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AEROSOL SAMPLING FROM FLUCTUATING FLOWS INTO SHARP-EDGED TUBULAR INLETS

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Abstract—Aspiration from the ambient air into an inlet and subsequent particle transport through the sampling tube may lead to essential bias of the initial aerosol concentration due to inertia, gravitational settling, and several other physical mechanisms. This study deals with the aerosol sampling efficiency of sharp-edged (or thin-walled) tubular inlets under harmonically varying wind conditions. Modelling of the components of the overall sampling efficiency was performed with semi-empirical equations for the aspiration and transmission efficiencies that have recently been developed for fixed isoaxial and non-isoaxial conditions. Based on these models, we have analyzed real-life situations when the wind velocity vector is not steady, but fluctuates around predominant average values of its magnitude and orientation. Two sampling environments, horizontal aerosol flow (ambient atmosphere) and vertical aerosol flow (industrial stacks) have been considered. To determine the values of sampling efficiency components when sampling aerosols from harmonically varying wind conditions, the time-dependent function of each component has been time averaged within the period of fluctuation. It has been found that even for small fluctuations in wind direction, i.e. for quasi-isoaxial sampling, the efficiency is less than that obtained for the mean wind direction, i.e. isoaxial sampling. This difference occurs mostly because of particle impaction in the entrance region of the sampling nozzle and is more significant for larger particles.

INTRODUCTION

To measure the characteristics of airborne particles in indoor and outdoor air environments, the aerosol is usually aspirated from the ambient air into a sampling inlet and then transported to a collection medium or the sensing unit of a direct-reading aerosol instrument. The sample must represent the original state of the aerosol in the ambient environment. Otherwise, one needs to have a reliable method for quantifying the extent of the sampling bias so that it can be used to correct the measured data. In general, the overall sampling efficiency of an inlet has to be determined for each aerosol size fraction of interest over the range of aerosol flow conditions encountered. The overall sampling efficiency of an inlet, E_s, is defined as the ratio of the sampled (and measured) concentration, C_s, to the concentration, C_0, in the ambient air:

$$E_s = \frac{C_s}{C_0}. \tag{1}$$

Major factors which affect the sampling efficiency are the following: (i) particle characteristics such as particle size, d_p, and density ρ_p; (ii) inlet characteristics such as its size, shape, orientation and inlet velocity, U_i, (iii) ambient air flow characteristics such as wind velocity, U_w. The inlet orientation is generally described relative to two vectors: the gravitational **g**-vector and the wind-directional $\mathbf{U}_w$-vector. The angles between inlet axis and the **g**- and $\mathbf{U}_w$-vectors are generally denoted by φ and θ, respectively.

Belyaev and Levin (1972) developed aspiration equations that are valid for tubular inlets which are either sharp-edged with the leading edge inclined backward at 15° or less, or thin-walled with a flat edge where the ratio of the exterior to the interior diameter does not exceed 1.10. These criteria are generally used in sampling with tubular inlets. Sharp-edged inlets are more common in aerosol sampling practice than the thin-walled ones. In field

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measurement practice, the inlet is usually oriented to face the wind (British Standards Institution, 1971; Environmental Protection Agency, 1971; Vincent, 1989).

For isoaxial sampling ($\theta = 0$) into a sharp-edged inlet, three types of aspiration are distinguished depending on the velocity ratio, $R = U_w/U_i$: isokinetic ($R = 1$), sub-isokinetic ($R > 1$), and super-isokinetic ($R < 1$). During isokinetic aspiration, the aerosol concentration at the inlet face is expected to equal the ambient aerosol concentration as the air stream lines remain straight near the inlet. During non-isokinetic aspiration, particles with sufficient inertia may cross the limiting stream surface. This leads to over-aspiration at $R > 1$ and to under-aspiration at $R < 1$ (Badzioch, 1959). Since this is an inertial effect, it is more pronounced for large particles. When sampling aerosols non-isoaxially at a fixed angle $\theta < 90°$ with respect to the wind, the particle concentration at the inlet face decreases with increasing θ (Vincent, 1989).

The aerosol concentration at the inlet face due to primary aspiration (Fig. 1) depends on the number of particles aspirated with the air and passing the cross-sectional area of the inlet. However, the total aerosol concentration at the inlet face, C_a, is also affected by secondary aspiration which depends on particle rebound, blow-off, roll-off, and re-entrainment from the inlet's external walls. It has been considered by Belyaev and Levin (1972, 1974) and Vincent and Gibson (1981) for thick-walled/disc-shaped inlets, and later by Lipatov *et al.* (1986, 1988) for thin-walled/sharp-edged inlets. The secondary aspiration effect can be minimized under certain conditions (Lipatov *et al.*, 1988; Grinshpun *et al.*, 1990). In that case, C_a is assumed to depend only on primary aspiration. The aspiration efficiency, E_a, is defined as

$$E_a = \frac{C_a}{C_0}. \tag{2}$$

Particle losses in the sampling tube may reduce the number of aspirated particles, i.e. $C_s \leqslant C_a$ (Fig. 1). Particle transmission through the entrance region is affected primarily by external conditions, such as the ambient wind velocity and direction. Transmission through the rest of the tubular inlet primarily depends on the efficiency of gravitational deposition, which is a function of the internal flow characteristics and the inlet's orientation with respect to the gravity vector. For a relatively short inlet, most inner wall losses usually occur near the inlet face. For example, Tufto and Willeke (1982) found that for a 20 μm particle in a horizontal aerosol flow, the particle deposition is a 20 cm long inlet nozzle ranges from 47

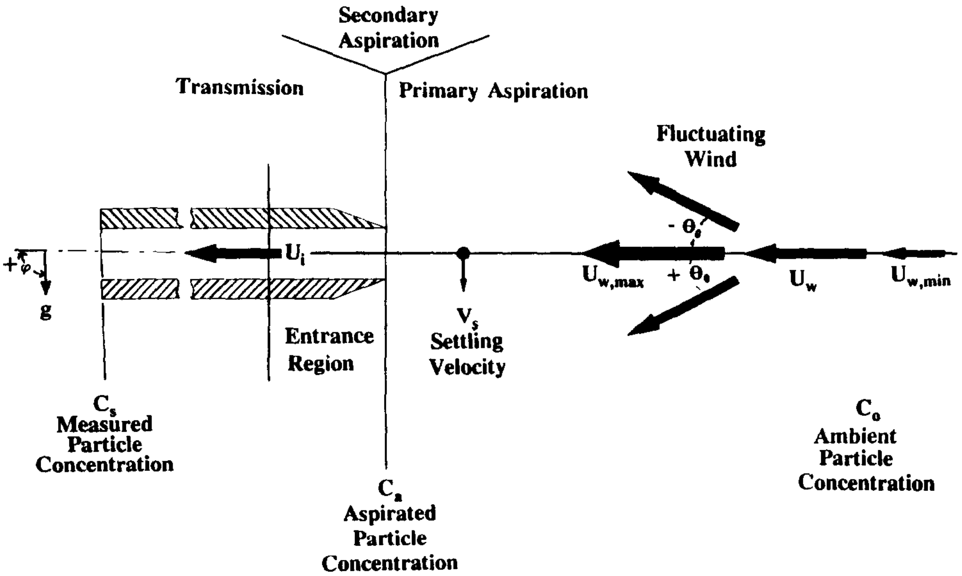

Fig. 1. Schematic representation of aerosol sampling from fluctuating wind.

to 60% in the first 1 cm from the inlet face, when $U_w = 500\ \mathrm{cm\,s^{-1}}$ and $R = 0.5$–2. For $d_p \geqslant 1\ \mu\mathrm{m}$, deposition in the entrance region is primarily caused by two inertial mechanisms: direct wall impaction (Liu *et al.*, 1989; Hangal and Willeke, 1990a) and turbulent deposition in the vena contracta (Hangal and Willeke, 1990a). Direct inner wall impaction may take place under any non-isoaxial condition, but may also occur for isoaxial conditions in a flow diverging situation when $R > 1$. A vena contracta is formed if the air flow upstream of the inlet face is convergent which occurs when $R < 1$. Thus, the transmitted aerosol concentration that accounts for the two inertial particle loss effects in the entrance region, C_{ti}, may be considerably lower than C_a at the inlet face.

The gravitational settling component in tubular sampling inlets has been analyzed by Okazaki and Willeke (1987) and Okazaki *et al.* (1987a–c). They considered the inertial injection of particles from outside the inlet into the boundary layer inside the inlet and their subsequent removal by gravity. Their results show that the gravitational settling loss just downstream of the inlet may be rather different from the one calculated for fully developed pipe flows (Fuchs, 1964).

Thus, the transmission efficiency, E_t, is the product of the inertial component, E_{ti}, and the sedimentation component, E_{ts}:

$$E_t = \frac{C_s}{C_a} = E_{ti}E_{ts} = \left(\frac{C_{ti}}{C_a}\right)\left(\frac{C_s}{C_{ti}}\right). \tag{3}$$

The overall inlet sampling efficiency for a thin-walled or sharp-edged inlet is the product of the aspiration efficiency, equation (2), and the transmission efficiency, equation (3):

$$E_s = E_a E_t. \tag{4}$$

Whenever possible, isoaxial alignment of the inlet with the ambient aerosol flow is preferable. However, the direction and magnitude of the wind vector may change or fluctuate with time, and the inlet's orientation and suction velocity should continuously be adjusted to reflect the varying wind conditions. While significant long-term changes in θ can be accommodated for in ambient sampling through a wind vane, small fluctuations in angle and velocity are impractical to accommodate for in ambient and stack sampling.

The effect of wind variability on the inlet sampling efficiency depends on sampling time, t_{samp}, and the period of wind fluctuation, T. Nonperiodical (chaotic) wind fluctuations can usually be approximated by harmonic functions of time with fixed fluctuation periods, where the magnitude of the wind velocity vector ranges from $U_{w,\min}$ to $U_{w,\max}$ and its direction from $-\theta_0$ to $+\theta_0$ as shown in Fig. 1. Variability of the atmospheric wind over a long time period of several hours generally does not affect the sampling efficiency as long as $t_{samp} \ll T$ (Slade, 1968), but sampling from rapidly fluctuating wind is non-isoaxial and non-isokinetic, even if the inlet's orientation is parallel to the average wind direction and U_i is equal to the average wind velocity. In this study we have calculated the aspiration and transmission efficiencies under such quasi-isoaxial or quasi-isokinetic conditions.

The turbulence scale and intensity may affect the overall sampling efficiency of an inlet (Vincent *et al.*, 1983, 1985). This effect is more pronounced for the transmission rather than for the aspiration component (Rader and Marple, 1988; Wiener *et al.*, 1988). The effect of periodical high-frequency fluctuations of the wind velocity magnitude on aspiration efficiency has been estimated to first approximation by Belyaev and Levin (1974) for sharp-edged isoaxial sampling. Since their publication, several new semi-empirical models for the aspiration and transmission efficiencies of isoaxially and non-isoaxially aligned inlets have become available for a wide range of ambient and sampling conditions (Hangal and Willeke, 1990a, b, 1992; Grinshpun *et al.*, 1993). These models have been developed for fixed inlet orientations with respect to the wind. In this study, we have applied them to situations where the wind direction fluctuates periodically around a predominant direction. The overall sampling efficiencies have been determined by integrating each sampling component over the period of wind fluctuation, assuming a sinusoidal, unimodal function with time.

SAMPLING AT FIXED WIND CONDITIONS

Various kinds of inlet configurations are available. Some of them are complicated in geometry, and are used to sample a relevant size fraction of the total aerosol. In order to understand the complex processes that take place while sampling aerosols, the simple geometry of a sharp-edged tubular sampling inlet is usually studied first and then, based on these studies, the characteristics of sampling efficiency are extended to more complex geometries. Therefore, this study deals with the aerosol sampling efficiency of sharp-edged (or thin-walled) tubular inlet operated in the two kinds of environment that are most common in aerosol sampling practice. The first case considers ambient aerosol flow that is horizontal with respect to its average direction and sampling from it through a horizontally fixed inlet. In this case, $\varphi = +90^\circ$ (Fig. 1). The second case considers an industrial stack aerosol flow that is vertical with respect to its average direction and the inlet is fixed vertically facing the wind. In this case $\varphi = 0$.

Aspiration efficiency

Many theoretical and experimental studies on aerosol aspiration has been conducted during the past three decades. Reviews of available equations for calculating the aerosol aspiration efficiency of tubular inlets sampling from moving air have been published by Vincent (1989), Hangal and Willeke (1990b), and Brockmann (1993). The available data for aerosol aspiration from calm air have been summarized in our earlier work (Grinshpun *et al.*, 1993). Using these data we have developed a semi-empirical equation for calculating the aspiration efficiency from calm air, and have then generalized this equation by combining it with the moving air equation, which has resulted in the following equations for aspiration efficiency, valid for wind conditions ranging from calm air to fast moving aerosol flows (Grinshpun *et al.*, 1993, 1994):

$$(E_a) = (E_a)_{\mathrm{mov},\theta}(1+\delta)^{0.5} f_{\mathrm{mov}} + (E_a)_{\mathrm{calm},\varphi}\, f_{\mathrm{calm}}, \tag{5}$$

$$(E_a)_{\mathrm{mov},\theta} = 1 - (1 - R\cos\theta)\beta_0, \tag{6}$$

$$(E_a)_{\mathrm{calm},\varphi} = \exp\left(-\frac{4\,\mathrm{Stk_i}(V_s/U_i)^{0.5}+1}{1+2\,\mathrm{Stk_i}}\right) + \frac{V_s}{U_i}\cos\varphi \quad \text{for } \varphi = 0\text{–}90^\circ, \tag{7}$$

$$f_{\mathrm{mov}} = \exp\left(-\frac{V_s}{U_w}\right), \qquad f_{\mathrm{calm}} = 1 - \exp\left(-\frac{V_s}{U_w}\right), \tag{8}$$

$$\delta = \frac{V_s}{U_w}\left(\frac{V_s}{U_w} + 2\cos(\theta \pm \varphi)\right), \tag{9}$$

$$\beta_\theta = \beta_\theta(\mathrm{Stk_i}, R, \theta), \tag{10}$$

where V_s is the settling velocity ($= \tau g$), $\mathrm{Stk_i}$ the internal Stokes number ($= \tau U_i/D_i$), D_i the interior inlet diameter, τ the particle relaxation time ($= \rho_p d_p^2/(18\eta)$), η the air viscosity, and ρ_p the particle density.

Equation (5) is valid for both vertical and horizontal aerosol flows. Under normal atmospheric conditions, if $U_w \gg V_s$, the particles follow changes in the fluid streamlines almost instantaneously. Therefore, the effect of particle settling velocity, V_s, which is a function of the particle relaxation time, τ, reduces to a negligible quantity and equation (5) can be written as

$$E_a = (E_a)_{\mathrm{mov},\theta}. \tag{11}$$

Equations (5)–(11) have been developed for fixed ambient conditions, when neither the magnitude nor the direction of the wind changes during sampling, i.e. all parameters in these equations are time-independent.

Transmission efficiency

Inertial component. For a short inlet, particle transmission through the inlet is primarily modified by particle removal inside the entrance region due to direct wall impaction and turbulent deposition in the vena contracta which is formed when $R < 1$. Particle removal by these two effects may be higher than by gravitational settling inside the inlet. For the wall impaction, I_w, and vena contracta, I_v, components, the equations developed by Hangal and Willeke (1990a, 1992) were used. Thus, the transmission efficiency after inertial particle removal is

$$E_{ti} = \exp(-75(I_w + I_v)^2). \tag{12}$$

Hangal and Willeke (1990a, 1992) simplified the particle velocity perpendicular to the inner wall, $V_\perp$, by introducing gravitational settling angle, α:

$$V_\perp = U_w \sin\theta - V_s \cos\theta = U_w \sin(\theta - \alpha). \tag{13}$$

This equation was developed for inlets sampling from horizontal aerosol flows, $\varphi = +90°$. In this case, the gravity effect can be expressed as

$$\alpha = \theta - \sin^{-1}\left(\sin\theta - \frac{V_s}{U_w}\cos\theta\right). \tag{14}$$

Thus, the wall impaction component of the transmission efficiency for ambient aerosol sampling is (Hangal and Willeke, 1990a, 1992)

$$I_w = \mathrm{Stk}_i\, R^{3/2} \sin(\theta + \alpha) \sin\frac{\theta \pm \alpha}{2} \quad \text{for } \varphi = 90°. \tag{15}$$

In the case of stack sampling ($\varphi = 0$), the gravitational settling velocity vector is parallel to the axis of the inlet, i.e. $\alpha = 0$ in equation (15):

$$I_w = \mathrm{Stk}_i\, R^{3/2} \sin\theta \sin\frac{\theta}{2} \quad \text{for } \varphi = 0. \tag{16}$$

Turbulent aerosol deposition due to the formation of a vena contracta does not depend on φ (Hangal and Willeke, 1990a):

$$I_v = 0.09[(1 - R)\,\mathrm{Stk}_i \cos\theta]^{0.3} \quad \text{for } R < 1, \tag{17a}$$

$$I_v = 0 \quad \text{for } R \geqslant 1. \tag{17b}$$

Since I_w depends on the direction and magnitude of the wind velocity, the entire transmission efficiency component E_{ti} becomes time-dependent if the wind fluctuates with time.

Gravitational component. According to the model of Okazaki and Willeke (1987), the gravitational settling component of transmission efficiency for horizontal inlets operating in ambient air environments can be calculated as follows:

$$E_{ts} = \exp(-4.7K^{0.75}) \quad \text{for } \varphi = 90°, \tag{18}$$

$$K = \left[\mathrm{Stk}_i R Z \frac{1}{\sqrt{\mathrm{Re}}}\right]^{1/2}, \quad \mathrm{Re} = \frac{D_i U_i \rho}{\eta}, \quad Z = \left(\frac{L}{D_i}\right)\left(\frac{V_s}{U_i}\right), \tag{19}$$

where L is the length of the sampling tube and ρ is the gas density. As seen, E_{ts} is not affected by fluctuations of the wind direction, and, for relatively long sampling lines, is expected not to be significantly dependent on fluctuations of the wind velocity magnitude.

In the case of stack sampling when the inlet is oriented downward ($\varphi = 0$), the effect of gravity does not lead to any particle deposition, and therefore

$$E_{ts} = 0 \quad \text{for } \varphi = 0. \tag{20}$$

SAMPLING FROM FLUCTUATING AEROSOL FLOWS

Static approach: sampling efficiencies calculated for different wind velocity vectors

If the range of time-dependent variations of the wind velocity vector is known, the variability of the sampling efficiency can be determined by calculating its values for the mean and the range limits of the wind vector's amplitude ($U_{w,avg}$, $U_{w,min}$, $U_{w,max}$) and angle ($\theta = 0, \; -\theta_0, \; +\theta_0$).

Equations (5)–(20) have been utilized to calculate the components of the inlet sampling efficiency for different wind velocity magnitudes and directions. As an example, we have considered a $\frac{1}{4}$ inch inlet, that is used for stack sampling and meterological measurements (Biswas, 1993; Porter *et al.*, 1991; Vincent, 1989). The same inlet size has been used in several of our previous publications.

Figure 2 shows the results of calculations for this $\frac{1}{4}$ inch horizontal tubular inlet ($D_i = 0.57$ cm, $L = 20$ cm) through which aerosols are sampled from the ambient environment quasi-isokinetically. In this example, the sampling velocity equals the average wind velocity, $U_i = U_{w,avg} = 300 \text{ cm s}^{-1}$ with a wind velocity variation of $\pm 50 \text{ cm s}^{-1}$ (Fig. 2A) and angle variation $\pm 20°$ (Fig. 2B). The efficiency values are plotted as a function of aerodynamic particle diameter, $d_{ae} = d_p(\rho_p/\rho_0)^{0.5}$, where ρ_0 is unit density ($\rho_0 = 1 \text{ g cm}^{-3}$).

Figure 2A shows that the inertial particle losses at the entrance region are highest for $U_{w,min} = 250 \text{ cm s}^{-1}$ (dotted line), i.e. in the presence of vena contracta when $R < 1$. For $U_{w,max} = 350 \text{ cm s}^{-1}$, there is no vena contracta, and no losses occur due to direct wall impaction, so that $E_{ti} = 1.00$ (solid line). This fact was pointed out by Badzioch (1959). For $U_w = U_{w,avg} = 300 \text{ cm s}^{-1}$, all streamlines are assumed to be parallel to each other and

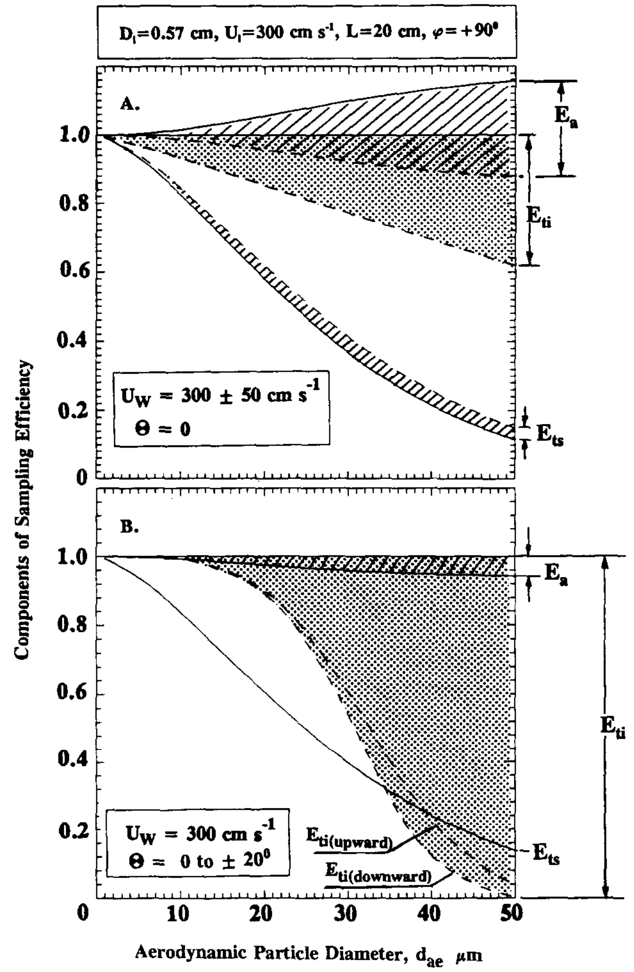

Fig. 2. Particle-size dependence of the aspiration, impaction and gravitational settling components of the sampling efficiency of a horizontal inlet. The efficiency values lie within the shaded area for the indicated horizontal wind direction and magnitude.

$E_{ti} = 1.00$ (upper solid line of dotted area). Thus, the integrated value of the inertial component, E_{ti}, for fluctuating wind velocity magnitudes lies between E_{ti} values which correspond to minimum and mean U_w of the dotted area. For the aspiration and gravitational settling components of sampling efficiencies, the average value for each component corresponds to a value between minimum and maximum wind velocity that is indicated by the striped shaded area.

Gravitational particle deposition is significantly higher than inertial deposition in this case. For example, the calculated value of the gravitational settling component of transmission efficiency is about 0.2 for $d_p = 40\ \mu m$. The small difference in gravitational deposition between $U_w = 250$ and $350\ cm\,s^{-1}$ represents the difference in aerosol particle behavior at the entrance region, where E_{ts} is still affected by external conditions. The insignificance of the E_{ts}-variation shows that the gravitational settling component in the inlet is essentially independent of fluctuations in magnitude of the wind velocity. The value of E_{ts}, however, may be quite low.

When $U_w = U_i = 300\ cm\,s^{-1}$ (Fig. 2B), fluctuations in wind direction, $\theta = \pm 20°$, cause under-aspiration. Since $E_a = 1$ for $\theta = 0$, and $E_a \leqslant 1$ for $\theta > 0$, the average value of aspiration efficiency, E_a, lies between $E_a = 1$ for $\theta = 0$ and the lowest E_a for maximal deviation from $\theta = 0$.

The value for E_{ts} is quite low for large particles, but is unaffected by θ-variations, since the inlet is oriented horizontally and U_i is fixed. The value for E_{ti} is unity for $\theta = 0$ (isokinetic condition). When the wind moves upward towards the inlet ($-\theta$, see Fig. 1), gravity pulls the impaction vector away from the inner wall. Thus, E_{ti} for $\theta_0 = -20°$ (upward flow) is higher than E_{ti} for $\theta_0 = +20°$ (downward flow). The mean E_{ti} for fluctuating θ lies between 1 and the values for $\theta = \pm 20°$.

In stack sampling ($\varphi = 0$), gravity does not affect the inertiai component, E_{ti}, but affects only the absolute magnitude of θ. The value for E_{ts} is stack sampling is 1.

Dynamic approach: integration of harmonic fluctuations

The instability of air environments may be very complex, as it may consist of harmonic (sinusoidal) and nonharmonic (nonsinusoidal) motions, and large- and small-scale turbulent fluctuations (Wiener *et al.*, 1988). To evaluate the aerosol sampling efficiency of inlets exposed to fluctuating aerosol flows, some approximations are needed to describe the fluctuations. Turbulent fluctuations are usually approximated by Fourier integrals. For simple harmonic wind fluctuations, however, the fluctuations may be approximated by single sinusoidal functions

$$\theta(t) = \theta_{avg} + \delta_\theta \sin \frac{2\pi t}{T_\theta}, \tag{21}$$

$$U_w(t) = U_{w,avg} + \delta_w \sin \frac{2\pi t}{T_w} \tag{22}$$

where δ_θ and δ_w are the maximal excursions in angle and wind velocity, respectively. We have considered only wind directional fluctuations, since we have found from the static approach calculations that the directional fluctuations have a more significant influence on the sampling efficiency than the magnitudinal ones.

Figure 3 shows the effect of fluctuations in wind direction when horizontally sampling aerosol particles from 10 to 50 μm in aerodynamic diameter with the previously used $\frac{1}{4}$ inch inlet ($D_i = 0.57$ cm). For a fixed wind velocity of $300\ cm\,s^{-1}$ the inlet velocity is varied from $100\ cm\,s^{-1}$ ($R = 3$, subisokinetic) to $900\ cm\,s^{-1}$ ($R = 0.33$, superisokinetic).

The gravitational component of transmission efficiency has been found to be least affected by fluctuations in wind direction, while its inertial component varies most significantly, especially for large particles. The aspiration efficiency also varies with time during the period of fluctuation. In the case of stack sampling (vertically oriented inlet), the variations in aspiration efficiency are the same as the ones shown in Fig. 3 for a horizontal

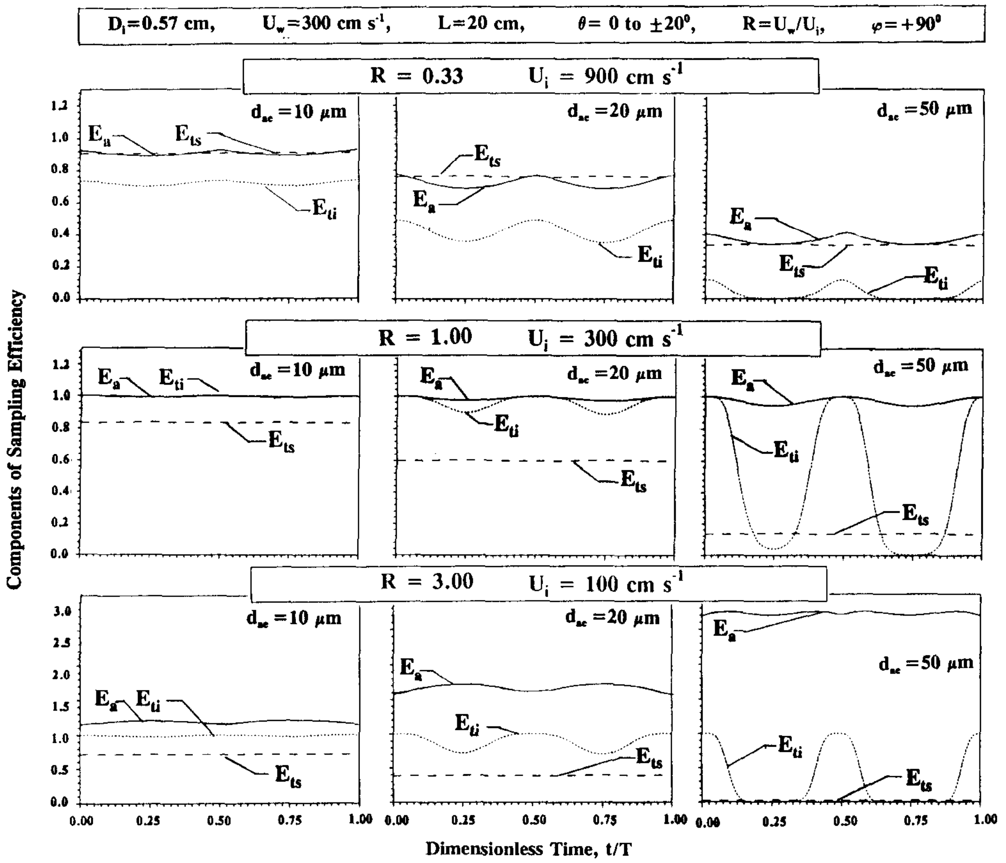

Fig. 3. Variations in the values of the sampling efficiency components due to fluctuations in wind direction when sampling horizontally.

inlet, as long as sampling is performed from relatively fast moving air, i.e. $U_w \gg V_s$. The inertial component of the transmission efficiency for a horizontally fixed inlet has significant variations during the period of wind-directional fluctuation, especially for larger particles. For a vertically oriented inlet, this component is nearly the same as for a horizontally oriented one. The gravitational component of transmission efficiency is equal to unity in the case of stack sampling, because of the inlet's vertical orientation.

In fluctuating aerosol flows, the average particle concentration depends on the integrated value of the particles flux. Each component of overall efficiency equals the ratio of the integrated particle fluxes across two cross-sectional areas. In the dynamic evaluation of the sampling efficiency's average value, the time-dependent variables of each component are integrated over the entire period of fluctuation. In this approach, the integrated value of each sampling efficiency component is calculated with the assumption that the sampling time is much higher than T_θ and T_w.

The fluid relaxation time, t_{fluid}, during which an effective change of the particle motion may occur was considered to be much smaller than the period of fluctuation, T_θ or T_w. The scale of the fluid relaxation time, t_{fluid}, is considered to be $\approx 5D_i/U_w$ (Wiener *et al.*, 1988):

$$t_{\text{fluid}} = \frac{5D_i}{U_w}, \tag{23}$$

where D_i is the inlet diameter. In our calculations we have assumed that

$$T_\theta \text{ or } T_w > 10t_{\text{fluid}}. \tag{24}$$

For example, for $D_i = 1$ cm and $U_w = 100$ cm s^{-1}, the fluid relaxation time is 0.05 s. We assume that the small periods of fluctuation are greater than 0.5 s.

The ratio of D_i to U_w in equation (23) appears in the definition of the external Stokes number = $\mathrm{Stk}_w = \tau U_w/D_i$. Thus, Stk_w is effectively equivalent to the ratio of particle relaxation time, τ, to the fluid relaxation time in the free stream, t_{fluid}. In the results discussed below, the velocity ratio, R, ranges from 0.33 to 3.00, i.e. the wind velocity, U_w, is of the same order of magnitude as the inlet velocity, U_i. This, Stk_w is of the same order of magnitude as Stk_i, and for the range of Stk_i from 10^{-1} to 10, considered below, the periods of fluctuation are much greater than the particle relaxation time:

$$T_\theta \text{ or } T_w > \tau. \tag{25}$$

The results of calculations for the same sampling conditions as before are illustrated in Figs 4–6. The data on the sampling efficiency components are presented in Figs 4 and 5 in non-dimensional form as a function of Stokes number for $\mathrm{Stk}_i = 10^{-1}$–10 (the range that covers most of the aerosol sampling situations). In order to make our results more relevant for the practioner, the overall sampling efficiency data are presented in Fig. 6 in dimensional form as a function of aerodynamic diameter.

In Fig. 4A, it is seen that the aspiration efficiency for aerosol flows fluctuating in the vertical direction by ± 20° relative to the horizontal inlet is not much affected by the fluctuations. Therefore, it is not important in this case which method of averaging is used for angular variations. Figure 4B and equations (18) and (19) show that the settling component of transmission efficiency decreases significantly over the range of indicated Stokes numbers, Stk_i, but it is not affected by angular fluctuations. For vertical sampling, there is no

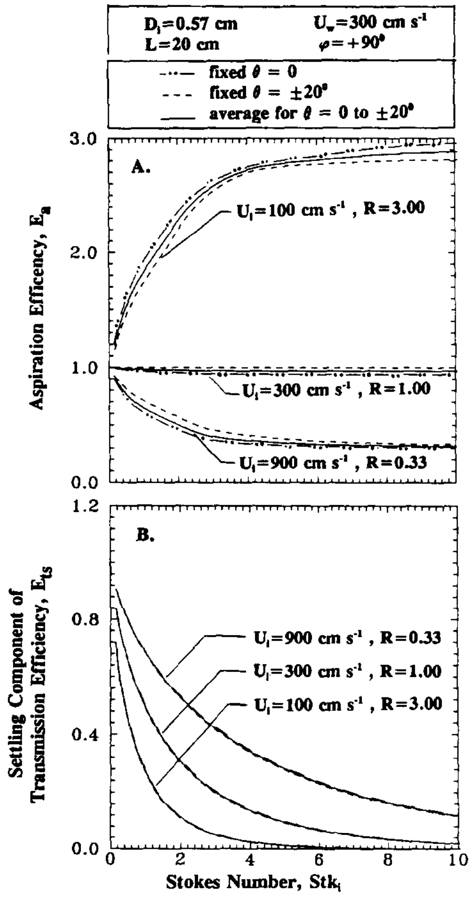

Fig. 4. Integrated values of the aspiration efficiency and the settling component of the transmission efficiency for a horizontal inlet sampling from an aerosol flow that fluctuates between ± 20° from the horizontal.

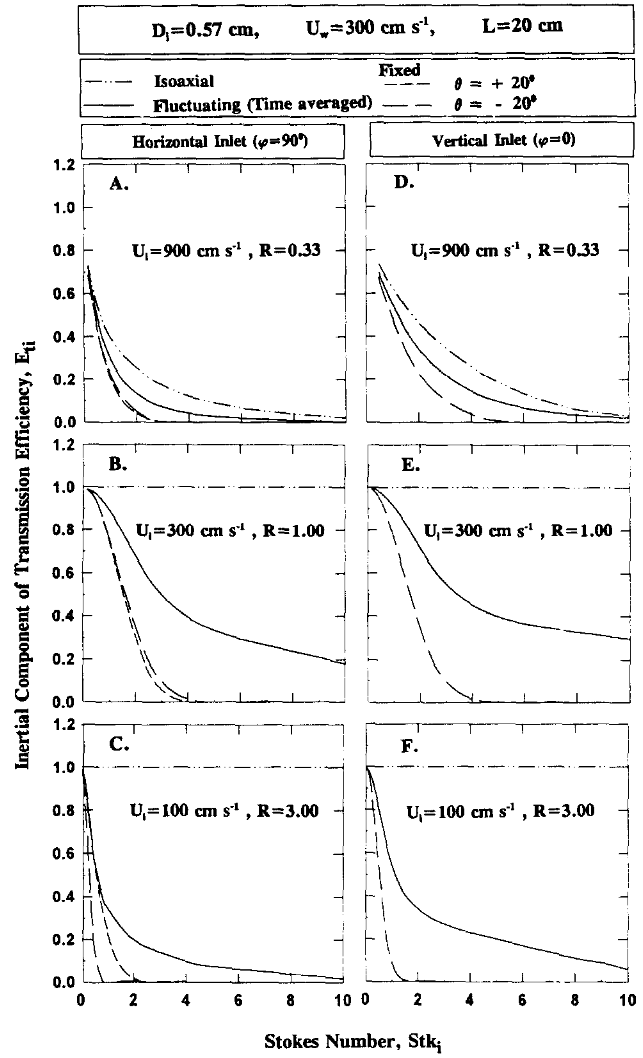

Fig. 5. Integrated values of the inertial component of the transmission efficiency for a sharp-edged inlet sampling from an aerosol flow that fluctuates between ± 20° from the inlet axis.

gravitational removal to the inlet wall ($E_{ts} = 1$) and the aspiration efficiency is the same as for horizontal sampling, as long as $U_w \gg V_s$.

As seen in Fig. 5, the inertial component of the transmission efficiency is significantly affected by angular variations in aerosol flow. For superisokinetic sampling into a horizontal inlet, Fig. 5A, the integrated efficiency value for this example approximately corresponds to the average between the efficiency values for $\theta = 0$ and $\theta = \pm 20°$. For quasi-isokinetic sampling, Fig. 5B, and subisokinetic sampling, Fig. 5C, the integrated values are not close to the averages of the extremes. They are closer to the $\theta = \pm 20°$ values than the $\theta = 0$ values. In the case of a vertical inlet, Figs 5D–F, there is no difference between $\theta = +20°$ and $\theta = -20°$, as the gravitational component is the same for both. While the efficiency values are somewhat different because of the difference in the gravitational vector, the conclusions are the same as for a horizontal inlet.

As seen from the above analysis, the use of the static approach may yield sampling efficiency values that are significantly different from the integrated ones. Figures 4 and 5 show that the sampling bias, particularly that caused by inner particle losses, increases rapidly with Stokes number for fluctuating aerosol flows sampled by horizontally or vertically oriented inlets.

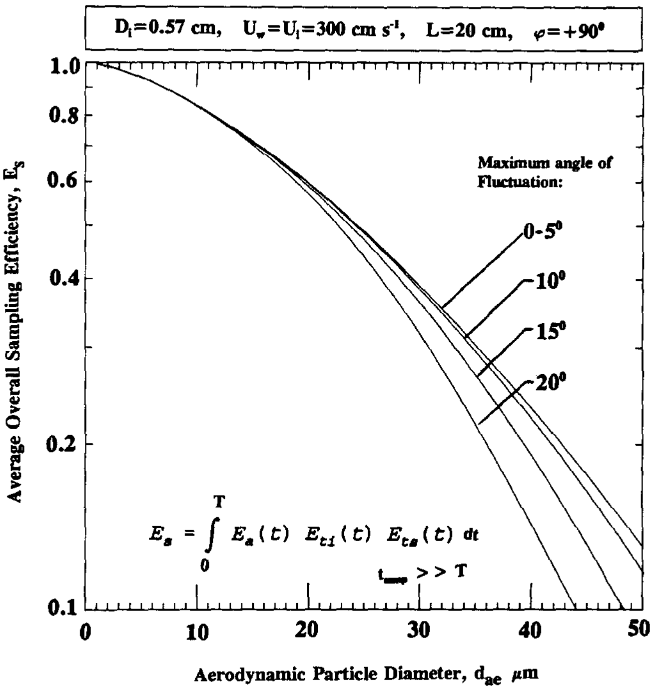

Fig. 6. Integrated overall sampling efficiency for a horizontal inlet sampling from aerosol flows that fluctuate over a range of angles.

Figure 6 shows the integrated overall sampling efficiencies, E_s, that include all three efficiency components for the same sampling conditions, as used in the previous examples. It is seen that for particles larger than $d_{ae} = 10$ μm the overall sampling efficiency of the inlet is noticeably less than unity, and decreases with increase in particle size. For $d_{ae} \geqslant 20$ μm, the overall sampling efficiency is noticeably affected by angular fluctuations: the higher the angular range, the more significant is the sampling bias. For example, the overall sampling efficiency for this horizontally aligned inlet is 20% for 45 μm particles if the aerosol flow is isokinetic. When fluctuating ± 20° from the horizontal, the overall sampling efficiency is reduced to 10%, half of its previous value.

CONCLUSIONS

Modelling of the components of the overall sampling efficiency utilizing the semi-empirical equations for the aspiration and transmission efficiencies has shown that small fluctuations of the wind direction may lead to considerable variations of an inlet's sampling efficiency. However, small variations in velocity magnitude had a much less pronounced effect on the sampling efficiency. Each time-dependent sampling efficiency component needs to be integrated over the period of fluctuation, especially for relatively large particles. For a horizontal inlet and Stokes numbers larger than 4, even small fluctuations in wind direction were found to affect significantly the inertial component of the transmission efficiency of an inlet whose axis is aligned with the average wind direction. Therefore, the sampling bias for this quasi-isoaxial sampling is higher than that obtained for isoaxial sampling. Wind fluctuations affect most significantly the particle losses that occur in the inlet's entrance region due to inertial impaction.

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