Pergamon

J. Aerosol Sci., Vol. 25, No. 8, pp. 1503–1522, 1994

0021-8502/94 $7.00 + 0.00

0021-8502(94)00084-0

INLET CHARACTERISTICS OF BIOAEROSOL SAMPLERS

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(*First received* 18 *March* 1993; *and in final form* 18 *October* 1993)

Abstract—The inlet sampling characteristics of several commercial bioaerosol samplers operating in indoor and outdoor environments have been analyzed by use of available and newly developed equations for sampling efficiency. With a focus on the physical aspects of sampling efficiency, the aspiration and transmission efficiencies have been calculated for the bioaerosol particle size range 1–30 μm, which represents single bacteria, bacteria aggregates, bacteria carrying particles, fungal spores, yeast, and pollen. Under certain sampling conditions, the bioaerosol concentration was found to be significantly over- or underestimated. At wind velocities between 0 and 500 cm s^{-1}, calculations show that the AGI-30 would sample 1–10 μm particles with an inlet sampling efficiency of 20–100%. The entrance efficiency of the 6-stage Andersen viable sampler is 90–150% when sampling isoaxially with respect to horizontal aerosol flows, and 8–100% when oriented vertically at a right angle to the horizontal aerosol flow. For the Burkard portable air sampler, an even wider range of deviation may occur. The bioaerosol samplers used for large particles such as pollen are even less accurate: e.g. 10 times the ambient concentration of *Lycopodium* spores has been calculated to be aspirated by the Lanzoni sampler when operated at 0.5 l min^{-1} facing the wind at wind velocity of about 500 cm s^{-1}.

The actual bioaerosol concentration can be calculated from the measured data by use of the indicated procedures. The sampling efficiency graphs presented can be used to bracket the sampling conditions that enable the investigator to avoid or minimize significant sampling biases for each sampler. The findings can also be used for the design of new samplers or for improving commercially available samplers.

INTRODUCTION

Bioaerosols are known as airborne particles of biological origin, such as viruses, bacteria, fungi, yeast, pollen, and various antigens. Since concern about air quality has grown in recent years, the study of bioaerosols has become increasingly important for such fields as occupational hygiene, medicine, and atmospheric and indoor air research (Gregory, 1973; Edmonds, 1979; Cox, 1987; Atlas, 1988; Faegri and Iversen, 1989; Owen *et al.*, 1992). For this reason, it is important for the investigator to be able to measure accurately the bioaerosol particle sizes, concentrations, and compositions. Many devices, each with different characteristics, have been designed for the sampling of bacteria, fungi, and pollen from air and their collection into or onto some medium for further identification (e.g. Drobenya, 1980; Tikhomirov *et al.*, 1986; Cox, 1987; Rantio-Lehtimäki *et al.*, 1987; Henningson, 1988; Kauppinen *et al.*, 1989; Kotenok and Kopysov, 1990). A variety of methods exist for the analysis of bioaerosol samples (e.g. Burge and Solomon, 1987). In turn, a number of experimental studies on the laboratory and field evaluations of the performance characteristics of these methods and devices have been published during past two decades (e.g. Fields *et al.*, 1974; Groeschel, 1980; Clark *et al.*, 1981; Lembke *et al.*, 1981; Nakhla and Cummings, 1981; Lundholm, 1982; Placencia *et al.*, 1982; Jones *et al.*, 1985; Verhoeff *et al.*, 1990; Buttner and Stetzenbach, 1991; Jensen *et al.*, 1992). These studies provide very useful quantitative information about the total recovery of microorgansims as well as the relative efficacy of bioaerosol samplers on the basis of their comparative analysis. It is important to emphasize that the overall (resulting) value of sampling efficacy, but not the values of its separate components, was usually a subject for investigation in most of the previous studies. At the

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same time, only multicomponent analysis of bioaerosol sampling, based on the separate evaluation of each component of the overall efficacy, can enable the investigator to optimize sampling procedures and conditions in order to achieve accurate and representative measurements. Such an approach is applicable for developing new high performance bioaerosol samplers and for modification of existing ones.

The performance of bioaerosol samplers in indoor and outdoor environments may be determined by, at least, three components:

(i) the inlet sampling efficiency (ISE) which is a combination of aerosol aspiration from the ambient environment and the efficiency of particle transport through the sampling line of the inlet;

(ii) the collection efficiency (CE) of a bioaerosol particle collector which quantifies the sampler's ability to collect the particles that have passed through the sampling line;

(iii) the microbiological aspects of the subsequent bioaerosol analysis.

The first two components are physical aspects of the sampling efficacy. The ISE is the subject of this paper; the CE has been analyzed by reference to the concept of aerodynamic stopping distance (Nevalainen *et al.*, 1992). At this time, no theoretical model appears to exist for analyzing the microbiological aspects (such as the survival of bacteria after their interaction with an impaction surface).

The ISE is the ratio of the particle flow concentration at the end of the sampling line to the actual particle concentration in the ambient atmosphere. For each particle size, the ISE depends on ambient and sampling conditions such as wind velocity, sampling orientation, sampling flow rate, and inlet geometry. It is known that the aspiration of particles into the inlet orifice and their transport through the sampling line may lead to significant biases of the initial aerosol concentration (Belyaev and Levin, 1974; Vincent, 1981, 1986, 1987, 1989; Hangal and Willeke, 1990a, 1990b; Willeke and Baron, 1990; Grinshpun *et al.*, 1990, 1991). While a number of methods exist for determining the ISE of aerosol measurement devices, almost none of the bioaerosol samplers have been analyzed as to the sampling efficiency of their inlets.

In the present study we have calculated the inlet characteristics of several bioaerosol samplers. The aspiration and transmission efficiencies of their inlets have been determined for different types of bioaerosol particles sampled under various conditions. Available and newly developed physical models have been applied for these calculations.

THEORETICAL BACKGROUND

The air flow may diverge or converge when it enters the sampling orifice depending on the ambient and sampling conditions. The flow of airborne particles would behave in the same way, but particles tend to continue their inertial movement in the forward direction (Fig. 1). This tendency is proportional to the mass of the particle and is more pronounced if there is a greater degree of divergence or convergence of the streamlines near the inlet. For this reason, the particulate flow, passing through the face of the inlet, can be either concentrated or diluted relative to the same flow within the limiting streamlines far from the inlet (i.e. in the undisturbed environment). As a result of the inertia effect, the size distribution of the sampled aerosol may be biased and so may not properly represent the aerosol in the environment. For instance, the aerosol is usually oversampled into the inlet face if the wind velocity, U_w, is parallel to and greater than the inlet sampling velocity, U_i. Conversely, the aerosol is usually undersampled if U_w is lower than U_i. In addition to particle inertia, particle gravitational settling (sedimentation) in the environment may also affect the ISE, especially when sampling aerosols from calm air or low-velocity flows (Grinshpun *et al.*, 1990).

Particle suction from the ambient atmosphere into the inlet face, without interaction with the external inlet surface, is defined as primary aspiration. The efficiency of primary

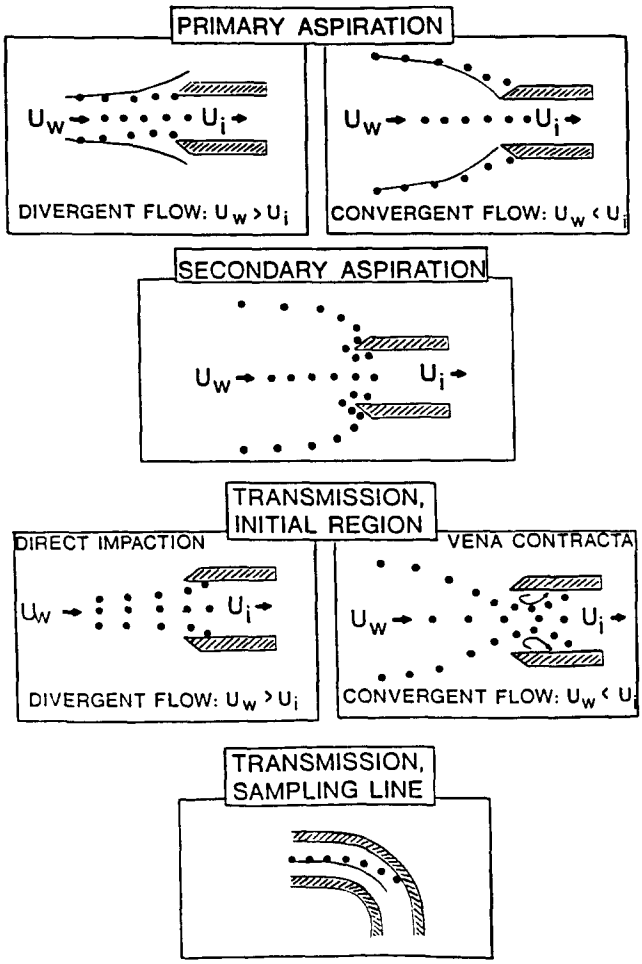


Fig. 1. Illustration of physical mechanisms that lead to sampling bias.

aspiration, E_a, is

$$E_a = \frac{C_a}{C_0} \tag{1}$$

where C_a is the aspirated "flow" concentration of particles of the given size at the inlet face, and C_0 is the "actual" concentration of the particulate fraction in the undisturbed environment (true particle concentration). This definition takes into consideration both the inertial effect as well as particle gravitational settling during aerosol aspiration from the ambient environment (Grinshpun *et al.*, 1990).

Various parameters which affect the primary aspiration efficiency can be subdivided into three groups: the first group represents the ambient air environment (wind velocity and direction), the second one represents the sampling conditions (inlet sampling velocity, inlet outer diameter, D_0, and its inner diameter, D_i), and the third one reflects the particles' characteristics (particle diameter, d_p, and density, ρ_p). The following dimensionless combinations of these parameters are taken into consideration (Vincent, 1989; Grinshpun *et al.*, 1990):

— the velocity ratio, R,

$$R = \frac{U_w}{U_i} \tag{2}$$

— the particle inertial parameter, defined as the Stokes number, Stk_i, based on the inlet sampling velocity,

$$Stk_i = \frac{\tau U_i}{D_i} \tag{3}$$

— the inlet bluntness ratio, b,

$$b = \frac{D_0}{D_i} \tag{4}$$

— the sedimentation factor, v,

$$v = \frac{V_s}{U_i} = \frac{\tau g}{U_i} \tag{5}$$

where V_s is the gravitational settling velocity of the particle; τ is the particle relaxation time, for airborne particles larger than 1 μm τ is expressed as

$$\tau = \frac{V_s}{g} \approx \frac{\rho_p d_p^2}{18\eta} \tag{6}$$

g is the gravitational acceleration; η is the air viscosity. In the case of a non-tubular inlet, the inner diameter D_i in equation (4) should be recognized as the corresponding equivalent geometric size (e.g. this is the slit width for a two-dimensional infinitely long inlet).

The primary aspiration efficiency also depends on angle θ between the axis of the inlet and the wind direction and on angle φ between the inlet axis and the field of gravity. When sampling outdoor bioaerosols, the wind usually blows in the horizontal direction, and the inlet is oriented either parallel with or perpendicular to the wind. This results in the following angular positions: $\theta = 0$, $\varphi = 90°$ (isoaxial sampling in the horizontal plane) or $\theta = 90°$, $\varphi = 0$ (non-isoaxial sampling in the vertical plane).

Convergence of the air flow outside the inlet promotes "secondary aspiration", i.e. the aspiration of particles into the inlet after they have bounced (or re-entered by blow-off, roll-off) off the outer surface of the sampler's body as illustrated in Fig. 1. The concentration of such "rebounded" particles, C_r, depends not only on fluid dynamic parameters but also on the phase and surface properties of the particles. Since the process of particle–wall interactions is very complex, the efficiency of secondary aspiration is not easily predictable. A number of methods have been used to measure secondary aspiration. Under certain conditions this effect is negligible, i.e. $C_r \ll C_a$ (Vincent, 1981, 1989; Lipatov *et al.*, 1988a). In the present analysis of available bioaerosol samplers, only primary aspiration is considered in the calculations.

After passing the inlet face, some particles may impact onto the inner wall at the entrance region of the inlet, as seen in Fig. 1. The length of this region is estimated to be about one inlet diameter. Particle deposition inside the sampling orifice just past the inlet face is primarily due to direct wall impaction (in the case divergent air flow near the inlet face) or due to the vena contracta effect (in the case of convergent air flow), as indicated by Hangal and Willeke (1990b). The concentration, C_{t0}, of particles that have passed this short entrance region defines the transmission efficiency of this region:

$$E_{t0} = \frac{C_{t0}}{C_a}. \tag{7}$$

The value of E_{t0} is primarily a function of inlet geometry and orientation as well as the velocity ratio [equation (2)], the Stokes number [equation (3)], and the bluntness ratio [equation (4)].

The further movement of aspirated aerosol particles through the inlet sampling line is affected by wall losses due to physical mechanisms such as gravitational settling, crosswise migration in shear flow, turbulent deposition, molecular diffusion, electrostatic migration, and thermophoresis. As a result, the sampled particle concentration, C_s, at the sampling line

outlet is generally less than C_{t0}. The transmission efficiency of the sampling line is expressed as

$$E_{t1} = \frac{C_s}{C_{t0}}. \tag{8}$$

The value of E_{t1} can be determined for each sampling situation through quantitative analysis of the longitudinal and crosswise particle motion within the sampling line and the resulting particle deposition on the inner wall (Brockmann, 1993). The individual particle removal mechanisms have been quantified (Liu and Agarwal, 1974; Schwendiman *et al.*, 1975; Crane and Evans, 1977; Heyder an Gebhart, 1977; Gorbis and Spokoinyi, 1977; Okazaki and Willeke, 1987; Pui *et al.*, 1987; Lipatov *et al.*, 1989, 1990; Hangal and Willeke, 1990b; Fan *et al.*, 1992). The E_{t1} component depends on the size, geometry and orientation of the sampling line, the flow conditions, and particle characteristics such as particle size and density.

The overall sampling efficiency of an inlet (that was introduced above the ISE), E_s, is the product of equations (1), (7) and (8):

$$E_s = E_a E_{t0} E_{t1}. \tag{9}$$

The product of the aspiration efficiency and the transmission efficiency of the initial inlet region is defined as the entrance efficiency, E_e:

$$E_e = E_a E_{t0}. \tag{10}$$

For inlets which do not have a significant distance between the sampling orifice and the collection medium (i.e. $E_{t1} = 1$), the overall sampling efficiency is approximately equal to the entrance efficiency. This is typical for many bioaerosol samplers, such as the Burkard and Lanzoni samplers which will be introduced further below.

BIOAEROSOL SAMPLERS AND PARTICLES EVALUATED

The characteristics of several commercially available or recently developed experimental bioaerosol samplers are listed in Table 1. As seen, these instrument (impactors and impingers) have been designed for a specific type of bioaerosol, such as bacteria, fungi or pollen, or can be used for more than one type. The inlets have different shapes and are oriented horizontally or vertically or either way. The sampling flow rates range from 0.5 to 200 l min^{-1} and the inner inlet sizes from a slit width of 0.1 cm to an inner diameter of 5.8 cm. Some of the samplers, such as the all glass impinger (AGI-30, Ace Glass Inc., Vineland, NJ, U.S.A.), 6-stage Andersen viable sampler AVS, Graseby Andersen Inc., Atlanta, GA, U.S.A.), Lanzoni sampler (Model VPPS-2000, Lanzoni Co., Bologna, Italy), Krotov's apparatus (KA, Ministry of Instrumentation, Moscow, Russia), Reuter centrifugal air sampler (RCS, Biotest Diagnostics Corp., Fairfield, NJ, U.S.A.), and the Burkard samplers (BPAS-AP and BRAS, Burkard Manufacturing Co. Ltd., Richmansworth, U.K.) are widely used in practice for indoor and outdoor bioaerosol measurements (Borovik *et al.*, 1983; Burge and Solomon, 1987; Cox, 1987; Henningson, 1988; Chatigny *et al.*, 1989; Nevalainen *et al.*, 1992). The sampler for airborne microorganisms (Model M-12, Pedagogical Institute, Kirov, Russia), the static particle size selective bioaerosol sampler (SPSSBS, Technical Research Centre of Finland, Espoo, Finland), and the sampler of bacteriological aerosols (Model PBA-1, Ministry of Instrumentation, Moscow, Russia) are less used at this time.

The inlet characteristics of several samplers have been calculated for particle sizes of 1, 5, 8, 10 and 30 μm. Table 2 introduces several examples of bioaerosol particles of these sizes reported in the literature. Particle sizes of 1, 5 and 10 μm represent single bacteria, bacteria aggregates and bacteria-carrying particles, respectively. The 5 μm particles also represent fungal spores, and the 8 μm particles represent yeast. The size of 30 μm has been chosen as typical example of pollen (Owen *et al.*, 1992). The ISE has been evaluated for wind

Table 1. Characteristics of several bioaerosol samplers

Sampler	Bioaerosols sampled	Flow rate ($l\,min^{-1}$)	Characteristics of inlet: Orientation of sampling inlet	Characteristics of inlet: Shape of inlet	Characteristics of inlet: Inner size of inlet (cm)
All glass impinger (AGI-30)	Bacteria	12	Horizontal	Sharp-edged tubular	0.8*
Andersen viable sampler (AVS)	Bacteria Fungi	28.3	Horizontal or vertical	Sharp-edged tubular	2.54*
Burkard portable air sampler for agar plates (BPAS-AP)	Bacteria Fungi	10† 20†	Horizontal or vertical	Sharp-edged tubular	2.7*
Burkard recording air sampler (BRAS)	Fungi Pollen	10	Vertical	Blunt slit	0.1 × 1.4
Lanzoni sampler (VPPS-2000)	Fungi Pollen	0.5‡ 11‡	Horizontal	Sharp-edged slit	0.2 × 1.4
Krotov's apparatus (KA)§	Bacteria	20	Vertical	Sharp-edged and blunt tubular¶	1*‖
Reuter centrifugal air sampler†† (RCS)	Fungi Pollen	40	Facing the wind	Sharp-edged tubular	5.8
Sampler for airborne microorganisms (M-12)‡‡	Bacteria Fungi Pollen	9–10	Vertical	Sharp-edged tubular	1*‖
Static particle size selective bioaerosol sampler§§	Fungi Pollen	18.5	Horizontal	Annular slit with circular cover	3.18 (width) 21.3 (diameter)
Sampler of bacteriological aerosols§ (PBA-1)	Bacteria	150–200	Vertical	Sharp-edged tubular	1*‖

*The inner diameter of inlet.
†10 $l\,min^{-1}$ is the standard flow rate, 20 $l\,min^{-1}$ is the maximal one.
‡0.5 $l\,min^{-1}$ is the minimal flow rate, 11 $l\,min^{-1}$ is the maximal one.
§Designed by the Ministry of Instrumentation, Moscow, Russia.
¶KA uses a number of sampling head—thin- and thick-walled tubular inlets.
‖This inlet inner diameter is the most common one used in practice; however, this sampler can be used with a variety of sampling heads of different sizes.
††Chatigny *et al.*, 1989.
‡‡Designed in the Pedagogical Institute, Kirov, Russia, 1990.
§§Developed by Kauppinen *et al.*, 1989.

velocities ranging from 0 (calm air) to 500 $cm\,s^{-1}$ (high-velocity flow). This velocity range represents all typical indoor and outdoor air flows.

EQUATIONS USED IN CALCULATIONS

Each component of the ISE for a specific sampler, namely the aspiration efficiency and the transmission efficiencies of the inlet's entry region as well as the sampling line, has been calculated through the equations presented in this section.

Aspiration efficiency

The aspiration efficiency, E_a, is affected by the inlet geometry of the sampler under consideration. Conventionally, inlets are classified by shape, rectangular (slit) versus round (tubular), and by thickness of the inlet material, thin-walled (sharp-edged) versus thick-walled (blunt).

The sampler is considered to be thin-walled, if $D_0/D_i < 1.1$ (Belyaev and Levin, 1974); in such a case the effect of the bluntness ratio on aspiration efficiency is neglected. Belyaev and Levin have shown that even when D_0/D_i is much larger than 1.1, the effect of the bluntness

Table 2. The particle diameters for several biaerosols

Type of bioaerosol	Subgroup	Example	Equivalent aerodynamic diameter, d_{ae} (μm)	Reference
Bacteria	Bacteria spores	Thermoactinomyces	1	Gregory (1973)
	Bacteria aggregates	*Micrococcus luteus* (8-cell-aggregate of 2 μm-diameter cells)	4.7	Atlas (1988) Buchanan and Gibbons (1974)
	Bacteria carrying particles	Cough droplet	9.2	Edmonds (1979)
Fungi	Fungi spores	*Aspergillus* spp.	5	Larone (1987)
	Yeast	*Cryptococcus neoformans*	8	Larone (1987)
Pollen	Pollen	*Lycopodium*	30	Gregory (1973)

ratio can still be negligible for a sharp-edged sampling inlet with an angle of taper not exceeding 15°. Most studies on aspiration efficiency have focused on aerosol sampling from moving air into a *thin-walled or sharp-edged tubular* inlet (Belyaev and Levin, 1974; Durham and Lundgren, 1980; Vincent, 1986, 1989; Wiener *et al.*, 1988; Lipatov *et al.*, 1988a; Grinshpun *et al.*, 1990; Hangal and Willeke, 1990a, b). All of the equations for the calculation of E_a, developed in these studies, are based on the "moving air model" and have the same general expression:

$$(E_a)_{mov} = 1 - (1 - R\cos\theta)\beta(\theta;\ R;\ \mathrm{Stk_i}) \tag{11}$$

where β is a semi-empirical function of the ambient and sampling conditions. The available equations for this function have been reviewed by Vincent (1989) and Hangal and Willeke (1990a).

Equation (11) can be used only for sampling from high-speed air flows because it quantifies the particle inertia effect but does not consider the effect of gravity. The latter is not negligible, if U_w is comparable with V_s, and becomes especially important when sampling aerosol from calm air (Grinshpun *et al.*, 1990, 1993). Traditionally, one has to decide whether the ambient aerosols are aspirated from calm air or fast moving environments. Indoor air environments, however, are generally neither of the two. In order to cover the entire range of field conditions from calm air to high-velocity air flows, a new universal equation has recently been developed for aerosol aspiration into sharp-edged tubular inlets (Grinshpun *et al.*, 1992–1994):

$$E_a \approx (E_a)_{mov}(1+\Delta)^{0.5} f_{mov} + (E_a)_{calm} f_{calm} \tag{12}$$

where

$$\Delta = \frac{V_s}{U_w}\left[\frac{V_s}{U_w} + 2\cos(\theta \pm \varphi)\right] \tag{13}$$

$$f_{mov} = \exp\left(-\frac{V_s}{U_w}\right), \qquad f_{calm} = 1 - \exp\left(-\frac{V_s}{U_w}\right) \tag{14}$$

$$(E_a)_{mov} = 1 - (1 - R\cos\theta)\beta_\theta$$

$$\beta_\theta = \begin{cases} 1 - [1 + (2R + 0.62)\mathrm{Stk_i}]^{-1} & \text{for } \theta = 0 \\ \dfrac{\{1 - [1 + (2R + 0.62)\mathrm{Stk_{i,\theta}}]^{-1}\}[1 - (1 + 0.55\lambda\ \mathrm{Stk_{i,\theta}} R)^{-1}]}{1 - (1 + 2.62\ \mathrm{Stk_{i,\theta}} R)^{-1}} & \text{for } 0 < \theta < 60° \\ 3(\mathrm{Stk_i} R)^{R^{-1/2}} < 1 & \text{for } 60° < \theta \leqslant 90° \end{cases} \tag{15}$$

$$\mathrm{Stk}_{i,\theta} = \mathrm{Stk}_i \exp(0.022\,\theta), \quad \lambda = \exp(0.25\,\mathrm{Stk}_{i,\theta}\,R) \tag{16}$$

$$(E_a)_{calm} = \exp\left[-\frac{4(\mathrm{Stk}_i)v^{1/2+1}}{1+2\,\mathrm{Stk}_i}\right] + v\cos\varphi. \tag{17}$$

The aspiration into *thick-walled* (*blunt*) inlets has been studied by a number of authors, most extensively by Vincent and his co-authors, and are summarized in a book on aerosol sampling by Vincent (1989). For blunt inlets equation (11) is modified by parameter b_u,

$$b_u = \left(\frac{D_i}{D_0}\right)^n \frac{U_i}{U_w} = b^{-n}R^{-1} \tag{18}$$

where $n=1$ for a two-dimensional inlet and $n=2$ for an axisymmetric one. The aspiration efficiency of a blunt tubular inlet can be presented as a product of two functions:

$$(E_a)_{mov,\,blunt} = E_1 E_2 \tag{19}$$

$$E_1 = 1 + \frac{G_1\,\mathrm{Stk}_1}{1+G_1\,\mathrm{Stk}_1}[B^2(\theta)b^{2/3}R^{1/3}\cos\theta - 1] \tag{20}$$

$$E_2 = 1 + \frac{G_2\,\mathrm{Stk}_2}{1+G_2\,\mathrm{Stk}_2}\left[\frac{R^{1/3}b^{-1/3}}{B(\theta)} - 1\right] \tag{21}$$

$$\mathrm{Stk}_1 = \mathrm{Stk}_i \frac{R^{4/3}b^{-1/3}}{B(\theta)}[\cos\theta + 4B(\theta)b^{1/3}R^{1/6}\sin^{1/2}\theta] \tag{22}$$

$$\mathrm{Stk}_2 = \mathrm{Stk}_i \frac{R^{2/3}b^{-2/3}}{B^2(\theta)} \tag{23}$$

where $B(\theta)$ is the semi-empirical function, and G_1 and G_2 are the empirical coefficients introduced by Vincent (1989). Summarizing data on the aspiration efficiency for blunt tubular (disk-shaped) samplers, Vincent presented ranges for B, G_1, and G_2:

$$B = 0.6\text{–}1, \qquad G_1 = 0.15\text{–}0.25, \qquad G_2 = 1.2\text{–}6.0 \tag{24}$$

depending on the geometrical size of the inlet and sampling conditions.

Some bioaerosol samplers have a slit as an inlet. Aerosol aspiration into slit inlets has been studied numerically by Addlesee (1980) on the basis of the potential flow model. A thin-walled inlet of long rectangular cross-section facing high-velocity flow has been examined. Although his model has not been incorporated into an equation for $(E_a)_{mov}$ that can be used in practice, the results of the numerical calculations are applicable to predict the aspiration efficiency for some commercial slot inlets. Addlesee's data on $(E_a)_{mov}$ are presented graphically as a function of velocity ratio and Stokes number. Therefore, using this data, we can determine the aspiration efficiency for each sampling situation related to Addlesee's model ($R = 1.5\text{–}20$, $\mathrm{Stk}_i \sim 10^{-1}\text{–}10^2$).

Transmission efficiency of the entrance region

Most bioaerosol samplers have a very short sampling line or practically none at all. For example, the impaction surface of the Burkard recording air sampler and the Lanzoni VPPS-2000 is located almost right after the sampling orifice, without any channel for particle transport from the entrance to the collection medium. Even in this case, considerable particle loss may occur in the short region right behind the sampling orifice, as indicated by Tufto and Willeke (1982), Okazaki and Willeke (1987), and Grinshpun *et al.* (1991). These losses are caused by direct impaction onto the inner wall in non-isoaxial sampling situations or when $U_w \neq U_i$ or by turbulent deposition in the vena contracta when $U_w < U_i$ (Hangal and Willeke, 1990b). For this reason, the transmission efficiency of the entrance region, E_{t0}, has to be quantified for inlets of any length.

A unified model for particle wall deposition in the entrance region of sharp-edged tubular inlets has been developed by Willeke and co-authors (Okazaki and Willeke, 1987; Hangal

and Willeke, 1990b, 1992) for aerosol sampling from moving air. The transmission efficiency resulting from impaction to the inner wall, $E_{t0}=E_{ti}$, has been expressed as a function of velocity ratio, the Stokes number, V_s/U_w, and sampling angle θ:

$$E_{ti}=\exp[-75(I_W+I_V)^2] \tag{25}$$

where direct wall impaction parameter, I_W, and vena contracta deposition parameter, I_v, are, respectively:

$$I_W=\mathrm{Stk}_i\, R^{1.5}\sin(\theta\pm\alpha)\sin\left(\frac{\theta\pm\alpha}{2}\right) \tag{26}$$

$$\begin{aligned} I_v &= 0{\cdot}09[(1-R)R^{-2}\,\mathrm{Stk}_i\cos\theta]^{0.3} \quad \text{for } R<1 \\ I_v &= 0 \qquad\qquad\qquad\qquad\qquad\qquad\quad \text{for } R\geqslant 1 \end{aligned} \tag{27}$$

Angle α is the gravity effect angle first introduced by Hangal and Willeke (1990b) and then simplified for two ranges of the sampling angle: $\theta=0$–$15°$ and $\theta=15$–$90°$ (Hangal and Willeke, 1990b, 1992). We have now expressed α in general as

$$\alpha=\theta-\left[\sin^{-1}\left(\sin\theta-\frac{V_s}{U_w}\cos\theta\right)\right]. \tag{28}$$

Transmission efficiency of the sampling line

If a sampling line of sufficient length exists between inlet face and collection medium (e.g. in the all glass impinger, AGI-30), the transmission efficiency, E_{t1}, of this line should be evaluated. The particles may migrate to the inner surface of the sampling line and deposit there due to gravity, inertia, diffusion, Saffman effect, etc. Available equations for various physical mechanisms causing particle loss in inner walls have recently been summarized by Brockmann (1993). Some of these mechanisms may lead to significant deposition of bioaerosol particles in a certain section of the sampling line; the influence of others is negligible. To calculate E_{t1}, the particle deposition due to each mechanism in each section should be evaluated. The equations which have been used in our calculations are given below.

Gravitational settling of particles in the first section of a tubular inlet has been quantified by Okazaki and Willeke (1987) and Hangal and Willeke (1990b). They developed the following semi-empirical equation for the gravitational-settling transmission efficiency when sampling aerosol from horizontal flow:

$$E_{t1,\,grav}=\exp(-4.7\,K_\theta^{0.75}) \tag{29}$$

where

$$K_\theta=\varepsilon_i\,\mathrm{Stk}_i^{1/2}\,\mathrm{Re}^{-1/4}(\cos\theta)^{1/2} \tag{30}$$

$$\varepsilon_i=\frac{L_i V_s}{U_i D_i}. \tag{31}$$

Here L_i is the length of the first section, the inlet region towards the sampling orifice; Re is the Reynolds number in this section,

$$\mathrm{Re}=\frac{U_i D_i \rho}{\eta} \tag{32}$$

ρ is the air density. It is important to note that the first section of the sampling line is not the same as the entrance region of the inlet. It is usually much longer and its length effects the transmission efficiency as seen from equations (29)–(31). Equation (30), introduced for horizontal wind, operates with the angle θ between the inlet axis and the wind direction. However, to characterize the particle deposition within an inclined inlet tube, we should use the angle φ of the inlet orientation in the gravitational field rather than the sampling angle

θ. For horizontal flows, $\varphi = 90^\circ - \theta$. Therefore, equations (29) and (30) can be rewritten as

$$E_{t1,\,grav} = \exp(-4.7\ K_\varphi^{0.75}) \tag{33}$$

$$K_\varphi = \varepsilon_i\ \mathrm{Stk}_i^{1/2}\ Re^{-1/4}\ (\sin\varphi)^{1/2}. \tag{34}$$

Equation (33) quantifies the gravitational settling of particles specifically in the first section of the inlet. At the same time, gravitational losses may also occur in the other non-vertical sections downstream the sampling line, e.g. after the aerosol flow changes direction in the bend or after passing an abrupt contraction. The gravitational-settling transmission efficiency of each such tubular section can be determined using the Heyder and Gebhart (1977) formula developed for laminar flow:

$$E_{t1,\,grav,\,laminar} = 1 - \frac{2}{\pi}\left[2\varepsilon_j(1-\varepsilon_j^{2/3})^{1/2} - \varepsilon_j^{1/3}(1-\varepsilon_j^{2/3})^{1/2} + \arcsin(\varepsilon_j^{1/3})\right] \tag{35}$$

where

$$\varepsilon_j = \frac{3}{4}\frac{L_j V_s}{U_j D_j}\sin\varphi \tag{36}$$

L_j and D_j are the length and diameter of the corresponding j-section, and U_j is the average air velocity in this section. If the flow in the j-section is turbulent, gravitational-settling transmission efficiency is expressed following Schwendiman *et al.* (1975) and Brockmann (1993) as

$$E_{t1,\,grav,\,turbulent} = \exp\left(-\frac{4}{\pi}\varepsilon_j\right). \tag{37}$$

The axial component of the particle settling velocity should always be relatively small. That is expressed by the following criterion:

$$\frac{V_s\cos\varphi}{U_j} \ll 1. \tag{38}$$

This criterion is applicable in both cases, the laminar and turbulent flows.

When the aerosol is transported through the bend, the particles may deviate from the air due to their inertia and deposit on the wall of the sampling line. A simple empirical equation for the corresponding component of the transmission efficiency has been developed for laminar flow by Crane and Evans (1977):

$$E_{t1,\,bend,\,laminar} = 1 - \frac{\pi}{2}\mathrm{Stk}_{bend}\,\omega \tag{39}$$

where

$$\mathrm{Stk}_{bend} = \frac{\tau U_{bend}}{D_{bend}} \tag{40}$$

is the Stokes number as a function of the bend diameter, D_{bend}, and the air velocity in the bend, U_{bend}; ω is the angle of the bend in radians. Pui *et al.* (1987) have found the equation applicable for turbulent flow in the bend:

$$E_{t1,\,bend,\,turbulent} = \exp(-2.823\ \mathrm{Stk}_{bend}\,\omega). \tag{41}$$

When the aerosol is transported through the vertical tube, the Saffman force drives particles towards the wall in the downward flow or from the wall to the tube centerline in the upward flow (Saffman, 1965, 1968). If the flow is laminar, the transmission efficiency can be determined following Lipatov *et al.* (1989) as a function of dimensionless parameter χ:

$$\chi = \frac{g\rho_p d_p^3 \rho}{4\eta^2}\frac{L_v}{D_v}\,\mathrm{Re}^{-1/2}. \tag{42}$$

Here L_v and D_v are the length and diameter of the vertical section. The data presented by Lipatov *et al.* (1989, 1990) can be used directly to determine the corresponding component of the transmission efficiency.

When the turbulence in the central region of the tube propels the particles into the laminar sublayer of the turbulent boundary layer, inertial deposition may occur. The turbulent-inertial transmission efficiency can be quantified following Liu and Agarwal (1974) as

$$E_{t1,\,\text{turbulent, inertia}} = \exp\left(-\frac{4L_{\text{turb}}V_{\text{turb}}}{D_{\text{turb}}U_{\text{turb}}}\right) \tag{43}$$

where

$$V_{\text{turb}} = (1.86 \times 10^{-7})\,\text{Stk}_{\text{turb}}^{2}\,\text{Re}^{11/8}U_{\text{turb}} \tag{44}$$

is the turbulent deposition velocity of the particles; L_{turb} and D_{turb} are the length and diameter of the section of the sampling line where the turbulent inertia is considered; U_{turb} is the average velocity of the air flow through this section; and Stk_{turb} is the Stokes number.

$$\text{Stk}_{\text{turb}} = \frac{\tau U_{\text{turb}}}{D_{\text{turb}}}. \tag{45}$$

The air turbulence in the sampling line may also lead to particle motion fluctuation which affects the crosswise migration of particles and, hence, the wall losses. This effect has been estimated using the model introduced by Gorbis and Spokoinyi (1977). It turned out that, for typical sizes of bioaerosol particles and typical flow rates of bioaerosol samplers, the fluctuation factor is not significant and should be neglected in the bioaerosol samplers' evaluation.

In addition to the above-considered models of particle transport through the sampling line, there are a number of equations available to quantify other mechanisms which cause wall loss, such as diffusion, thermophoresis, electrostatic migration, etc. (Brockmann, 1993). However, these mechanisms do not play an important role when sampling bioaerosol particles.

RESULTS AND DISCUSSION

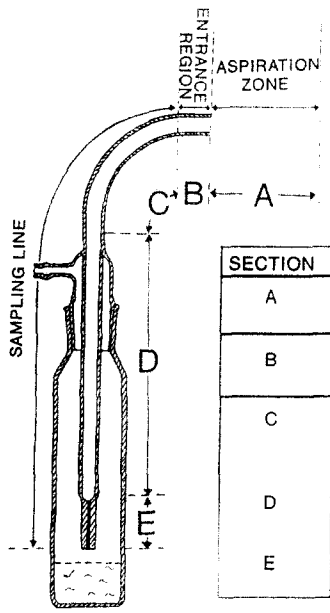
The models and equations, described above, have been used to calculate the inlet sampling efficiency of selected bioaerosol samplers.

AGI-30 impinger

The design of the AGI-30 impinger is schematically represented in Fig. 2. This bioaerosol sampler is used primarily for bacteria measurements in indoor and outdoor air and in a smaller extent for fungi monitoring. It has been chosen for evaluation because its inlet requires a discussion of all three ISE components, equation (9), and of all physical mechanisms affecting the inlet sampling efficiency. Particle inertia and gravitational sedimentation of particles in the ambient environment lead to over- or undersampling during aspiration (Zone A); inertial impaction or vena contracta deposition in the entrance region (Zone B) as well as wall losses due to phenomena such as gravitation, inertia, turbulence, and Saffman's particle migration (Zones B–E) affect transmission efficiencies E_{t0} and E_{t1}.

Since the AGI-30 has a sharp-edged tubular inlet, equation (12) has been used to calculate its aspiration efficiency. The transmission efficiency of the entrance region has been determined using equation (25). Equations (32), (35), (39), (41), and (43) have been used to determine the transmission efficiency of the impinger sampling line.

The results of the sampling efficiency calculations for the AGI-30 are shown in Fig. 3. The bioaerosol particles of unit density ($\rho_p = 1\ \text{g cm}^{-3}$) ranging 1–10 μm in diameter are extracted from a variety of wind velocities (0–500 cm s^{-1}) into an inlet of 0.8 cm in diameter. In



SECTION	MECHANISM	COMPONENT
A	INERTIA, SEDIMENTATION	E_a
B	IMPACTION, VENA CONTRACTA	E_{ti}
C	GRAVITATIONAL SETTLING, IMPACTION IN BEND, TURBULENT INERTIA	E_{tl}
D	SAFFMAN EFFECT, TURBULENT INERTIA	
E	SAFFMAN EFFECT, TURBULENT INERTIA	

Fig. 2. Mechanisms which affect the inlet sampling efficiency of the AGI-30.

general, the density of bacteria and fungi ranges 0.9–1.24 g cm^{-3} (Orr and Gordon, 1956; Luria, 1960; Bratbak and Dundas, 1984); we assumed $\rho_p = 1$ g cm^{-3}. The particle size, d_{ae}, indicated in Fig. 3 and successive figures, is an equivalent aerodynamic diameter which is a diameter of spherical particles of the same gravitational settling velocity, V_s:

$$d_{ae} \approx \zeta d_p \left(\frac{\rho_p}{\rho_0}\right)^{1/2} \tag{46}$$

where ζ is a product of the particle shape correction factor and the slip correction factor (Baron and Willeke, 1993); and ρ_0 is unit density. As has been indicated above, wind velocities up to 500 cm s^{-1} (= 5 m s^{-1} = 1000 fpm = 18 mph) represent most of the indoor and outdoor air environments polluted by bioaerosols: $U_w \leqslant 100$ cm s^{-1} for indoor, and $U_w > 100$ cm s^{-1} for outdoor air. The sampling air velocity of the AGI-30 is set at 400 cm s^{-1}, corresponding to a flow rate of 12 l min^{-1}.

As shown in the top figure, the aspiration efficiency, E_a, of the AGI-30 may be either higher or lower than 1 depending on whether the sampling velocity is lower or higher than the wind velocity. The most significant aspiration bias can occur when sampling aerosols from near-stagnant flow, which is typical for indoor air environments. For a given wind velocity below the inlet velocity, the reduction in aspiration efficiency increases with increasing particle size above 1 μm.

The middle figure of Fig. 3 shows the transmission efficiency due to direct wall impaction and vena contracta deposition in the entrance of the sampler, $E_{ti} = E_{t0}$. Equation (25) has been applied to these calculations. It has been found that E_{t0} decreases with increasing particle size. Here, also, the most significant decrease of E_{t0} from unity occurs at near-stagnant conditions.

In order to calculate the overall sampling efficiency of the inlet of the AGI-30, the possible physical mechanisms of particle loss which affects the transmission efficiency along the sampling line (E_{tl}) have been considered. The loss due to gravitational settling in zone B (Fig. 2) of 1 cm length and 0.8 cm diameter has been calculated by equation (33). It turns out to be negligible (< 4%), if d_{ae} is less than 10 μm. The gravitational settling in the 90° bend C of the transmission line (length is about 8 cm) does not exceed 5%. The particle deposition due to inertial impaction in the bend C, equations (39) and (41), turns out to be negligible for single bacteria of 1 μm in equivalent aerodynamic diameter; however, it

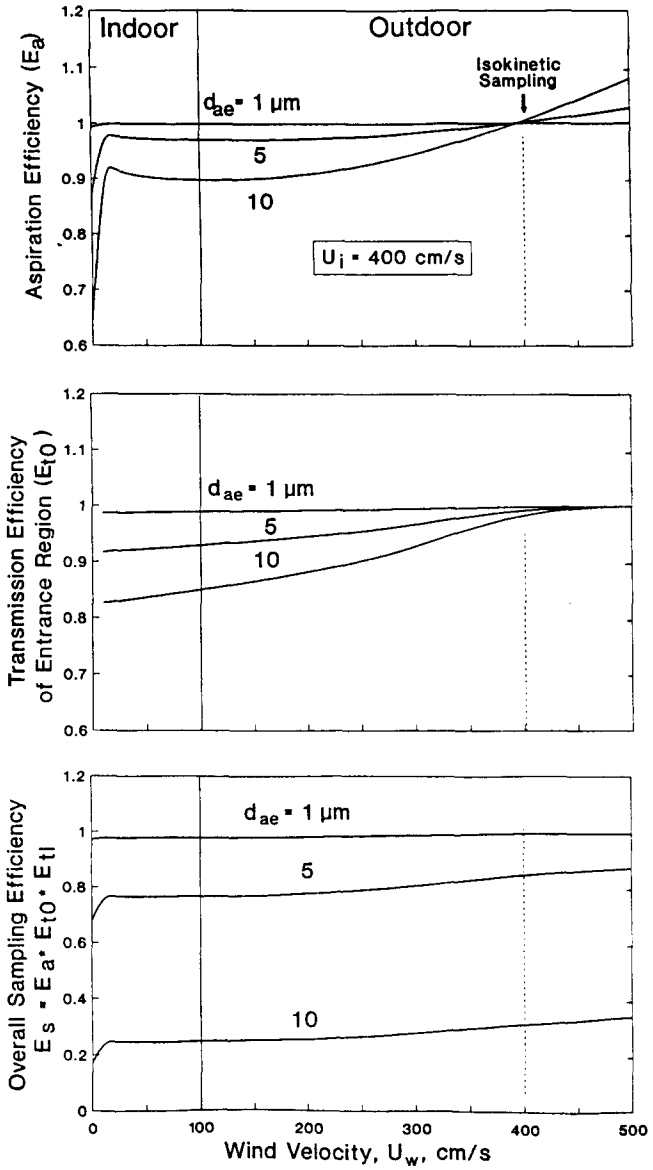


Fig. 3. Components and overall sampling efficiencies of the AGI-30 impinger.

becomes significant for bacteria agglomerates and other particles as soon as d_{ae} exceeds 3 μm: from 6% to 15% losses for $d_{ae}=5$ μm and up to 44% for $d_{ae}=10$ μm. The total turbulent inertial deposition in bend C and vertical tube D (total length is about 26 cm) has been calculated by equation (43) and turns out to be considerably smaller (about 1–2%) for d_{ae} = 1–10 μm. The loss in zone D caused by the Saffman effect is negligible. The Saffman effect does not lead to considerably more efficient inner deposition in capillary E either. However, turbulent inertial deposition in capillary E can be significant: it is less than 5% for d_{ae} = 1–5 μm; however, it increases rapidly for larger particles, and leads to 40% loss for d_{ae} = 10 μm. All these results have been considered in the calculations of E_{t1}.

By multiplying E_a, E_{t0}, and E_{t1}, the overall sampling efficiency of the AGI-30 inlet (ISE) has been obtained, as shown at the bottom of Fig. 3. As seen, the ISE is close to 100% for 1 μm particles, but is significantly reduced for 5 μm and larger particles. For 10 μm particles, the ISE is only 20–30%. In the latter case, the ISE is mostly affected by highly effective particle deposition on the inner walls of the sampling line.

6-Stage Andersen viable sampler

The ISE of the 6-stage Andersen viable sampler, AVS, is affected by particle aspiration from the ambient environment into the inlet and by direct wall impaction and vena contracta deposition inside the inlet. There is no separate sampling line in this sampler (i.e. $E_{t1} = 1$ according to its definition). In other words, the entrance efficiency introduced by equation (10), represents the ISE of the AVS. The bluntness effect is neligible since the tubular inlet is sharp-edged. The components of E_a and E_{t0} have been calculated by use of equations (12) and (25), respectively, for single bacteria (1 μm), bacteria agglomerates and fungal spores (5 μm), yeast (8 μm), and bacteria-carrying particles (10 μm). The AVS is typically used for bioaerosols in this particle size range. Figure 4 shows its entrance efficiency. It indicates that E_e depends on the orientation of the sampler relative to the wind direction. When the wind velocity exceeds the inlet sampling velocity of 93 cm s^{-1}, the entrance efficiency may exceed 100% (oversampling) for particles larger than 1 μm if the sampler faces the wind, as shown in the top graph of Fig. 4. The entrance efficiency may be significantly less than 100% (undersampling) if the sampler is placed upright at 90° to the wind direction, as shown in the bottom graph of Fig. 4. The larger the particle, the more significant is the deviation of the entrance efficiency from 100%, as already seen with the AGI-30. For example, 10 μm particles are almost totally lost in the entrance region of the AVS when the sampler is positioned upright at 90° to wind of about 500 cm s^{-1}. Figure 4 shows that the entrance efficiency of the AVS is about 100% or a little less for sampling from indoor air environments. It may be significantly less than 100% when sampling from outdoor air environments.

Burkard portable air sampler for agar plates

The entrance efficiency of the Burkard portable air sampler, BPAS-AP, has been calculated by use of equations (12) and (25). This bioaerosol sampler is mostly used for the

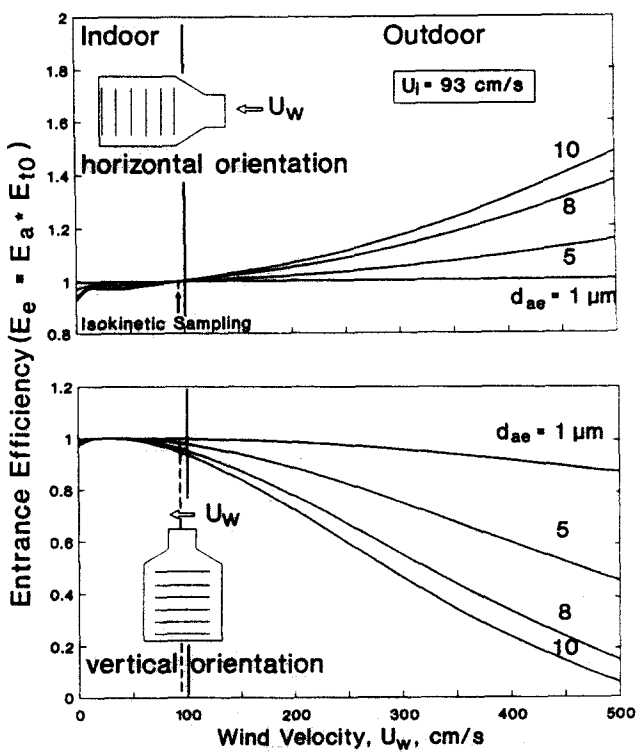


Fig. 4. Entrance efficiency of the Andersen viable sampler.

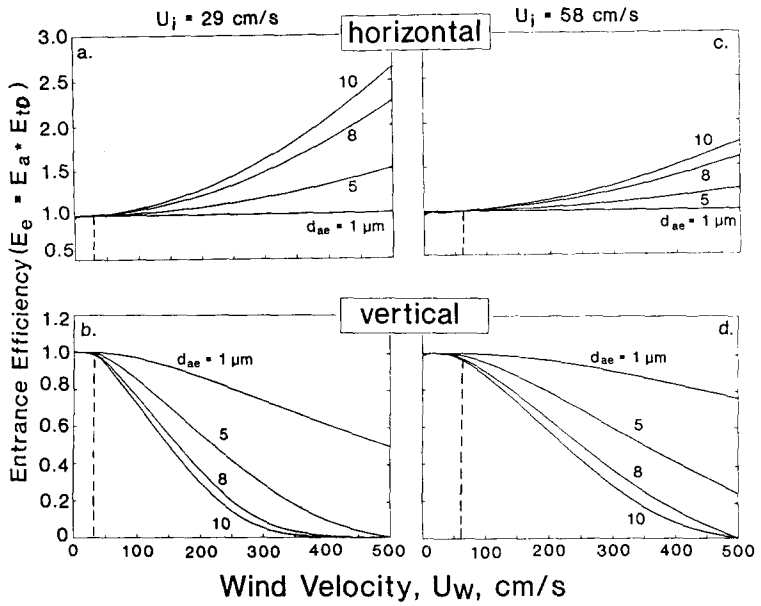


Fig. 5. Entrance efficiency of the Burkard portable air sampler for agar plates.

collection of bacteria and fungi over the same particle size range 1–10 μm as the AVS. The results of our calculations are shown in Fig. 5. The calculations have been carried out for the standard inlet sampling velocity of 29 cm s^{-1} and the maximal inlet sampling velocity of 58 cm s^{-1}. Horizontal versus vertical orientation of the sampler relative to the horizontal wind direction has also been considered, similar to the evaluation shown in Fig. 4. As indicated in Fig. 5, the sampler orientation relative to the wind direction changes the trend of the entrance efficiency as the wind velocity increases. When the BPAS-AP is placed horizontally parallel to the wind direction, the entrance efficiency exceeds 100%. When it is placed upright at 90° to the horizontal wind direction, the entrance efficiency may be significantly reduced from 100%. Figure 5 illustrates sampling situations for which particle gain or loss may be especially significant. For instance when the wind velocity is 450 cm s^{-1} (not a common situation for this sampler) and the particles are sampled at 29 cm s^{-1}, the entrance efficiency for 10 μm particles is close to 250% (particle gain of 150%) in the horizontal sampler position, and close to 0% (total particle loss) in the vertical sampler position. It appears that sampler positioning at an angle between horizontal and vertical orientations may result in less dependence on wind velocity.

Lanzoni sampler

Similar to the widely used Burkard recording air sampler (BRAS), the Lanzoni sampler has been designed with a slit inlet to sample fungi and pollen mostly from outdoor air. Unlike the BRAS, the Lanzoni sampler has a thin-walled inlet and a wind vane orients the inlet into the wind. To determine the aspiration efficiency of this sampler, the Addlesee (1980) data, which graphically present the E_a dependence on the Stokes number and velocity ratio, have been used directly. The values of Stk_j and R have been calculated using the sampling characteristics of the Lanzoni sampler (Table 1) for particle sizes of 5, 8 and 30 μm and wind velocities ranging from 30 cm s^{-1} (isokinetic sampling) to 500 cm s^{-1} (highly anisokinetic sampling). The results of the E_a determination are shown in Fig. 6. When the wind velocity is larger than the inlet sampling velocity of 30 cm s^{-1} (at a flow rate of 0.5 l min^{-1}), the aspiration efficiency of the sampler is greater than 100%. The larger the particle, the more significant is the deviation of aspiration efficiency from 100%. The aspiration bias becomes especially high when sampling pollen of $d_{ae} = 10$ μm and larger; e.g. the aspiration efficiency for 30 μm particles is 1000% at a wind velocity of 500 cm s^{-1}. This

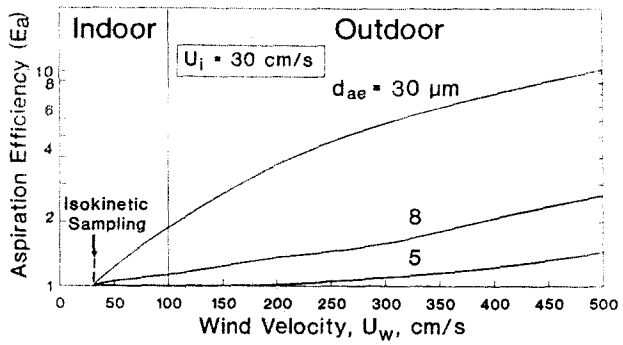


Fig. 6. Aspiration efficiency of the Lanzoni sampler, Model VPPS-2000.

shows that the indicated aerosol concentration may be as much as 10 times the actual concentration. Such significant oversampling due to anisokinetic aspiration has been obtained with the assumption of isoaxial aspiration. However, in the field, the wind vane does not line up perfectly—which may result in particle loss due to non-isoaxial inlet orientation. In addition, some internal losses may occur as well (there are no equations available in the literature to evaluate the inner loss for the slit inlet). The decrease of the aerosol concentration caused by the two above-mentioned reasons may partially compensate for the considerable oversampling illustrated in Fig. 6.

The calculations of ISE have also been carried out for some of the other bioaerosol samplers indicated in Table 1. The newly developed model of aerosol aspiration into sharp-edged or thin-walled tubular inlets, equations (12)–(17), and the unified model of the entrance transmission efficiency, equations (25)–(28), have been applied to determine the entrance efficiency of the Reuter centrifugal air sampler, a high-volume sampler that was designed to collect relatively large bioaerosol particles from outdoor air environments. The ISE has been calculated for the following ambient conditions: $U_w = 50$–$500\ \mathrm{cm\ s^{-1}}$, $\theta = \pm 30°$, $d_{ae} = 5$–$30\ \mu\mathrm{m}$. It turns out that this device provides reasonably accurate measurements (with efficiency of 95–110%) not only for fungi of 5 μm but also for pollen of 30 μm (a high bias is usually expected for the larger size). The model developed by Vincent (1987, 1989) and introduced above by equations (19)–(24) has been used for the calculation of the aspiration efficiency into the thick-walled tubular inlet of the Krotov apparatus, KA. It has been found that the bias caused by aspiration is comparatively small (<5%) for a single bacteria of about 1 μm in size. For bacteria agglomerates and fungi spores of 5–10 μm in diameter, the KA seems to be accurate when operating in indoor air environments ($U_w \leqslant 100\ \mathrm{cm\ s^{-1}}$); however, the aspiration bias is considerably higher (up to 50%) if sampling from outdoor air environments ($U_w = 500\ \mathrm{cm\ s^{-1}}$). The high-volume sampler of bacteriological aerosols PBA-1, in contrast, is less reliable when sampling aerosol from indoor air (up to 30% losses for $d_{ae} = 3\ \mu$m). A wide range of the ISE, from about 20 to 800%, has been found for such recently developed bioaerosol samplers as the M-12 and the SPSSBS listed in Table 1. The sampling efficiency of the latter sampler has been determined on the basis of data obtained by Lipatov *et al.* (1988b) for an inlet of similar design. It turns out that the most significant bias occurs when both of the above-mentioned samplers are used for pollen.

The results reported in the literature of field comparison studies performed with different bioaerosol samplers (summarized by Nevalainen *et al.*, 1993) are not easily comparable to each other. To conduct an accurate comparison of their performance characteristics is not possible because, in most studies, ambient conditions, sampling regime, and operational parameters varied within and between different tests and were not reported. In addition, the results of field comparison studies provide data on the overall efficacy which includes not only ISE, but also collection characteristics and microbiological bias.

Nevertheless, the field testing results are experimental evidence of the sampling efficiency dependence of bioaerosol measurement devices on environmental parameters and the

bioaerosols studied. Under different conditions, two bioaerosol samplers may perform differently relative to each other. For instance, according to Placencia *et al.* (1982) and Groeschel (1980), the Reuter centrifugal sampler performs better than the slit-to-agar sampler in laboratory environments and hospitals at low bacteria concentration while, in the same paper, Groeschel reports the opposite tendency: the slit-to-agar sampler performs better than the RCS when sampling bacteria of high concentration in hospitals (this tendency has also been confirmed by Verhoeff *et al.*, 1990, for fungal spores sampled from home air environments). However, the performance of a certain sampler relative to another one should not depend on the particle concentration in the air environment. We postulate that a major reason for the noted difference in sampler performance may be samplers' dependence on the wind speed and predominant particle size which may have been different in different tests as well as on sampling velocity and inlet geometry which are different for each device. In other words, when conducting different tests, we deal with different velocity ratios, R, the Stokes numbers, Stk_i, and other parameters which affect, in particular, the aspiration and transmission efficiencies as has been illustrated in our calculations. As seen from Figs 3–6, under certain conditions bioaerosol particles can be sampled unbiased while, if conditions change, significant bias may occur for the same instrument. This fact has an experimental confirmation: Raynor (1970), who measured the efficiency of several sampling heads using uranine crystals of typical bacteria size (0.68 μm), *Ustilago* spores (6 μm), and *Ambrosia* pollen (20 μm), showed that efficiency varied from under 1% to over 100%. Another experimental confirmation of a considerably high sampling bias found in our calculations is laboratory data on the aspiration and transmission efficiencies of tubular inlets obtained by Grinshpun *et al.* (1991) for *Lycopodium* spores. It should also be expected that the aspiration and transmission efficiencies were among the factors that affected the performance characteristics of bioaerosol samplers evaluated by Jensen *et al.* (1992) while their influence was not predominant under most of the laboratory conditions used in that study.

CONCLUSIONS

As shown by the ISE calculations, the concentration of bioaerosol particles recorded by bioaerosol samplers can be highly biased and, thus, different from the actual concentration levels in indoor or outdoor air environments. Under certain sampling conditions, the recorded concentration of particles, which represents single bacterium, bacterial aggregates, bacteria carrying particles, fungal spores, yeast and pollen, was found to be significantly over- or underestimated. For instance, at wind velocities up to 500 cm s^{-1}, calculations show that the AGI-30 would sample 1–10 μm particles with an inlet sampling efficiency of 20–100%. The entrance efficiency of the 6-stage Andersen viable sampler is 90–150% when sampling isoaxially with respect to horizontal wind and 8–100% when oriented vertically at a right angle to horizontal wind. For the Burkard portable air sampler, the range of deviation of E_e from 100% may be even wider. The bioaerosol samplers, used mostly in outdoor environments to collect large particles such as pollen, are even less accurate: e.g. 10 times the ambient concentration of *Lycopodium* spores has been calculated to be aspirated by the Lanzoni sampler when operated to 0.5 l min^{-1} facing the wind at wind velocity of about 500 cm s^{-1}. At the same time, the calculation showed that several bioaerosol measurement devices (such as Krotov's apparatus and Reuter centrifugal air sampler) have reasonable good inlet efficiency under wide ranges of ambient conditions and particle size.

The inlet sampling efficiency primarily depends on the physical characteristics of the bioaerosol particles to be sampled (such as the size and density) as well as the inlet face characteristics (such as its size, geometry and orientation) and the environmental conditions (such as wind velocity and direction). In addition, the configuration of the sampling line, e.g. the bend and the capillary tube of the AGI-30, also affects the sampling efficiency.

The actual bioaerosol concentration level can be determined in each situation by dividing the measured concentration by the inlet sampling efficiency. The graphs on the inlet

sampling efficiency of several bioaerosol samplers, presented in this paper, can be used to bracket the sampling conditions that enable an investigator to avoid or minimize significant sampling bias for each sampler. The equations and graphs can also be used for the design of new samplers or for modifying commercial ones in order to improve their performance.

It should be noted that the inlet characteristics relate only to one aspect of the sampling efficacy of a bioaerosol sampler. Bias may also be associated with the different impaction or impingement velocities in the samplers which may damage the microorganisms as they are projected against the collection medium. Bias may also result for microbiological analysis of viable particles (the latter relates to "survivability" of microorganisms). Similar to the inlet sampling efficiency, the collection efficiency of bioaerosol samplers and "survivability" may add uncertainty to the bioaerosol measurement. Therefore, these characteristics should be separately quantified and optimized in the design of new bioaerosol samplers.

Acknowledgements—We appreciate the financial support of the Center for Indoor Air Research which stimulated the efforts described in this paper through Contracts Nos. 90–16 and 93–11. We are also grateful to Suresh Kalatoor for his valuable help in reviewing the manuscript.

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