The Analyst

Annular Aspiration Slot Entry Efficiency of the CIP-10 Aerosol Sampler*

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The CIP-10 personal or static aerosol sampler is designed to sample the respirable, thoracic or inhalable aerosol fraction by using the appropriate selector. All these versions have the same downward-oriented annular aspiration slot. The annular slot entry efficiency at a flow rate of 10 l min^{-1} was studied as a static sampler in an experimental wind tunnel, at first for a 1 m s^{-1} wind velocity. Glass beads were generated as a test aerosol by a fluidized bed aerosol generator. A sharp-edged thin-walled isokinetic probe was used for reference sampling. The particle size-dependent efficiency was deduced from the particle size distributions of both reference and annular slot samples. Particle size distributions were measured as functions of the volume equivalent diameter D_v by the Coulter Multisizer technique. The aerodynamic particle diameter D_{ae} was deduced from D_v by using particle density and Reynolds number. The entry efficiency of the CIP-10 annular aspiration slot at 1 m s^{-1} is between 0.9 and 0.4 for the whole range of particle aerodynamic diameters within the range 10–60 μm. By minimizing the inner particle deposit under the protecting cup of the selector, the instrument can meet the CEN sampling criteria for sampling of inhalable aerosol as shown on the bias and accuracy maps.

Keywords: *Aerosol; inhalable fraction; sampling performance; bias; accuracy*

Introduction

The overall sampling efficiency of an aerosol sampler is the product of several efficiencies such as entry efficiency, inner deposition efficiency (or wall losses) and collection efficiency of the filtration stage. The size-dependent sampling efficiencies for health-related aerosol fractions have recently been standardized by the standards organizations CEN[1] and ISO[2] and also adopted by the ACGIH.[3]

For the least selective of these fractions, the inhalable fraction, the overall sampling efficiency of a sampler is often limited by the entry efficiency of its aspiration orifice. It is possible to take into account the wall losses into the sample when the overall sampling efficiency is too low, but before doing so one should ensure that all particles composing the inhalable fraction enter the sampling orifice.

The CIP-10 aerosol sampling instrument was first developed as a respirable dust sampler.[4] Recently it was equipped with a thoracic[5] and inhalable aerosol selector.[6] Whereas the respirable and thoracic versions meet well the sampling conventions,[7,8] the inhalable version under some conditions (low external wind speeds, 0.5–1 m s^{-1}; torso-mounted sampler) can undersample the inhalable fraction.[9] The inner wall losses were suspected to be the cause of this behaviour. However, prior to an investigation of the wall losses, it seems logical to ensure that the whole inhalable fraction enters the sampler orifice. The aim of this study was to determine the entry efficiency of the CIP-10 used as a stationary sampler operating at 10 l min^{-1} in a wind speed of 1 m s^{-1}.

Experimental

The inhalable sampling head of the CIP-10 personal or static aerosol sampler is shown in Fig. 1. The air inlet orifice of the instrument is designed as a downward-oriented annular aspiration slot. It ensures omni-directional acrosol sampling, which is less sensitive to the sampler orientation. The downward aspiration avoids direct entry of sedimenting coarse particles. The dimensions of the aspiration slot are as follows: external diameter, 36.0 mm; inner diameter, 30.4 mm; and aspiration area, 292 mm^2. With the nominal flow rate of the sampler, which is 10 l min^{-1} for the inhalable and respirable versions, the aspiration velocity of the annular orifice is about 0.6 m s^{-1}.

The experimental trials were performed in an experimental wind tunnel which has been described elsewhere.[10] The wind tunnel inner diameter is 30 cm. The sampling head and the sharp-edged thin-walled isokinetic reference probe were placed simultaneously in the tunnel (Fig. 2). The sampling orifice was

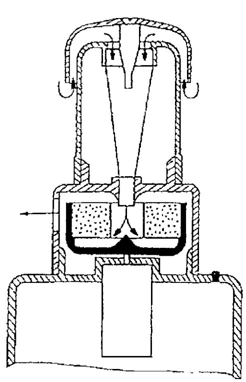

Fig. 1 CIP-10 instrument sampling head, inhalable version.

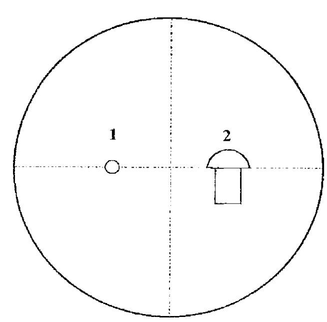

Fig. 2 Schematic diagram of the reference sampler position and the annular slot sampling head position in the wind tunnel. 1, Reference sampler; 2, CIP-10 sampling head.

* Presented at AIRMON '96, Sälen, Sweden, February 5–8, 1996.

tested as a static sampler, without any manikin or other flow-perturbing body. The blockage of the tunnel flow by both samplers together is less than 3%. The relative deviation between the mean velocity measured at any location of the sampling zone and the mean velocity measured at the central point remains within ±5%. The turbulence intensity varies between 3 and 8%.

The aerosol particles are generated by a fluidized-bed generator,[11] and are injected into the tunnel air flow 4.5 m upstream of the sampling point. The generated material is made of spherical glass beads. Their particle density is ρ_p = 2.60 g cm^{-3}. The relative deviation between the mean aerosol concentration at any location along the horizontal axis of the sampling zone (Fig. 2) and the mean concentration measured at the central point remains within ±10%. However, a high concentration gradient was observed on the vertical axis of the sampling zone, due to the coarse particle sedimentation. This is why the tested sampling orifice and the reference sampler were placed on the same horizontal level symmetrically with respect to the tunnel axis (Fig. 2). The time stability of the aerosol concentration was also determined. The RSD of the mean aerosol concentration at the central point, calculated from several successive measurements of 30 min each, remained within ±7%

Particles in the measuring zone were sampled by a 10.6 mm circular reference probe, working under isokinetic isoaxial conditions, on to a 25 mm Nuclepore polycarbonate membrane filter (nominal pore size 2.0 μm). The particle size distributions were measured by the electrical sensing zone method[12] using a Coulter Multisizer (Coulter Electronics, Luton, UK). The electrolyte solution used for this measurement was the Isoton II (Coultronics France, Andilly, France) mixed with 20% by mass of glycerol to decrease the particle sedimentation velocity in the liquid suspension. A few drops of surface-active agent were also added.

The measured volume equivalent particle diameter D_v was transformed into the aerodynamic diameter D_{ae} by solving the following equation by means of an iterative process:[13,14]

$$\frac{\rho_o\, K_c(D_{ae})\, D_{ae}}{K_d(D_{ae})} = \frac{\rho_p\, K_c(D_v)\, D_v}{K_{rv}\, K_d(D_v)} \quad (1)$$

where ρ_p = 2.60 g cm^{-3} is the particle density measured by pycnometry, ρ_o is the density of 1 g cm^{-3}, K_c is the Cunningham slip correction factor, K_d is the drag coefficient and K_{rv} is the dynamic shape factor (K_{rv} = 1 because of the particle sphericity). The Reynolds number Re_p of large particles can exceed 0.1, the upper limit of the Stokes regime. In that case, a correction due to non-linearity of the relationship between drag coefficient and Re_p was calculated by using the following equation:[15]

$$K_d = 24/Re_p\,[1 + 0.1315\, Re_p^{(0.82 - 0.05 \log Re_p)}],\ 0.01 \leq Re_p \leq 20 \quad (2)$$

At a wind velocity of 1 m s^{-1}, the particle size distribution in the measuring zone of the tunnel yields a number-median aerodynamic diameter (NMAD) of about 18 μm, which corresponds to a mass-median aerodynamic diameter (MMAD) of about 27 μm. The geometric standard deviation (GSD) is within 1.4–1.5. This ensures a sufficient concentration of coarse particles in the measuring zone up to about 60 μm in aerodynamic diameter.

The annular orifice sample and the reference sample were collected simultaneously for analysis. To measure the entry efficiency of the annular orifice, the internal wall losses inside the sampling head and the reference probe were quantitatively recovered by washing all internal surfaces and added to the samples. Details of all experimental operations were given by Witschger.[13] Both total particle mass and particle size distribution were measured for each sample. The particle size-dependent experimental entry efficiency of the annular slot $E_a(D_{ae})$ can be calculated from

$$E_a(D_{ae}) = dC_a(D_{ae})/dC_r(D_{ae}) \quad (3)$$

where $dC_a(D_{ae})$ is the particle aerosol concentration which enters the annular slot for an aerodynamic diameter within [D_{ae}; $D_{ae} + dD_{ae}$] and $dC_r(D_{ae})$ is the size dependent reference concentration for the same aerodynamic diameter. The efficiency $E_a(D_{ae})$ can be calculated from eqn. (3) by using either number or mass concentrations. In our case, the number concentrations were used in the efficiency calculation because of the Coulter particle size analysis. This analysis yields primarily the number distribution of volume equivalent particle size.

The experimental values of the annular slot entry efficiency are reported in Fig. 3 *versus* particle aerodynamic diameter. The experimental points are plotted with their confidence intervals evaluated from the experimental procedure. These intervals correspond to $\pm 2\sigma(E_a)$, where $\sigma(E_a)$ is the standard deviation calculated by analysis of error propagation on the basis of all elementary experimental variables. The spatial variability of aerosol concentration and the error in particle counts and sampled volumes were taken into account.[13]

Data Treatment

The weighted experimental efficiency data were fitted by a polynomial law to obtain an analytical expression of the efficiency function $E_c(D_{ae})$:

$$E_c(D_{ae}) = P_2 \times D_{ae}^2 + P_1 \times D_{ae} + 1 \quad (4)$$

A Newton–Gauss fitting algorithm for minimizing a weighted least-squares function χ^2 was used, where

$$\chi^2 = \Sigma\, w_i\, (E_{ai} - E_{ci})^2 \text{ and } w_i = 1/\sigma^2(E_{ai}) \quad (5)$$

E_{ai} and E_{ci} are the experimental efficiency and the corresponding calculated efficiency from the mathematical model, respectively. As the statistical errors of the experimental data are taken into account in the fitting algorithm, the parameters P_1 and P_2 are calculated with their standard deviation σP_j. The resulting parameters are as follows:

$$P_1 = (-1.08 \pm 0.23) \times 10^{-2} \quad (6)$$

$$P_2 = (+2.32 \pm 0.03) \times 10^{-5} \quad (7)$$

The entry efficiency function was then used to simulate the sampler behaviour for a wide range of aerosol distributions with

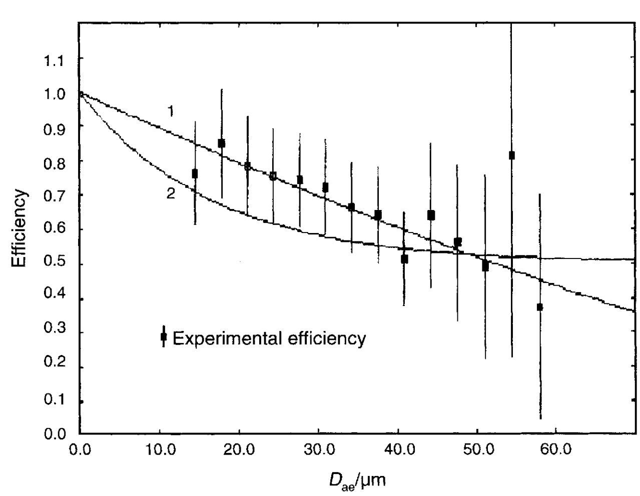

Fig. 3 Experimental entry efficiency of the CIP-10 annular aspiration slot at a 1 m s^{-1} wind speed. The error bars are the 95% confidence intervals. 1, Polynomial model of the experimental data; 2, CEN,[1] ISO[2] and ACGIH[3] inhalable convention.

MMAD ranging from 1 to 25 μm in steps of 1 μm and GSD from 1.5 to 3.5 in steps of 0.25 according to the CEN (Comité Européen de Normalisation) draft document *Assessment of Performance of Instruments for Measurement of Airborne Particles*.[16] The range of aerosol distributions used covers adequately most situations which might occur in the field of occupational hygiene.[16,17]

The theoretical inhalable mass concentration C_I and the annular slot mass concentration C_A were calculated[7,18] by using the conventional inhalable sampling efficiency[1–3] $E_I(D_{ae})$ and the annular slot efficiency $E_c(D_{ae})$, respectively:

$$C_I = C_0 \int_0^\infty E_I(D_{ae}) \times F_m(D_{ae}) \times \mathrm{d} \ln D_{ae} \quad (8)$$

$$C_A = C_0 \int_0^\infty E_c(D_{ae}) \times F_m(D_{ae}) \times \mathrm{d} \ln D_{ae} \quad (9)$$

where $F_m(D_{ae})$ is the aerosol mass distribution function, $E_I(D_{ae})$ is the conventional probability of penetration, $E_c(D_{ae})$ is the modelled sampling efficiency [eqn. (4)] of the instrument and C_0 is the concentration of total ambient aerosol, taken here as unity. A particle aerodynamic diameter of 100 μm was taken as the upper limit of the numerical integration, because above this limit the inhalable fraction is not defined.[1]

The concentration bias Δ of the annular slot was calculated for each aerosol with respect to the conventional concentration C_I:

$$\Delta = (C_A - C_I)/C_I \quad (10)$$

The bias for all aerosol distributions is shown in the bias map in Fig. 4. The CEN draft[16] proposes that a top-class sampling device should not exceed a bias of ±10%.

The standard deviation of the bias characterizes the uncertainty in the bias estimation and can be calculated as follows:

$$\sigma(\Delta) = \sigma(C_A/C_m)/(C_I/C_m) \quad (11)$$

where C_m is the ambient aerosol mass concentration in the tunnel, measured by the reference probe under isokinetic isoaxial conditions. The standard deviation $\sigma(C_A/C_m)$ was calculated according to Fabriès[19] by using the curvature matrix **U** of the χ^2 function and the variance–covariance matrix $\boldsymbol{V}$ of the optimized model parameters $\boldsymbol{P}$:

$$U_{jk} = \delta^2\chi^2/\delta P_j\, \delta P_k \text{ with } j = 1, 2; k = 1, 2 \quad (12)$$

$$\boldsymbol{V} = S^2\, \boldsymbol{U}^{-1} \quad (13)$$

$$S^2 = \chi^2/\nu \quad (14)$$

where $\nu = (n-p)$ is the number of degrees of freedom calculated from the number of experimental data (n) and the number of fitted parameters (p). Finally, one can deduce[20] that:

$$\sigma^2(C_A/C_m) = \boldsymbol{T}^t\, \boldsymbol{V}\, \boldsymbol{T} \quad (15)$$

$$T_j = \delta(C_A/C_m)/\delta P_j \quad (16)$$

where $\boldsymbol{T}^t$ means the transposed vector of vector $\boldsymbol{T}$ and δ numerical derivation.

The upper limit of the absolute bias at 90% confidence level can be calculated:[16]

$$\text{upper } \Delta = |\Delta| + t\, \sigma(\Delta) \quad (17)$$

where t is the value of the Student function for $\alpha = 0.1$ (90% level) and for ν degrees of freedom. In our case, the number of experimental efficiency values is $n = 14$ and the number of fitted parameters is $p = 2$. Hence, there are $\nu = 12$ degrees of freedom and the Student function value is $t = 1.782$. The total sampler precision[16,21] in terms of the RSD is composed of inter-specimen variations, flow rate variations, analytical errors, *etc*. Such information is often missing, and in this case the CEN draft[16] recommends estimating an upper limit of the total sample precision of RSD = 2%.

On the basis of the bias with its uncertainty and the total sampler precision, it is possible to calculate the sampler accuracy by iterative solution of the Bonferroni equation at suitable confidence level as described by Bartley and Fischbach.[22] For an aerosol sampler it is admitted[16,23] that its inaccuracy should not exceed 30%.

Results and Discussion

The results of the experimental assessment of the CIP-10 annular aspiration slot entry efficiency are plotted in Fig. 3 along with both the numerical model $E_c(D_{ae})$ and the inhalable sampling convention $E_I(D_{ae})$, as a function of particle aerodynamic diameter. The sampler bias and accuracy of an aerosol sampler vary with the ambient aerosol particle size distribution. They depend on the position of the sampler efficiency curve $C_A(D_{ae})$ and the conventional efficiency curve $C_I(D_{ae})$ within the particle aerodynamic diameter interval covered by the aerosol distribution. The sampler bias and accuracy are currently used for the sampler performance evaluation.[18,21,22,24,25] Therefore, they were calculated for a wide range of aerosol distributions covering most occupational hygiene situations, as described above.

The results of these calculations are shown in the bias (Fig. 4) and accuracy (Fig. 5) maps. The MMAD and GSD of the

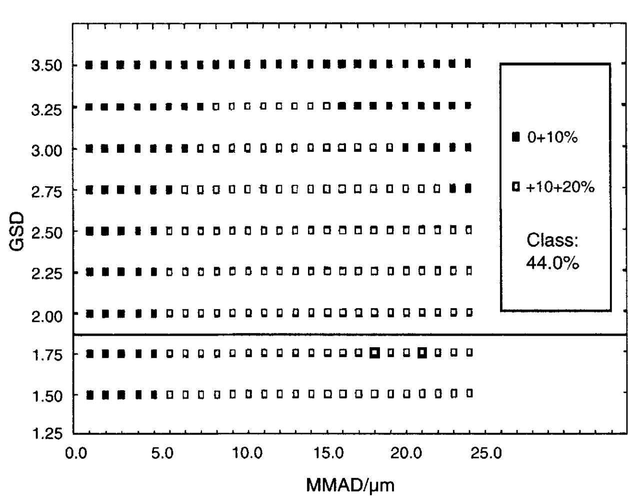

Fig. 4 Bias map of the annular inlet entry efficiency.

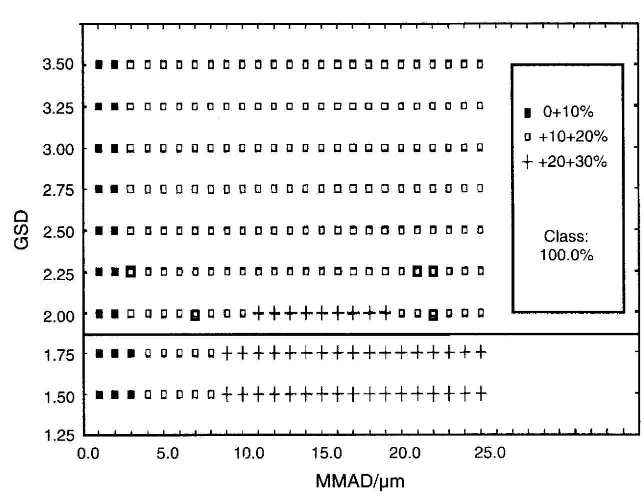

Fig. 5 Accuracy map of the annular inlet entry efficiency.

aerosol distributions used are reported on the abscissa and ordinate, respectively. Thus, each point on the map represents some aerosol distribution. The shape-coded points correspond to a bias or accuracy level that would be met by the sampler placed in any given aerosol distribution. For sampler performance evaluation, only aerosols with GSD $\geqslant$ 2 (performance evaluation area) are taken into account.[16] The number of aerosols for which the bias and inaccuracy do not exceed the limit of ±10% and +30%, respectively, is compared with the total number of aerosols inside the evaluation area of the maps. The ratio gives an indication of the sampler performance, (see Figs. 4 and 5).

The entry performance of the CIP-10 sampler annular aspiration slot satisfies 44% of test aerosols in bias (Fig. 4) and 100% of aerosols in accuracy (Fig. 5). The minimum bias is +2.3% for MMAD = 1 µm and GSD = 2, the maximum bias is +15.2% for MMAD = 15 µm and GSD = 2 and the maximum inaccuracy is 21.3% for MMAD = 14 and GSD = 2.

As shown by these results, the CIP-10 annular aspiration slot, used as a static aerosol sampler in an external wind of 1 m s^{-1}, slightly oversamples the conventional inhalable fraction with a satisfactory accuracy. By minimizing inner wall losses located mainly under the protective cap of the selector, or by taking them into account, the overall sampling efficiency of the device could meet the conventional sampling criteria[1–3] for the inhalable aerosol fraction. To extend the sampler performance evaluation to higher wind speeds or to personal sampling, further investigations should be carried out.

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Paper 6/01004K
Received February 12, 1996
Accepted April 11, 1996