the equivalent concentration determined with the original passive sampler approach.
- The sampling characteristics even for very large (>100 µm) particles is well characterized. Thus, any hypothetically biologically relevant size fraction can be calculated.

Overall, the results of this study have demonstrated the validity of the passive sampling principle and the ability to determine size distributions and inhalable and 'total' mass concentrations involving even large particles, based on optical microscopy of particles sampled on the upward facing foil.

**APPENDIX**

**Drag**

The drag $C_D$ in the ultra-Stokesian region (see for example Brockmann and Rader, 1990) can be calculated as

$$ C_D = \frac{24}{Re} \left( 1 + 0.155 Re^{0.678} \right)^{0.14} \left( \frac{\Phi}{\chi} \right)^{2/3} $$

where

$$ Re = \frac{\rho p D_e (U_g - V_p)}{\mu} $$

$U_g$ is the gas and $V_p$ the particle velocity and $\mu$ is the dynamic viscosity of air. The sphericity factor $\Phi$ is related to the dynamic shape factor $\chi$ as

$$ \Phi = \left( \frac{2.188}{\chi} \right) - 1.275 + 0.087 \chi^3 $$

**Deposition model**

Key equations from the model used by Schneider et al. (1994) are given below.

The particle flux $J$ described by the steady-state diffusion equation of particles in a constant external force field inducing a drift velocity $v_d$ is

$$ J = -(D + D_{ep})(dC/dz) + v_d C $$

where $D$ is the Brownian and $D_{ep}$ the effective particle turbulent diffusivity. $C$ is the concentration at distance $z$ from the surface. The air turbulent diffusivity $D_e$ is estimated as

$$ D_e(z) = k_e z^2 $$

and it is assumed that $D_{ep} = D_e$. The friction velocity $u^*$ is defined as

$$ u^* = \left( \frac{f_0}{\rho_a} \right)^{1/2} $$

where $f_0$ is the wall shear stress and $\rho_a$ the density of air. For homogeneous turbulence in a closed vessel $u^*$ can be estimated as

$$ u^* = \frac{u_{RMS}}{0.63} $$

where $u_{RMS}$ is the root mean square air velocity.

**REFERENCES**


