Inhaled Particles X, (23–25 September 2008, Manchester) IOP Publishing
Journal of Physics: Conference Series **151** (2009) 012061 doi:10.1088/1742-6596/151/1/012061

High efficiency CIP 10-I personal inhalable aerosol sampler

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Abstract. The CIP 10 personal aerosol sampler was first developed by Courbon for sampling the respirable fraction of mining dust. This respirable aerosol sampler was further improved by Fabries, then selectors for sampling thoracic and inhalable aerosols were designed. Kenny *et al.* evaluated the particle-size dependent sampling efficiency of the inhalable version in a large-scale wind tunnel using a life-size dummy. The authors found that the overall sampling efficiency decreases more rapidly than the CEN-ISO-ACGIH target efficiency curve. Görner and Witschger measured the aspiration efficiency of the CIP 10 omni-directional inlet. They found that the aspiration efficiency was high enough for inhalable aerosol sampling. This result led to the conclusion that the low sampling efficiency is due to some internal losses of the aspirated particles before they reach the final sampling stage, namely the CIP 10 rotating filter. Based on the assumption that the inhalable particles are selected at selector aspiration level, an experimental research project was conducted to improve particle transmission to the collection stage of the sampler. Two different inhalable selectors were designed by Görner and tested in a laboratory wind tunnel. The transmission efficiency of both models was measured by Roger following an experimental protocol described by Witschger. The T-shaped air flow circuit was finally adopted to draw the aspirated particles into the final collection stage of the CIP 10. Actually, in this selector, the almost horizontally aspirated particles should be conducted vertically to the rotating cup. In two previous prototypes, particles could be deposited in certain places by inertia (where the aerosol was forced to deviate drastically) or by sedimentation (where the aerosol decelerated). The aerodynamic behaviour of the adopted solution causes the particles to accelerate radially between two horizontal plates before they enter a vertical tube. This acceleration avoids the particles being deposited on the lower horizontal plate. At the beginning of the vertical tubing, the mutually opposing particle trajectories limit particle wall deposition by virtual impaction effect. The inner selector walls are polished to avoid particles being stopped by eventual surface asperities. Particle size-dependent sampling efficiency was measured in the laboratory wind tunnel. The experimental aerosol was composed of polydisperse glass micro-spheres. The size analysis of the particles collected was done by the Coulter Counter technique. The transmission efficiency (reciprocal to wall losses) was found to be close to 100 % for the entire range of particle sizes, and indicated no particle loss. The overall sampling efficiency was measured using a rotating bluff body at an external wind speed of 1 m/s. The rotating bluff body represents a scaled torso of an operator. The "high efficiency" CIP 10-I (I for inhalable) responds fairly well to the conventional CEN-ISO-ACGIH criteria for sampling the inhalable health-related aerosol fraction.

1. Introduction
The CIP 10 personal aerosol sampler was first developed as an individual version of the static coal-mine respirable dust sampler CPM3 [1]. The sampler is based on a rotating cup principle described by Quinot [2]. The efficiency of the rotating filter and its flow rate as a function of rotating speed were studied by Görner *et al.* [3]. The respirable aerosol selector of the CIP 10 was further improved [4],

and the performance of the CIP 10 was laboratory tested by [5] along with fourteen other respirable samplers used in occupational hygiene all over the world. A selector for sampling the thoracic fraction of aerosols was then designed for the CIP 10 sampler [6, 7]. The sampling of the inhalable fraction by the CIP 10 was achieved simply by directing the aspirated particles directly into the rotating cup with no additional selection unit. This resulting in the CIP 10 sampler being able to mesure any of the three conventional health-related aerosol fractions [8, 9, 10]. Finally, a special rotating cup was developed for biological aerosol sampling into a liquid medium [11, 12]. The CIP 10 sampler is operated at a flow rate of 10 L.min^{-1}, except for the thoracic version which is operated at 7 L.min^{-1}.

Kenny *et al.* [13, 14] evaluated the particle-size dependent sampling efficiency of the original version of the inhalable selector of the CIP 10-I (I for inhalable) in a large-scale wind tunnel using a full-scale dummy. A series of quasi monodisperse aluminium oxide (Aloxite) particles was used to generate the test aerosol. The authors found that the sampling efficiency decreased more rapidly than the CEN-ISO-ACGIH [8, 9, 10] target efficiency curve (figure 1).

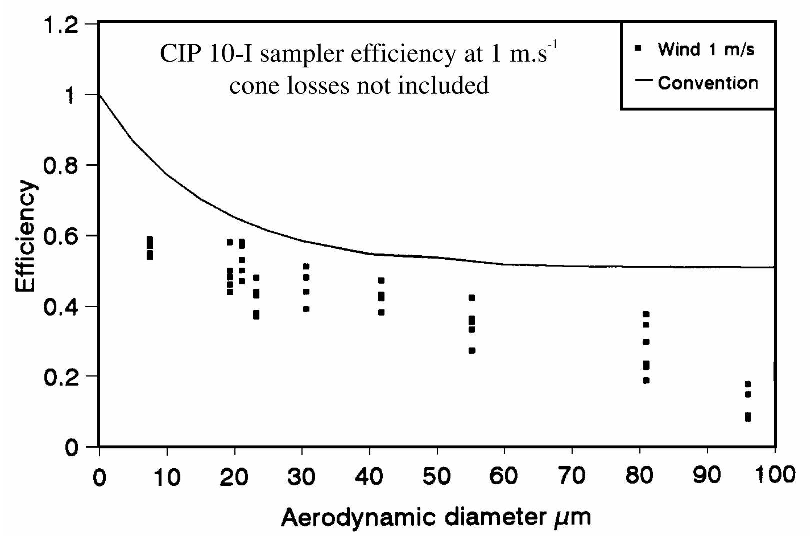

Figure 1. Overall sampling efficiency of the original CIP 10-I inhalable aerosol sampler as a function of particle size, measured in a large wind tunnel with rotating full-size mannequin.

A hypothesis was made that the low efficiency could be due to wall losses inside the selector (figure 3a).

Görner *et al.* [15] measured the aspiration efficiency of the CIP 10 omni-directional inlet using a polydisperse aerosol of glass microspheres. They found that the entry efficiency of the aspiration slot was sufficiently high for inhalable aerosol sampling (figure 2). This result led to the conclusion that the low sampling efficiency is actually due to the internal losses of the aspirated particles in the original selector.

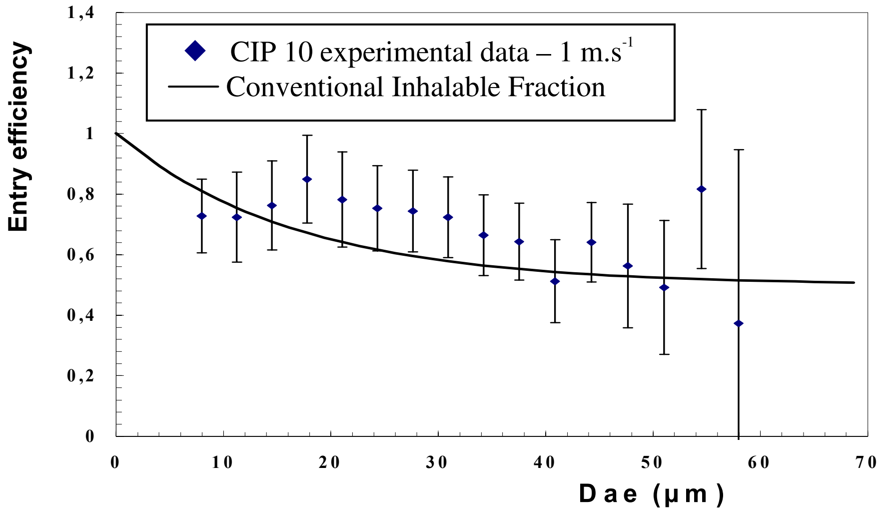

Figure 2. Experimental entry efficiency of the CIP 10 aspiration slot as a function of particle size. Sampler in isolated static position (with no bluff body).Sampler flow rate: 10 $L.min^{-1}$ - Tunnel wind speed: 1 $m.s^{-1}$

2. Design of "high efficiency" inhalable selector

The aerosol is aspirated through an omni-directional aspirating slot shielded by a protective cap. Based on the assumption that the inhalable particles are selected at aspiration slot level, an experimental research project was conducted to improve particle transmission to the collection stage of the sampler. First, we looked for the main position of the particle deposit inside the selector. The deposit was formed by impaction in flow deviation under the protective cap near the six inlet orifices of the selector body (as represented in figure 3a). A second inhalable selector with a modified air circuit was designed (figure 3b). However, this second prototype still exhibited an unsatisfactory transmission efficiency, and the deposits of particles were mainly observed in the enlarged conical section, probably due to flow turbulences and sedimentation in decelerated flow.

The third prototype designed uses an annular aspiration slot with two circular horizontal plates connected to a vertical cylindrical tubing (figure 3c).

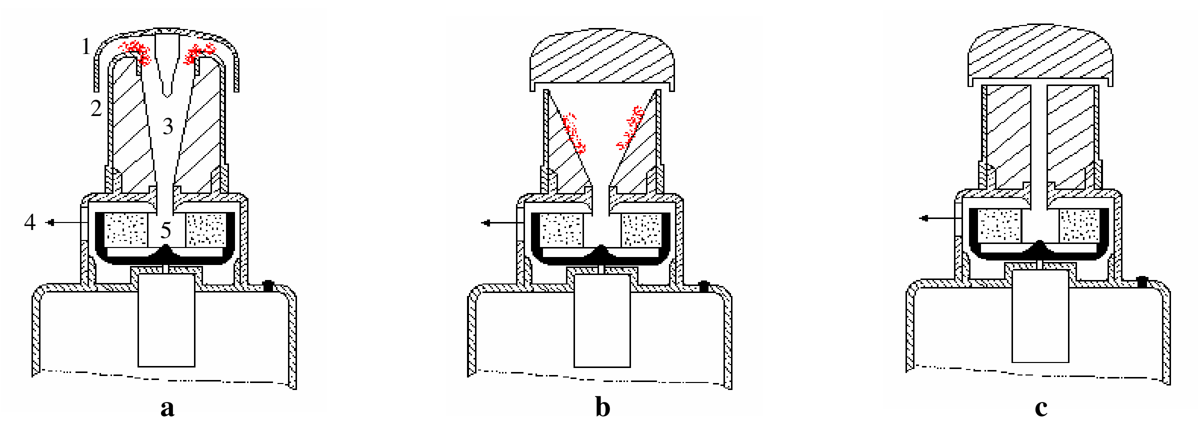

Figure 3. Schematic of design progress in the development of the CIP 10 Inhalable selector.
1- Protective cap, 2- Air inlet, 3- Selector body, 4- Air outlet, 5- Rotating cup.
a – Original selector (wall losses under the protective cap)
b – Second selector (wall losses in large conical duct)
c – Final, T-shape selector (no wall losses)

This geometric configuration was studied earlier by Witschger *et al.* [16] and Roger *et al.* [17], but not in connection with the CIP 10 sampler [18]. The solution in figure 3c avoids the six orifices of the original selector and the large conical section of the second prototype, where the particle losses were concentrated. In the final prototype, the air velocity is accelerated in a radial path through the annular slot, as indicated in figure 4. The acceleration is due to the decreasing section of the slot toward its centre (provided the height of the sampling slot is constant, as shown in figure 3c). The horizontal acceleration as well as the following downward vertical flow minimise the possibility of particle deposit between the aspiration slot and the rotating cup, which is the final particle collector.

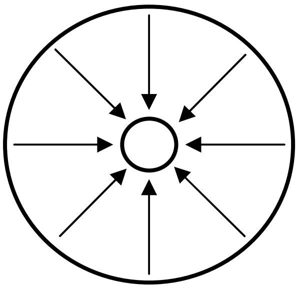

Figure 4. Schematic of radial air flow acceleration between the sampling slot and the central cylindrical duct.

The transmission efficiency of the particles, defined as the difference between aspiration and overall sampling efficiency, was measured by Roger for all three models following an experimental protocol described by Witschger *et al.* [19] using a polydisperse glass sphere aerosol. The particle size-dependent transmission efficiency of the two first selectors from figures 3a and 3b was situated approximately between 60 and 80 %, meaning that the inner wall losses represent about 20-40 % of the aspirated aerosol. The transmission efficiency of the final selector (figure 3c) is close to 1 for all particle sizes, and clearly higher than those of the two previous prototypes (figure 5). This means that the wall losses were minimised and that almost 100 % of the aspirated particles of any size reach the collecting stage, i.e. the rotating cup.

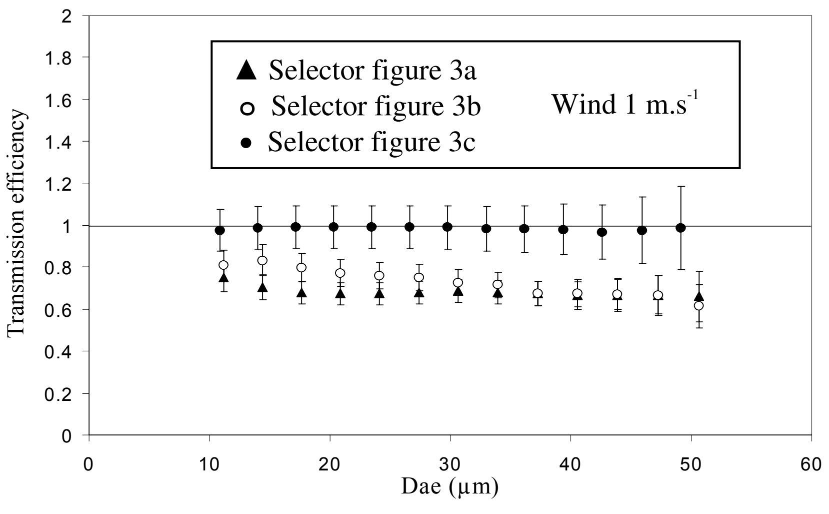

Figure 5. Transmission efficiency (reciprocal to wall losses) of the three inhalable aerosol selectors from figures 3a,b,c.
Sampler in isolated static position (with no bluff body).
Sampler flow rate: 10 $L.min^{-1}$ - Tunnel wind speed: 1 $m.s^{-1}$

3. Measurement of overall sampling efficiency

The particle-size dependent sampling efficiency of the final version of the CIP 10-I was studied in an experimental wind tunnel using glass beads to generate the aerosol. In the case of the inhalable fraction, the wind conditions in the vicinity of the sampler should be taken into account because of their influence on particle aspiration. The sampling efficiency of personal aerosol samplers is influenced by the operator wearing the sampler. Therefore, the personal samplers are tested attached to a mannequin modelling the operator's body. To simulate a moving operator, the sampler wearing mannequin rotates. This means that the sampler is exposed to the experimental aerosol at different angles. An optimal experimental method to measure sampler efficiency is described in the EN 13205 [20] standard. A large-scale experimental wind tunnel containing a full-sized mannequin is required. Consequently, high flow rates are necessary and some problems with particle size and concentration homogeneity over the entire measuring zone can be expected. Several authors have worked to reduce this by scaling the dimensions of the experimental equipment without deteriorating the experimental results [21-23]. Promising results were obtained by Paik and Vincent [24] using a rectangular, three-dimensional bluff body. We checked that our experimentation with a cylindrical bluff body 110 mm in diameter and 55 mm in width, rotating at 2 rpm, led to results similar to those of Paik and Vincent.

A detailed description of the wind tunnel used and its flow parameters, along with their spatial and time stability, were given by Witschger *et al.* [19]. Polydisperse aerosol generation and determination of the aerodynamic particle diameter (Dae) using the Coulter-Counter technique are described in Görner *et al.* [18].

The overall sampling efficiency of a sampler is defined as the ratio of the size-resolved particle concentration sampled on the final support versus the free stream particle concentration measured by a reference probe. The thin-walled, sharp-edged cylindrical reference probe (10 mm inner diameter) was designed in accordance with the geometric criteria of Belyaev and Levin [25] for unbiased sampling when operated in isokinetic isoaxial conditions. In the case of sequential sampling, used in our case, the sampler on test and the reference probe are placed consecutively one after the other right in the tunnel axes. This solution was preferred to parallel sampling because of better time stability than the space stability of the aerosol concentration in the tunnel [19].

4. Results

The resulting overall sampling efficiency of the final CIP 10-I inhalable aerosol sampler, measured at a wind speed of 1 $m.s^{-1}$, is reported in figure 6. The sampling efficiency of the well-known IOM sampler was also measured and is reported to compare the results of both samplers in the same experimental conditions. The particle size-resolved efficiencies are represented by experimental points along with their error bars corresponding to $\pm$ 2 SD at 95 % confidence level. (SD being Standard Deviation from 3 experimental runs). The CEN-ISO-ACGIH conventional Inhalable penetration is also reported.

The sampling efficiencies of the two samplers are close to each other and decrease around the conventional penetration curve. The final version of the CIP 10 Inhalable aerosol sampler performs much better (figure 6) than the original version of this sampler (figure 1).

To quantify the sampling performance of the sampler placed in various polydisperse aerosols situations, the bias and accuracy maps were elaborated according to the EN 13205 specifications. The goal of this numerical calculation is to simulate the inhalable mass concentration assumed to be measured by the sampler and to compare it to the conventional inhalable concentration (target aerosol fraction), for any given aerosol with a known particle mass distribution. The calculation were made for a large range of log-normally distributed polydisperse aerosols.

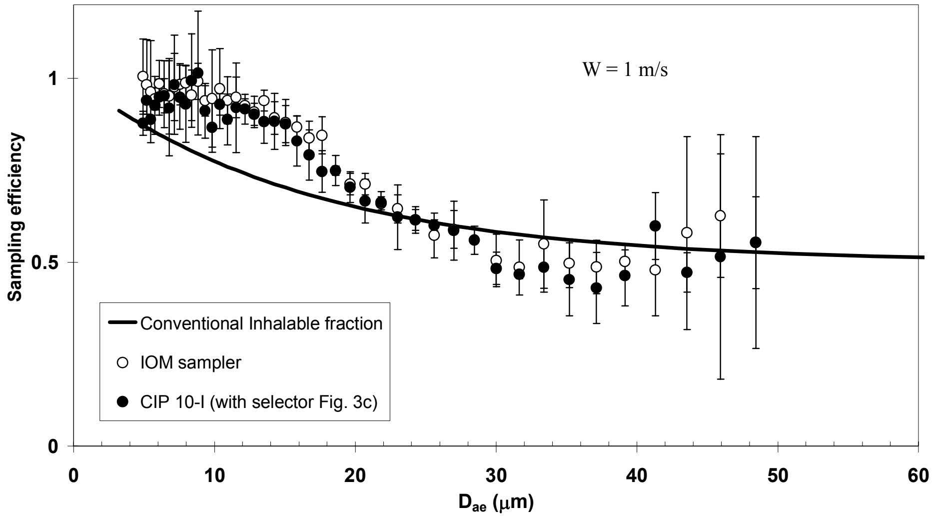

Figure 6. Overall sampling efficiency of the CIP 10-I "high efficiency" inhalable sampler (figure 3c) along with the efficiency of the IOM sampler, measured in the same experimental conditions. Samplers attached to a rotating bluff body. Sampler flow rate: CIP 10-I 10 L.min^{-1}, IOM 2 L.min^{-1} – Tunnel wind speed: 1 m.s^{-1}

The experimental efficiency values were fitted by a polynomial model of second degree to obtain an analytical expression of the sampling efficiency as a function of aerodynamic diameter of particles. The Newton-Gauss least-squares algorithm was used to optimise the parameters of the model [26]. The model fits quite well the sampler efficiency in the interval of experimental data (0 – 50 µm) but it was found that it idealises the sampler efficiency in the extrapolated interval (50 – 100 µm), keeping the efficiency close to a horizontal line at a level of about 45%. It is obvious that the real sampler efficiency decreases with increasing particle size. The more realistic, decreasing, model was reached by minimising the first fitted parameter of the polynomial model. The resulting sampling efficiency function "E_s" used in bias and accuracy calculations is as follows:

$$E_s(D_{ae}) = 1.10^{-12} . D_{ae}^{\ 2} - 0.0138 . D_{ae} + 1.028$$

The detailed method for bias and accuracy calculations is fully described elsewhere [6, 27]. The bias and accuracy maps of the CIP 10-I "high efficiency" inhalable aerosol sampler are represented in figures 7 and 8. Bias and accuracy are expressed in percentage of sampled mass concentration compared to the concentration which would be measured by a device with the efficiency following exactly the CEN-ISO-ACGIH conventional penetration curve, for each aerosol distribution.

The bias and accuracy are calculated for a series of aerosol distributions with the MMAD (Mass Median Aerodynamic Diameter) within an interval from 1 to 25 µm (step of 1 µm) and the GSD (Geometric Standard Deviation) from 1.5 to 3.5 (step of 0.25). The EN 13205 standard require the bias within –10% to +10% and accuracy within 0 to +30% for a first quality sampler. The bias and accuracy performance criteria were defined by Görner *et al.* [28] as a percentage of the aerosols in the map for which the EN 13205 requirement is met. More the criterion approaches 100%, more versatile is the sampler, i.e. its using is suitable for any aerosol distribution.

It is possible to use the bias and accuracy maps to predict the sampler behaviour in workplace in the case of respirable aerosol measurement. In the case of inhalable samplers, high caution is recommended. Actually, the sampling of smaller particles (respirable aerosol fraction) is less influenced by the external wind speed and by the operator in the vicinity of the sampler. A difference between experimental conditions and workplace conditions has low impact on sampling efficiency of the sampler. In the case of inhalable fraction, coarse particles having big inertia are involved in sampling procedure and the sampler efficiency become extremely sensible to the external flow conditions. For this reason the bias and accuracy maps of inhalable aerosol samplers are less predictive in workplace conditions which can be different from the conditions of experimental run. The experimental measurement of the CIP 10-I sampling efficiency was made at a wind speed of 1 $m.s^{-1}$, the sampler rotating with a scaled bluff body. The reported bias and accuracy maps (figures 7 and 8) correspond to such flow and operating conditions.

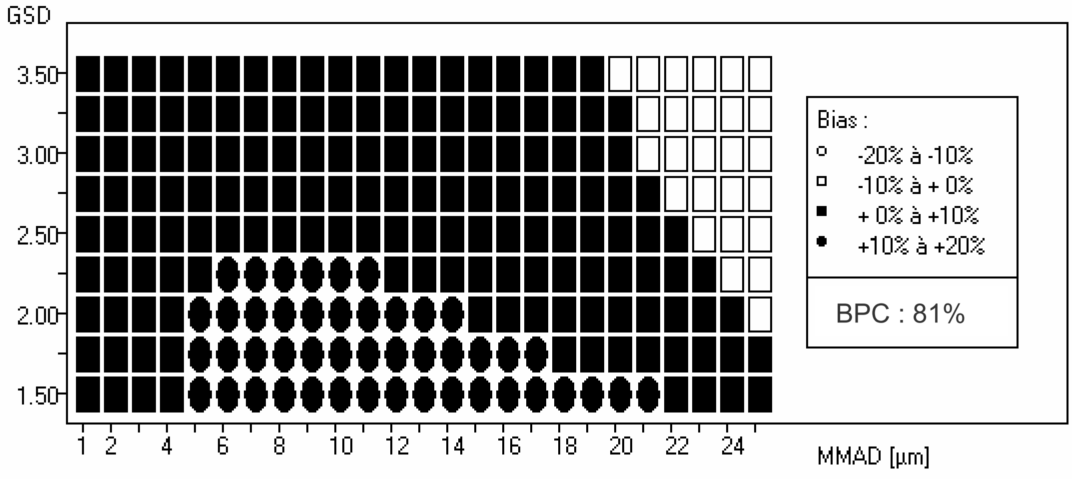

Figure 7. Bias map of the "high efficiency" CIP 10-I.
BPC: Bias Performance Criterion

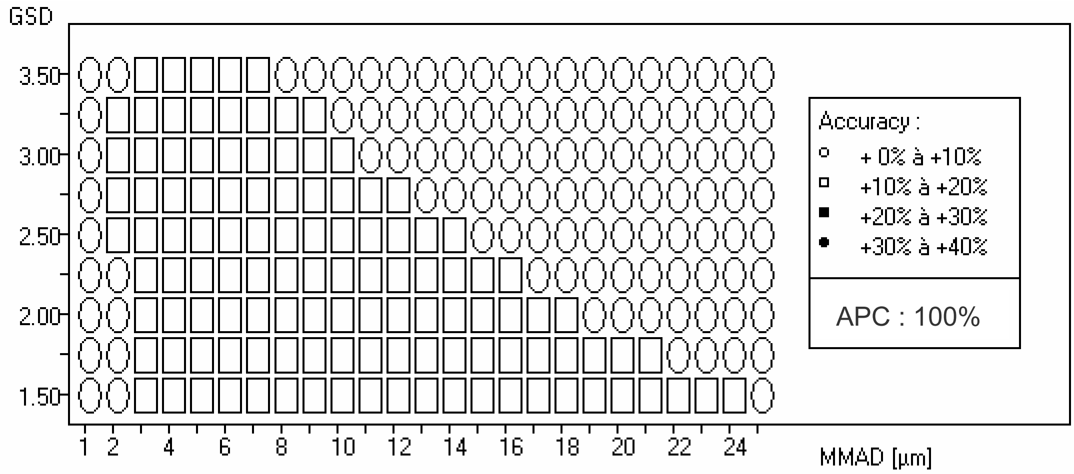

Figure 8. Accuracy map of the "high efficiency" CIP 10-I.
APC: Accuracy Performance Criterion

5. Conclusion

The three-dimensional T-shaped air flow circuit inside the CIP 10-I selector was adopted (figure 3c) to draw the aspirated particles into the final collecting stage of the sampler [29]. In the two previous prototypes, particles could be deposited in certain places due to inertia (where the aerosol was forced to deviate drastically) or sedimentation (where the aerosol decelerated). This kind of wall loss brings down the overall sampling efficiency of the sampler. The aerodynamic behaviour of the adopted solution (figure 3c) causes the particles to accelerate radially between the two horizontal plates before they enter a vertical tube. This acceleration avoids the particles being deposited on the lower horizontal plate. At the beginning of the vertical tube, the mutually opposing particle trajectories limit particle wall deposit by virtual impaction effect. The inner selector walls are polished to avoid particles being stopped by eventual surface asperities.

The "high efficiency" CIP 10-Inhalable aerosol sampler meets fairly well the conventional CEN-ISO-ACGIH criteria for sampling the inhalable health-related aerosol fraction.

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