Dry aerosol particle deposition on indoor surface: review of direct measurement techniques

Delphine Costa, Jeanne Malet, Evelyne Gehin

Original Article

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D. Costa[a,b], J. Malet[a], and E. Géhin[b]

[a]Institut de Radioprotection et de Sûreté Nucléaire (IRSN), PSN-RES, SCA, LEMAC, Gif-sur-Yvette, 91192, France; [b]Univ Paris Est Creteil, , CERTES, F-94000 Creteil, France

CONTACT D. Costa delphine.costa-upec@irsn.fr PSN-RES/SCA/LEMAC, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Gif-sur-Yvette, 91192, France

ABSTRACT

Localizing and measuring aerosol deposition is essential to gain knowledge on contaminants and their transfer mechanisms, cleanliness of people's environments and consequently on health. However, examining aerosol deposition is challenging, as it is based on several different mechanisms linked to aerosols, surfaces and air flow properties. Many techniques exist to measure aerosol deposition, but only a few techniques directly measure aerosol deposition without modifying the deposition itself. This paper gathers and details the existing measurement techniques, which directly measure a depositing flux of aerosol particles on indoor surfaces. They are classified according to whether they measure a mass or a number surface deposition concentration. Among the mass concentration measurement techniques, a few are the most commonly used in the literature and are well-known, whereas the family of micro-sensors was recently developed and continue to be improved in laboratory experiments. Micro-sensors request to know more about theoretical and technical aspects for building and implementing. The features of micro-sensors entail generally an ability to carry *in situ* and close to real-time measurement. The number concentration measurement techniques are essentially based on optical systems. Commercial devices apart, these techniques are adaptable and their configurations depend on the experimental constraints. They also require some theoretical consideration depending on which kind of aerosol deposition is observed. On the contrary, the commercial devices are turnkey solutions and are developed for specific domains, such as cleanroom deposition measurement, in order to provide user-friendly devices and an easier reached repeatability in the measurement protocol.

1. Introduction

Monitoring and measuring aerosol deposition on surfaces enable to gain knowledge about airborne contaminant transfers in different fields such as outdoor pollution, indoor air quality, ventilation and industrial safety. Measurement techniques used for that purpose are varied, regarding the size distribution of the particles, the properties of the studied surfaces or the environment of the experiment.

A great part of experimental aerosol deposition studies aims to determine outdoor deposition on different surfaces, such as natural covers (e.g. Petroff et al. 2008 on vegetation cover or Slinn and Slinn 1980; Hoppel 2002; Hsu et al. 2010 on sea) and artificial covers (e.g. Roed 1985; Maro et al. 2014 on buildings). The interest is mainly to study the transfer of aerosol particles, which depends on various atmospheric parameters. Wind is the most common one, since wind influences the nature of deposited particles that can be found in one place (Uematsu et al. 1983; Kindap et al. 2006; Kondo et al. 2010). Another parameter is rain, which can wash-out a part of suspended particles (Chate and Pranesha 2004; Andronache 2003; Volken and Schumann 1993). Most of these studies concern field deposition measurements. Some of them focus on laboratory experiments and are specifically designed to reproduce outdoor conditions (Garland and Cox 1982; Roupsard et al. 2013). In all the studies regarding outdoor aerosol deposition, measurements are mostly carried out by using indirect methods: the concentration of the deposited matter is not directly measured, but indirectly determined by other measured parameters, which are combined together in a model allowing the determination of a deposition value (generally a deposition velocity).

Another field involving aerosol deposition concerns deposition in closed indoor rooms or environments. The objective of such studies is close to the one of outdoor research activities, i.e. the characterization of particle transfers related to contamination, pollution and air quality. These studies gather different applications on air quality in cleanrooms (Menant et al. 2015; Tovena Pecault, Godefroy, and Escoubas 2017), car cabin (Gong, Xu, and Zhu 2009; Ding et al. 2016), classrooms (Shaughnessy and Vu 2012; Laiman et al. 2014), offices (Smolík et al. 2005; Nygren 2006) or at home (Lai 2002). The most common measurement method in indoor environment is the determination of the deposition rate coefficient

(Lieberman and Rosinski 1962; Jonas and Lindenthal 2000; Vette et al. 2001; Mosley et al. 2001), which is an indirect technique, but some recent optical developments for cleanrooms use also a direct method of surface concentration measurement.

Another large field of applications involving aerosol deposition measurement techniques is the field concerned by ventilation systems in various industrial sectors and buildings. The focus point is the same as for indoor applications: particle transfers need to be known and monitored. In nuclear safety for example, deposition of radioactive particles is essential for the characterization of the radioactive mass arriving on the last barrier of containment before environmental release, i.e. the High Efficiency Particulate Air filters (Burkett et al. 1984; Herranz et al. 2010). It is also important to determine where the radioactive deposit mainly occurs, the radioactive load is therefore known for the protection of maintenance workers against radioactive contamination. In other industrial plants or in public buildings, aerosol deposition in ventilation ducts is also a concern of safety: contamination of the ventilation ducts in the food-processing industry (Ben Othmane et al. 2010; Da et al. 2015), contamination of indoor spaces in electronics or pharmaceutical industry (Whyte and Eaton 2016; Litvak et al. 2000; Farrance and Wilkinson 1990), as well as the recent concern relative to the COVID-19 pandemic, where SARS-CoV-2 aerosol loss rate by deposition is a topic of discussion in reduction of the infection risk (Miller et al. 2020). Beyond these safety considerations, air quality from HVAC systems is an important preoccupation for human comfort and monitoring deposition enables to define criteria to measure the cleanliness of the ventilation ducts (Lavoie et al. 2010, 2011; Zuraimi 2010). In all these studies involving aerosol deposition in laboratory ducts, local measurement techniques are preferentially used to characterize deposition using numerous direct techniques for measuring a mass or a number aerosol concentration on an inner surface of the ventilation duct.

At a smaller scale compared to ventilation ducts, many studies have been carried out on particle deposition in aerosol sampling lines. These sampling lines are used to sample aerosol particles and convey particles to a size and/or concentration measurement device (Stenger and Bajura 1982). Deposition in sampling lines is historically one of the main applications of aerosol deposition studies.

Many experimental and theoretical work have been done in that field and have led to many correlations and modeling issues, as it is essential in aerosol metrology. The sampling tubes are generally small (diameter range from mm to cm), of circular cross-sections and with a minimum number of singularities to avoid deposition (Chen and Pui 1995; McFarland et al. 1997). Deposition in sampling lines is generally characterized by measuring an aerosol penetration, which can be direct (e.g. by using fluorescence spectroscopy) or indirect measurement techniques (e.g. upstream and downstream bulk concentrations).

Another field where aerosol deposition is a main concern today is deposition in the respiratory system, as much in the upper airway as in the pulmonary alveolar region. This deposition increases the risk of diseases like respiratory infections, asthma and cardiovascular diseases (Newman et al. 1982; Falcon-Rodriguez et al. 2016). From another point of view, by better knowing where and how particles deposit in airways, respiratory drug delivery and efficiency could be more controlled (Duan et al. 2020; Darquenne 2012; Heyder 2004). Experimental studies of deposition in the respiratory tracts are very specific (Schlesinger 1985) and the few deposition measurement studies use generally indirect techniques.

As we have seen, aerosol deposition is measured in many different applications and deposition is not a ready-to-measure parameter: a review of the actual methods and developments therefore appears necessary. The objective of this review is to describe the direct deposition measurement techniques existing for aerosol deposition characterization and used in the different fields of application previously mentioned. These measurement methods are, for the most part, laboratory-based ones. In a first theoretical part, the aerosol deposition variables and the associated equations are briefly presented and classified under local and global measurements, leading to the selection of the measurement techniques specifically focusing on direct measurements of the deposition flux. The paper is then organized in two parts: one for the presentation of deposited mass concentration measurement techniques and the other one for the deposited number concentration measurement techniques. These different techniques are then detailed, focusing on their principles, their sensitivity, their dependence on environmental parameters and their level of development and applicability.

2. Theory

In order to qualify and monitor aerosol deposition measurement, the first question to be asked is if the deposition is observed on a specific place or on the whole system. Two measurements are classified: a) the global deposition measurement integrates all the variations over a surface: no matter the local variations, the measurement will give a "mean" value without information on the homogeneity of the deposition on the surface; b) the local deposition measurement enables to measure deposition in specific places. The size of the surface does not define if we are working with a local or a global technique. For example, in nuclear context, a local measurement technique can be useful to know the quantity of deposited radioactive particles, which is essential to detect hotspots. In food industry, global deposition measurement can help to determine if the system is unclean.

2.1. Global deposition measurement

Global deposition measurement is intensively used in many different applications, such as sampling tubes (Pui, Romay-Novas, and Liu 1987) and chambers or rooms (Thatcher et al. 2002). Two ways exist to qualify deposition with a global approach. It consists on the determination of the deposited fraction F_d or the determination of the particle concentration decay throughout a particle deposition rate β_d (s^{-1}). Figure 1 and Figure 2 illustrate these two relations. Figure 1 shows the deposited fraction including the deposited particles, regarding the initial concentration at an upstream sampling point and final concentration got in a downstream sampling point. Here, the measured volume concentration upstream and downstream of the channel allows the determination of the deposited fraction. In the case of a constant volume flow the deposited fraction F_d is expressed as:

$$F_d = 1 - \frac{C_{out}^v}{C_{in}^v}, \quad (1)$$

with C_{in}^v the inlet (or initial or upstream) and C_{out}^v the outlet (or final or downstream) volume concentration (particles.m^{-3} or kg.m^{-3}) for all the surface contained between the two sampling points. In that case, the measurement of the inlet and outlet concentrations is representative of the concentration on the tube section if the aerosol concentration over the tube section is homogeneous, which is generally the

case for sampling tubes, since the concentration profile has had time to fully develop. Measuring F_d does not provide a local deposition measurement, as deposition is integrated over the whole length of the tube between the two points.

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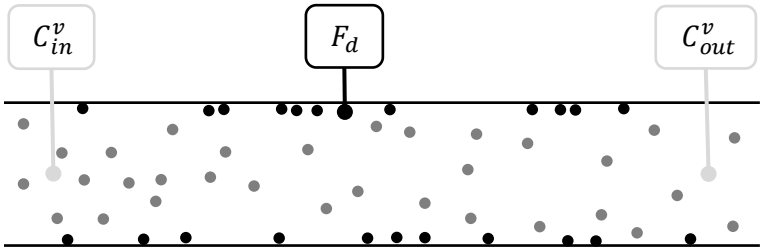

Figure 1: Global deposition in a channel with flux conservation

Figure 2 represents the second way to get the global deposition by determining the particle deposition decay rate β_d (s^{-1}) only considering aerosol deposition and ventilation as sink terms and constant source terms. The decrease of aerosol volume concentration over time (Lai et al. 2002; Xu et al. 1994) is:

$$\frac{dC^v(t)}{dt} = -(\beta_d + \beta_v)C^v(t) + \sum_i Source_i, \quad (2)$$

with $C^v(t)$ volume concentration at time t; $Source$ represents all the possible source terms, such as aerosol injection, and β_v the particle decay rate (s^{-1}) related to ventilation. The concentration in the considered volume (generally a room or a chamber) must be homogeneous to apply this relation, which is a first drawback of this technique. When solving this differential equation considering the concentration decrease (namely no particle injection and no source term; with $C^v(0)$ the initial volume concentration), the concentration over time is:

$$C^v(t) = C^v(0)e^{-(\beta_d+\beta_v)t}, \quad (3)$$

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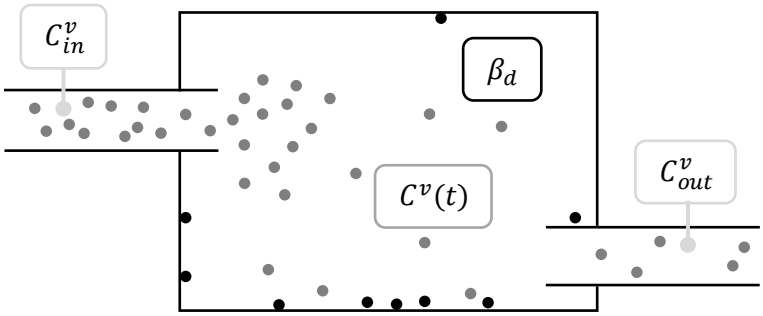

Figure 2: Global deposition in a room with flux conservation

with the second and main drawback of this technique being that the influence of the orientation of the surface on deposition can generally not be evaluated, although the effect of gravity is noticeable on largest particles by increasing deposition on floor surface, in opposition to ceiling surface. Some authors (Abadie, Limam, and Allard 2001) introduce a specific modeling, so that a decay rate of each surface (vertical, oriented, horizontal, etc.) can be deduced. As a conclusion, the major drawback of deposition rate is the requirement of a homogeneous concentration and steady flow, and the difficulty to conclude on the deposition on the different oriented surfaces.

These two methods of determination of a deposited fraction or the deposition rate are based on volume concentration measurements, which can be performed with conventional techniques of aerosol concentration measurement. As a result, the associated measurement techniques will not be detailed in this paper and the reader should refer to standard aerosol concentration measurement, well described in some reviews (Soysal et al. 2017; Amaral et al. 2015; Wilson et al. 2002; Baron and Willeke 2001; Prévost 1997).

2.2. Local deposition measurement

Local deposition is characterized by J the deposition flux on the surface (particles.m^{-2}.s^{-1} or kg.m^{-2}.s^{-1}).

J depends on many different mechanisms: sedimentation, turbulent and Brownian diffusion, inertia, interception, turbophoresis, electrophoresis and thermophoresis.

J can be measured, either by counting deposited particles or by measuring a mass on a surface S:

$$J = \frac{C^s}{\Delta t} = \frac{m_d}{S \times \Delta t}, \quad (4)$$

where C^s (particles.m^{-2} or kg.m^{-2}) is the surface concentration, m_d is the number or the mass of particle on the surface and Δt is the time of exposition to the deposition (s).

The deposition flux can also be obtained by measuring concentration gradient. The concentration gradient measurement is generally used for outdoor quantification of aerosol deposition, as measuring concentration gradient is easily done in atmospheric constant flux layer (Garland and Cox 1982; Phillips 2004; Matsuda et al. 2010). To compare, the atmospheric constant flux layer can reach several hundreds of meters, whereas in a ventilation duct, the boundary layer is in the order of a few millimeters (Ben Othmane 2011; Taheri, Khoshnevis, and Lakzian 2020). For atmospheric measurements the flux in the boundary layer is usually expressed as (Phillips 2004; Matsuda et al. 2010):

$$J = -(D_B + D_t)\frac{d\overline{C^v}}{dz}, \quad (5)$$

with $\frac{\partial J}{\partial z} = 0$ as the flux is assumed constant. D_B and D_t are respectively the Brownian and turbulent diffusion coefficient (m².s^{-1}), $\overline{C^v}$ the mean volume concentration in the boundary layer (particles.m^{-3} or kg.m^{-3}), z the height regarding the surface.

The deposition flux can also be expressed by eddy correlation, based on the covariance between the instantaneous aerosol volume concentration (C^v) and the instantaneous vertical velocity (w – m.s^{-1}) (Roupsard 2013):

$$J = Covariance(wC^v) - v_g\overline{C^v}, \quad (6)$$

with v_g the sedimentation velocity (m/s). This method is also greatly used in outdoor studies: to get a flux value, the vertical wind velocity and the concentration need to be measured. The devices used for these measurements shall have a quick enough measurement frequency in order to catch all the variations. This implies that the devices do not have to disturb the flow. Many other assumptions are made to apply the formula (6), which are detailed by Burba (2013).

In this review, we will focus on techniques providing deposited particle mass or deposited particle number measurements, which will be presented in details, respectively in Sections 3 and 4. A drawback of local measurement is also the representativeness of this measurement: if the aerosol deposition is not

uniform over the whole considered surface, the extrapolation of a local deposition flux over the whole surface is questionable. For example, in large ventilation ducts with variation of curvature (bend) or section (reduction), several local deposition measurements should be performed in order to extrapolate the results over the whole singularity.

2.3. Synthesis

Table 1 summarizes the information about global and local parameters used to characterize the aerosol deposition.

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Table 1: Synthesis of deposition parameters

	Deposition parameter	**Measure value**	**Measured value**	**Difficulties related to the measurement of the deposition parameter**
Global deposition	F_d	$F_d = 1 - \frac{C_{out}^v}{C_{in}^v}$	Volume concentration at the inlet and at the outlet	-
	β_d	$C^v(t) = C^v(0)e^{-(\beta_d+\beta_v)t}$	Volume concentration over time	-
Local deposition	J	C^s	Surface concentration	-
		$\frac{d\overline{C^v}}{dz}$	Volume concentration gradient in boundary layer	Difficulties of measuring in thin boundary layer (adapted to atmospheric boundary layer)
		$wC^v, \overline{C^v}$	Volume concentration and velocity in boundary layer	

As we can see from this table, most of the methods to determine local or a global deposition are based on aerosol volume concentration. Many devices and techniques can be used to measure aerosol volume concentration, as described in the book of Baron and Willeke (2001). The major part of these devices are necessary used with aerosol sampling, which raises its own constraints (deposition in sampling lines, necessity of isokinetic sampling for polydisperse aerosols, etc.).

The measurement of a decay rate is also concerned by sampling considerations. It is a simple parameter, commonly used in indoor environments, but the homogeneity of the concentration inside the chamber needs to be checked and the deposition does not distinguish the different surfaces of the chamber, except if some semi-empirical modeling is introduced to the mass balance equation.

The local deposition flux can be extrapolated over a whole surface if the flow conditions do not change and should be used carefully under specific flow with geometrical variations of the deposited surface. However, the local measurement of surface concentration is the only method which considers a direct measurement of the aerosol deposited over a surface. This method will therefore be explored in details in this paper, by focusing on two ways to determine the concentration collected on a surface:

- mass of aerosol deposited on a surface (surface mass concentration, $kg.m^{-2}$),
- number of aerosol particles deposited on a surface (surface number concentration, $particles.m^{-2}$).

These two variables can be measured with different techniques, which will be described in the two next sections.

3. Mass surface deposition measurement

In this part are presented measurement techniques, which provide a mass concentration of deposited aerosol particles over a surface by collecting these particles. As it will be seen, different techniques can be found, each of them being generally laboratory based and not "ready-to-use" techniques. A description of the principle of each technique is given hereafter. To be able to interpret the measured deposited mass surface concentration, the aerosol size distribution should be monodisperse for all these techniques.

Other techniques require sampling particles to analyze deposited particles on a surface (Peillon et al. 2020; Lavoie et al. 2007; Holopainen et al. 2002) and others showed an interest in estimating deposition by studying the darkening of a surface due to deposited particles (Landis et al. 1996; Schneider et al. 1996). The techniques requiring sampling particles and those studying surface darkening will not be detailed as the first ones modify the deposition (particles are sampled, not collected) and the second ones only studied the surface darkening by the deposited particles and do not give a mass measurement.

3.1 Weighing

The most basic technique for measuring a mass concentration is to weigh the surface of deposition before and after aerosol deposition. The weighing technique is essentially used to weigh filters or material on which the deposition takes place (Lai et al. 2017; Licina and Nazaroff 2018).

Weighing samples entails that the deposited mass (namely the deposited concentration) is weighty enough, as the most precise ones reach a precision of 0.1 µg. The most precise weighing scales are the electronic ones. The ISO 15767:2009 standard recommends some practices to avoid bias and minimize measurement uncertainty, regarding workplace atmospheres.

To conclude, the advantage of this technique is its user-friendliness. This technique is well known and commonly used; however it provides neither an *in situ* (the sample containing collected deposited particles needs to be retrieved and brought to the weighing) nor a real-time measurement and is not suitable for low mass deposition. For example, to get a mass of 10 µg on a filter of 47 mm diameter, the deposited mass concentration should at least be 6 µg/cm².

3.2 Fluorometry

Fluorometry, also called fluorescence spectroscopy, is used in many different applications, such as environmental particles deposition (Maro et al. 2014), in resuspension phenomenon (Wu, Davidson, and Russell 1992) or ventilation systems (Da et al. 2015). Fluorometry method requires a fluorescent tracer and a fluorescent spectrometer.

Fluorescence spectroscopy is based on excitation of fluorescent molecules, which consequently emit fluorescent light – corresponding to a specific wavelength – caught by a detector. By using a simplified version of the Beer-Lambert law, the tracer volume concentration C_d^v (g.l^{-1}) in a solution is linked to the fluorescence emission intensity I_f.

Different fluorescent particles are used in scientific community depending on the led experiments. All forms of fluorescent molecules are useable, such as fluorescein solved in oil or aqueous solutions. For example, Okazaki and Willeke (1987) use a uranine oleic acid solution to generate their fluorescent aerosol, whereas Sato, Chen, and Pui (2002) use an aqueous solution of ammonium fluorescein. Different

fluorescent molecules are used indiscriminately, as ammonium fluorescein (Sippola and Nazaroff 2004; Lai and Nazaroff 2005) or sodium fluorescein, also called uranine (Da et al. 2015; Okazaki and Willeke 1987; Wu, Davidson, and Russell 1992; Sato, Chen, and Pui 2002; Maro et al. 2014; Sow, Leblois, and Gensdarmes 2019). Other researchers use vitamin E (Wilson et al. 2002) to lead deposition measurements in ninety-degree pipe bend; or vitamin B_2 (riboflavin) (Cohen Hubal et al. 2005). Riboflavin is used to play the role of pesticide and allows to quantify residues and pesticide exposure.

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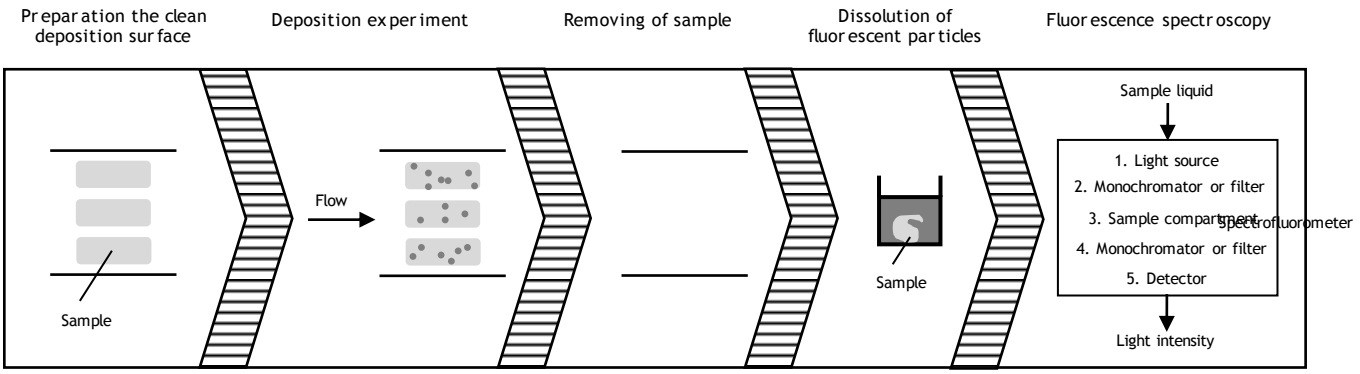

Figure 3: Fluorescence spectroscopy – stages

To obtain the particle deposition concentration with fluorometry, the different steps are presented chronologically on Figure 3. The first step is to choose a deposition surface. Sometimes the sample is fixed to the wall and then removed after the deposition of aerosols on this sample (case presented on Figure 3), e.g. Wu and Young (2012) coat their bend with transparent film to collect particles on the bend surfaces. In most experiments performed with the use of fluorometry, the surface is a filter (Sow, Leblois, and Gensdarmes 2019; Thatcher et al. 2002; Chen and Pui 1995). However, using a removable sample induces a change of the surface wall in a hydrodynamic sense (i.e. a change of the roughness, boundary layer, and flow), hence a change of the aerosol deposition. On the contrary, the deposition surface can be delimited by a sort of stencil installed after deposition then wiped, as used by Da et al. (2015), or the surface itself can be removable (wall panel) and washed after the particles have deposit (Sippola and Nazaroff 2004). In these cases (wiping or washing) no hydraulic boundary layer differences are induced. As in the third part of Figure 3, the substratum, if removable (like filter), is put in a specific volume to

dissolve all fluorescent particles. If the deposition surface is irremovable, the same treatment is applied for wipes used for cleaning the delimited surface. Attention needs to be paid to the whole dissolving of fluorescein (Kasavan and Doherty 2000) and to the nature of the dissolving solution (for example, the use of uranine requires an alkaline solution). The deposited mass surface concentration can be simply obtained by multiplying C_d^v by the dissolving volume, divided by the surface of deposition collection.

Fluorescence spectroscopy is not an *in situ* technique, as the deposited mass is not measured directly at the deposition location. The accuracy is really high as the minimum concentration measurements are low (Sow, Leblois, and Gensdarmes (2019) present a limit of detection for C_d^v of 10 ng/l) but to our knowledge, no limit of detection of deposited mass were presented in studies in the literature. The impossibility of real-time measurement is restrictive and the technique is time-consuming (Lai 2002).

A similar technique, providing a volume concentration, is used for bioaerosols deposition measurement. The deposited particles traced with fluorescent molecules are treated in solution according to a specific protocol, generally to isolate bioaerosols from aerosols (Araya, Cazorla, and Reche 2019). The volume concentration is then measured by flow cytometry: particles pass one by one through a laser beam and are counted using light scattering (Brussaard 2004). Some experimenters use this technique to measure dry deposition of viruses and bacteria (Morales-Baquero and Pérez-Martínez 2016; Reche et al. 2018).

To conclude, fluorometry presents a high sensitivity and adaptability. This technique is well known and commonly used. Fluorometry also enables to choose the size of the deposition surface. Depending on the chosen protocol, the surface deposition is not necessarily modified by the deposition measurement protocol. However, this technique provides neither an *in situ* nor a real-time measurement.

3.3 Photovoltaic signal

Another laboratory-based technique for the determination of the particles mass collected on a surface is based on a current intensity delivered by a photovoltaic cell, which plays the role of the deposition surface.

Rondeau (2015) chooses to correlate the power produced by a photovoltaic cell to the deposited concentration, based on the principle that the power produced by the photovoltaic cell is sensitive to light

obscuration due to particle deposition. The calibration is performed by building a graph with several known quantities of aerosol deposited on the photovoltaic cell according to the intensity crossing the solar cell. The solar cell is weighed with deposition to measure the deposited mass. The surface concentration is therefore known beforehand. The corresponding fit curve is the calibration curve, which is then used during the experiment to deduce the surface concentration from a current intensity measurement.

Extinction with photovoltaic cell allows an *in situ* measurement. It can be adapted to a "sequential" real-time measurement as soon as the deposited mass allows a significant variation of the light and before the cell is saturated. However, the technique is harder to set up on a large surface due to the difficulty of having homogeneous light flux over the whole surface. The measured concentration on the photovoltaic cell is the most precise for surface concentration lower than 2 $mg.cm^{-2}$ according to El-Shobokshy and Hussein (1993), as photovoltaic cells are more sensitive to deposited mass variations when surface concentration is below this value. To our knowledge, no limit of the detection was presented in the open literature. However this limit depends on the capacity of the cell to detect a change of light resulting of deposited particles. Besides, the experimenters should verify that particles deposit in only one layer over the surface to increase the sensitivity of photovoltaic signal technique.

Even if the measurement of a photovoltaic signal is not often used, studies focused on aging of photovoltaic cells due to dust deposition are abundant (Jiang et al. 2011; Mani and Pillai 2010; Darwish et al. 2015; Saidan et al. 2016; Kazem et al. 2020) and should bring some new advances to aerosol deposition measurements in the future.

To conclude, photovoltaic signal measurement technique is not a commonly used technique to measure aerosol deposition. Its sensitivity depends on the quality of the photovoltaic cells. This technique provides an *in situ* measurement without modifying the deposition surface and a sequential real-time measurement.

3.4 Acoustic wave mass sensors

The Surface Acoustic Wave (SAW) sensors are miniaturized devices used in R&D studies, so they are not ready-to-use sensors: the mass deposited on their surface can be correlated to a shift of frequency correlated to a mass load. All acoustic wave mass sensors are composed of a piezoelectric part that

produces an acoustic wave. By studying the velocity and amplitude changes of the acoustic wave, deductions can be made on resonance frequency. The frequency is measured with a frequency counter. The precision of the counter depends on its timebase stability. The precision is also enhanced by measuring over a long time. All acoustic wave mass sensors play the role of deposition surface.

SAW sensors are built with two transducers and the SAW propagates in between, as on Figure 4. Bowers, Chuan, and Duong (1991) develop a SAW microbalance for mass measurement to collect monodisperse olive oil particles by impaction on the resonator and reached a 3 pg limit of detection. Hao et al. (2014) provide the applying equations of the mass measurement of a SAW focused on $PM_{2.5}$ monitoring. The limit of detection of their sensor is estimated at 0.17 ng. A SAW sensor dedicated to particulate matter detection is developed by Thomas et al. (2016). They measure masses lower than 1 ng on experiments performed with five different types of particles for eight different diameters. It should be notices that SAW sensors are sensitive to ambient conditions, such as temperature and humidity (Liu et al. 2016).

Figure placement callout

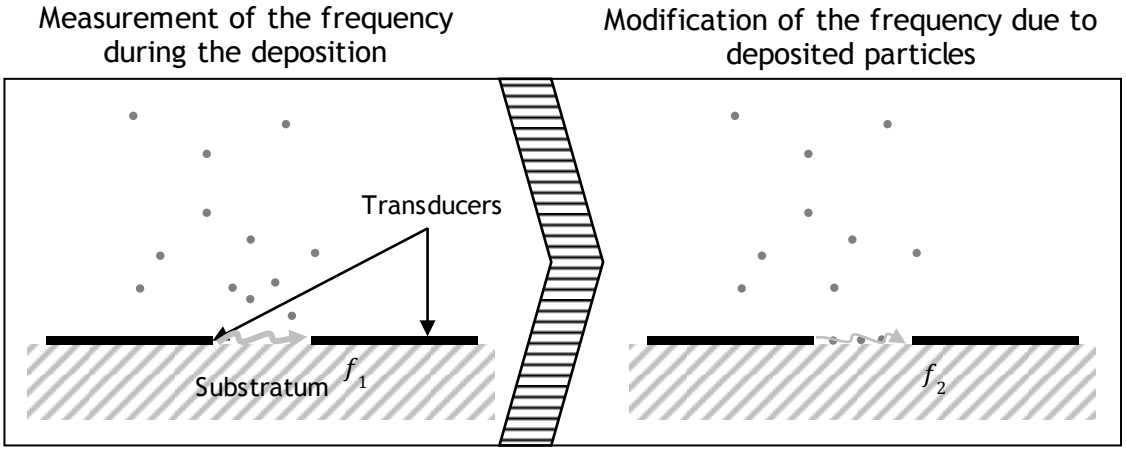

Figure 4: Operation of a Surface Acoustic Wave (SAW) sensor

Another acoustic wave mass sensor is the Film Bulk Acoustic Resonator (FBAR). This resonator is built with two electrodes, a top and a bottom, and a piezoelectric film in between (see Figure 5). The structure is suspended over an air gap that maximizes the reflection of the propagated acoustic wave. Campanella et al. (2006) present a FBAR for biomolecular applications. They obtain a minimum detectable mass change of 1 pg for a deposition of a distributed loading (magnesium fluoride vapor deposition) and of 7 fg

for a localized loading (amorphous compound containing carbon, platinum and gallium). Campanella et al. (2008) also reveal an effect of loading location on the sensor response. FBAR are also used by Paprotny et al. (2013) who collect particles using thermophoretic precipitation and measured particulate matter from diesel exhaust and tobacco smoke.

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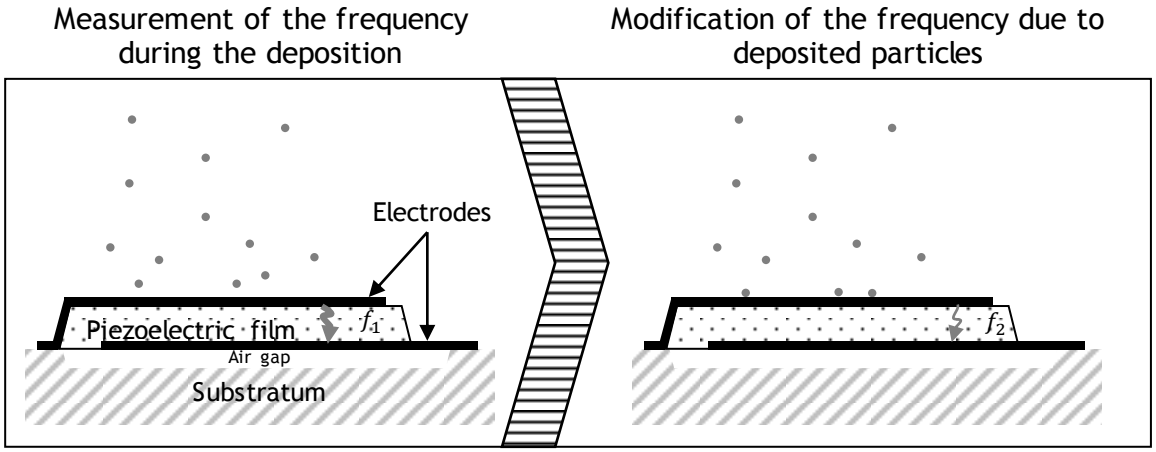

Figure 5: Operation of a Film Bulk Acoustic Resonator (FBAR)

To conclude on acoustic wave sensors, which gather SAW sensors and FBAR, it can be said that they are very small sensors with high sensitivity. They imply a modification of the deposition surface since they are placed on the given surface. The thickness of the surface of these sensors is around 1 or 2 mm. These sensors provide an *in situ* measurement and a "sequential" real-time measurement: the real-time measurement is interrupted by saturation.

3.5 Resonant mass sensors

Micro-Electro-Mechanical Systems (MEMS) and Nano-Electro-Mechanical Systems (NEMS) are respectively micro and nanoscale small detectors, involved in many research fields, even if they are still being developed and cannot be considered as ready-to-use sensors. An extensive review of aerosol mass concentration measurements (Soysal et al. 2017) presents evolution and progress made these last years on these sensors. These systems have a vibrating structure, where particles can deposit, therefore modifying

the vibration frequency, which is related to mass concentration. MEMS/NEMS works as mechanical damped harmonic. For example, a cantilever MEMS is presented on Figure 6.

Figure placement callout

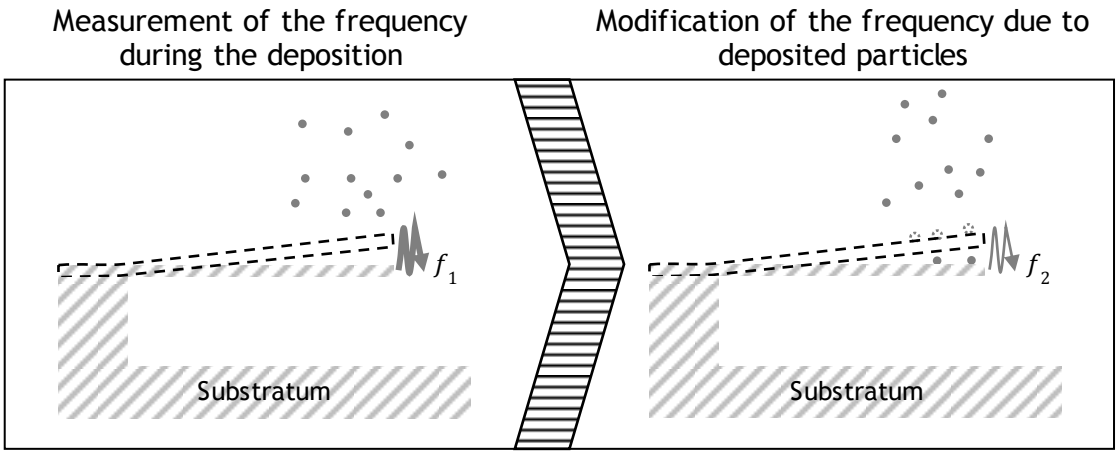

Figure 6: Operation of a cantilever Micro-Electro-Mechanical System (MEMS)

Hajjam, Wilson, and Pourkamali (2011) define MEMS/NEMS resonance frequency (s^{-1}) as:

$$f = 1/2\pi\sqrt{k_{eff}/m_{eff}}, \quad (7)$$

where k_{eff} is the effective spring constant ($kg.s^{-2}$) and m_{eff} (kg) is the effective mass of the resonator.

The mass MEMS/NEMS limit of detection m_{min} is calculated by:

$$m_{min} = \frac{m_{eff}}{QF}, \quad (8)$$

where QF is the quality factor of the sensor and is defined as the ratio between the frequency and the resonance width. To perform very sensitive mass measurement, MEMS/NEMS should have high frequency and high QF and be light. For the moment, MEMS/NEMS mass sensors are essentially found in R&D field and are not manufactured.

MEMS and NEMS are used to measure different kinds of aerosols. Bioaerosols are studied with MEMS resonators (Nugaeva et al. 2007; Gupta, Akin, and Bashir 2004). Zielinski et al. (2016) measure particle mass on a piezoelectric bulk acoustic mode resonator with an impactor to collect aerosols.

NEMS have a lower limit of detection than MEMS due to their smaller size (around a few µm). Yang et al. (2006) measure *in situ* and in real-time zeptogram-scale mass with adsorbed gaseous species. A mass

resolution of 740 ag has been reached from diffusion to inertial impaction on a nanomechanical resonant fiber (Schmid et al. 2013) to 31.6 fg with electrostatic precipitation of particles on a silicon nanowire NEMS resonator (Wasisto et al. 2013). Hajjam, Wilson, and Pourkamali (2011) improve the level of frequency and Q-factor value by thermally actuating the MEMS. It allows a more uniform mass sensitivity than other actuation methods. However, as Davila et al. (2007) highlight, long cantilever are less sensitive than smaller ones due to irregular sensitivity of MEMS sensors with cantilever (Park et al. 2012). Dohn et al. (2007) work on linking the position and the mass of deposited particles and their influence on sensor frequency. MEMS and NEMS are really sensitive to ambient conditions (pressure, temperature, relative humidity, etc.). Also, the active surface of these sensors is really small so it quickly saturates. Consequently, QF decreases and the sensor effectiveness decreases too. Dry and wet cleaning procedures have been developed to fully withdraw particles of the surface. These procedures are efficient but they generally require that the sensors are removed from the experiment to be cleaned, thus interrupting the real-time measurement. New procedures need to be developed to provide a real-time regeneration process. Additionally, the response time of MEMS and NEMS is short, so real-time measurement seems possible to reach. These sensors also have the advantage of presenting a relatively low cost production for the equipped laboratory as the production process is done by batch, and their power consumption is really low.

To conclude, MEMS and NEMS are macro and nanoscale sensors with the lowest limit of detection among the mass surface deposition measurement techniques. Due to their very small size, they are very sensitive to ambient conditions. These sensors imply a modification of the deposition surface. These sensors provide an *in situ* measurement and a "sequential" real-time measurement (interruption by the sensor saturation). MEMS and NEMS are laboratory techniques but are rapidly developing.

3.6 Soot sensors (conductive particles)

Some sensors have been developed in order to quantify soot deposition, more generally conductive particles deposition. It is especially used for on-board diagnosis for car industry, for example applications on Diesel Particulate Filter (DPF). Development of micro and nano-sensors is consequently important,

even though they yet remain non-commercial products. Even though all acoustic wave mass sensors can be adapted and/or used to soot deposition measurement, different kinds of sensors for soot measurement applications are developed: resistive sensors and capacitive ones are presented below.

Resistive sensors are made of two electrodes on a substratum. The conductance G measured between the two electrodes is equal to zero before deposition. When particles deposited between the electrodes, bridges are created thanks to the conductive properties of soot particles (mostly carbon-based), as presented on Figure 7. The measured conductance increases according to deposited mass. The speed with which conductance increases is linked to soot deposition concentrations, particle size and particle composition (Feulner et al. 2015). The sensor needs to be regenerated by burning soot particles after reaching saturation point, using a resistance that heats and burns the soot particles to about 600°C (Grondin et al. 2016). The orientation of electrodes plays a role in the signal measurement (Hagen et al. 2014). The effect of particle size on the percolation time (the time it takes for bridges to appear) is investigated by Reynaud et al. (2019). They notice that small particles increase this percolation time. These sensors are sensitive to ambient conditions, such as relative humidity and the orientation of the sensors is also important (Kort et al. 2019, 2021).

Figure placement callout

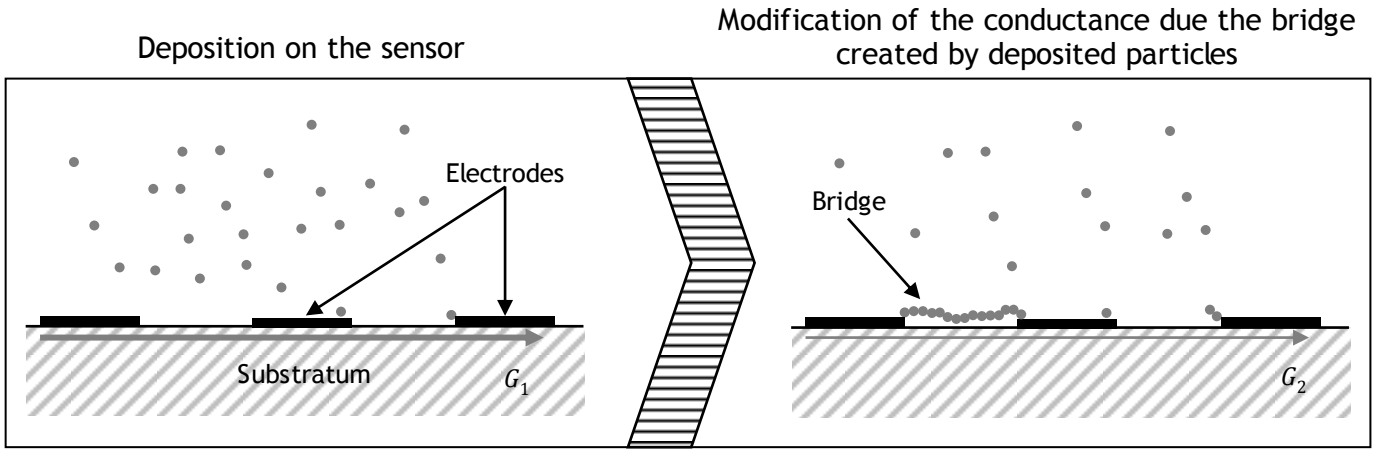

Figure 7: Operation of a resistive sensor

Among soot sensors, capacitive sensors are similar to resistive sensors but their electrodes are covered with an insulating material (see Figure 8). Capacitance measurement Cp is performed, and C_p decreases

with the mass loading. Kondo et al. (2011) work on improving their capacitive sensor by using base metal electrodes, rather than noble metal ones, as commonly used (like platinum for example). Furthermore, the sensor performance can be improved by enhancing the imposed voltage between the two electrodes. However, this voltage imposes a modification of particle collection phenomenon: electrophoresis enhances soot deposition on the sensor. Hagen et al. (2018) study the effect of different voltage values imposed between the electrodes. As the voltage is enhanced, soot temperature rises and causes thermophoresis to occur. Comparing capacitive sensors to resistive ones, capacitive sensors are more complex, as measuring small capacitances with high resolution is more difficult than measuring current value (related to conductance).

Figure placement callout

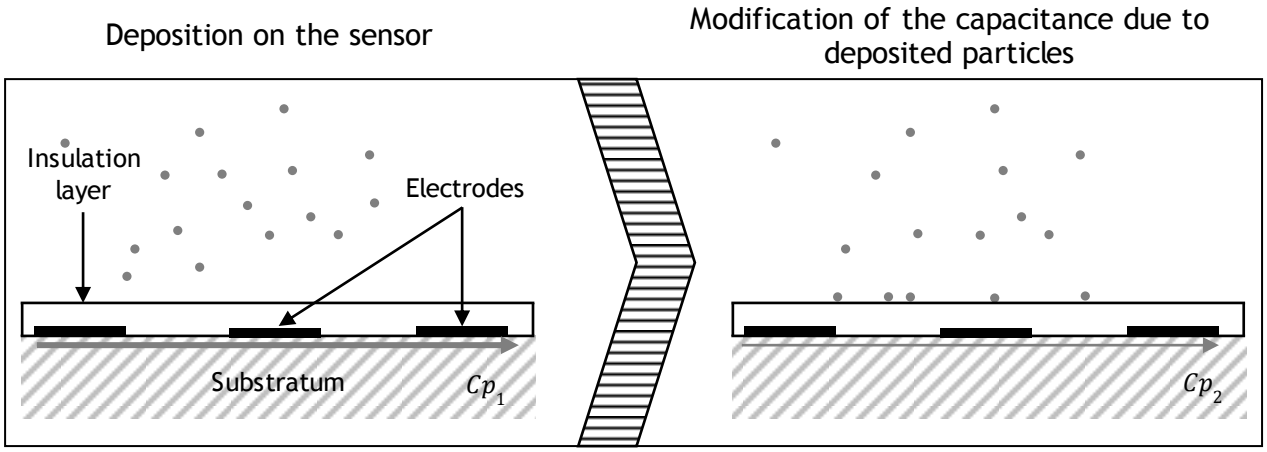

Figure 8: Operation of a capacitive sensor

To conclude, soot sensors gather resistive and capacitive sensors. The size of these sensors (i.e. the size of the deposition surface) is linked to the number of electrodes chosen during the creation process. Soot sensors imply a modification of the deposition surface and are sensitive to ambient conditions. They provide an *in situ* measurement and — a "sequential" real-time measurement, as the measurement is interrupted by saturation.

3.7 Synthesis

The specific characteristics of the different methods found to determine mass concentration on a surface are synthesized in Table 2.

Table placement callout

Table 2: Measurement techniques of mass surface deposition

Techniques		Limit of detection	Size of the deposition surface	*In situ* measurement	Real-time measurement	Intrusiveness (Surface modification)	Measured value	References
Weighing scale		0.1 µg (depends on the manufacturer)	-	No	No	Yes	Mass	Licina and Nazaroff (2018); Lai et al. (2017)
Fluorometry	**With substratum**	Depends on the fluorometer	No matter	No	No	Yes	Fluorescence intensity	Thatcher et al. (2002); Sow et al. (2019)
	By wiping or washing			No	No	No		Sippola and Nazaroff (2004); Da et al. (2015)
Photovoltaic signal		Better precision under 2 $mg.cm^{-2}$	No matter	Yes	Sequential	Yes	Current	El-Shobokshy and Hussein (1993)
Acoustic wave mass sensors	**SAW**	3 pg	1 cm^2	Yes	Sequential	Yes	Frequency	Bowers, Chuan, and Duong (1991)
	FBAR	9 fg	50 x 70 μm^2	Yes	Sequential	Yes	Frequency	Campanella et al. (2006)
Resonant mass sensors	**MEMS**	9 fg	17.6 x 5 μm^2	Yes	Sequential	Yes	Frequency	Hajjam, Wilson, and Pourkamali (2011)
	NEMS	740 ag	138 x 3 μm^2	Yes	Sequential	Yes	Frequency	Schmid et al. (2013)
Soot sensors	**Resistive sensor**	Starting from the first soot bridge	Depends on the number of electrodes	Yes	Sequential	Yes	Conductance/ Current	Feulner et al. (2015)

Capacitive sensor	Starting from the first soot bridge	Depends on the number of electrodes	Yes	Sequential	Yes	Capacitance	Hagen et al. (2016)

Concerning the real-time measurement, acoustic wave mass sensors, resonant mass sensors and soot sensors present similar characteristics. They do not perform real-time deposition measurement but a kind of sequential real-time measurement: even though the measurement frequency is high, saturation of the sensors interrupts the measurement.

On one hand, all the sensors are intrusive aerosol deposition measurement techniques. As deposition is directly measured on the surface of the sensors, these sensors need to be installed on the surface where deposition will take place, hence changing the nature of the deposition surface. On the other hand, all the sensors provide an *in situ* measurement, unlike the weighing technique and fluorometry, as the experimenters can install the sensors on the surface of the experiment and the measurement is performed where the deposition takes place.

Concerning the calibration process, the sensors are more difficult to handle than weighing scales: the sensors are not yet marketed (on the contrary, weighing scales are easily found on the market) so the experimenters need to develop them at their laboratory and then qualify the sensors. In general, these sensors also need to be calibrated almost every time an experiment is carried out due to the difficulty of controlling several parameters, such as ambient and intrinsic conditions.

When looking at the size of the deposition surface, weighing scales, photovoltaic signal and fluorometry techniques can provide a deposition measurement on larger surfaces than the ones studied with the small sensors (SAW, MEMS, etc.) and photovoltaic signal technique (difficulties to get a homogeneous light flux over large surfaces).

Concerning the intrusiveness of the techniques, fluorescence spectroscopy associated with wiping or washing the deposition surface is the only technique which provides an aerosol deposition measurement without modifying the deposition surface, as most of the other techniques requires either a specific surface (like a transparent surfaces) or an added surface which is generally the sensor itself.

Concerning the directly measured variable, weighing scales are the only way to directly get a value of deposition measurement; whereas with the other techniques, a first variable is measured (for example frequency), which must then be converted into deposited mass, inducing calibration processes.

Concerning the specificity of the techniques, fluorescence spectroscopy and soot sensors are both techniques that require a specific type of aerosols, respectively a fluorescent aerosol (or an aerosol traced with fluorescent material) and a conductive aerosol. For the other techniques, any type of aerosol can be used.

4. Number surface deposition measurement

For all the techniques described in this part, the studied aerosols can have either a monodisperse or a polydisperse size distribution.

4.1 Optical counting on surfaces – laboratory-developed techniques

Optical counting is a method that provides deposited particle number concentration measurement. The technique is presented on Figure 9. The deposition surface needs to be delimited first and is lighted by a lighting system, which provides contrasted luminosity, helping the differentiation between particles, noises and substrate material. The delimited surface is faced by an optical detector, such as a microscope or a macro-objective connected to a camera. In the past, particle counting was manually performed by the user, as does McCready (1986) by performing particle deposition on a transparent plate and using a microscope. More recently, Wagner and Leith (2001) and Boor, Siegel, and Novoselac (2013) choose to study the deposition on a filter using a microscope equipped with a camera, whose pictures were post-processed with a morphometry program or image analysis software to realize the particle counting. Image analysis has been extensively developed allowing the use of open-source imaging software (Barth et al. 2013) or commercial software (Wagner and Leith 2001), by programing the imaging analysis (Boor, Siegel, and Novoselac 2013) or by using deep learning-based method for size analysis (Frei and Kruis 2020).

Figure placement callout

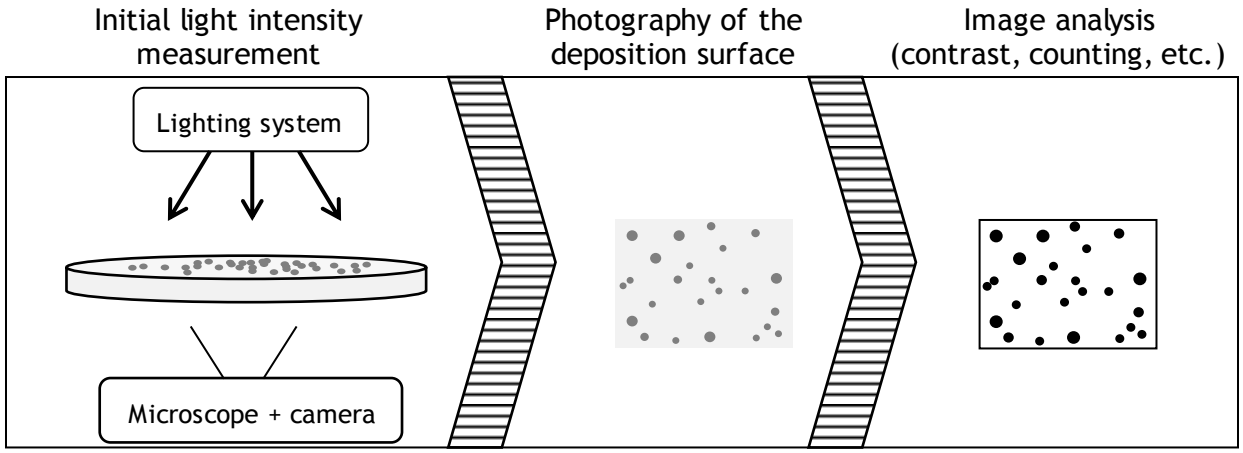

Figure 9: Operation of microscope and camera counting

With this imaging technique, the lighting system is placed in front of the aerosol sample (the need of a transparent surface is necessary here) facing the photodetector (technique also called shadowgraphy). This technique is used by Barth et al. (2013). In some studies, a lighting system is already integrated into the microscope (Wagner and Leith 2001; Boor et al. 2013) and the observed surface can be a filter for example.

To analyze the image given by the microscope, the magnification gives the enlarged size SO_e of the object of size SO_i, as it is expressed as:

$$M = \frac{SO_e}{SO_i} \tag{9}$$

Regarding digital microscope linked to a camera, the total magnification M_{total} can be expressed as:

$$M_{total} = M_O \times M_D \tag{10}$$

with M_O the optics magnification, defined as the product of magnification of each optics instrument: $M_O = \prod_i M_{O,i}$; and M_D the digital magnification, defined as the ratio between the monitor screen size and the camera sensor size on the sensor $M_D = \frac{Screen\ size}{Sensor\ size}$. If 4 pixels are considered the minimum to represent one particle in the image and the camera has a pixel size D_{pix} of 7 µm and the magnification is 2, the minimum aerosol size D_{max} that can be observed is:

$$D_{max} = \frac{4 \times D_{pix}}{M} = \frac{4 \times 7}{2} = 14\ \mu m. \tag{11}$$

However, D_{max} is limited by the existence of the Airy disk, due to the diffraction of light, in case of reflection microscopy. Shadowgraphy can be used to avoid this limit, by observing the shadow of the particle thanks to the photodetector facing the lighting system.

As the counting distinguishes the different diameters of particles, the aerosol size distribution can be polydisperse. Besides, in most cases, optical counting methods are not intrusive and therefore does not modify deposition. Optical counting is an *in situ* measurement technique, as the deposited particles are directly observed on the deposition surface; and the uncertainty depends on the optical devices used for the experiment. Barth, Lecrivain, and Hampel (2013) estimate uncertainty around 20%, whereas Boor, Siegel, and Novoselac (2013) presents a 5% uncertainty on particle counting.

Optical counting enables to determine exactly the number of deposited particles, regarding the diameters of these deposited particles. The quality of this technique rests on the quality of a) the utilized optical (objective and camera) instruments, b) the lighting system and c) the accuracy of the image processing. Besides the working distance (WD – m) is dependent on the magnification M. The following empirical formula provides a relationship between WD and the focal length FL (m) and M:

$$WD = FL(\frac{1}{M} + 1), \tag{12}$$

However when M is increased, WD decreases, which is challenging as "standard" manufactured systems do not have a great magnification combined with a working distance over 40 cm.

To conclude, optical counting technique is a laboratory-developed technique. The experimental protocol can vary very differently from an experiment to another, as optical instruments and image processing are chosen by the experimenter. Consequently, the optical counting techniques are adaptable to different experiment configurations and to different particle diameters. Optical counting technique induce a modification of the surface, except in the case of using shadowgraphy in an experiment entirely made of transparent surfaces. The minimum size of particles that can be counted and sensitivity of optical counting technique also depends on the choice of instruments and processing. Besides, the choice of instruments and processing must be done related to the possible working distance and the size of the studied particles in the experiment. Optical counting technique provides an *in situ* measurement.

4.2 Marketed counting techniques

These devices do not allow to measure aerosol deposition on a given surface, but only on their own surface. All their surfaces are transparent. Only the global measuring principle is detailed for each device in this part and the technical characteristics are listed in Table 3.

The Cleapart-100 (Bertin Instruments) measures particle deposition by counting and classifying particles by their size. The Cleapart-100 was developed initially by Winlight company to monitor air quality in cleanroom environments. The measuring system is an optical system placed under the surface, based on a microscope lens and a camera. According to Tovena Pecault, Godefroy, and Escoubas (2017), the uncertainty is estimated at 1%.

The Particle Deposition Meter (PDM, SAC) is close to the Cleapart-100The PDM also contains an optical system, but the circular deposition surface can be examined after the deposition experiment, by placing the surface on the PDM device.

The Advanced Particle Deposition MONitor (APMON, Technology of Sense) is based on a holographic method: deposited particles generate interferences in laser beam waves, which are then analyzed using Fourier transformation method to enable the count of particles. The device is composed of a cartridge containing glass plates oriented at 45 degrees. Aerosols deposit on the glass plates and thanks to the holographic method, the size distribution is provided.

The PFO 1000 MONITOR (XCAM) is constituted of four CMOS sensors associated with an algorithm, which analyzes deposited particles. Alarms can be programed by the user to be notified when the detection surface is close to be completely obscured.

The Micro-sensor for cleanrooms (CNES) has been developed (Menant 2016) to provide a better resolution than the other presented devices for space applications As this micro-sensor can be used for cleanroom application, the developers supposed that particles larger than 20 µm are removed by the airflow control system. The Micro-sensor for cleanrooms is based on optical detection (Menant et al. 2015). The deposition surface is transparent and the scanning system is made of two parts, one on each

side of the surface: a laser diode and a focusing assembly is placed on one side and the detection system is on the other side.

4.3 Synthesis

Table placement callout

Table 3: Measurement techniques of number surface deposition

	Techniques	Particle size	Size of the deposition surface	*In situ* measurement	Real-time measurement (measure/unit time)	Surface modification
Lab.-developed techniques	Optical counting	> 2 µm	-	Yes	No	No
Marketed techniques	Cleapart-100 (Bertin Instruments)	> 5 µm (5 classes of diameter)	100 x 100 mm²	Yes	1 / 7 min.	Yes
	PDM (SAC)	> 5 µm (90% reliability) or > 10 µm (98% reliability) (9 classes of diameter)	49 cm² - Circular	Yes	~1 / 12 sec. (> 1 / 20 sec.)	Yes
	Apmon (Technology of Sense)	> 15 µm	Not available	Yes	1 / 5 min.	Yes
	PFO 1000 Monitor (XCAM)	> 5 µm and < 750 µm	4 cm²	Yes	10 / 1 hour	Yes
	Micro-sensor for clean rooms (CNES)	> 1 µm and < 20 µm	Not available	Yes	✓ (No data)	Yes

Table 3 details the principal features of number surface concentration measured by deposition measurement techniques. These techniques are gathered in two groups: laboratory-developed techniques and marketed counting ones. All these techniques enable to get quite high frequency measurement but do not provide a real-time measurement, as the optical systems need to move to scan the whole surface. Any type of solid aerosols larger than 10 µm, can be used with these techniques. However, the surface of deposition is an integrated part of the devices: the device can only be used for scanning its own deposition surface.

Laboratory-developed techniques have the advantage of being more adaptable. Each experimenter can choose and decide the best fitting equipment. Also, the optical devices can be chosen according to the experimenter's need: optical devices are not necessarily the same between counting small particles (around 4 µm for example) and large particles (around 50 µm). The treatment of the images can be performed with a dedicated software or with an in-house developed code. For example, there are recent developments of image treatment by using deep learning. Besides, the experimenter can choose the size of his or her deposition measurement surface. Consequently, laboratory-developed optical counting techniques require some precise theoretical knowledge to be implemented: the monitoring system, the detection system and the image processing system need to be properly considered and arranged.

On the other side, marketed devices are all-in-one and turnkey techniques. A software is provided to monitor deposition, so these devices are more user-friendly. Most of the marketed devices were developed and studied in the framework of cleanrooms, but could be used in other applications, such as contaminant deposition at home or in industries (for example in food-processing industries). The measurement performed by these devices are all based on an optical system, which provides particle classification in size, except for the PFO 1000 Monitor, which analyzes the obscuration of the deposition surface. Marketed devices are less adaptable than laboratory-developed techniques, especially as the marketed ones have their own deposition surface, so the surface size and type cannot be decided by the experimenter and consequently imposing a surface modification for aerosol deposition and not to being

directly applicable in the applications where the objective is to study the deposition over a specific surface (such as deposition in ventilation ducts).

5. Conclusion

In this paper, the theory behind global and local aerosol deposition measurement techniques has first been described in a general way. The local aerosol deposition measurement techniques have then been chosen to be developed in more details. Nine techniques are then presented in this paper each providing directly either a mass or a number concentration measurement in order to obtain a surface deposition flux. These nine techniques are observed under five major criteria: limit of detection; aerosol size distribution; possibility of *in situ* measurement; possibility of real-time measurement and whether the technique requires a modification of the surface or not. The choice between all these techniques must be made judiciously to ensure precise measurements regarding the conducted experiments.

Small sensors (acoustic wave mass sensors, MEMS and NEMS) have been greatly developed over the last decade. Their limits of detection are the lowest of the nine techniques. They are still developed in laboratory and as they have become smaller, the measurement is quite dependent on atmospheric conditions. These sensors can be used for small and large solid aerosols. They have to be put on the surface of interest, modifying the hydraulic conditions near the surface. They can provide some real-time measurements by sequences since they need to be cleaned regularly.

On the contrary, optical techniques often require bulky instruments. They have the advantage of being *in situ* and adaptable: each parts can be chosen by the experimenter according to their characteristics. Considering a good accuracy, they are only suitable for very large solid aerosols (over 10 µm). The marketed devices for optical counting are generally not used to characterize the deposition over a given surface, but they estimate the deposition over a surface included in the device. They generally provide a measurement with a low frequency (around the minute).

For a specific use of particles traced with fluorescent material, fluorescence spectroscopy is the most largely used technique. With this technique many different experimental protocols can be designed:

fluorescence spectroscopy is adaptable to different setups. This technique does not provide a real-time measurement but can be used on the real surface deposition. It is generally used for aerosol below 10 µm. However, this technique requires the use of a fluorescent traced aerosol of a monodisperse size distribution which makes its use very restrictive to specific studies. The limit of detection of fluorometry can be very low for a standard quality fluorescent spectrometer, but the spectrometer quality obviously influences the limit of detection.

The study of photovoltaic signal is also based on aerosol observation under light but requires a different observation: the darkening of the depositing surface is correlated to the number or mass of deposited particles. This technique cannot be considered as validated nowadays, but is very promising since a lot of research is made on dust deposition over photovoltaic surfaces, which could bring some new features to develop this technique and the associated calibration. Photovoltaic surfaces could then be used for solid aerosol of various sizes in low concentration environment.

A different family of sensors gathers soot sensors. They were specifically designed for the deposition quantification of conductive aerosols. They are not manufactured yet, as the calibration based on the correlation between the quantity of deposited particles and the measured value (in this case, capacitance or conductance) is challenging.

Most of the nine techniques are laboratory-developed ones. The ones that are already manufactured are only a few and were specifically designed to quantify aerosol deposition in cleanrooms. They have the advantage of being turnkey products, but are consequently less adaptable to different setups.

Regarding physical properties, the monodisperse aspect of the aerosol size distribution is essential for interpreting mass surface concentration.

Many improvements have been realized on sensors these last years, especially on miniaturized sensors and optical techniques. It is mandatory to consider all the issues related to deposition mechanisms, as it provides a) information on which techniques are the most suitable for one's experiment and b) better and more precise interpretation and understanding of data. Investigations on aerosol deposition need to be

carried on to provide more knowledge and data thus help to improve the overall comprehension of air quality.

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Captions

Figure 1. Global deposition in a channel with flux conservation.

Figure 2. Global deposition in a room with flux conservation.

Table 1. Synthesis of deposition parameters.