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Laboratory Study of Selected Personal Inhalable Aerosol Samplers

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Assessment of inhalable dust exposure requires reliable sampling methods in order to measure airborne inhalable particles' concentrations. Many inhalable aerosol samplers can be used but their performances widely vary and remain unknown in some cases. The sampling performance of inhalable samplers is strongly dependent on particle size and ambient air velocity. Five inhalable aerosol samplers have been studied in two laboratory wind tunnels using polydisperse glass-beads' test aerosol. Samplers tested were IOM sampler (UK), two versions of CIP 10-I sampler, v1 and v2 (F), 37-mm closed face cassette sampler (USA), 37-mm cassette fitted up with an ACCU-CAP™ insert (USA), and Button sampler (USA). Particle size-dependent sampling efficiencies were measured in a horizontal wind tunnel under a 1 m s^{-1} wind velocity and in a vertical tunnel under calm air, using a specific method with Coulter® counter particle size number distribution determinations. Compared with CEN–ISO–ACGIH sampling criteria for inhalable dust, the experimental results show fairly high sampling efficiency for the IOM and CIP 10-I v2 samplers and slightly lower efficiencies for the Button and CIP 10-I v1 samplers. The closed face cassette (4-mm orifice) produced the poorest performances of all the tested samplers. This can be improved by using the ACCU-CAP™ internal capsule, which prevents inner wall losses inside the cassette. Significant differences between moving air and calm air sampling efficiency were observed for all the studied samplers.

Keywords: ACCU-CAP; aerosol sampling efficiency; button sampler; CIP 10-I; closed face cassette; inhalable convention; IOM sampler

INTRODUCTION

Industrial dust pollution in both the workplace and the environment remains a topical problem in developed and developing countries (WHO, 1999). Measurement of worker exposure to harmful dust is commonly undertaken in occupational hygiene management. Conventional health-related aerosol fractions represent target specifications for size-selective sampling of particles. The inhalable aerosol fraction is sampled for most particulate air pollutants, e.g. wood dust. This fraction, defined by CEN (1993), ISO (1995), and ACGIH (1994–1995) conventions, describes the efficiency with which particles are aspirated into the nose and mouth with respect to particle aerodynamic diameter, within a 0- to 100-μm interval and a 0- to 4-m s^{-1} wind velocity range. The need for a specific 'calm air' inhalable convention has recently been expressed by Lidén and Harper (2006), based on scientific progress in particle inhalability measurements (Aitken *et al.*, 1999; Brown, 2005). Indoor workplace wind speed measurements of Baldwin and Maynard (1998) indicate that a calm air inhalable convention would be appropriate to many working situations today (air velocities usually $\leq$0.3 m s^{-1}).

Around 3.5 million workers (2% of all employees in 25 European Union countries) are currently exposed to wood dust (Kauppinen *et al.*, 2006).

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Woodworker nasal cancer is the second most frequent occupational cancer in France (INRS, 2006). In Europe, the threshold limit value (TLV) for wood dust in the workplace varies from 1 to 5 mg m^{-3}. These TLVs must usually be applied to the inhalable aerosol fraction. In France, the former TLV of 5 mg m^{-3} was reduced to 1 mg m^{-3} in 2003, the latter value being applicable from 2005 (legislative Decree, 2003).

Accurate assessment of inhalable dust exposure requires reliable sampling methods for measuring the inhalable concentration of airborne particles. Many sampling techniques are available worldwide, but their efficiency varies and remains unknown in some cases. A selection of suitable samplers is listed in the CEN (2005) 'sampling guide', along with their performance characteristics extracted from the scientific literature.

The sampling efficiency of aerosol samplers is usually measured in a wind tunnel using monodisperse or polydisperse aerosols. Aerosol sampler efficiency is defined by the ratio of sampled and reference aerosol concentrations with respect to particle aerodynamic diameter. Theoretical and experimental evaluations of aerosol sampler performance show that sampling efficiency is strongly dependent on particle size and ambient air velocity. Laboratory evaluation of sampling efficiency can be performed under high wind speed conditions (Buchan *et al.*, 1986; Chung *et al.*, 1987; Vincent and Mark, 1990; Vincent *et al.*, 1990; Kenny *et al.*, 1997; Witschger *et al.*, 1997; Bartley, 1998; Aizenberg *et al.*, 2000a,b, 2001; Li *et al.*, 2000; Kennedy *et al.*, 2001; Paik and Vincent, 2004, for example) or in very slow moving air conditions (Kenny *et al.*, 1999; Roger, 2000; Witschger *et al.*, 2004; Schmees *et al.*, 2008). Personal inhalable sampler performance has been mostly evaluated in moving air and few studies have been conducted in really calm air (Kenny *et al.*, 1999; Görner *et al.*, 2008).

We selected five samplers for in-depth testing in the laboratory and at the workplace. This paper presents and analyses results of wind tunnel aerosol sampling efficiency measurements at 1 m s^{-1} and in the calm air conditions. Comparative field trials with wood dust sampling by the same samplers in various industrial workplaces are presented by Kauffer *et al.* (2010).

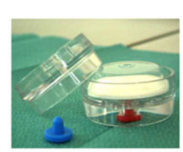
MATERIALS AND METHODS

Inhalable aerosol sampling techniques

Personal inhalable aerosol samplers used in this study are listed and represented in Table 1 along with their nominal flow rates. Choice of samplers was guided by availability, expected efficiency, and experience in using and handling them.

The IOM sampler (Mark and Vincent, 1986) was selected because it is used worldwide for personal inhalable sampling. Particles are drawn into the device through a 15-mm circular inlet orifice under a suction flow rate of 2 l min^{-1}. The sampler incorporates an internal plastic cassette, which is weighed together with the 25-mm filter it contains. Most particles passing through the inlet orifice are collected on the filter and the remainder are deposited on the cassette inner walls. This sampler is known to meet inhalable sampling criteria in moving air (Kenny *et al.*, 1997; Kennedy *et al.*, 2001) for particle aerodynamic diameters <100 µm and when the sampler is not facing a wind (Li *et al.*, 2000) or coarse projected particles, which can occur in the workplace.

Table 1. Tested inhalable aerosol samplers

Sampler	IOM sampler	CIP 10-I	37 mm closed face cassette	ACCU-CAP™	Button sampler
Provider	SKC (UK)	ARELCO (F)	MILLIPORE (US)	OMEGA (US)	SKC (US)
Flow rate ($L.min^{-1}$)	2	10	1; 2	1; 2	4
Photograph					

Knowledge of its performance in very slow moving air is limited to a few investigations, namely Roger *et al.* (1998) and Kenny *et al.* (1999).

The CIP 10-I inhalable sampler has been developed from its former respirable and thoracic versions (Courbon *et al.*, 1988; Fabriès *et al.*, 1998). The principle of the CIP 10 sampler is based on the aerosol aspiration through a narrow annular orifice under a suction flow rate of 10 l min^{-1} and air filtration by a rotating porous foam filter (Görner *et al.*, 1990). This sampler is commonly used in the French wood industry because of its high flow rate and its shielded multidirectional sampling head, which limits sampling of projected coarse particles.

Historically, there are two known versions of the CIP 10-I inhalable sampler. The first version (v1), in which some inner wall losses could occur (Kenny *et al.*, 1997), was recently improved by incorporating a horizontal annular aspiration slot (Görner *et al.*, 2008) to give the final version (v2), patented (Görner *et al.*, 2003) and fully described by Görner *et al.* (2009). Both versions were laboratory tested in this study. However, the v2 version was not available in sufficient numbers to be extensively used in field trials during an associated study of Kauffer *et al.* (2010).

The 37-mm diameter closed face cassette (CFC) is the most commonly used aerosol sampler, despite its recognized low sampling efficiency for particles >30 μm (Kenny *et al.*, 1997) and its several limitations (inner wall losses, bypass leakage, non-uniform deposition on collection filter, and under-sampling when inlet orifice is oriented downward—Demange *et al.*, 1990; Paskar *et al.*, 1991; Baron *et al.*, 2002; Demange *et al.*, 2002). Historically, a 'closed face cassette' means a cassette with a 4-mm circular aspiration orifice, not the filter diameter orifice (called 'open cassette'). The three-piece non-conductive polystyrene cassette was designed before the other samplers tested. It remains widely used because of its simplicity and low cost. It is usually operated at a flow rate of 2 l min^{-1}. This sampler is traditionally used in France at a flow rate of 1 l min^{-1} to meet the 1.25 m s^{-1} ter Kuile (1978, 1984) aspiration velocity criterion.

The ACCU-CAP™ is not a complete sampler but an accessory sampling capsule, which can be inserted inside the 37-mm diameter cassette to prevent wall losses. This capsule is used with a two-piece cassette and supporting pad. The ACCU-CAP™ dome-shaped capsule is moulded from clear static-dissipative plastic and is heat-sealed on the sampling filter.

The Button sampler (Kalatoor *et al.*, 1995, Aizenberg *et al.*, 1998, 2000a) is included in this study because of its promising screening performance with respect to very large particles potentially projected by woodworking machines (Harper and Muller, 2002; Harper *et al.*, 2004). Particles are drawn into the sampler at a flow rate of 4 l min^{-1} and are collected on a 25-mm diameter filter. The Button sampler has a hemispherical metal screen inlet with 381-μm diameter mesh openings, amounting to 21% of the total inlet area. Few laboratory data have been published in relation to Button sampler performance characteristics in low air movement environments.

Other samplers could have been included in the study, but these are of limited usage in France (German PGP-GSP, 3.5 l min^{-1}) or complicated, very recent, or expensive. One of them is the RESPICON personal sampler, operated at a flow rate of 3.1 l min^{-1} (Koch *et al.*, 1999, 2002). This modern and useful sampler is equipped with an annular slot inlet and is therefore less sensitive to sampler orientation. The device was tested for wood dust sampling by Rando *et al.* (2005). In France, its use is not sufficiently widespread and therefore it cannot take part in future field trials. However, we measured its sampling efficiency in laboratory conditions and it does help us to understand shielded annular sampling slot behaviour, especially in a calm air environment.

Laboratory equipment for sampling efficiency measurement

Previously validated experimental set-up and methods (Witschger, 1996; Witschger *et al.*, 1997; Roger *et al.*, 1998; Roger, 2000, Görner *et al.*, 2008) were re-implemented for performing the experimental investigations described in this study. In the case of the inhalable fraction, wind conditions in the vicinity of the sampler were taken into account because of their influence on large particle aspiration. Particle inhalability is shown to differ in calm air from its values in moving air (Aitken *et al.*, 1999; Brown, 2005). That is why particle size-dependent sampling efficiency was measured in a horizontal wind tunnel under a wind velocity of 1 m s^{-1} and in a vertical wind tunnel under calm air conditions. An experimental polydisperse spherical particle aerosol was used.

The experimental 1 m s^{-1} wind tunnel provided a horizontal supply of test aerosol particles to a measuring zone where samplers under test or reference probe can alternatively be exposed.

The calm air tunnel provided a downward vertical supply of aerosol particles to a measuring zone where samplers under test or reference probe were alternatively exposed.

The test aerosols were generated from polydisperse glass micro-sphere powder using a fluidized-bed aerosol generator (Guichard, 1976). The mass median aerodynamic diameter (MMAD) and the geometric standard deviation (GSD) were MMAD = 24 μm and GSD = 1.4 in the horizontal 1 m s^{-1} wind tunnel; MMAD = 27.5 μm and GSD = 1.6 in the vertical calm air tunnel. Using spherical particles allowed us to overcome certain problems in determining the aerodynamic diameter from the measured volume diameters (Witschger *et al.*, 1997). Such a polydisperse test aerosol enabled us to determine several experimental sampling efficiency points within a wide range of particle aerodynamic diameters (from a few micrometre to ~70 μm) in just one experiment.

Full descriptions of the two wind tunnels and attached laboratory equipment (including schematic diagrams and further details about airflow and test aerosol parameters) are given in Appendix A.

Each tunnel has its own specific reference probe.

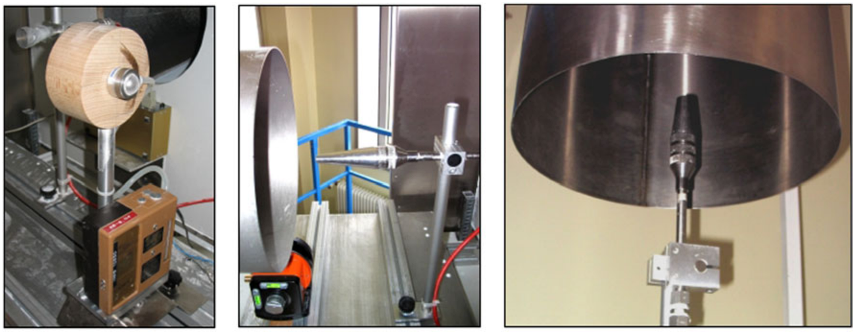
Reference probe used in horizontal wind tunnel—wind speed 1 m s^{-1}

Measurement of the aerosol reference concentration C_{ref} in moving air is relatively straightforward because usage of the isokinetic probe is well understood. A sharp-edged, thin-walled tube was isokinetically applied to measure the reference concentration of the test aerosol in the wind tunnel working section. The reference probe was 105-mm long and its aspiration circular orifice diameter was 10.6 mm (Fig. 1b). Its conical internal section provided a 20-mm diameter filtration surface. Particles were collected on a 25-mm diameter Nuclepore membrane filter (2.0-μm pore size). To recover wall deposits, the internal surface of the reference probe was washed with purified water and this suspension was filtered on a second Nuclepore filter (25-mm diameter, 0.8-μm pore size). This procedure ensured good recovery of all the wall deposit. Particulate material collected from the probe filter and inner tube wall deposit were weighed separately on an electronic balance (Mettler Toledo model MX5). The combined particle mass collected on the primary 25-mm filter plus the wall deposition mass was used to determine the aerosol particle size-resolved reference concentration $C_{n,\mathrm{ref}}$ (D_{ae}).

The reference probe was connected to a system comprising a mass flow meter with controller and a sliding-vane pump. To perform isokinetic sampling, the probe airflow was calculated for each test, based on the surface area of the opening orifice and the average air velocity measured in the wind tunnel working section. This reference sampling flow rate was 5.6 l min^{-1} and calibrated with a Gillibrator® bubble flow meter.

Reference probe used in vertical calm air tunnel

For calm air, the reference measurement method is problematic because there is no close agreement between representative sampling criteria and an isokinetic sampling is impossible. One solution is to use the circling pseudo-isokinetic probe method proposed by Aitken *et al.* (1999), in which a thin-walled probe is mounted on a rotating arm such that the sampling velocity is the same as the relative velocity between the rotating sampler and the calm air. However, this method remains uncertain in our case because of the open working section of the vertical calm air tunnel. The reference probe should be placed in the axis of the tunnel at the same point as the sampler being tested. All experiments in the vertical calm air tunnel were conducted using a thin-walled cylindrical reference probe facing vertically upwards (Fig. 1c). This method takes into account a number of sampling criteria found in the



a b c

Fig. 1. Photographs of working zones in horizontal and vertical tunnels. (a) Button sampler attached to a 110 × 55-mm cylindrical bluff body rotating at 2 r.p.m.. (b) Reference probe used in the horizontal 1 m s^{-1} wind tunnel. (c) Reference probe used in the vertical calm air tunnel.

literature (Davies, 1968; ter Kuile, 1979; Agarwal and Liu, 1980; Ogden, 1983; Grinshpun *et al.*, 1990). Reference sampling was therefore carried out with a 76-mm long probe (20-mm diameter circular opening) at a flow rate of 10 l $\min^{-1}$. The aspiration efficiency of this type of reference probe is within 90–100% for a particle aerodynamic diameter <50 μm (theoretical calculations based on models described in the literature—Davies, 1977; Grinshpun *et al.*, 1993; Su and Vincent, 2004). The models diverge for larger particle sizes. We performed a mathematical particle-flow simulation using Fluent®/UNS software based on a two-dimensional quadrilateral grid. The results showed an efficiency >90% up to 70 μm, the particle size limit in our experiment. Aitken *et al.* (1999) made an experimental comparison of a static probe with rotating reference probe. They found 0.75 concentration ratio (static : rotating) for particles of 90 μm. Roger (2000) made the same comparison up to 50 μm and she found the ratio close to 1. Combining these results it can be stated that for 70 μm particles, the efficiency of static reference probe could be close to the value calculated by Fluent® (85–90%).

Method of sampling efficiency measurement

Sampler efficiency measurement in wind and calm air tunnel experimental set-ups was based on comparing number concentrations between the sampler under test and a reference probe, for different particle sizes.

In the horizontal wind and vertical calm air tunnels, test and reference sampling were undertaken on the tunnel axis (in the centre of the working zone). Reference probe sampling was divided in two periods: before and after the studied device sampling period. The particle number concentration uniformity in space and time and the aerosol size distribution were previously checked in the working section of both tunnels (Witschger, 1996; Witschger *et al.*, 1997; Roger, 2000). During each experiment, the aerosol concentration stability in the working sections was measured using a 15-channel optical particle counter (Grimm® 1.108).

Depending on the sampler being tested, particles were collected on 25 mm (2.0-μm pore size) or 37 mm (0.8-μm pore size) Nuclepore membrane. The sampling airflow dictated the use of different aspiration systems: a lubricated sliding-vane pump connected to a mass flow meter with controller, a Gilian Gilair personal sampling pump, or a volumetric high-flow pump (TCR Tecora series Air Guard model Bravo/H2). Sampler nominal flow rates were measured before each experiment using either a Gillibrator bubble flow meter for flow rates up to 6 l $\min^{-1}$ or a Gallus G4 diaphragm gas meter for higher flow rates.

The filters were weighed before and after particle sampling using an electronic balance (Mettler Toledo model MX5) to determine the sampled mass concentrations. The particles were then recovered from the filters in the Isoton electrolyte solution for particle counting and particle size number distribution determination using the Coulter® counter method. This allowed us to calculate the size-resolved number concentrations measured by the sampler and the reference probe, respectively. Finally, the experimental efficiency data provided in this paper represent the sampling efficiency of the tested sampler as a function of the aerodynamic particle diameter (efficiency curve). A synthesis of calculation procedure of particle size-dependent sampling efficiencies, previously explained in Witschger *et al.* (1997) and Görner *et al.* (2000), is described in Appendix B.

COMMENTS ON RELIABILITY OF EXPERIMENTAL METHODS

Prior to presenting our experimental results, we wish to comment on a number of particular features of the experimental methods applied and on their impact on the results for the different samplers. Experimental sampling efficiency was measured under standardized laboratory conditions, which are not necessarily the same in industrial site. Sampler behaviour can therefore be different in the laboratory and in the workplace (Lidén *et al.*, 2000). That is why the samplers were studied also in workplace (Kauffer *et al.*, 2010). However, using the modelled laboratory conditions makes it possible to study and to evaluate the sampling process of each tested sampler and to compare them.

Moving air laboratory conditions

Standard EN 13205 (CEN, 2001) recommends using a rotating manikin for personal sampler testing, thereby averaging sampler space orientation with respect to the external wind. This experimental set-up try to simulate variability of sampler position in the workplace ensuring that the sampler was exposed to the experimental aerosol at different angles.

Isolated sampler. In the case of an isolated sampler (not fitted to a manikin or bluff body), measurement of its rotating unidirectional orifice efficiency represents an average between maximum (facing towards the wind) and minimum (from 90° to 180°) efficiencies (Li *et al.*, 2000). A sampler is never rotated 360° in the workplace, so this average value does not represent any realistically imaginable workplace efficiency.

An omni-directional sampling slot has the same efficiency when rotating or not and, in the workplace, it is expected to operate with an efficiency similar to that measured experimentally.

Using a manikin. The average sampling efficiency of a unidirectional orifice is slightly altered, when a manikin or bluff body is included in the experiment. This is similar to the omni-directional sampling slot, except at directional angles, at which the sampler is shielded from the airflow behind the manikin, where the manikin shielding effect causes a dramatic reduction in the quantity of sampled aerosol. For a unidirectional orifice, this shielding effect is minimal because orientation of the sampler itself causes most of the drop in efficiency. However, this position is rare in workplace. The worker is probably directed more towards than away from his work tool.

We can expected that workplace efficiency of omni-directional slots would exceed their efficiency based on experiments involving a rotating manikin or bluff body. Their workplace efficiency would probably be akin to an experimental efficiency obtained with a non-rotating manikin.

Validity of the results obtained with the cylindrical bluff body used in this study. A standardized experimental method for measuring sampler efficiency is described in EN 13205 (CEN, 2001). A large-scale experimental wind tunnel housing a full-scale manikin is required. High airflow rates are therefore necessary and some particle size and concentration uniformity problems can be expected in the large measuring zone. Several authors have attempted to reduce these problems by scaling down the experimental equipment without downgrading their experimental results (Witschger *et al.*, 1998; Ramachandran *et al.*, 1998; Kenny *et al.*, 2000; Li *et al.*, 2000; Aizenberg *et al.*, 2000b, 2001; Kennedy *et al.*, 2001; Paik and Vincent, 2004). Recently, Vincent (2006) has proposed a better experimental procedure for testing aerosol samplers and EN 13205 is currently under revision to take into account the contributions of other aerosol sampling specialists.

For example, Kennedy *et al.* (2001) used a simplified manikin to evaluate IOM sampler performance. The simplified manikin was constructed using a 33-cm wide × 20-cm deep × 20-cm high, inverted plastic wastebasket and was tested in a 1.6 × 1.6 m cross-section wind tunnel (blocking 2.6% of the wind tunnel cross-section). IOM samplers were exposed to narrow size distribution ($1.16 < \text{GSD} < 1.34$) aluminium oxide test dust particles with aerodynamic diameters of 7, 22, 52, 82, and 116 µm. Orientation-averaged results were calculated as the arithmetic average of values for 0°, 90°, 180°, and 270° angles with respect to wind direction (no manikin rotation during sampling).

Other encouraging results were obtained by Paik and Vincent (2004). In this case, the sampler was mounted on a simplified, 3D rectangular bluff body (120-mm high × 120-mm wide × 60-mm deep), simulating the manikin. This body was rotated at a 2 r.p.m. constant speed to ensure 360° orientation averaging.

We verified that the experiments using a 55-mm wide, 110-mm diameter cylindrical bluff body used in this study (Fig. 1a) gave similar results (Fig. 2). IOM efficiency data, previously obtained by Kenny *et al.* (1997; Kenny, 1995) in a very large wind tunnel (10-m long, 2.5-m high, and 2.5-m wide) and a life-size manikin, have also been reported on the figure.

Calm air laboratory conditions

Strictly calm air conditions are achieved in the calm air tunnel, resulting in the particles moving vertically downwards. Figure 3 illustrates that the Button sampler can sample particles, which sediment directly inside the sampler, because of it is directed partially upwards. IOM and cassette samplers aspirate particles horizontally and deviate them 90° to their initial vertical trajectory. The considerably smaller orifice of the cassette sampler requires a sharper trajectory deviation for the particle to be sucked into the device than the larger IOM orifice (Fig. 3).

The CIP horizontal sampling slot is partly covered by a protective cap, which prevents sampling of unwanted projected particles. For perfectly vertically downward particle trajectories, the particles need to deviate 180° and therefore move almost vertically upwards to be sampled. This may explain the differences in particle sampling results for the tested devices in totally calm air (see Results section). This effect was checked using a RESPICON aerosol sampler fitted with a similar, partly covered (shielded) sampling slot. Under these conditions, its efficiency also decreases rapidly as particle sizes increase (Fig. 11).

Perfectly calm air conditions are very unlikely in the workplace, even when we consider there is no wind, because of the turbulences created by workers and work process. In the case of personal sampling, movement of operator wearing the sampler makes it impossible to achieve conditions involving particles falling exclusively downwards with respect to the

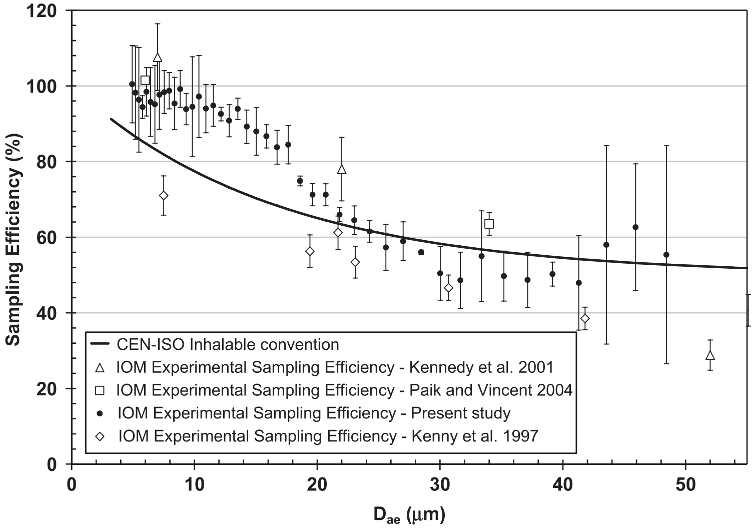


Fig. 2. Comparison of IOM sampling efficiencies with respect to aerodynamic particle diameter, measured in (i) large wind tunnel described by Kennedy *et al.* (2001) (open triangles, simplified manikin, 1 m s^{-1} airflow velocity, samples taken at four angles relative to the airflow direction, quasi-monodisperse aluminium oxide aerosol with GSD < 1.34); (ii) small wind tunnel described by Paik and Vincent (2004) (open squares, rectangular bluff body rotating at 2 r.p.m., 1 m s^{-1} wind speed, quasi-monodisperse fused alumina aerosol with GSD < 1.30); (iii) small wind tunnel of present study (closed circles, cylindrical bluff body rotating at 2 r.p.m., 1 m s^{-1} wind speed, polydisperse glass spheres aerosol; (iv) large wind tunnel described by Kenny *et al.* (1997) (open diamonds, life-size manikin rotating at 2 r.p.m., 1 m s^{-1} wind speed, quasi-monodisperse aloxite aerosol with GSD between 1.28 and 1.52) (error bars correspond to coefficients of variation of the arithmetic mean calculated from three or more experimental runs).

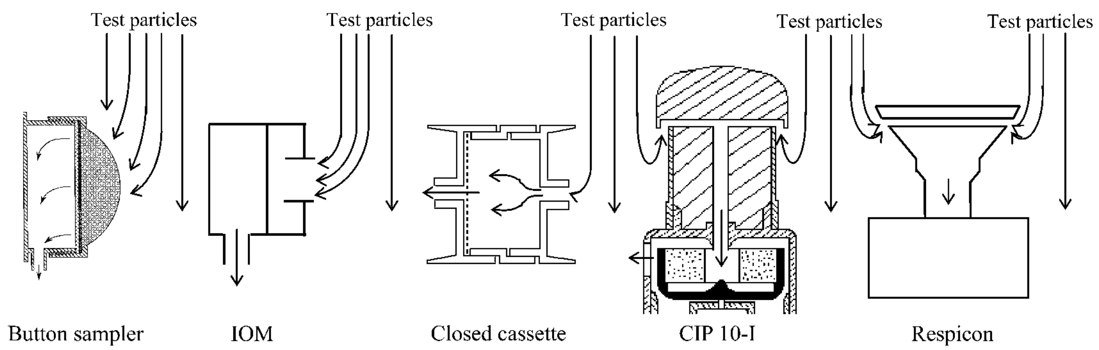


Fig. 3. Inlet geometries of samplers in relation to particle movement in vertical calm air tunnel.

sampler. For these reasons, the calm air efficiency under working conditions is higher than the perfectly calm air efficiency measured in the laboratory. Baldwin and Maynard (1998) have described frequently encountered working conditions (80%), in which the air is moving slightly. In particle sampling terms, this is not really calm air (Fig. 4), but it is also far from a 1 m s^{-1} wind or more (Lidén and Harper, 2006). Sampling slightly moving air attenuates the differences between sampling efficiencies of samplers used in strictly calm air and the efficiencies of samplers used in ultra-low wind speeds (Schmees *et al.*, 2008; Sleeth and Vincent, 2009) or in the workplace (Kauffer *et al.*, 2010).

Finally, it can be stated that moving or calm air laboratory experiments, even when designed to be an ideal model of workplace sampling, have different impact to each type of samplers. It means that an experimental sampling efficiency depends on experimental conditions, that different experimental conditions do not have the same effect on all sampler types.

Laboratory experimental efficiencies do not exactly correspond to sampler performance in the workplace, but they do make it possible to compare the sampling behaviour of different samplers under controlled conditions, based on known parameters. This contributes to understanding the sampling process.

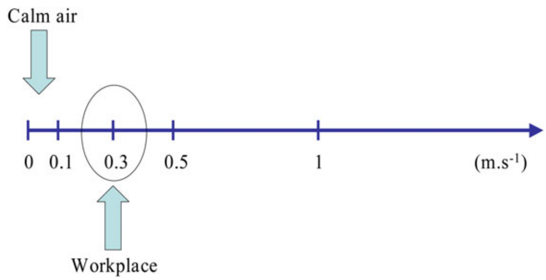


Fig. 4. Workplace wind speed scale with the most frequent wind conditions described by Baldwin and Maynard (1998).

RESULTS

Results of particle size-dependent experimental sampling efficiencies in moving and calm air

Experimental data plots relating to sampling efficiency for different particle sizes are reported here.

Each figure is associated with one tested sampler and includes experimental data recorded in both moving and calm air. The following symbols are used—open squares: moving air, sampler attached on a cylindrical bluff body, rotational speed 2 r.p.m., wind velocity 1 m s^{-1}; closed squares: calm air experimental data, no bluff body. These combined data were fitted by a fourth degree polynomial function plotted through the experimental points in each figure (light grey colour curves). These curves represent an approximate efficiency trend as a function of particle size. The chosen model follows well most experimental results and visually helps to evaluate the tendency of measured efficiencies and to compare them. The fitted model was used neither for extrapolation nor calculation purposes. Each figure also displays the CEN–ISO inhalable convention curve (solid lines) and experimental inhalabilities (dotted lines, dashed lines obtained by Aitken *et al.* (1999) in low air movement conditions for inhalation flow rates of 20 and 10 l min^{-1}, respectively).

An experimental error interval was calculated at the 95% confidence level, for each efficiency value, as the coefficient of variation of the arithmetic mean calculated from three experimental runs. However, error bars were not plotted for the experimental points to preserve the legibility of the figures. The reader can appreciate the reproducibility of the experimental results in the Table 2, in which minimum, mean, and maximum variation coefficients are recorded for each sampler and for both experimental conditions. The reader can also estimate the range of error bar values in Fig. 2 where an example of experimental efficiency data is plotted with its coefficients of variation, as a function of the aerodynamic particle diameter. Only 7.2% of all experimental points plotted on the next seven figures (all samplers and both tunnels) are associated with a variation coefficient >20%. Most of these points correspond to particle diameters exceeding 40 μm because of the small number of these particles in the test aerosol.

It should be noted that the CIP 10-I sampler was not tested with its conventional collector stage (rotating cup with foam filter). The inhalable sampling heads were mounted on a filter holder to collect the particles on a Nuclepore membrane filter, thereby facilitating particle recovery for subsequent particle size analysis. The flow rate in this system was maintained at 10 l min^{-1} by an external pump. Sampling head selectivity was therefore unchanged and collected particle recovery was considerably simplified for the size distribution analysis.

The ACCU-CAP™ system did not permit particle recovery for analysis. The conventional three-part closed cassette and filter was used. However, particles deposited on the cassette inner wall surfaces, which are logically collected in the ACCU-CAP™ capsule, were recovered by water washing and liquid filtration on a 25-mm diameter Nuclepore membrane (0.8-μm filter pore). This combination ensured that all particles aspirated in the 37-mm cassette were effectively taken into account in size distribution analysis.

The experimental sampling efficiencies can be compared to the CEN–ISO–ACGIH (1993–95) inhalable convention curve. Particle inhalability in calm air is represented by straight lines, in accordance with Aitken *et al.* (1999). They show that the aspiration efficiency in low air movement environments is higher than that specified by the current inhalable convention. They represent no conventional agreement and will only be considered a qualitative comparison with experimental efficiency data of the sampler tested in calm air. Both conventional and calm air inhalability were measured using a human head model featuring oral breathing (Vincent *et al.*, 1990; Aitken *et al.*, 1999). In the case of wood dust, nasal breathing is

Table 2. Minimum (Cv_{min}), mean (Cv_{moy}), and maximum (Cv_{max}) coefficients of variation calculated for experimental data points on sampling efficiency curves

Sampler	Flow rate (l min^{-1})	Horizontal tunnel			Vertical tunnel		
		Wind speed = 1 m s^{-1}			Calm air		
		Cv_{min} (%)	Cv_{moy} (%)	Cv_{max} (%)	Cv_{min} (%)	Cv_{moy} (%)	Cv_{max} (%)
IOM sampler	2	0.51	5.20	26.05	1.45	7.76	38.50
Button sampler	4	1.41	8.34	22.22	1.46	6.71	20.69
CIP 10-I v1	10	1.76	10.30	32.18	2.59	10.30	50.14
CIP 10-I v2	10	0.50	7.37	33.24	1.22	7.69	30.01
37-mm closed cassette	1	0.89	7.93	33.00	1.77	15.69	55.34
ACCU-CAP™	1	0.26	10.05	25.23	0.89	8.02	51.55

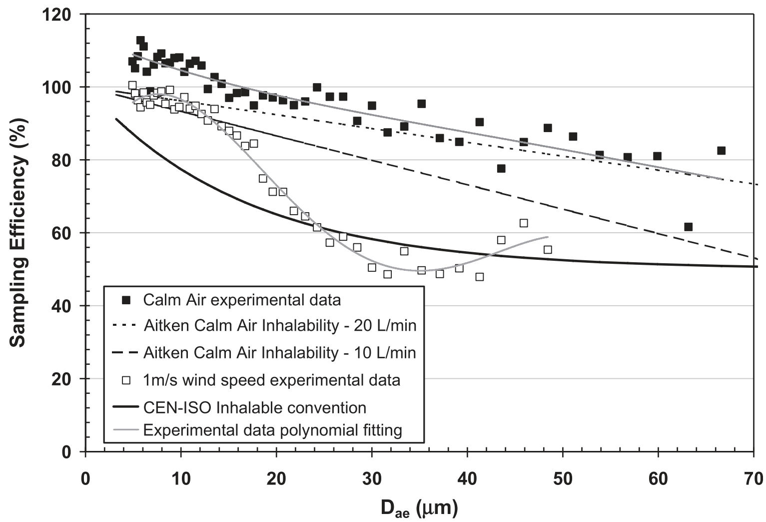


Fig. 5. Sampling efficiencies for IOM sampler (2 l min^{-1}) with respect to aerodynamic diameter of collected particles.

significant with respect to the critical health effect resulting from this dust, namely nasal cancer. We consider that, in oro-nasal breathing, the flow rate is divided between these two paths and the resulting inhalability is lower than the oral-only inhalability. This is why we plotted the Aitken inhalability lines at both higher (20 l min^{-1}) and lower (10 l min^{-1}) flow rates, considering that the inhalability relevant to wood dust could be located somewhere between these two lines, perhaps closer to the 10 l min^{-1} line or even lower.

Existing aerosol sampling criteria are now being discussed at international level (Vincent, 2005) and in the CEN and ISO standard organizations. This process should enhance the regulations based on new scientific knowledge concerning aerosol inhalation. Only the existing inhalable sampling convention and the Aitken inhalability were retained for comparison with experimental results for the efficiency of tested samplers.

The experimental sampling efficiency of the tested inhalable aerosol samplers are plotted in Figs 5–11.

DISCUSSION

Particle size-dependent experimental sampling efficiencies

The laboratory testing procedure used in moving air for measuring personal inhalable aerosol sampler performance is similar to the testing method described in Standard EN 13205 (CEN, 2001). The number of coarse particles in the testing zone of the horizontal wind tunnel was somewhat small for statistically significant analysis. The experimental errors were considered to be too significant to allow plotting of results for large particles and so results have only been plotted up to $D_{ae} \approx 50$ µm.

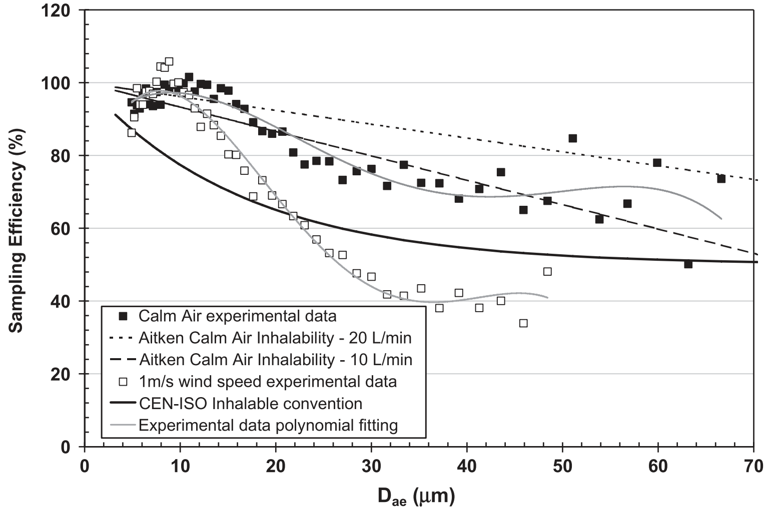


Fig. 6. Sampling efficiencies for Button sampler (4 l min^{-1}) with respect to aerodynamic diameter of collected particles.

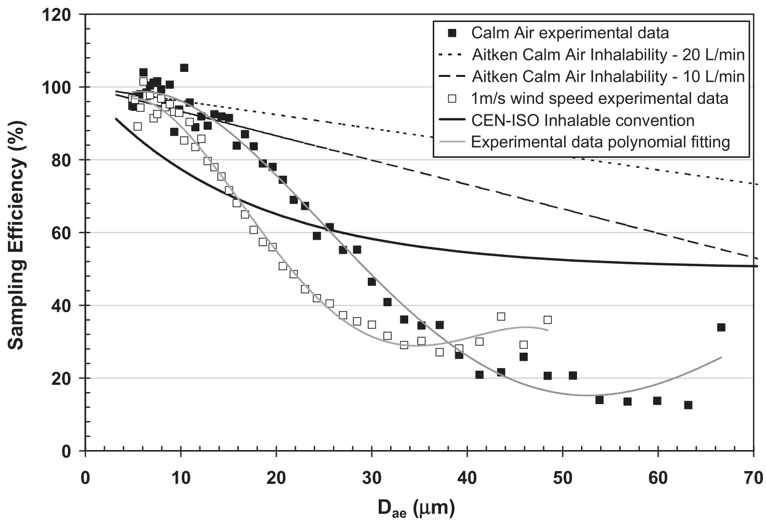


Fig. 7. Sampling efficiencies for CIP 10-I v1 sampler (10 l min^{-1}) with respect to aerodynamic diameter of collected particles.

Measurement of personal inhalable aerosol sampler performance in the vertical calm air tunnel provides complementary results. These data provide information on the behaviour of the sampler in perfectly calm air conditions. Experimental results are plotted up to $D_{ae} \approx 70$ μm.

Figs 5–11 illustrate that the IOM sampler and the new version of the CIP 10-I (v2) sampler give the experimental sampling efficiency curves for 1 m s^{-1} moving air that best fit the CEN–ISO inhalable convention (Figs 5 and 8). This fact is further confirmed by the results of measuring the experimental particle mass concentration (Table 3—discussed later in this section).

Experimental efficiency of the newest version of the CIP 10-I v2 sampler is notably higher than that of the previous version (v1) (Figs 7 and 8). Some particle losses were detected by Kenny *et al.* (1997; Kenny, 1995) in the original version (v1). In the new version (v2), elimination of six circular orifices originally located beneath the protective cap has considerably enhanced the transmission efficiency between the annular aspiration slot and the collecting stage of the CIP 10-I. Development of the new CIP 10 inhalable sampler is described in detail in Görner *et al.* (2009).

Button sampler efficiency results (Fig. 6) are only slightly inferior to those for the IOM and the CIP 10-I

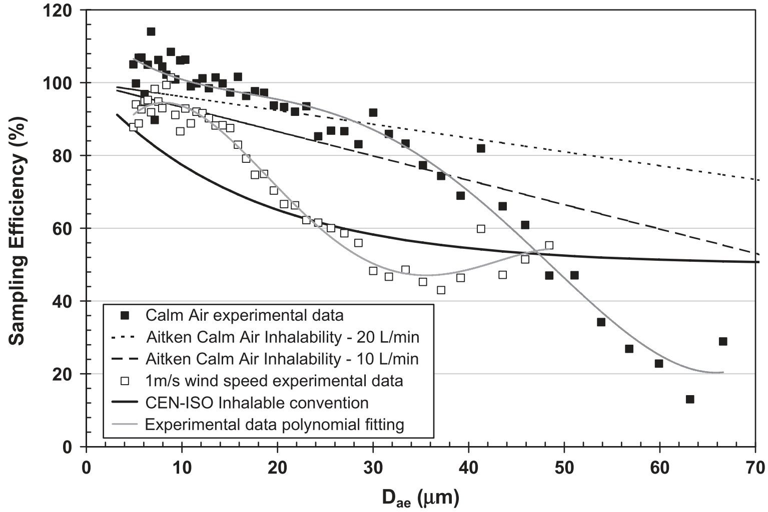


Fig. 8. Sampling efficiencies for CIP 10-I v2 sampler (10 l min^{-1}) with respect to aerodynamic diameter of collected particles.

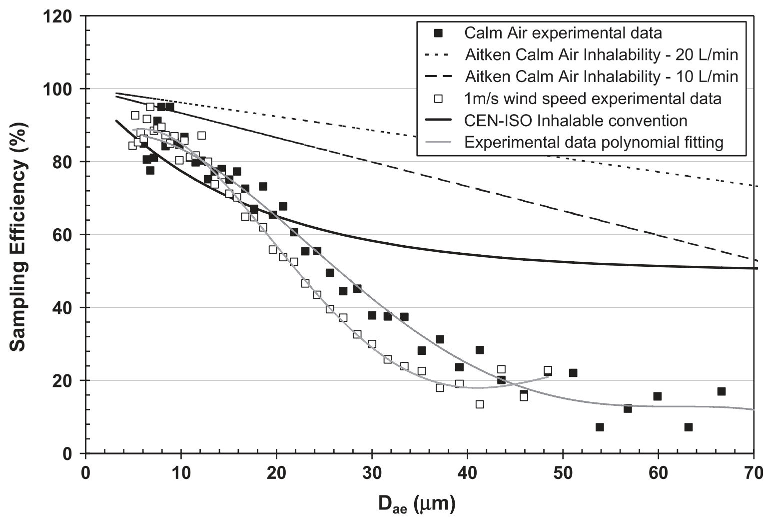


Fig. 9. Sampling efficiencies for 37-mm diameter closed cassette (1 l min^{-1}) with respect to aerodynamic diameter of collected particles.

v2 devices. Experimental values underestimate the CEN–ISO inhalable convention curve for particle diameters D_{ae} >25 μm and this tendency is more pronounced than for the two previous samplers. A certain proportion of larger particles are likely to not be transmitted towards the collection filter and may be trapped by the inlet screen (around or into the many equally spaced 381-μm diameter orifices representing 21% inlet porosity—Aizenberg, 2000a).

Sampling efficiency for the 37-mm CFC gave the worst results for the assessed methods (Fig. 9). Experimental points for particle diameters D_{ae} >20 μm severely underestimate both the CEN–ISO inhalable convention and the Aitken calm air inhalability. Table 3 confirms that the closed cassette is the sampler that gives also the lowest mass concentration ratio with respect to the reference probe.

Sampling efficiency of the ACCU-CAP™ device fitted with a 37-mm diameter cassette is superior to that of the cassette without the ACCU-CAP™ (Fig. 10). ACCU-CAP™ sampling efficiency is similar to the aspiration efficiency of the 4-mm cassette orifice, which is logically higher than the overall sampling efficiency of the cassette because of wall losses.

In calm air, the IOM sampler follows well the Aitken inhalability at 20 l min^{-1}.

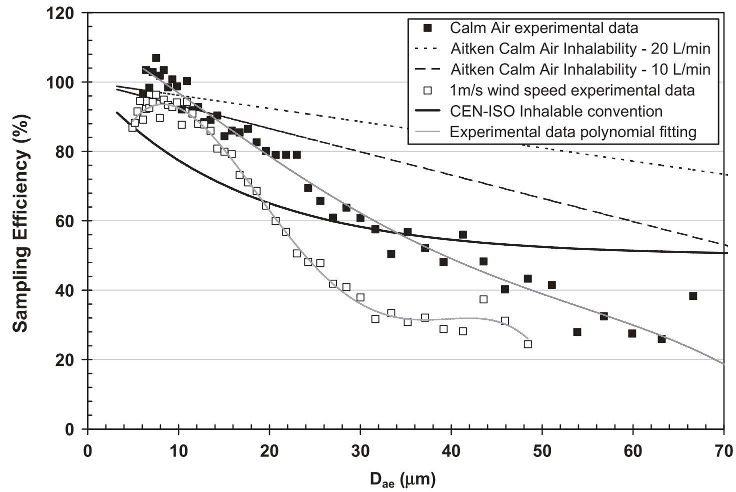


Fig. 10. Aspiration efficiencies for 37-mm diameter closed cassette (1 l min^{-1}) with respect to aerodynamic diameter of collected particles (possibly similar to sampling efficiencies for ACCU-CAP™).

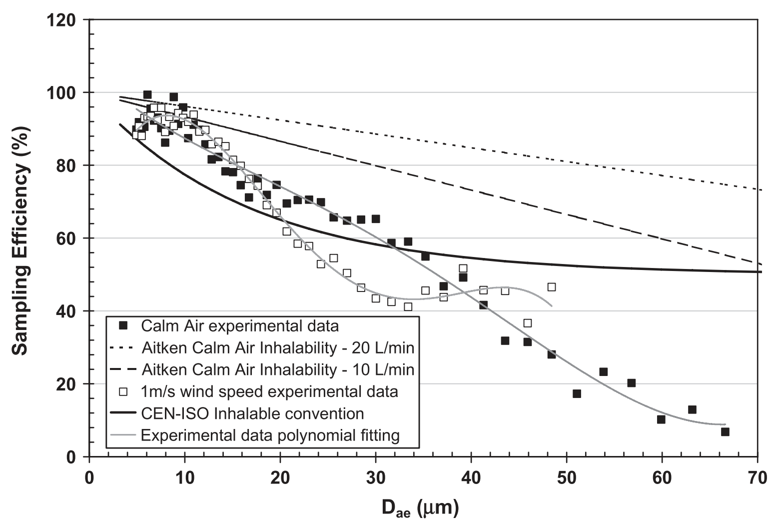


Fig. 11. Sampling efficiencies for RESPICON sampler (3.1 l min^{-1}) with respect to aerodynamic diameter of collected particles.

The efficiency of the CIP 10-I v2 is again clearly higher than that of v1. The protective cap offers an 'umbrella' or shielding effect over the aerosol inlet, preventing penetration of unwanted projected particles into the device. On the other hand, in strictly calm air conditions characterised by particles falling vertically downwards, the protective cap causes a drop in efficiency. This effect was previously discussed in the section *Calm air laboratory conditions* and can be observed also for the RESPICON sampler (Fig. 11) due to its shielded aspiration slot (Fig. 3).

Laboratory efficiency of the Button sampler is close to the Aitken inhalability at 10 l min^{-1}.

Identically as in moving air, the CFC efficiency is the lowest one among tested samplers. Using the ACCU-CAP™ capsule improves its performance.

Experimental particle mass concentration ratio between inhalable fraction and total aerosol

The mass concentration measured by each sampler was divided by the reference probe mass concentration in order to obtain an aerosol fraction which is noted $f_{m,s,\text{sampler}}$. It corresponds to the 'inhalable fraction' measured by the sampler. It can be compared to the 'real inhalable aerosol fraction' present in the tunnel. The latter one is deduced from

Table 3. Particle mass concentration ratios (sampler : reference inhalable concentration) obtained in two laboratory tunnels with glass sphere aerosol (Cv($f_{m,s,sampler}$) = variation coefficient based on three experimental tests)

Horizontal tunnel - wind speed = 1m.s^{-1}		
$f_{m,s,\mathrm{sampler}}$ (%)	Cv($f_{m,s,\mathrm{sampler}}$) (%)	Sampler
67.0	2.1	IOM sampler
63.0	3.5	CIP 10-I v2
52.5	6.8	ACCU-CAP™
50.9	9.5	Button sampler
45.1	10.5	CIP 10-I v1
42.7	1.9	37-mm closed cassette
61.8	-	CEN-ISO inhalable convention

Vertical tunnel - calm air		
Sampler	$f_{m,s,\mathrm{sampler}}$ (%)	Cv($f_{m,s,\mathrm{sampler}}$) (%)
IOM sampler	**92.0**	10.0
Button sampler	**78.2**	2.3
CIP 10-I v2	**75.4**	4.5
ACCU-CAP™	**60.8**	7.3
CIP 10-I v1	**51.9**	5.0
37-mm closed cassette	**41.6**	8.4
Aitken calm air inhalability at 20 l min^{-1}	**87.9**	-

the total aerosol concentration measured by the reference probe, by using aerosol size distribution and the mathematical definition of inhalability.

The particle mass concentration ratios f_m are calculated using the following equation.

$$f_{m,s,\mathrm{sampler}} = \frac{C_{m,s,\mathrm{sampler}}}{C_{m,a,\mathrm{ref}}}, \qquad (1)$$

with $C_{m,s,\mathrm{sampler}}$, mass concentration of particles sampled (s) by tested sampler (mg m^{-3}); $C_{m,a,\mathrm{ref}}$, mass concentration of particles aspirated (a) into reference probe (mg m^{-3}).

Particle mass concentrations were calculated using the following equation.

$$C_{m,j,x} = \frac{M_x^{\mathrm{part}}}{V_x^{\mathrm{air}}}, \quad \begin{array}{lll} x = \text{sampler} & \text{for tested sampler} & j = s \\ x = \text{ref} & \text{for reference probe} & j = a \end{array} \qquad (2)$$

with M_x^{part}, mass of particles sampled by tested sampler or aspirated by reference probe; V_x^{air}, air volume sampled during test (m^3).

The conventional inhalable aerosol fraction in the moving air tunnel is calculated using experimental aerosol size distribution (Fig. A3) and the inhalable convention efficiency equation $E(D_{\mathrm{ae}}) = 0.5 \times [1 + \exp(-0.06 \times D_{\mathrm{ae}})]$ (Görner and Fabriès, 1996). As it can be seen in Table 3, this value is equal to $f_{m,\text{CEN–ISO inhalable convention}} = 61.8\%$ and can be compared to the sampler mass concentration ratios obtained in the horizontal tunnel.

The same type of calculation has been made for the calm air tunnel experiments using the Aitken experimental calm air inhalability efficiency equation at 20 l min^{-1} ($E(D_{\mathrm{ae}}) = 1 - 0.0038 \times D_{\mathrm{ae}}$) and the aerosol size distribution in this tunnel (Fig. A5). In this case, the value of the ratio is $f_{m,\text{Aitken calm air inhalability}} = 87.9\%$; it can be compared to the sampler mass concentration ratio obtained in the calm air tunnel.

Table 3 gives the particle mass concentration ratios obtained for each sampler in both tunnels for the experimental glass sphere test aerosols along with the calculated inhalable fractions. Each tabulated value represents an average of three experimental aerosol concentration measurements.

Discussion on Experimental particle mass concentration ratio

Values of f_m are higher in calm air than in air moving at 1 m s^{-1}, except for the CFC. A sampler classification based on particle mass concentration ratios is different for moving and calm air conditions (Table 3). The Button sampler in fact ranks two steps higher in calm air probably due to its partially upward orientation, as explained in Fig. 3.

Independently of operating conditions, the IOM sampler has the highest mass concentration ratio (Table 3). However, the IOM sampler overestimates either the inhalable particle mass concentration, which would be obtained by an ideal sampler capable of sampling the glass sphere aerosol with the same efficiency as that of the CEN–ISO conventional curve for moving air ($f_{m,\text{CEN–ISO inhalable convention}} = 61.8\%$), or the inhalability curve obtained by Aitken *et al.* (1999) in calm air, for a 20 l min^{-1} inhalation flow rate ($f_{m,\text{Aitken calm air inhalability}} = 87.9\%$).

It should be noted that the CIP 10-I v2 particle mass concentration ratio obtained in the horizontal tunnel (63.0%) is very close to the value attributed to sampling precisely in compliance with the CEN–ISO inhalable convention (61.8%).

The difference in CFC performance, with and without the ACCU-CAP™, is clearly demonstrated by the ratios in Table 3: the concentration ratios between the cassette and the ACCU-CAP are

Table 4. Comparison of sampled ($f_{m,s,\text{cass.}}$) and aspirated ($f_{m,s,\text{cass.}}$) particle mass concentration ratios for 37 mm diameter closed cassette at 2 air flow rates (1 and 2 L.min^{-1}) and under both air movement conditions (1 m.s^{-1} wind speed and calm air). Cv($f_{m,s,\text{cass.}}$) and Cv($f_{m,s,\text{cass.}}$) are the variation coefficient for ratio $f_{m,s,\text{cass.}}$ and the variation coefficient for ratio $f_{m,s,\text{cass.}}$ based on 3 experimental runs

Tunnel	Horizontal tunnel—wind speed = 1 m s^{-1}		Vertical tunnel—calm air	
Airflow rate (l min^{-1})	1	2	1	2
Cassette ratio (%), $f_{m,s,\text{cass.}}$ (Cv($f_{m,s,\text{cass.}}$))	42.7 (1.26)	44.5 (2.19)	41.6 (5.84)	42.0 (11.39)
ACCU-CAP™ ratio (%), $f_{m,a,\text{cass.}}$ (Cv($f_{m,a,\text{cass.}}$))	52.5 (3.73)	52.2 (1.82)	60.8 (3.48)	65.3 (1.13)

significantly higher when wall losses are recovered by ACCU-CAP™ and differences reach ~10% in moving air and ~20% in calm air conditions.

The 37-mm CFC and ACCU-CAP™ performance with respect to sampling flow rate

A CFC with a 4-mm diameter sampling orifice is used in many countries with a 2 l min^{-1} flow rate. In France, this sampler is often used at 1 l min^{-1} for compliance with the ter Kuile (1979) sampling criterion. We examined the difference in sampled concentrations for these two flow rates. Table 4 contains particle mass concentration ratios for the 37-mm diameter closed cassette and the ACCU-CAP™ with respect to sampling flow rate and external wind conditions. These ratios were computed in the same way as in the previous section, using the particle size distribution of the test aerosol.

Sampled particle mass concentration ratio (collected on cassette filter):

$$f_{m,s,\text{cass.}} = \frac{C_{m,s,\text{cass.}}}{C_{m,a,\text{ref}}}, \quad (3)$$

with $C_{m,s,\text{cass}}$, mass concentration of particles sampled by 37-mm cassette (mg m^{-3}); $C_{m,a,\text{ref}}$, mass concentration of particles aspirated by reference probe (mg m^{-3}).

Aspirated particle mass concentration ratio (collected on cassette filter and on cassette inner surfaces):

$$f_{m,a,\text{cass.}} = \frac{C_{m,a,\text{cass.}}}{C_{m,a,\text{ref}}}, \quad (4)$$

(Equation (4) is similar to $f_{m,s,\text{ACCU-CAP™}} = \frac{C_{m,s,\text{ACCU-CAP™}}}{C_{m,a,\text{ref}}}$) with $C_{m,a,\text{cass.}}$, mass concentration of particles aspirated (a) into 37-mm diameter cassette (mg m^{-3}); $C_{m,s,\text{ACCU-CAP™}}$, mass concentration of particles sampled (s) by ACCU-CAP™ (mg m^{-3}); $C_{m,a,\text{ref}}$, mass concentration of particles aspirated (a) into reference probe (mg m^{-3}); $C_{m,a,\text{cass.}} = C_{m,s,\text{cass.}} + C_{m,d,\text{cass.}}$; $C_{m,d,\text{cass.}}$, mass concentration of particles deposited (d) on cassette inner surfaces (mg m^{-3}).

Cv($f_{m,s,\text{cass.}}$) and Cv($f_{m,a,\text{cass.}}$) are the variation coefficient for ratio $f_{m,s,\text{cass.}}$ and the variation coefficient for ratio $f_{m,a,\text{cass.}}$ based on three experimental runs.

Discussion on CFC and ACCU-CAP™ performance with respect to flow rate

Table 4 demonstrates the very low sensitivity of the 37-mm diameter closed cassette to a 1–2 l min^{-1} change in airflow rate. Under given operating conditions, cassette or ACCU-CAP™ performance is little influenced by this change. At the 1 m s^{-1} wind speed, the cassette aspiration efficiencies for 1 or 2 l min^{-1} flow rates were never >30% different to each other within the investigated particle size interval. Kauffer *et al.* (2010) obtained results in the workplace which confirm low sensitivity of the CFC to flow rate variation from 1 to 2 l min^{-1}.

The Table 4 values are of course higher, when all aspirated particles are taken into account (filter + wall losses), than values corresponding to particles only collected on the filter. These results confirm that using an ACCU-CAP™ capsule effectively increases the overall sampling efficiency of the closed cassette.

The 37-mm diameter CFC performance with respect to inlet inclination

The 37-mm diameter CFC usage is described in Standard NF X 43-257 (AFNOR, 2008), which specifies that the inlet orifice axis should be horizontally directed during sampling. However, in practice, the cassette is often used with its inlet orifice axis inclined downwards and typically suspended on its air sampling tube above the worker's shoulder (usually called the '45° angle position' even though this angle can vary widely).

Figure 12 allows us to compare the aspiration efficiency of a horizontally directed cassette and a cassette inclined at 45°, measured in the vertical calm air tunnel. Each data point represents an average value based on three experimental runs.

Kenny *et al.* (1999) also measured the sampling efficiency of a 37-mm diameter CFC under minimal air movement. The inlet of the cassette was directed downwards at a 45° angle. Measurements were taken using aluminium oxide test aerosols with four aerodynamic diameters from 6 to 58 µm (see Fig. 12). Tests were conducted in an ~1 m^2 cross-sectional

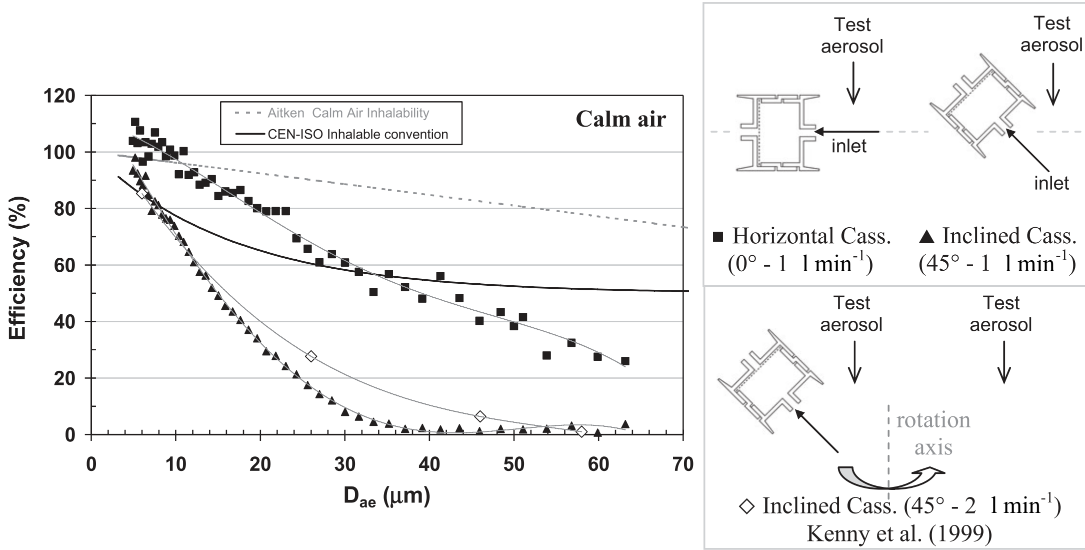


Fig. 12. Comparison of 37-mm diameter CFC efficiencies, when inlet orifice axis is horizontal or inclined at 45°. Data points measured in: (i) the vertical calm air tunnel used in this study (closed squares for horizontal cassette and closed triangles for 45° inclined cassette, 1 l min^{-1} sampling flow rate, isolated static sampler, polydisperse glass sphere aerosol); (ii) an aerosol calm air chamber (1 m^2 cross-section × 3-m height) used by Kenny *et al.* (1999) (open diamonds, 45° inclined cassette, 2 l min^{-1} sampling flow rate, isolated rotating sampler located 0.36 m from vertical axis, rotation 1 r.p.m., quasi-monodisperse aluminium oxide aerosols with mass median aerodynamic sizes of 6, 26, 46, and 58 μm, 1.2 < GSD < 1.4).

area, 3 m overall vertical height aerosol chamber. The cassette and reference probe were located at a radius of 0.36 m from the vertical axis of the chamber and rotated at 1 r.p.m. to reduce the effects of any positional variations in aerosol concentration. The results are also reported in Fig. 12.

There is a fair agreement between our results and those obtained by Kenny *et al.* (1999) for the inclined cassette experiments even though the experimental methods were different.

Other tests have been previously conducted in moving air (1 m s^{-1}) by Buchan *et al.* (1986), who investigated 37-mm diameter closed cassette performance in a large rectangular wind tunnel, using three particle sizes and two cassette inclination angles (Fig. 13). The experiments conducted by Buchan *et al.* (1986) involved a cassette sampler mounted on a static manikin facing the wind (at 47° to the airflow, five replications, open squares) and a cassette hanging downwards without a manikin (at 90° to the airflow, five replications, open triangles). The variation coefficients were too small to be plotted. The figure also illustrates our sampling efficiency measurements for a horizontally oriented cassette mounted on a cylindrical bluff body rotating at 2 r.p.m. (at 0° to the airflow, three replications, closed diamonds). A 2 l min^{-1} cassette flow rate was used in all these experiments (see Fig. 13 caption for further details).

There is only a limited possibility of comparing Buchan's results with the CEN–ISO inhalable convention and data acquired in this study because cassette efficiency has not been evaluated over a wide aerosol particle size range and tests on the manikin were conducted without rotating it through 360°. The 47° and 90° inclined cassette values (open squares and open triangles) obtained by Buchan *et al.* (1986) should therefore have been lower, if the test had involved a rotating manikin instead of one facing the wind.

Discussion on CFC performance with respect to inlet inclination

Figure 12 clearly shows that the 37-mm diameter closed cassette aspiration efficiency in calm air decreases significantly, if the sampler is directed downwards at 45°. It should be noted that in this position, the external cassette structure shields the sampling orifice which is especially negative in the case of calm air, in which particles only fall under the influence of gravity. Under these conditions, the loss of aspiration efficiency due to the sampler inclined position could be more pronounced than under high wind speed conditions. However, Fig. 13 illustrates that also under windy conditions, the sampling efficiency decreases, when the cassette is inclined down from the horizontal direction.

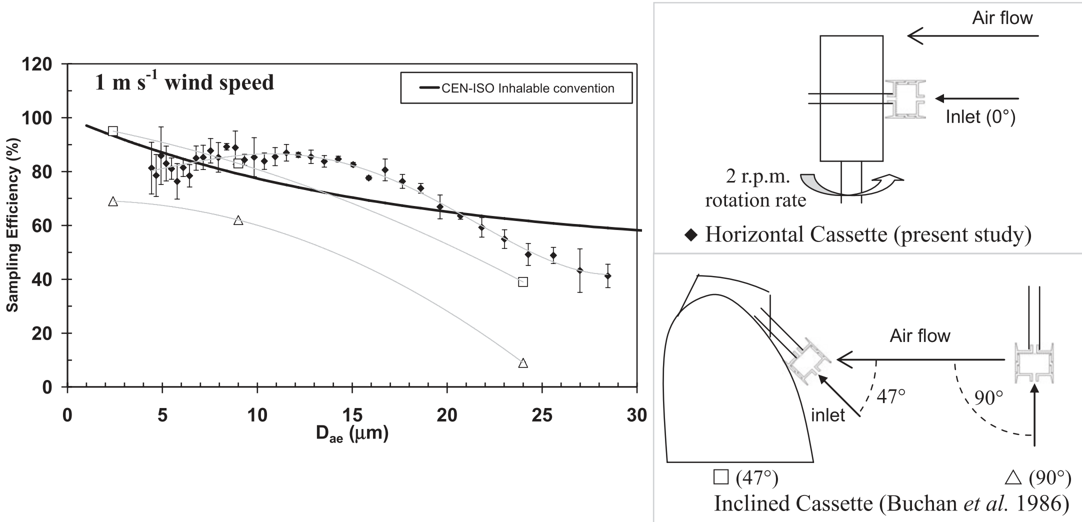


Fig. 13. Comparison of 37-mm diameter closed cassette (2 l min^{-1}) sampling efficiency, when inlet orifice axis is horizontal (present study) or inclined at 47° or 90° (Buchan *et al.*, 1986). Data points measured in: (i) horizontal wind tunnel used in this study (closed diamonds, cassette horizontally oriented, 2 l min^{-1} flow rate, rotating cylindrical bluff body 2 r.p.m., 1 m s^{-1} wind speed, polydisperse glass sphere aerosol); (ii) rectangular (50-cm wide × 70-cm high) wind tunnel used by Buchan *et al.* (1986) (open squares, cassette hanging on static manikin at 47°, towards airflow at 1 m s^{-1} wind speed, quasi-monodisperse aerosol of MMAD of 2.4 µm (iron), 9.0 µm (tungsten), and 24.0 µm (aluminium), 1.56 < GSD < 1.68); (iii) rectangular (50-cm wide × 70-cm high) wind tunnel used by Buchan *et al.* (1986) (open triangles, cassette directed downwards at 90° to airflow, no manikin, 1 m s^{-1} wind speed, same test aerosol).

The 37-mm diameter closed cassette inlet orifice direction represents one of the major parameters influencing the sampling efficiency of this aerosol sampler. Our results reveal the effectiveness of a cassette holder, which can be fastened to the worker's clothes to keep the cassette orifice axis horizontal.

CONCLUSION

The method of assessing laboratory sampling efficiency is similar to the method recommended in Standard EN 13205. It uses air in movement and the sampler mounted on a rotating bluff body modelling the operator. Results of these measurements are used for classifying the studied samplers in relation to the sampling objective represented by international convention CEN–ISO–ACGIH. Efficiency measurements in calm air are complementary and provide information on sampler behaviour under these conditions.

For all samplers, experimental efficiencies for coarse particles (D_{ae} > 50 µm) are still decreasing and are never constant as predicted by the CEN–ISO convention. The partly horizontal profile of the convention between 50 and 100 µm implies that particle inertia is constant within this size interval. This paradox came from the convention's historical context: the conventional curve is an average inhalability combining a multitude of different conditions (wind speeds), some of them with increasing efficiency as a function of particle size (case of high wind speeds).

For all tested samplers, the shape of the sampling efficiency in calm air is different from this in moving air. This pleads for definition of a specific calm air or 'ultra-low wind speed' convention.

IOM and CIP 10-I new version (v2) samplers embody the two methods, which best meet the convention efficiency criteria for sampling inhalable aerosol (Figs 5 and 8). The IOM has also the highest efficiency of all samplers in calm air.

CIP 10-I v2 efficiency significantly exceeds that of this sampler's first version (v1) (Figs 7 and 8). Efforts to develop a new CIP 10-I sampling head (Görner *et al.*, 2009) are reflected by closer compliance of version v2 sampling efficiency with the inhalable convention. The protective cap partly masks the annular inlet to protect the device from large particles projected or falling under gravity. This is why we observed a decrease in sampling efficiency for particles exceeding 40 µm in strictly calm air, characterized by particles moving only from top to bottom. These very calm air conditions are rare in the case of personal sampling in the field due to the movements of worker wearing the sampler.

Sampling efficiency of the Button sampler in moving air is only slightly less than that of the IOM and CIP 10-I v2 samplers (Fig. 6). It underestimates the inhalable convention values for particle diameters >25 µm. It is probable that the largest particles cannot reach the collection filter because of the particle deposition on the protective grid covering the sampling head. The Button sampler ranks higher among the samplers in calm air than in moving air (Table 3). It is probably due to its partially upward orientation making it possible to better aspirate vertically sedimenting particles.

Sampling efficiency of the 37-mm diameter CFC was the lowest of the assessed methods (Fig. 9). This low efficiency is only partly improved by using the ACCU-CAP™ device, which allows one to take into account possible deposition on the inner walls of the cassette (Fig. 10).

Table 4 provides information on the low sensitivity of the 37-mm CFC efficiency with respect to the airflow. The sampled fractions are very similar for sampling flow rates of 1 and 2 l min^{-1}. Cassette aspiration efficiencies at these two airflows do not differ by >30% over the particle size range <60 µm in diameter.

The results illustrated in Figs 12 and 13 show clearly the marked drop in closed cassette efficiency, when this sampler is inclined 45° downwards. Cassette inclination, thus its aspiration direction, with respect to a horizontal position is a prime parameter in relation to this device's sampling efficiency. These results reconfirm the usefulness of a cassette holder, whose attachment to worker's clothing allows to keep the cassette orifice axis horizontal.

Laboratory testing of inhalable samplers under closely controlled experimental conditions allows us to understand the behaviour of each sampler in relation to its design and external sampling parameters. Additionally, the process allows us to compare sampler efficiencies under identical conditions, although these conditions may not necessarily correspond to those in the workplace. Analysis of laboratory test results reveals that two samplers (the IOM and the CIP 10-I v2) comply closely with the inhalable sampling convention under the experimental conditions applied. The IOM sampler operating at a 2 l min^{-1} flow rate and having a wide open circular orifice inlet may be sensitive to coarse particles when facing the wind or when large particles are projected by the industrial process. The CIP 10-I sampler operating at 10 l min^{-1} and having a horizontal omni-directional sampling slot, partly shielded by a protective cap, may be less sensitive to wind direction and projected particles. The protective cap may influence coarse particle sampling in strictly calm air. Performance of the other tested samplers may be satisfactory providing they are used under certain favourable sampling conditions.

A field study of these samplers tested in real workplace conditions was conducted in various industrial woodworking processes. Results of these industrial trials and conclusions on wood dust sampling and exposure measurements in workplace are reported in Kauffer *et al.* (2010).

Acknowledgements—This study was initiated by Jean-François Fabriès, who sadly passed away in April 2006, while working on this project.

APPENDIX A

Complementary information on laboratory equipment

Horizontal wind tunnel. The experimental wind tunnel operated at a controlled flow rate can generate wind velocities of 1–4 m s^{-1}. The tunnel comprised a centrifugal fan, a high-efficiency (HEPA) filter, a fluidized-bed aerosol generator, a corona charge aerosol neutralizer, an aerosol homogenization chamber, and a 5-m long, 300-mm diameter tubular duct (Fig. A1). The samplers under test were exposed at the tubular duct outlet in a custom-designed working section. The aerosol was extracted from the working section towards a terminal filter and the air was ultimately exhausted from the building. A detailed description of the wind tunnel and all flow and aerosol parameters, along with their spatial and time stability, is provided by Witschger *et al.* (1997).

The free stream air velocity in the horizontal wind tunnel was kept constantly close to 1 m s^{-1} during all the experiments reported in this paper. Air velocity at the sampling point was measured systematically using an anemometer (DANTEC 54T21—calculating the mean of 60 measurements taken every 2 s). The tunnel ensures air velocities ranging from 1.01 to 1.09 m s^{-1}. The turbulence in the sampling plane had an intensity within 3–8%. Typical turbulence scale was ~0.6 cm (Witschger *et al.*, 1997).

The cylindrical bluff body wearing the sampler has a diameter of 110 mm and thickness of 55 mm. The aerosol is sampled at the tunnel 300-mm outlet in a 1 m^2 measuring zone (see Fig. A1). The surface blockage ratio is therefore reckoned to be 13.5% in the worst and 1.2% in the best case.

The test aerosol was generated from polydisperse glass micro-sphere powder (BL 0-50 Verre Industrie—Fig. A2) with a particle density of 2.46 g cm^{-3}, using a fluidized-bed aerosol generator (Guichard, 1976). This provided particles with a MMAD close to 24 µm and GSD close to 1.4 (Fig. A3). The size distribution of aerosol particles collected by the isokinetic reference probe was determined using the electrical

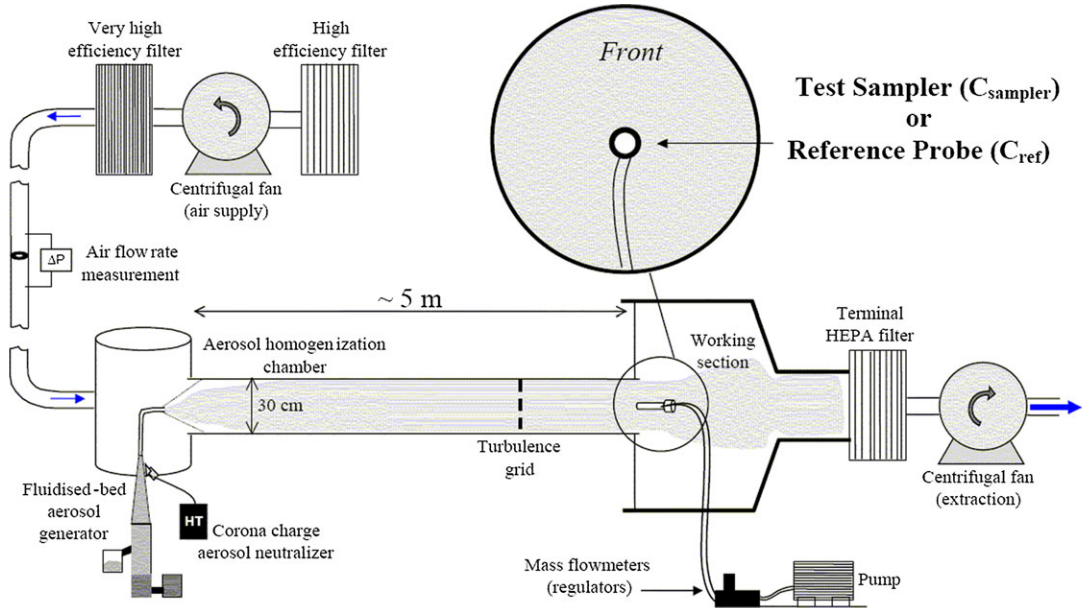


Fig. A1. Schematic diagram of experimental horizontal high-speed wind tunnel for measuring the sampling efficiency of inhalable aerosol samplers.

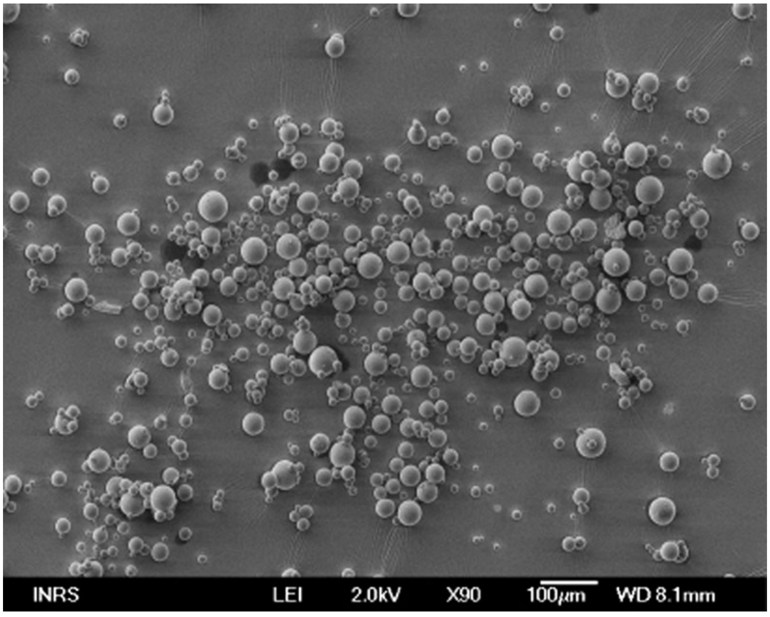


Fig. A2. Glass micro-sphere powder used as polydisperse test aerosol.

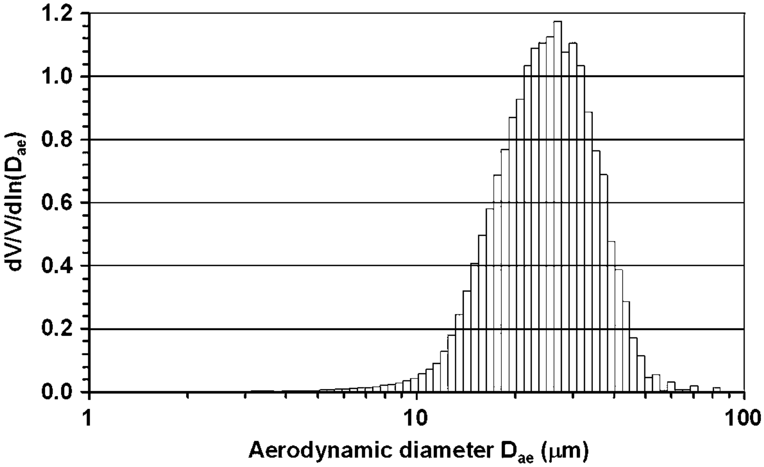


Fig. A3. Volumetric particle size distribution of glass sphere aerosol used in horizontal wind tunnel. MMAD = 24 μm; GSD = 1.4 (Coulter® counter particle size analysis of reference probe sample).

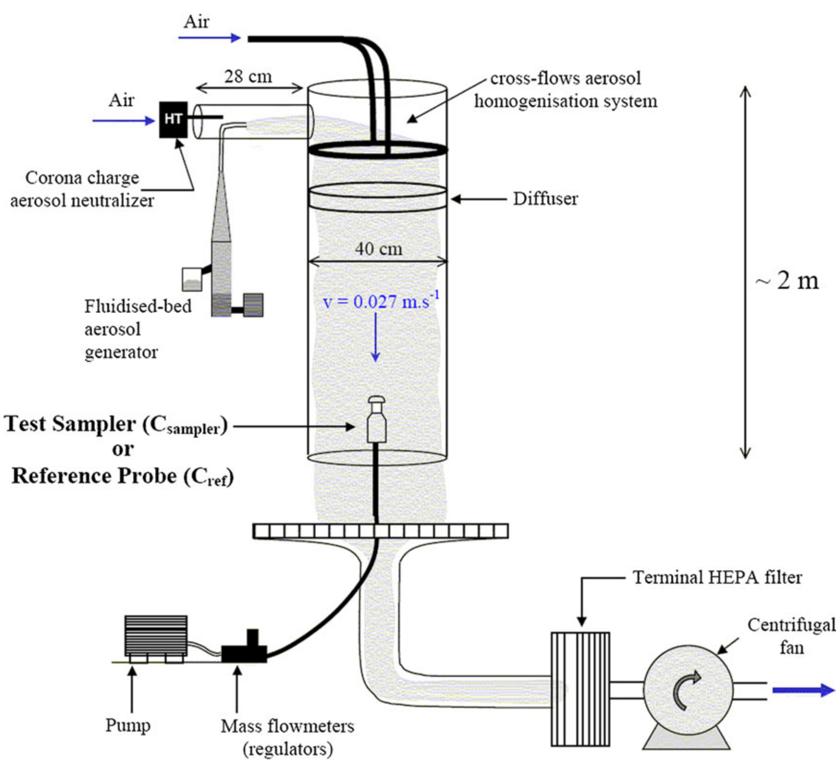


Fig. A4. Schematic diagram of experimental vertical calm air tunnel for measuring sampling efficiency of inhalable aerosol samplers.

sensing zone method—Coulter® counter. The generated particles were neutralized by corona discharge (Elcowa SC 67). The particle mean mass concentration in the working section could be controlled within an 18–43 mg m^{-3} interval.

Vertical calm air tunnel. The calm air tunnel provides a downward vertical supply of aerosol particles to its measuring zone. Only the particle generator and small dilution air streams enter the 400-mm cylindrical section, making the airflow very close to calm air

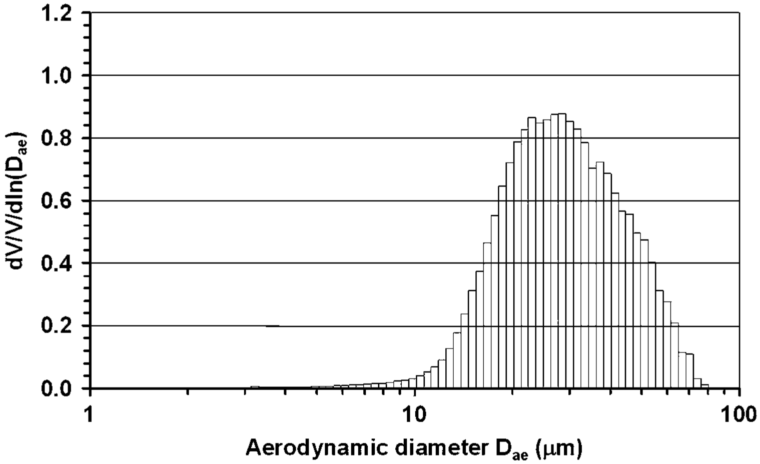


Fig. A5. Volumetric particle size distribution of glass sphere aerosol used in vertical calm air tunnel. MMAD = 27.5 μm; GSD = 1.6 (Coulter® counter particle size analysis of reference probe sample).

(0.027 m s^{-1}). This equipment has been described in detail by Roger (2000). Figure A4 illustrates the experimental set-up.

Polydisperse glass micro-sphere powder (BL 0-50 Verre Industrie) with a density of 2.46 g cm^{-3} was used to generate the test aerosol in the upper part of the tunnel. The particles were aerosolized using an air-blown fluidized bed (Guichard, 1976), which generated a test aerosol of MMAD of ~27.5 μm and GSD of ~1.6 (Fig. A5). The generated aerosol particles were neutralized using corona discharge (Elcowa SC 67). The average particle mass concentration in the working zone could be controlled within a 34- to 45-mg m^{-3} interval.

Test and reference samplers were positioned ~0.1 m upstream of the vertical duct outlet. No rotating manikin or bluff body was used in calm air trials.

APPENDIX B

Calculation of size-resolved experimental sampling efficiency

Each set of experimental values of sampling efficiency represents an average of three experimental runs. One run is one sampling efficiency measurement based on the measured concentration 'sampler : reference' ratio (concentrations are particle size resolved). Reference and sampler concentrations were measured sequentially as half-time reference – full-time sampler – half-time reference. This order was chosen to ensure no concentration shift during the run.

Each point of an efficiency curve is calculated as a ratio of two particle number concentrations using the following equation.

$$E_s(D_{ae}) = \frac{C_{n,\text{sampler}}(D_{ae})}{C_{n,\text{ref}}(D_{ae})}, \qquad \text{(B1)}$$

with D_{ae}, particle aerodynamic diameter (μm); $C_{n,\text{sampler}}$ (D_{ae}), number concentration of particles of diameter between D_{ae} and (D_{ae} + dD_{ae}), which have been sampled by the tested sampler (# l^{-1}); $C_{n,\text{ref}}$ (D_{ae}), number concentration of particles of diameter between D_{ae} and (D_{ae} + dD_{ae}), which have been drawn into the reference probe (# l^{-1}).

Aerosol size distributions and the number concentrations were determined using a Coulter® Multisizer 3 particle counter. Particles to be analysed were recovered by ultrasonic washing and dispersed in an electrolytic solution to form a suspension. The Coulter® glass tube, filled with electrolytic solution and fitted with a 100-μm calibrated aperture, was then plunged into the analysis beaker. The particle suspension was drawn through the 100-μm aperture, inducing an electric current between a platinum electrode in the glass tube and a second electrode which plunged into the suspension for analysis. The voltage applied across the aperture creates a 'sensing zone' (Lines, 1991). As a particle passes through the aperture, it displaces its own volume of electrolyte, momentarily increasing the impedance of the aperture. This impedance change produces a pulse in direct proportion to the particle volume (Allen, 1981). Analysing these electric pulses allows us to deduce a size distribution in terms of equivalent volume diameter D_v (μm). Furthermore, a metering device is used to draw a known volume of particle suspension through the aperture and counting the number of pulses can then yield the particle concentration in each size channel used (64 size channels were used in this study).

Some glycerol (15% in mass) was added to increase the electrolyte viscosity and reduce particle sedimentation. The suspension was continuously stirred to prevent particle losses due to sedimentation. The analysed particle volume was calculated from both the particle size distribution and the original sample weight, taking into account the relevant dilutions. A 10% bias between particle volumes was tolerated; otherwise the analyses were repeated (Görner *et al.*, 2000).

Volume diameter of a particle D_v can be converted into aerodynamic diameter D_{ae} by applying the following equation.

$$\rho_0 D_{ae}^2 C_u(D_{ae}) = \rho_p \frac{D_{ae}^2 C_u(D_v)}{\chi}, \tag{B2}$$

with ρ_0, density equal to 1 g cm^{-3}; $C_u(D)$, Cunningham correction factor for a diameter D(#); χ, particle dynamic shape factor (#); ρ_p, particle density (g cm^{-3}).

Consider the glass particles to be spherical ($\chi = 1$) and the ratio of the Cunningham correction factors to differ negligibly from unity ($C_u(D) \approx 1$) for particle diameters exceeding 5 μm, we can then apply the following simplified equation.

$$D_{ae} = D_v \sqrt{\frac{\rho_p}{\rho_0}}, \tag{B3}$$

Particle number concentrations were calculated using the equation:

$$C_{n,x}(D_{ae}) = \frac{N_x(D_{ae})}{V_x^{air}}, \quad \begin{array}{ll} x = \text{sampler}, & \text{for tested sampler} \\ x = \text{ref}, & \text{for reference probe} \end{array} \tag{B4}$$

with $N_x(D_{ae})$, total number of sampled particles of diameter D_{ae}(#); V_x^{air}, air volume sampled during the test (l).

$$N_x(D_{ae}) = N_x^{multisizer}(D_{ae}) K_x, \tag{B5}$$

with $N_x^{multisizer}(D_{ae})$, average particle number of diameter D_{ae} counted by Multisizer 3, when analysing a total particle volume $V_x^{multisizer}$; the average particle number $N_x^{multisizer}(D_{ae})$ is calculated from three different measurements taken on the same sample; K_x, dilution coefficient for sample analysis.

$$K_x = \frac{V_x^{part}}{V_x^{multisizer}}, \tag{B6}$$

with $V_x^{multisizer}$, total volume of particles counted during Multisizer 3 size distribution for 64 size channels (μm^3); V_x^{part}, volume of sampled particles (μm^3).

$$V_x^{part} = \frac{M_x^{part}}{\rho_p} \times 10^9, \tag{B7}$$

with M_x^{part}, mass of sampled particles (gravimetric determination—mg); ρ_p, particle density (g cm^{-3}).

REFERENCES

ACGIH (1994–1995) Threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

AFNOR. (2008) NF X 43-257: 2008. Qualité de l'air. Air des lieux de travail. Prélèvement d'aérosol à l'aide d'une cassette (orifice 4 mm). Paris-La-Défense: AFNOR.

Agarwal JK, Liu BYH. (1980) A criterion for accurate aerosol sampling in calm air. Am Ind Hyg Assoc J; 41: 191–7.

Aitken RJ, Baldwin EJ, Beaumont GC *et al.* (1999) Aerosol inhalability in low air movement environments. J Aerosol Sci; 30: 616–26.

Aizenberg V, Bidinger E, Grinshpun SA *et al.* (1998) Air flow and particle velocities near a personal aerosol sampler with curved, porous aerosol sampling surface. Aerosol Sci Technol; 28: 247–58.

Aizenberg V, Choe K, Grinshpun SA *et al.* (2001) Evaluation of personal aerosol samplers challenged with large particles. J Aerosol Sci; 32: 779–93.

Aizenberg V, Grinshpun SA, Willeke K *et al.* (2000a) Performance characteristics of the button personal inhalable aerosol sampler. Am Ind Hyg Assoc J; 61: 398–404.

Aizenberg V, Grinshpun SA, Willeke K *et al.* (2000b) Measurement of the sampling efficiency of personal inhalable aerosol samplers using a simplified protocol. J Aerosol Sci; 31: 169–79.

Allen T. (1981) Particle size measurement. 3rd edn. London: Chapman and Hall.

Baldwin PEJ, Maynard AD. (1998) A survey of wind speeds in indoor workplaces. Ann Occup Hyg; 42: 303–13.

Baron PA, Khanina A, Bennett JS *et al.* (2002) Investigation of filter by-pass leakage and a test for aerosol sampling cassettes. Aerosol Sci Technol; 36: 857–65.

Bartley DL. (1998) Inhalable aerosol samplers. Appl Occup Environ Hyg; 13: 274–78.

Brown JS. (2005) Particle inhalability in low wind speeds. Inhal Toxicol; 17: 831–7.

Buchan RM, Soderholm SC, Tillery MI. (1986) Aerosol sampling efficiency of 37 mm filter cassettes. Am Ind Hyg Assoc J; 47: 825–31.

CEN. (1993) EN 481: 1993. Workplace atmospheres—size fraction definitions for measurement of airborne particles. Bruxelles, Belgium: Comité Européen de Normalisation.

CEN. (2001) EN 13205: 2001. Workplace atmospheres—assessment of performance of instruments for measurement of airborne particle concentrations. Bruxelles, Belgium: Comité Européen de Normalisation.

CEN. (2005) TR 15230: 2005. Workplace atmospheres—guidance for sampling of inhalable, thoracic and respirable aerosol fractions. Bruxelles, Belgium: Comité Européen de Normalisation.

Chung KYK, Ogden TL, Vaughan NP. (1987) Wind effects on personal dust samplers. J Aerosol Sci; 18: 159–74.

Courbon P, Wrobel R, Fabriès JF. (1988) A new individual respirable dust sampler: the CIP 10. Ann Occup Hyg; 32: 129–43.

Davies CN. (1968) The entry of aerosols into sampling tubes and heads. Br J Appl Phys; 1: 921–31.

Davies CN. (1977) Sampling aerosols with a thin-walled tube. Atmospheric Pollution. Amsterdam, the Netherlands: Elsevier; pp. 433–46.

Demange M, Gendre JC, Hervé-Bazin B *et al*. (1990) Aerosol evaluation difficulties due to the particle deposition on filter holder inner walls. Ann Occup Hyg; 34: 399–403.

Demange M, Görner P, Elcabache JM *et al*. (2002) Field comparison of 37-mm closed-face cassettes and IOM samplers. Appl Occup Environ Hyg; 17: 200–8.

Fabriès JF, Görner P, Kauffer E *et al*. (1998) Personal thoracic CIP 10-T sampler and its static version CATHIA-T. Ann Occup Hyg; 42: 453–65.

Görner P, Fabriès JF. (1996) Industrial aerosol measurement according to the new sampling conventions. Occup Hyg; 3: 361–76.

Görner P, Witschger O, Roger F *et al*. (2008) Aerosol sampling by annular aspiration slots. J Environ Monit; 10: 1437–47.

Görner P, Wrobel R, Fabriès JF. (1990) Air filtration by rotating porous media. In Proceedings of the 5th World Filtration Congress, Nice, 5–8 June; Cachan, France: Société Française de Filtration; pp. 165–7.

Görner P, Wrobel R, Fabriès JF. (2000) Experimental method to determine the efficiency of aerosol samplers using the Coulter Counter. J Aerosol Sci; 3 (Suppl. 1): 268–9.

Görner P, Wrobel R, Simon X. (2009) High efficiency CIP 10-I personal inhalable aerosol sampler. In Inhaled Particles X, 23–25 September 2008, Sheffield; Journal of Physics. Conference Series 151. Manchester, UK: IOP Publishing.

Görner P, Wrobel R, Witschger O *et al*. (2003) Sélecteur de particules en suspension dans une atmosphère et dispositif d'échantillonnage pourvu d'un tel sélecteur. Patent no. 03 02322. Institut National de la Propriété Industrielle: Paris.

Grinshpun SA, Lipatov GN, Sutugin AG. (1990) Sampling errors in cylindrical nozzles. Aerosol Sci Technol; 12: 716–40.

Grinshpun SA, Willeke K, Kalatoor S. (1993) A general equation for aerosol aspiration by thin-walled sampling probes in calm and moving air. Atmos Environ; 27A: 1459–70. Corrigendum (1994) Atmos Environ; 28: 375.

Guichard JC. (1976) Aerosol generation using fluidised beds. In Liu BYH editor. Fine particles; New York: Academic Press; pp. 173–93.

Harper M, Akbar MZ, Andrew ME. (2004) Comparison of wood-dust aerosol size-distributions collected by air samplers. J Environ Monit; 6: 18–22.

Harper M, Muller BS. (2002) An evaluation of total and inhalable samplers for the collection of wood dust in three wood products industries. J Environ Monit; 4: 648–56.

INRS. (2006) Questions écrites—poussières de bois. Information Juridique no. 3, Paris: Institut National de Recherche et de Sécurité.

ISO. (1995) IS 7708: 1995. Air quality—particle size fraction definitions for health-related sampling. Geneva, Switzerland: International Standards Organisation.

Kalatoor S, Grinshpun SA, Willeke K. (1995) New aerosol sampler with low wind sensitivity and good filter collection uniformity. Atmos Environ; 29: 1105–12.

Kauffer E, Wrobel R, Görner P *et al*. (2010) Site comparison of selected aerosol samplers in the wood industry. Ann Occup Hyg; 54: 188–203.

Kauppinen T, Vincent R, Liukkonen T *et al*. (2006) Occupational exposure to inhalable wood dust in the member states of the European Union. Ann Occup Hyg; 50: 549–61.

Kennedy NJ, Tatyan K, Hinds WC. (2001) Comparison of a simplified and full-sized mannequin for the evaluation of inhalable sampler performance. Aerosol Sci Technol; 35: 564–8.

Kenny LC. (1995) Pilot study of CEN protocols for the performance testing of workplace aerosol sampling instruments. EC contract MAT1-CT92–0047 final report. Sheffield: Health and Safety Laboratory.

Kenny LC, Aitken RJ, Baldwin PEJ *et al*. (1999) The sampling efficiency of personal inhalable aerosol samplers in low air movement environments. J Aerosol Sci; 30: 627–38.

Kenny LC, Aitken R, Chalmers C *et al*. (1997) A collaborative European study of personal inhalable aerosol sampler performance. Ann Occup Hyg; 41: 135–53.

Kenny LC, Beaumont G, Gudmundssen A *et al*. (2000) Small-scale aerosol sampler testing systems. J Aerosol Sci; S31: 406–7.

Kenny LC, Lidén G. (1991) A technique for assessing size-selective dust samplers using the APS and polydisperse test aerosols. J Aerosol Sci; 22: 91–100.

Koch W, Dunkhorst W, Lödding H. (1999) Design and performance of a new personal aerosol monitor. Aerosol Sci Technol; 31: 231–46.

Koch W, Dunkhorst W, Lödding H *et al*. (2002) Evaluation of the Respicon as a personal inhalable sampler in industrial environments. J Environ Monit; 4: 657–62.

Legislative Decree. (1993) Ministère des affaires Sociales, du Travail et de la Solidarité. Décret no 2003-1254 du 23 décembre 2003 relatif à la prévention du risque chimique et modifiant le code du travail. JORF n°300 du décembre 2003: 22329–34.

Li S-N, Lundgren DA, Rovell-Rixx D. (2000) Evaluation of six inhalable aerosol samplers. Am Ind Hyg Assoc J; 61: 506–16.

Lidén G, Harper M. (2006) Analytical performance criteria. The need for an international sampling convention for inhalable dust in calm air. J Occup Environ Hyg; 3: D94–D101.

Lidén G, Juringe L, Gudmundsson A. (2000) Workplace validation of the laboratory evaluation test of samplers for inhalable and "total" dust. J Aerosol Sci; 31: 199–219.

Lines RW. (1991) The electrical sensing zone method (the Coulter principle). In Stanley-Wood NG and Lines RW editors. Particle size analysis. Cambridge: Royal Society of Chemistry, 351–73.

Mark D, Vincent JH. (1986) A new personal aerosol sampler for airborne total dust in workplaces. Ann Occup Hyg; 30: 89–102.

Ogden TL. (1983) Inhalable, inspirable and total dust. In Marple VA and Liu BYH, editors. Aerosols in the mining and industrial work environments, Vol. 1. : Ann Arbor, MI: Ann Arbor Science; pp. 185–204.

Paik SY, Vincent JH. (2004) The orientation-averaged aspiration efficiency of IOM-like personal aerosol samplers mounted on bluff bodies. Ann Occup Hyg; 48: 3–11.

Paskar MA, Harkins JM, Moomey JD *et al*. (1991) Internal wall losses of pharmaceutical dusts during closed-face, 37-mm polystyrene cassette sampling. Am Ind Hyg Assoc J; 52: 280–6.

Ramachandran G, Sreenath A, Vincent JH. (1998) Towards a new method for experimental determination of aerosol sampler aspiration efficiency in small wind tunnels. J Aerosol Sci; 29: 875–91.

Rando R, Poovey H, Mokadam D *et al*. (2005) Field performance of the RespiCon for size-selective sampling of industrial wood processing dust. J Occup Environ Hyg; 2: 219–26.

Roger F. (2000) Etude des performances d'un échantillonneur d'aérosols à fente annulaire dans l'air calme et dans l'air en mouvement—Expériences et simulations numériques. Thèse de doctorat de l'Université Paris XII.

Roger F, Lachapelle G, Fabriès JF *et al*. (1998) Behaviour of the IOM aerosol sampler as a function of external wind velocity and orientation. J Aerosol Sci; 29 (Suppl. 1): S1133–4.

Schmees DK, Wu Y-H, Vincent JH. (2008) Experimental methods to determine inhalability and personal sampler performance for aerosols in ultra-low windspeed environments. J Environ Monit; 10: 1426–36.

Sleeth DK, Vincent JH. (2009) Inhalability for aerosols at ultra-low windspeeds. In Inhaled particles X, 23–25 September 2008, Sheffield. Journal of Physics: Conference Series, 151, 012062. Manchester, UK: IOP Publishing.

Su W-C, Vincent JH. (2004) Towards a general semi-empirical model for the aspiration efficiencies of aerosol samplers in perfectly calm air. J Aerosol Sci; 35: 1119–34.

ter Kuile WM. (1978) Dust sampling criteria. A contribution to standardisation of ''total dust'' measurements. In Aerosole in Naturwissenschaft, Medizin und Technik—Dynamik und Nachweis ultrafeiner Aerosole. 26–28 September 1978, Wien. Mainz, Germany: GAF; pp. 365–73.

ter Kuile WM. (1979) Dust sampling criteria. J Aerosol Sci; 10: 241–2.

ter Kuile WM. (1984) Vergleichmessungen mit verschiedenen Geräten zur Bestimmung der Gesamtstaubkonzentration am Arbeitsplatz—Teil II. Staub—Reinhalt Luft; 44: 211–6.

Vincent JH, Mark D. (1990) Entry characteristics of practical workplace aerosol samplers in relation to the ISO recommendations. Ann Occup Hyg; 34: 249–62.

Vincent JH, Mark D, Miller BG *et al*. (1990) Aerosol inhalability at higher windspeeds. J Aerosol Sci; 21: 577–86.

Vincent JH. (2005) Health-related aerosol measurement: a review of existing sampling criteria and proposals of new ones. J Environ Monit; 7: 1037–53.

Vincent JH. (2006) Testing personal inhalable aerosol samplers: a suggested improved protocol based on new scientific knowledge. J Environ Monit; 8: 53–62.

WHO. (1999) Hazard prevention and control in the work environment: airborne dust. Geneva, Switzerland: World Health Organisation, WHE/SDE/OEH/99.14.

Witschger O. (1996) Etude théorique et expérimentale des facteurs physiques d'échantillonnage des polluants particulaires—Application aux capteurs à fente annulaire. Thèse de doctorat de l'Université Paris XII.

Witschger O, Grinshpun SA, Fauvel S *et al*. (2004) Performance of personal inhalable aerosol samplers in very slowly moving air when facing the aerosol source. Ann Occup Hyg; 48: 351–68.

Witschger O, Willeke K, Grinshpun SA *et al*. (1998) Simplified method for testing personal inhalable aerosol samplers. J Aerosol Sci; 29: 855–74.

Witschger O, Wrobel R, Fabriès JF *et al*. (1997) A new experimental wind tunnel facility for aerosol sampling investigations. J Aerosol Sci; 28: 833–51.