Review over Inertial and Diffusional Spectrometer (SDI) for aerosol sampling

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TITRE

Revue du spectromètre Inertiel et Diffusionnel (SDI) pour le prélèvement d'aérosols

ABSTRACT

We present a particle Inertial and Diffusional Spectrometer (SDI) based on the combination of an Andersen mark II impactor and a diffusion battery consisting of six channels, five of which are glass beds of different diameters, the sixth allowing an upstream measurement of the submicron fraction of the aerosol. This device covers a range of aerosol dimensions between 0.005 and 15 µm with very high concentrations.

RESUME

Nous présentons un Spectromètre Diffusionnel et Inertiel (SDI) dont l'objectif est de couvrir un domaine de dimensions compris entre 0,005 et 15 µm avec de hautes concentrations. Il est une association d'un impacteur Andersen Mark II et d'une batterie de diffusion avec six canaux dont cinq contiennent des billes de verre et un sixième de référence permettant de fournir une mesure en amont de la fraction submicronique.

KEYWORDS: Aerosol, Impactor, Diffusion battery, SDI **MOTS-CLÉS:** Aérosol, Impacteur, Batterie de diffusion, SDI

1. INTRODUCTION

The estimation of the mass distribution of particles throughout nearly the whole size range from a few 10^{-3} µm to 10 µm using a simple and affordable approach is one of the challenges encountered by experts in aerosol metrology. None of the available automated equipment can accommodate this size range (cascade impactors, diffusion batteries, optical particle counters, electrical analyzers). Additionally, because these tools are based on various physical principles, it is difficult to determine behavior-related particle size in issues with inhalation, occupational hygiene and/or contamination. They are often not designed for the measurement of large mass concentrations in the mentioned size range. These numerous needs can be satisfied by the presented SDI 2001 (Diffusional and Inertial Spectrometer) instrument. This SDI 2001 is the modified version of the SDI 2000 and the detailed description over SDI 2000 is available in literature (Boulaud and Diouri.,1988). The uniqueness of this instrument SDI comes from the union of two methods that were applied separately. The first technique collects the biggest particles according to their aerodynamic diameter (inertial classification) using a Mark II Andersen impactor and the second technique is based on the diffusion of the sub-micron size particles using a 6 channels diffusion battery. Thus, this spectrometer can detect particles of a size between 0.005 µm and 15 µm.

2. HISTORY OF INSTRUMENT SDI

Diouri et al., 1987 has developed the first version of Diffusional and Inertial Spectrometer (SDI) which is known as SDI 2000 and its objective is to cover a range of dimensions between 0.0075 and 15 µm. The SDI 2000 is a combination of an impactor and a diffusion battery. This device makes it possible to determine the particle size distribution between approximately 0.01 µm and 10 µm. The inertial precipitation is carried out by a MARK II cascade impactor whose aerodynamic cut-off diameters, determined experimentally, are between 0.35 µm and 7.5 µm. The cascade impactor's flow rate (28.3 lpm) is the overall flow rate. There is no filter on the final stage of the SDI 2000 impactor. Thus, the fraction of the aerosol not impacted on the filters of the impactor passes through the diffusion battery. The diffusion battery is made up of 5 channels arranged in parallel, four of which contain glass balls with a diameter ranging from 1 to 5 mm and a fifth for reference to provide the upstream concentration of the submicron fraction. The height of the bead bed is between 6 and 16 cm. SDI 2000 was used by Diouri et al., 1987 for the characterization of aerosols emitted by diesel engines. Boulaud and Chouard, 1989 used the SDI 2000 with three impactor stages and 4 diffusion channels to measure the particle size of aerosols and radon progeny in a uranium mine. Indeed, the SDI 2000 was used to measure the distribution in dimension of the global alpha activity. In addition, a set of grids was sized to trap the free fraction of radon progenies and placed upstream of the SDI. Comper, 1989 has studied the possibilities for the characterization of a uranium generator allowing the control of HEPA (High Efficiency Particulate Air) filters in nuclear power plants using SDI 2000. The experiments of Roult, 1990 made it possible to carry out the calibration of the SDI 2000 diffusion battery by verifying the law of capture of submicron particles by beds of beads. The experiments were carried out in the diffusional regime using a monodisperse aerosol of Di(2-ethylhexyl) sebacate (DEHS). It was concluded that the empirical

expression of Otani et al., 1989 describes the collection efficiency of the SDI 2000 broadcast battery and was therefore used for data processing. Marduel et al., 1987 studied the effect of a DIESEL aerosol on various biological materials.
To improve the resolution of SDI 2000, a new version called SDI 2001 (Figure 1(a)) was released with the same impactor (Figure 1(b)) and a six channels diffusion battery (Figure 1(c)). The reference channel is the sixth tube which was kept empty. The SDI 2001 could be used in several applications, for the measurement of combustion aerosols such as the aerosols produced by the exhaust pipes of diesel engines, or the aerosols produced by laser ablation. Charuau et al., 1993 characterized the erosion products in the JET (Joint European Torus) vessel and the behavior of the desorbing tritium from the wall components after the "First Tritium Experiment" (FTE). Tymen et al., 1991 utilized this new version of instrument during the pilot campaign to characterize the progenies of natural radon. Fauvel et al., 2005 carried out a study concerning the industrial applications of Power Lasers with the aim of characterizing the aerosols emitted during the cutting of evaporator elements by a 4 kW Nd-YAG laser operating continuously and SDI 2001 was used for the measurement of the particle size distribution in their study.

Figure 1: SDI 2001 components: a) SDI 2001, b) Cascade Impactor, c) Diffusion Battery

3. THEORETICAL BACKGROUND

Fractional capture of aerosols with the use of the SDI is based on two different mechanisms which depend on particle size. These mechanisms are summarized below.

3.1. IMPACTION

When a jet of air carrying particles is directed at a surface, the particles with enough inertia will contact the surface, while the tiniest particles will follow air streams deflected by 90 degrees and will not be caught. Then, a cut-off diameter may be established at which 50% of the particles are removed from the stream and caught. The geometry of the collector, speed of stream, and the aerodynamic properties of the particles all affect this cut-off diameter (size, shape, density). Aerosols are divided into several size ranges by working with many stages in succession for increasing speeds, from which particle size distribution is achieved. However, to identify the real efficiency curve as a function of the characteristics of the collection medium, calibration with a standard aerosol should be carried out in practice. It is theoretically possible to designate a very definite cut-off for the suitable size (Boulaud and Diouri.,1988).

3.2. CAPTURE BY BROWNIAN DIFFUSION IN THE DIFFUSION BATTERY

The Brownian diffusion mechanism can be used for separation of sub-micron size particles as the inertial properties of these particles are not sufficient to categorize them based on size. The movement of ultra-fine particles (d = 10^{-3} to 0.2 µm) is influenced by the collisions with gas molecules, which encourages deposition of the particles on surfaces or impediments positioned in the path of stream. Diffusion Batteries are utilized for the measurement of particles using the mentioned characteristics of sub-micron size particles. The necessary factors for selection of diffusion battery for this purpose depends upon the knowledge of diffusion laws, the risk of clogging of diffusive medium during sampling of highly concentrated aerosols, and the cost of the diffusive medium and of the building of the diffusion battery. The two types of diffusion batteries that are most frequently used have parallel plates and screens or bundles of tubes. The main obstacle to major development is prohibitive bulk and/or cost. In the presented setup, we have developed an affordable battery type that might produce equivalent outcomes. This was accomplished by passing an aerosol through a bed of glass beads that was positioned inside of a cylindrical duct. Although this medium is frequently employed in gas cleanup issues, here it has been used as a diffusion medium in a diffusion battery.

4. OPERATION AND DATA PROCESSING

The polydisperse aerosols of potassium chloride (KCl) with fluoresceine were generated by the atomizer (TSI, 3076) and fed to the two consecutive columns of silica gel-based diffusion dryers before being sent to the Aerodynamic aerosol classifier (AAC) (Combustion, A-423). AAC selects the particles based on their aerodynamic diameter (Da) and in the present experiment we have selected the particles of size 100 nm. After AAC, this mono dispersed stream of aerosols goes into the cylindrical chamber for uniform mixing with the particle free air. Once the particle concentration is approached to the steady state, stream goes into the SDI 2001 and the SMPS system. We have removed the impactor of SMPS system to allow the whole aerosol stream to enter the Differential Mobility Analyzer (DMA) of Scanning Mobility

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Particle Sizer (SMPS). The sampling time was fixed to 15 minutes for this experiment. The schematic of experimental setup is presented in the figure 2.

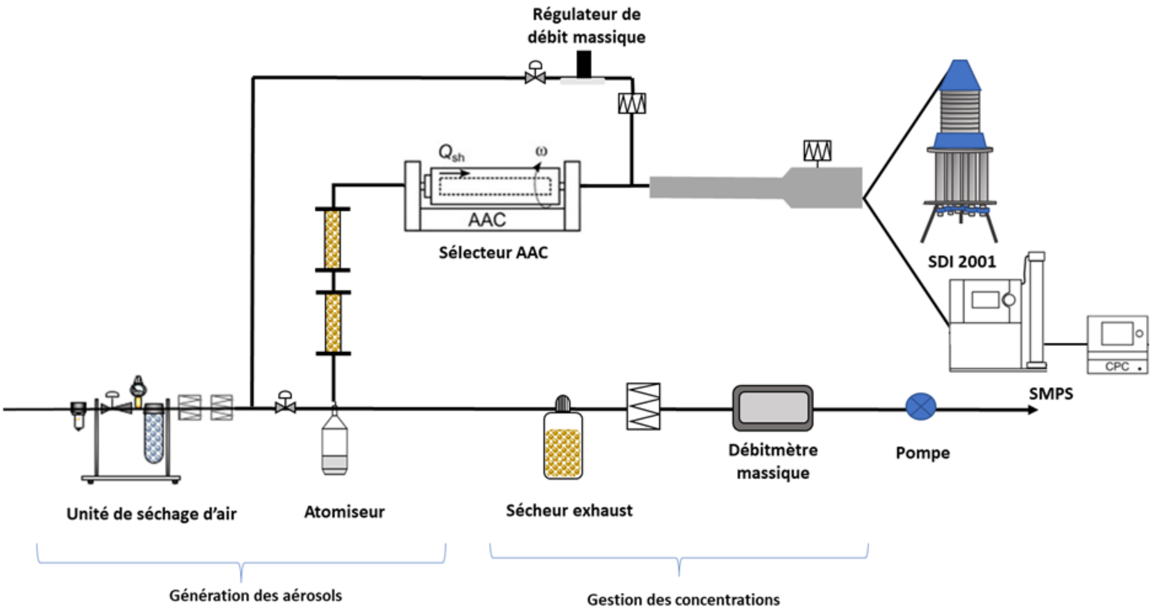

Figure 2: Experimental Setup

When the collection filters have been inserted into the different stages of the impactor and in the six filters holders placed after the diffusion pipes, sampling is initiated by switching on the pump at a flow rate corresponding to that of the impactor used (28.3 lpm in the case of the Andersen Mark II impactor). The sampling time, and hence the sample volume, depend on the concentration of the aerosol and on the method used to determine the mass of the fraction collected on the inertial and diffusional stages. This determination can be carried out either simply by weighing or by chemical or physicochemical analysis.
The data of impactor stages or diffusion battery backup filters is processed using a data inversion technique which is based on a mathematical inversion treatment of Fredholm's equation using the non-linear iterative method introduced and well described in Twomey (2013).
For the data processing of SDI 2001, we have developed a calculation program "FRSDI" (simulated FRactions collected by the SDI), on the Microsoft Excel Platform, which calculates the mass fractions collected by the impactor stages and diffusion batteries of the SDI, when we give an aerosol stream a unimodal log-normal distribution (MMD, σ) using the equation 1 with utilizing relation 2.

$$M_i = \int_D E_i(x) f(x) dx \, , \qquad (1)$$

$$f(D) = \frac{1}{\sqrt{2\pi}\log\sigma} \exp\left(-\frac{\log D - \log (MMD)^2}{2\,\log^2\sigma}\right) , \qquad (2)$$

where Ei(x) is the probability for a particle of aerodynamic diameter D to be collected on stage or channel i. For the bimodal distribution (MMD1, σ1; MMD2, σ2), our program provides the mass fractions collected by each stage or channel using relationship 3 with utilizing relation 4.

$$M_i = \int_D E_i(x)\big(f_1(x) + f_2(x)\big) dx \, , \qquad (3)$$

$$f_1(D) = \frac{1}{\sqrt{2\pi}\log\sigma_1} \exp\left(-\frac{\log D - \log (MMD_1)^2}{2\,\log^2\sigma_1}\right) \qquad (4)$$

$$f_2(D) = \frac{1}{\sqrt{2\pi}\log\sigma_2} \exp\left(-\frac{\log D - \log (MMD_2)^2}{2\,\log^2\sigma_2}\right) , \qquad (5)$$

Once the simulated mass fractions, collected by the stages and channels of the SDI are calculated with the use of program "FRSDI", we plot the histograms corresponding to the distribution studied.

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5. COMPARISION OF SDI 2001 RESULTS WITH SMPS SYSTEM

We have measured the particle concentration on the filters collected from SDI 2001 following the standard procedure of fluorometric analysis using a fluorometer device (Dialunox, FLUO SENS DD 002). The SMPS selects the aerosol particles based on their mobility diameter and SDI 2001 collects the particles based on their aerodynamic diameter. For the comparison of results of both instruments, we have processed the SMPS data to obtain an equivalent particle size distribution based on their aerodynamic diameter with the method suggested by (Khlystov et al., 2010).
Results of this experiment are shown in Figure 3. The agreement between results of SDI 2001 and SMPS is quite good within the limitation of experimental error during the handling of filters of SDI 2001.

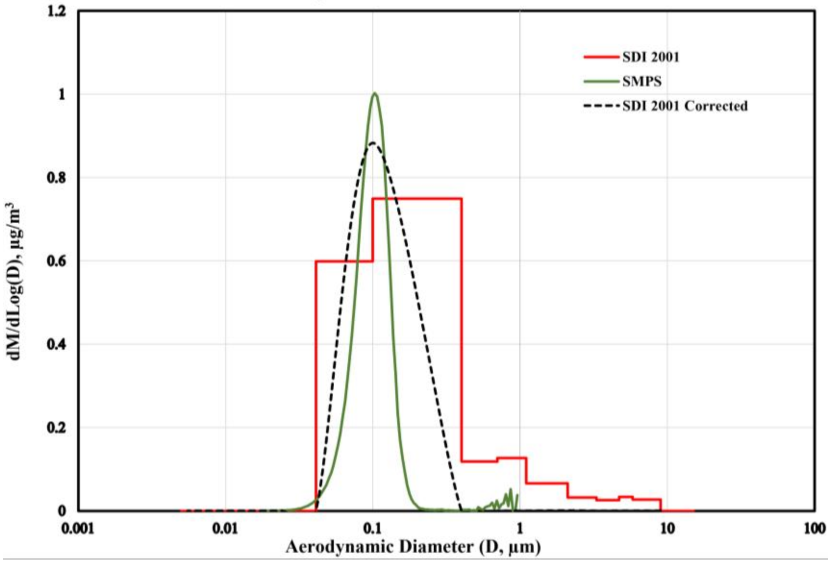

Figure 3: Comparison of SDI and SMPS response to monodispersed aerosols

6. CONCLUSIONS

Although SDI 2001 can be used for all cases encountered in practice, it is particularly suitable for determination of the size distribution of highly concentrated aerosols with an extended range of sizes (emission measurement, combustion aerosol, diesel aerosol, evaporation/condensation processes), and a non-negligible submicronic component which could happen in case of a long-range transport aerosol. The SDI 2001 spectrometer, which already exists in prototype form, represents an advance in the determination of the size distribution of particles encountered in practice. It allows simple technical characterization of the submicronic part of the aerosol phase. Until now, this has only been possible using costly and sophisticated equipment and techniques. In addition, because of its design and operating principle, the ranges of maximum sensitivity can be optimized by modifying either sampling rates, or the characteristics of the inertial and diffusional stages.

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