An experimental protocol for measuring aerosol deposition in industrial-sized ventilation ducts

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Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Abstract

In the literature, studies on aerosol deposition in ventilation ducts mainly focus on ventilation ducts with a hydraulic diameter (D_h) of around 15 to 25 cm and with circular or square cross-sections. However, to our knowledge, common industrial-sized ventilation ducts ($D_h \sim 50$ cm) with rectangular cross-sections have not been studied. As a result, experimental aerosol deposition measurement protocols relative to ventilation ducts of smaller sizes are not suitable for measurement in industrial-sized ducts. Therefore, a new experimental protocol is proposed here, which can be used without destruction of the surface or addition of a substrate on the duct surface and could be applied in industrial ventilation networks as soon as certain conditions are met. In this paper, we present an experimental protocol developed to measure aerosol deposition adapted for large-scale ventilation ducts. First, the collection and measurement technique, the type of aerosol and the injection method are chosen. Second, the experimental protocol relative to the collection of aerosols deposited on duct surfaces is developed, based on a so-called "wiping" technique. Many verifications are presented here to ensure repeatable and reproducible measurements. Third, a repeatability study is conducted, as well as a validation process. In the last section of this paper,we present some results on aerosol deposition obtained on a test facility compared to two other studies.

Keywords: aerosol deposition, metrology, experimental protocol

Introduction and state of the art

It is now essential to further our knowledge of particulate contaminant transfer mechanisms in ventilation networks, especially with regard to contaminant deposition on surfaces. Indeed, in health applications, for example, particles can deposit in the respiratory system, which is linked to indoor air quality and, therefore, to the ventilation system [1–3]. The same conclusion is seen in industry, as the development of micro-organisms in ventilation networks can become a contamination source [4,5]. Another example is nuclear facilities, where a better understanding of deposition mechanisms and localization helps determine the quantity of particles remaining inside a ventilation duct and, consequently, helps prevent hazardous accumulations of radioactive particles in specific locations [6,7]. Consequently, experimental studies need to be conducted to further our knowledge on deposition of particles.

However, in the literature, most experimental studies on particle (aerosol) deposition are about small diameter tubes [8–10], such as sampling lines. These small tubes have circular sections and a diameter of around 1 cm. A few studies focus on medium-sized ventilation ducts, i.e. ducts with circular or square sections with a hydraulic diameter of between 15 and 25 cm [11–13]. To our knowledge, no work focuses on "industrial"-sized ventilation ducts with rectangular sections, i.e. ducts with a hydraulic diameter greater than 30 cm.

Additionally, only low masses of aerosols deposit on industrial-sized duct surfaces over a period of a few hours, as the dilution flow rate in industrial ducts is high (flow rate can reach 50,000 m^3/h). Consequently, to obtain measurable masses of deposited aerosols, the experiment duration must be a few weeks. Thus, a compromise must be found between generating enough aerosols to limit the experiment duration and finding a technique with a low limit of detection to be able to measure deposition. The choice of the measurement technique will then determine the type of aerosol that can be

used for the experiment, which in turn determines the type of aerosol generator.

Several techniques for measuring aerosol deposition are described in the literature [14]. The best-known techniques are weighing, fluorescence spectroscopy, micro-sensors and optical techniques. To measure aerosol deposition in industrial-sized ventilation ducts, the measurement technique must measure deposition locally, be very sensitive, non-intrusive and must not require duct handling. Costa *et al.* [14] show that the detection limit of the weighing technique is too high for this purpose; micro-sensors are intrusive, as their presence in the ducts modifies the flow boundary layer; and optical techniques require transparent ducts. The most suitable deposition measurement technique is fluorescence spectroscopy: deposited fluorescent aerosols are collected and put in a dissolving volume of solution. After dissolution, the solution is analyzed using fluorescence spectroscopy to provide a deposited mass by calibration of the spectrometer. Three methods exist for collecting aerosols, which can be combined with fluorescence spectroscopy:

- a substrate is fixed on the surface of the duct, such as a filter (see [15], for example). After deposition, the substrate is removed from the surface and placed in a dissolving volume;
- part of the surface of the duct is designed to be removable. After deposition, the surface is removed and washed with water (for example [11]), which is directly analyzed by fluorescence spectroscopy;
- part of the surface of the duct is delimited by a sort of stencil, which is fixed on the duct after deposition; this delimited surface is then wiped with humidified wipes and the wipes are put in a dissolving volume [12].

Only the wiping technique combined with fluorescence spectroscopy provides a very sensitive local measurement of deposition without modifying the boundary layer and without duct handling. As a result of this review of the literature, we conclude that Ben Othmane and Da *et al.* [12,13] conducted the only studies developing this wiping technique combined with fluorescence spectroscopy applied to medium-sized ventilation ducts. Ben Othmane dismantles the duct upstream from the test section, then fixes a sort of stencil on the duct wall after deposition and collects particles within the surface delimited by the stencil by wiping with humidified wipes. The wipes are held by the operator. With at least 3 wipings, Ben Othmane succeeds in collecting all the particles deposited. However, Ben Othmane's protocol is applied to medium-sized ducts (D_h of 20-25 cm) with circular cross-sections, requires duct handling (due to the absence of access hatches) and does not explicitly give any general verification criteria.

Consequently, there is a need to develop an experimental protocol with verifications and criteria to measure aerosol deposition in industrial-sized rectangular ventilation ducts.

The objective of this paper is to present the development and validation of an experimental protocol for directly measuring aerosol deposition on the surface of industrial-sized rectangular ventilation ducts, inspired by the measurement technique developed by Ben Othmane and Da *et al.* [12,13]. The paper is divided into four parts. In the first part, we present the required variables. The second part focuses on the experimental aerosol deposition measurement protocol. In the third part, we describe in detail an application of this protocol in a test facility. In the fourth part, we present the validation of the experimental protocol.

Measured variables

Different variables can be used to represent aerosol deposition and not all of them are directly measured [14]. Deposition velocity v_d (m/s) is a most common deposition parameter used in the literature. v_d is expressed as:

$$v_d = \frac{J}{C_{bulk}} \quad (1)$$

where J is the deposition flux over a surface (kg/m²/s) and C_{bulk} is the volume concentration in the bulk (kg/m^3) (Figure 1).

Consequently, these two parameters (J and C_{bulk}) need to be measured.

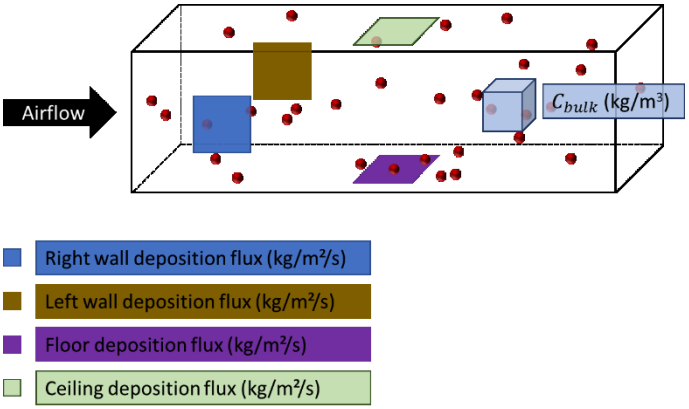

Figure 1. Presentation diagram of deposition flux

Deposition measurement techniques provide a deposited mass of aerosol (m_d in kg), which is linked to J:

$$J = \frac{m_d/S}{\Delta t} \quad (2)$$

where S is the deposition surface (m²) over the duration of the experiment Δt (s).

In the case of fluorescence spectroscopy, a fluorescent aerosol needs to be generated and collected after deposition. Collected aerosols are placed in a volume V (m^3) of ammonia water for dissolution and once the fluorescent aerosols have dissolved, the spectrometer is used to measure the fluorescence intensity of the solution I, which, by a

calibration process, provides a volume concentration of fluorescein C_v (kg/m^3):

$$m_d = C_v \times V \quad (3)$$

$$C_v = a \times I + b \quad (4)$$

and

where a and b are the coefficients provided by the calibration.

C_{bulk} is obtained by sampling fluorescent aerosols inside the duct, using a sampling line connected to a filter. The sampling line must be installed as close as possible to the location of deposition measurement and sampling must be performed in isokinetic conditions. The aerosols are sampled throughout the entire duration of the experiment. After the end of the experiment, the filter is collected. The inside of the sampling tube is also washed with specific volumes of ammonia water to collect all the aerosols that may have been deposited during the sampling process. In other ventilation networks, this protocol should be conducted once to determine the number of washings that need to be performed to collect deposited aerosols in sampling lines, which is specific to flow rates and aerosol generator. An example of this kind of verification is presented in Section 3.2.2.

The total collected mass is obtained from the mass deposited inside the sampling line (m_{sl} in kg) and the mass collected on the filter (m_f in kg):

$$C_{bulk} = \frac{m_f + m_{sl}}{V_a} \quad (5)$$

where V_a (m^3) is the volume of air sampled over the duration of the experiment. m_f and m_{sl} are also obtained by dissolution in ammonia water and fluorescence spectroscopy measurement and calculated the same way as m_d (Equation (3).

Experimental protocol development for deposition measurement in straight ducts

2.1 Wiping protocol

2.1.1 Material. A new type of stencil has been developed that can easily be inserted and fixed on ducts. These are called "masks" and are 3D-printed pieces that delimit the collection surface. Usually, in industrial ventilation networks, hatches are present (for maintenance for example) to give access to the inside of the ducts: the masks can be inserted into the duct through these hatches and then fixed on the duct surface after the deposition experiment. For example, on galvanized steel ducts, magnets can be used to fix the masks to the ducts. The measurement is performed in two steps: a "blank" measurement after cleaning the considered surface, and the deposition measurement after the experiment. These two measurements need to be done at exactly the same place, so a specific mask is used for each step. The 3D-printed "blank" masks must have a slightly larger inner surface than the deposition masks to ensure wiping across the entire deposition surface (see example showing the disappearance of green lines in Figure 2). Each mask is associated with a "stamp" to hold the wipe (Figure 3 on the left and Figure 4).

As masks are 3D-printed, they can easily be adapted to any type of duct, such as circular ducts for example (Figure 3 on the right).

The masks and stamps used for the blank measurement and the collection of aerosols after deposition are washed with tap water after each experiment to ensure their cleanliness. They are then dried in an oven at 25°C minimum for at least 24 hours.

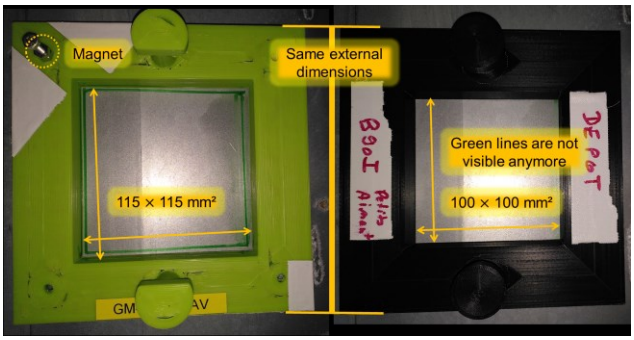

Figure 2. 3D-printed blank mask (left) and deposition mask (right)

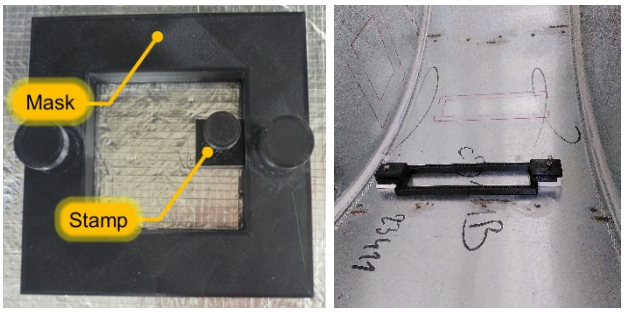

Figure 3. Example of a mask and its stamp (left) and a curved mask fixed on a curved duct (right)

To wipe the surface delimited by the mask, i.e. the collection surface, a wipe is held on the stamp by the operator (Figure 4). Both the use of solid masks and the use of a stamp contribute to reducing any potential contamination of the wipe, compared to existing protocols [12] or washing processes [11]. The wipe is then humidified with demineralized water. The delimited surface is wiped with the stamp (Figure 4) following specific steps for wiping: the edge of the surface is wiped first followed by the inside of the surface. One so-called 'wiping' entails performing the two steps twice.

Figure 4. Photograph of an operator performing a wiping

For each experiment, a blank and a deposition measurement are systematically performed and vials are kept in the dark (to avoid degradation of fluorescence by light [16]) after placing the wipes inside.

2.1.2 "Blank" measurement. To ensure the cleanliness of the surfaces studied prior to an experiment, each surface is wiped a specific number of times, established after many experiments (see an application of the protocol in Section 3.2.3): a "blank" measurement is performed after wiping the surface and analyzing the wipe using fluorescence spectroscopy. A criterion has been set for this purpose: the deposited mass collected with the "blank" wiping (m_{d_0} in kg) must be lower than a maximum deposited mass ($m_{d_{0_{max}}}$ in kg) decided based on many preliminary experiments:

$$m_{d_0} < m_{d_{0_{max}}} \quad (6)$$

i.e. 10 ng, which corresponds to a deposited concentration of 0.08 ng/cm².

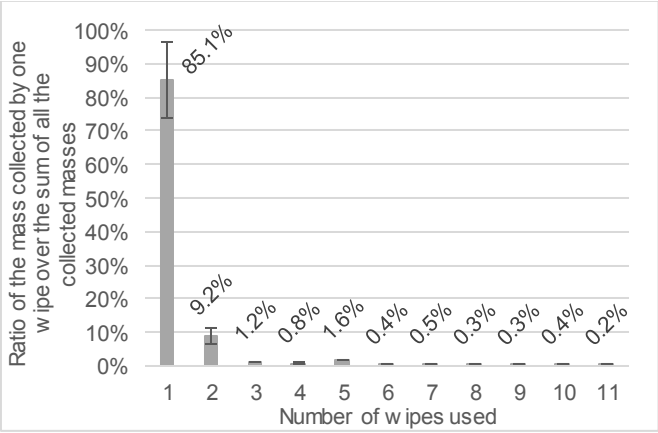

Figure 5. Aerosol collection with each wiping on a galvanized steel surface with deposition around 8 ng/cm²

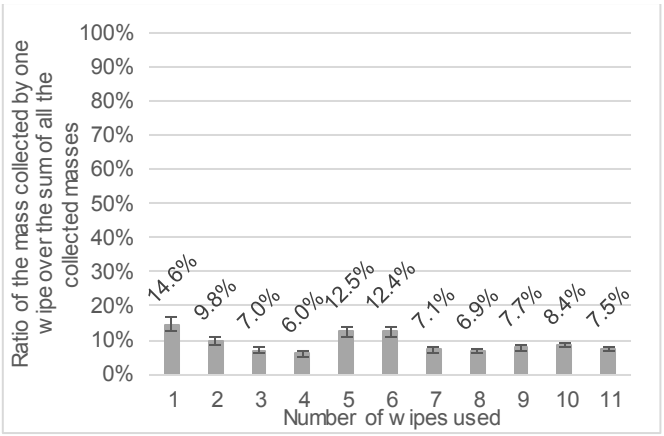

Figure 6. Aerosol collection with each wiping on a galvanized steel surface with deposition around 0.5 ng/cm²

2.1.3 Deposition measurement. An important feature of the protocol is the determination of the number of wipings needed to ensure the full collection of deposited aerosols. Preliminary experiments have shown, as expected, that the number of wipings depends on the deposited concentration. For this purpose, a specific protocol is thus applied once to determine how many wipings need to be performed: each wipe used to collect aerosols is put in its own vial and analyzed by fluorescence spectroscopy. The results for each wipe (i.e. two wipings of the surface) used on a surface with much deposition (C_d ~ 8 ng/cm²) on the duct after deposition of an aerosol with a mean mass median aerodynamic diameter (mean MMAD) of around 3 µm is presented in Figure 5. The results may lead to the conclusion that 10 wipes are enough to collect all deposited aerosols; however, Figure 6 shows that the decrease of collected deposition on the wipes for a surface with little deposition (C_d ~ 0.5 ng/cm²) is not as direct. Consequently, 10 wipings ensure the full collection of deposited particles. This result is important since in previous study, the number of wiping was not given as a function of the collected mass. Furthermore, to verify that all particles are collected, a criterion has been set regarding the last wipe: the deposited mass collected with the last-used wipe, considered to be the residual mass (m_{d_n} in kg), must be lower than 20% of the sum of the deposited mass collected with each wipe (m_{d_i} in kg):

$$m_{d_n} < 20\% \sum_{i=1}^{n} m_{d_i}. \quad (7)$$

where i is the number of wipes. The 20% value has been determined after many experiments applying this protocol.

Finally, the protocol developed here is described as follows (Table 1): the delimited surface is wiped 11 times using 7 wipes: wipe #1 is used for 1 wiping; wipes #2 to #5 are used for 2 wipings, as the wipe is not saturated in fluorescein and this step enables the operator to save time; wipe #6 is used for 1 wiping. These first 6 wipes (corresponding to 10

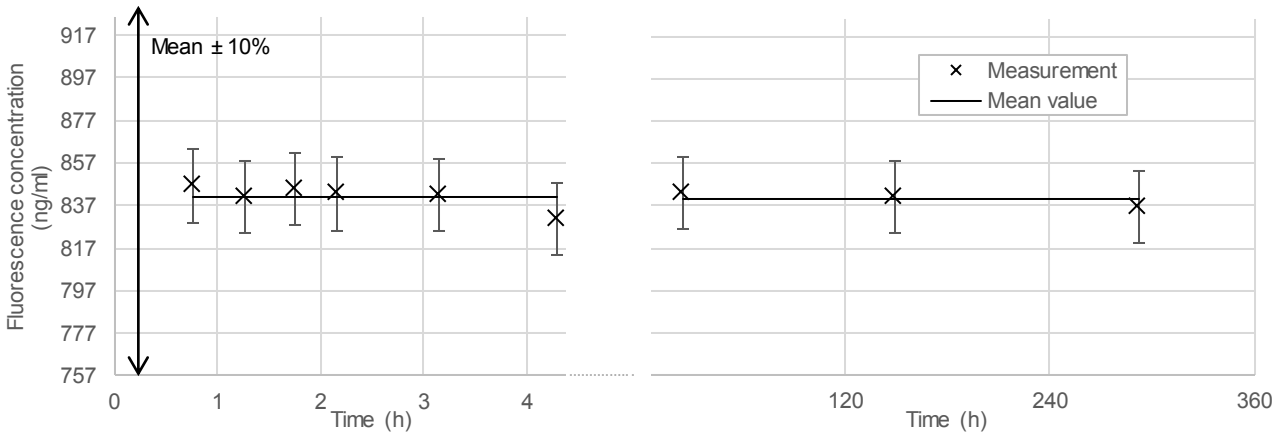

Figure 7. Fluorescence measurement evolution over time

wipings) are put in vial #1, which will provide $\sum_{i=1}^{n-1} m_{d_i}$ in Equation (7). Wipe #7, which will provide m_{d_n} in Equation (7), is used for 1 wiping and is put in vial #2 to verify that all deposited aerosols have been collected. A specific volume of ammonia water is put in each vial (usually for $C_d \geq 0.4$ ng/cm²: 50 mL in vial #1 containing 6 wipes and 10 mL in vial #2 containing 1 wipe) for a later fluorescence spectroscopy analysis.

Table 1. Number of wipings for aerosol deposition collection

Vial number	Number of wipings	Wipe number	
#1	1	#1	$\sum_{i=1}^{n-1} m_{d_i}$
	2 for each wipe	#2 to #5	
	1	#6	
#2	1	#7	m_{d_n}

Depending on the duct material, the surface roughness could entail a modification of the number of wipings required to collect all deposited particles.

2.2 One-time verifications

2.2.1 Cleanliness of ammonia water distribution. Before each distribution of ammonia water, a fluorescence spectroscopy measurement of ammonia water is performed. The measured value is below the detection limit of the spectrometer.

2.2.2 Cleanliness of the vials. A specific volume of ammonia water is put in the vial and analyzed by fluorescence spectroscopy after some time. The measurement provides the same value as ammonia water itself (background noise of the spectrometer): unused vials are clean regarding fluorescent particles.

2.2.3 Cleanliness of the wipes. One unused wipe is put in a vial and six unused wipes are put in a vial. Then, a specific volume of ammonia water is added in each vial. After an interval to allow for virtual dissolution, the ammonia water is analyzed, and the fluorescence spectrometer used to detect fluorescent masses of 0.24 and 0.21 ng respectively. We consider these two values as our background limit.

2.2.4 Fluorescence stability over time. A verification of the stability of fluorescence in the vials is performed over more than 240 hours of dissolution. For this purpose, a filter with fluorescent aerosols is placed in a dissolving volume and fluorescence is measured at different times following dissolution. The vial is kept in the dark between all the measurements and in the same place to avoid temperature variation. Stability of fluorescence is verified, as presented in Figure 7, for a duration of almost 300 hours.

2.3 Uncertainty calculation

Uncertainties of J and C_{bulk} are calculated from Equations (1), (2), (3), (4) and (5).

Table 2. Bias errors and absolute uncertainties for each parameter involved in the deposition velocity expression

C_v	Bias error $E_{j_{C_v}}$: $C_{v_{corrected}} = C_v - E_{j_{C_v}}$	$E_j = a_{E_j} \times I + b_{E_j}$
	Fluorescence spectrometer uncertainty u_{sp}	$u_{sp} = \frac{a_{U_{sp}} \times I + b_{U_{sp}}}{2}$
V	Uncertainty calculated with a rectangular law with the precision of the bottle top dispenser	$\sqrt{N_{use}} \times \frac{P \times V_{max}}{\sqrt{3}}$
L	Uncertainty calculated with a rectangular law with a set MPE for one side of the collection surface ($S = L \times l$);	$\frac{MPE_L}{\sqrt{3}}$

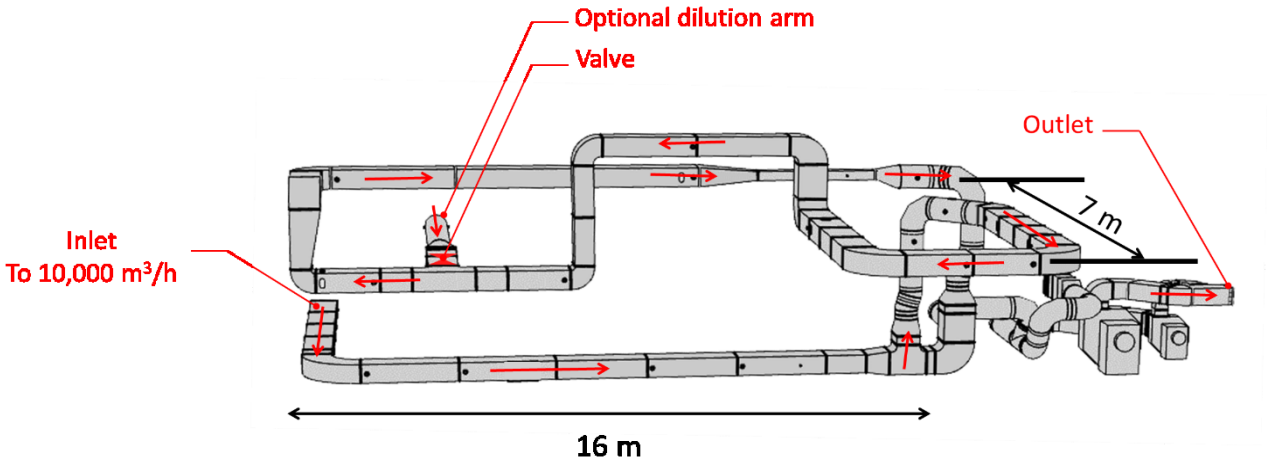

Figure 8. Lateral view of the test facility

	must be applied for l too	
Δt	Uncertainty calculated with a rectangular law with a set MPE	$\frac{MPE_{\Delta t}}{\sqrt{3}}$
V_a	Bias error E_{jV_a} linked to the sampling flowrate Q_i: $V_{a_{corrected}} = V_a - E_{jV_a}$	$\frac{V_{standard_{Q_i}} - V_{Q_i}}{V_{standard_{Q_i}}}$
	Rectangular law with a set MPE	$\frac{MPE_V}{\sqrt{3}}$

Table 2 presents the calculations to obtain bias errors and absolute uncertainties of each parameter involved in deposition velocity calculation, where a_{E_j}, b_{E_j}, $a_{U_{sp}}$ and $b_{U_{sp}}$ values come from the calibration certificate (home calibration process based on 5 calibration solutions and three measurements performed by three different operators); V_{max} and the precision of the bottle top dispenser P are provided by the supplier (the bottle top dispenser is the device used to dispense specific amounts of ammonia water for fluorescent particle dissolution); N_{use} is the number of times the bottle top dispenser is used; L is one side of the collection surface; Maximum Permissible Errors (MPE) are chosen wisely by the operator; $V_{standard_{Q_i}}$ is the volume sampled by the standard volumetric gas meter at Q_i flowrate. Values of the uncertainties used in this study are given in Section 3.2.2.

Mean MMAD uncertainty includes standard deviation of 5 measurements performed over 30 seconds each. Air speed uncertainty includes time standard deviation of airflow measurement over the duration of the experiment.

For all the graphics, uncertainties are calculated with a confidence interval of 95% (i.e. coverage factor equals 2).

Application on a dedicated facility

3.1 Experimental test facility

3.1.1 Description. A test facility to study aerosol deposition in industrial-sized ducts was used for the development and validation of the experimental protocol developed. The total length of this network is around 60 m (Figure 8). It is a ventilation network with rectangular ducts and a hydraulic diameter D_h of 48 cm (sections of 400 mm × 600 mm) made of galvanized steel (Figure 9) and thermally insulated. This facility enables H13 filtrated air flow (99.95% filtration rate) from 2,000 to 10,000 m^3/h by exhaust ventilation, temperature regulation (from 6 to 50°C) and regulation to reduce humidity. An Air Handling Unit (AHU) is installed upstream of the inlet. Hatches and air intake ISO KF flanges provide access to the inside of the facility ducts for deposition measurement (Figure 9).

3.1.2 Aerosol generation. Using fluorescence spectroscopy entails the use and tracing of aerosols thanks to a fluorescent molecule: soda-based fluorescein aerosols are generated. Fluorescence spectroscopy associated with wiping also requires an aerosol with a monodisperse size distribution. Ben Othmane [12] and Sippola and Nazaroff [11] generated monodisperse fluorescent particles with a Vibrating Orifice Aerosol Generator (VOAG, TSI). However, their experiment durations were very long (several days). In this study, the airflows are much higher than [11,12], so generated concentrations need to be much higher too to avoid very long experiments. To generate high particle concentrations as monodisperse as possible, fluorescent aerosols are generated with: a LIXEA Atomizer (Serie BA – 500 kHz, SinapTec) for mean MMAD of around 2 and 5 µm and a Flow Focusing Monodisperse Aerosol (FMAG 1520, TSI) generator for a mean MMAD of around 10 µm.

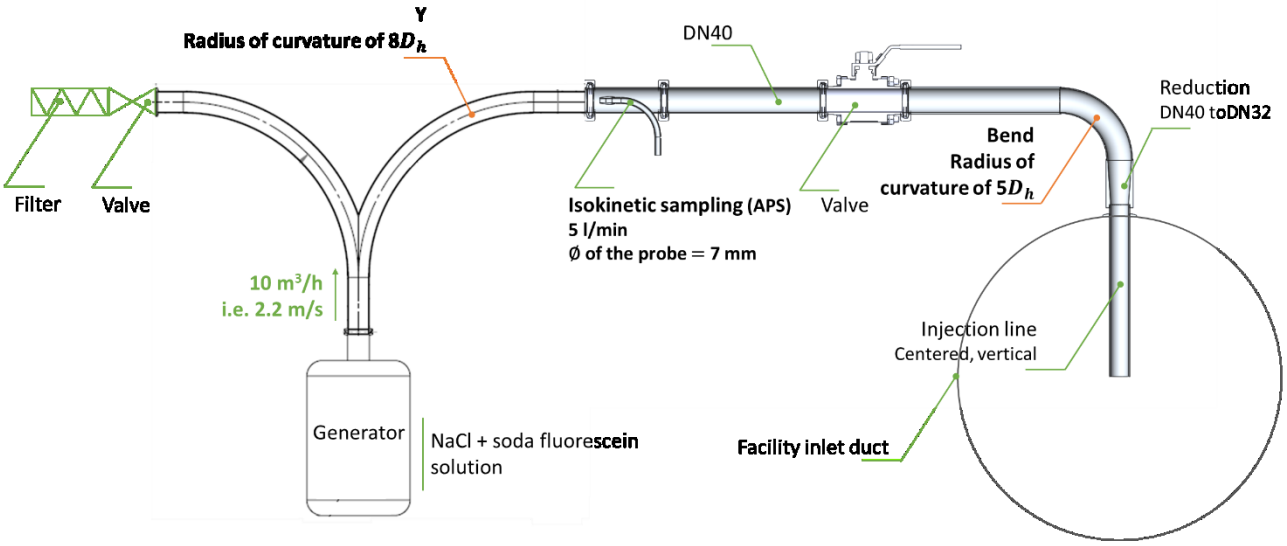

Figure 10. Presentation diagram of the test facility aerosol injection line

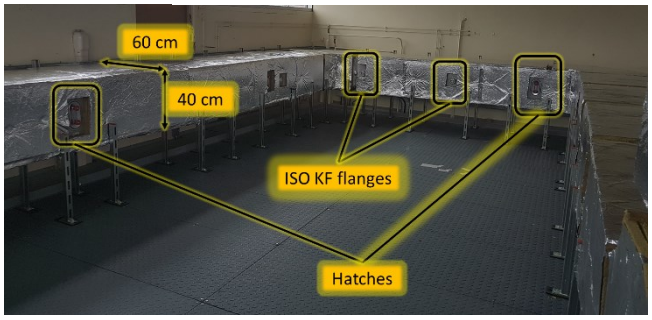

Figure 9. Photograph of a section of rectangular ducts of the test facility

The LIXEA is a generator with a vibrating ceramic. To generate the aerosols with the LIXEA, the atomized solution contains:

- uranine and sodium chloride (NaCl) at a concentration of 1.6 g/L and 14.5 g/L respectively for 2 µm aerosols;
- uranine and sodium chloride (NaCl) at a concentration of 25 g/L and 227 g/L respectively for 5 µm aerosols. The addition of salt allows us to obtain a diameter of 5 µm: a solution with only fluorescein to generate 5 µm aerosols would be too viscous, as the solubility limit of fluorescein would almost be reached.

The FMAG generates aerosols by using a solution of uranine and sodium chloride (NaCl) at a concentration of 0.5 g/L and 4.7 g/L respectively for 10 µm aerosols

Generation also relies on the injection line. The injection line designed for the test facility (with the LIXEA as an example) is presented schematically in Figure 10. During development of the injection line, the total length and the number of disturbances (valve, bends, and reductions) were minimized to reduce aerosol deposition inside. For this purpose, the curvature ratios of both bends are $8D_h$ and $5D_h$ respectively.

3.2 Experimental method

3.2.1 Stages in an experiment using the facility. To perform aerosol deposition tests in straight ducts in the facility, the experimental protocol is based on different steps:

- the first part covers the pre-experiment stages:
  - 30 min of ventilation;
  - the "blank" wiping;
  - the blank analysis; according to the "blank" criterion (Equation (6), if the surface is not clean, the wiping process is repeated;
- the second part covers the experiment stages:
  - ventilation and waiting for a dynamic and thermal balance of the clean air;
  - fluorescent aerosol is injected;
  - during the injection, the injected aerosol is sampled for C_{bulk} concentration measurement;
  - aerosol size distribution is measured during the injection duration using an Aerodynamic Particle Sizer (APS 3321, TSI) and an aerosol diluter (Aerosol Diluter 3302A, TSI) by isokinetic sampling in the injection line (Figure 10);
  - after the aerosol injection is stopped, the ducts are again ventilated for 30 min;
- the third part covers the post-experiment stages:
  - sampling lines are washed;
  - all the surfaces of interest are wiped;
  - deposited concentrations associated with each surface, each filter and each sampling

line are measured by fluorescence spectroscopy.

3.2.2 C_{bulk} *measurement in the facility*. During the injection, air is sampled for m_f concentration measurement using a sampling tube of 9 mm diameter (no profiled probes), 55 cm length and a 90° bend on a filter (fiberglass filter, 47 mm diameter). The sampling line is connected to a pump, with flow set to reach isokinetic conditions, and the pump is connected to a volumetric gas meter for V measurement.

For m_{sl} measurement, sampling lines are washed with the same solution used for dissolution of deposited fluorescent aerosols on wipes or filters.

To determine how many times the sampling lines must be washed to collect all aerosols, two sampling lines with a similar deposition quantity within them are first analyzed by measuring deposited mass collected with each washing using fluorescence spectroscopy. The results obtained with 5 mL washing are presented in Figure 11(a), which presents the mass collected at each washing (m_{sl_i}) divided by the sum of the n mass collected at each washing ($\sum_{i=1}^{n} m_{sl_i}$), in order to obtain a percentage. The results in Figure 11(a) could lead us to conclude that the sampling lines are clean after 5 washings. However, as the first five washings are grouped within only one value, the same test is conducted on 3 sampling lines, where the two first have been exposed to similar aerosol concentrations, whereas the third has been exposed to significantly more aerosols. They are washed only 6 times using 10 mL for each washing. Measurements are presented in Figure 11(b) and clearly show that 5 washings with 10 mL are sufficient to consider the sampling lines clean. Three washings might be sufficient, but 5 washings are performed here to provide more confidence in the results.

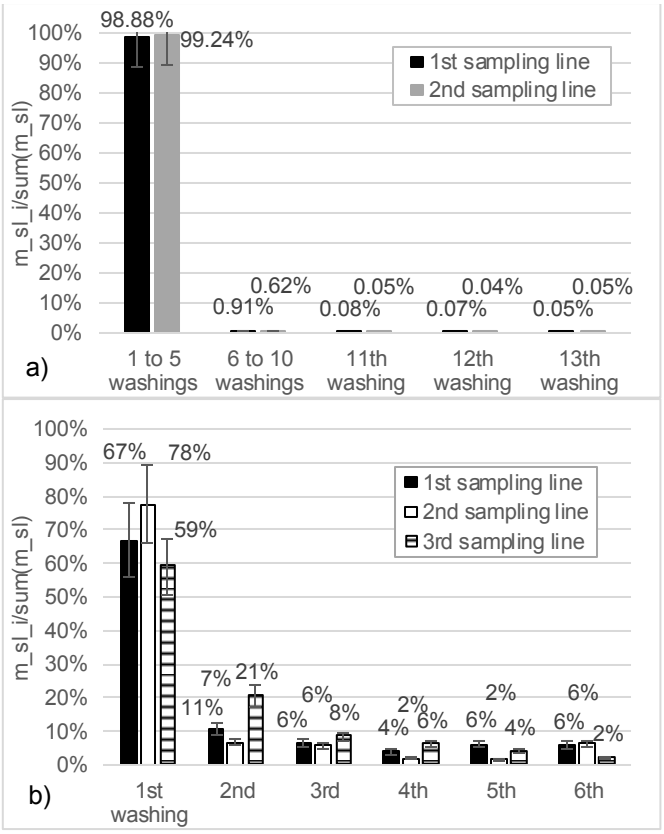

Figure 11. Collection of deposition in sampling lines by washing with a) 5 mL washing and b) 10 mL washing

3.2.3 Wiping protocol application. In the rectangular ducts of the facility, deposition velocity is measured on one surface of each wall: on a surface of the floor of the duct, on a surface of the ceiling and a surface on each vertical wall (one on the left wall regarding the flow direction and one on the right).

Masks are inserted into the ducts through access hatches measuring 100 mm × 200 mm. The inner surface of the blank mask is 115 mm × 115 mm. For deposition collection, masks have an inner surface of 100 mm × 100 mm (Figure 2). On the back of the masks, some holes enable us to attach magnets on the galvanized steel walls of the ducts.

The wiping process is performed using wipes designed for delicate tasks (Kimtech™ Science). The number of wipings to ensure a valid blank measurement in the facility with a 400 mm × 600 mm duct is presented in Table 3.

Table 3. Usual number of wipings performed for blank measurement in the facility

Surface orientation	Number of wipings
Ceiling	10
Floor	20
Vertical (left and right)	15

For fluorescence spectroscopy, a FLUO LOG Handheld (ESE) with a FLUO SENS DD 005 f6 (ESE) spectrometer are used.

Values set for uncertainty calculations are listed in Table 4 regarding uncertainties for each parameter involved in the deposition velocity expression (Table 2).

Table 4. Values of uncertainty parameters

Parameter	Uncertainty parameter	Value
$L = l \sim 100$ mm (square collection surface)	$MPE_L = MPE_l$	4 mm
$\Delta t \sim 30$ min	$MPE_{\Delta t}$	10 s
V_a	MPE_V	3.5% of V_a
V	P of the $V_{max} = 100$ mL bottle top dispenser	0.5% of the read value
	P of the $V_{max} = 10$ mL bottle top dispenser	0.5% of the read value

3.3 Repeatability

The last step in validating the experimental protocol of aerosol deposition measurement in industrial-sized ventilation ducts is to check the repeatability of the deposition velocities obtained. For this purpose, we verify:

- the stability of the generated diameter;
- the stability and repeatability of aerosol dilution in the duct;
- the repeatability of deposition velocity results.

The next sub-parts each focus on these aspects.

3.3.1 Stability of the generated aerosol diameter. To check if the generated aerosol diameter is stable over time, the size distribution of the generated aerosol is measured during an injection in the test facility by sampling particles every 60 seconds 30 times, for a total measurement time of 30 minutes.

Mean MMAD and geometric standard deviation (GSD) are measured using an APS combined with a diluter (3321 and 3302A respectively, TSI). Figure 12 shows 30 size distributions and that the stability is verified. The stability of the generated mass flow is not of interest, as the deposition measurement is performed over the same duration as the sampled volume concentration, assuming that deposited mass fluctuation is proportional to generated mass flow fluctuation.

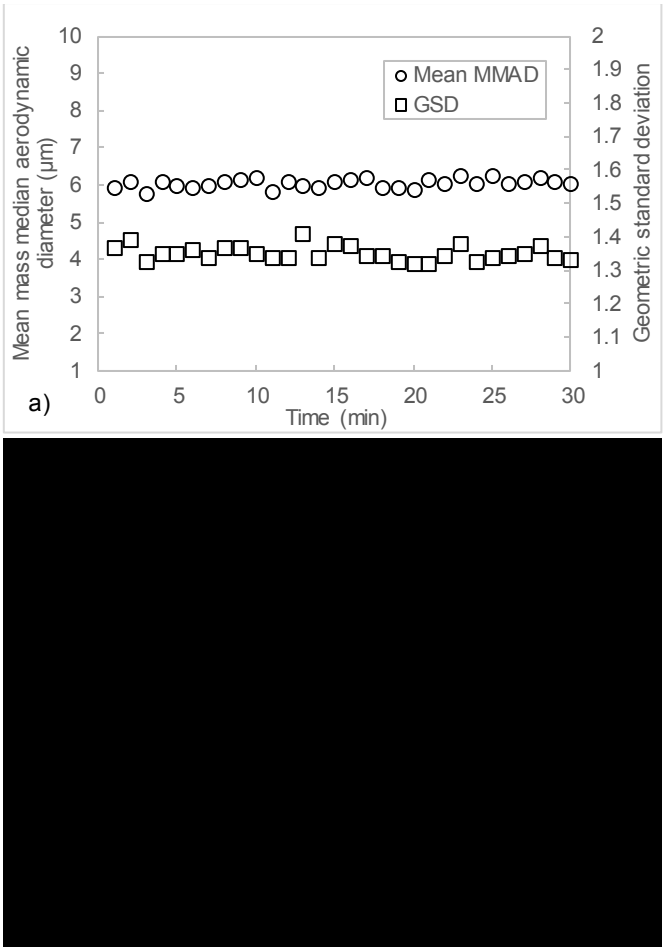

Figure 12. a) Mean MMAD and GSD over 30 minutes and b) example of measured size distributions over 30 minutes

3.3.2 Aerosol dilution in the facility. The air speed profile in one location must be the same from one experiment to the next. Profiles of the horizontal component of the duct air speed $8D_h$ downstream of a flow disturbance on different days for the 4 flow rates (air speed from around 3 to 11 m/s) are measured and presented in Figure 13. The 'R' at the end of some key entries means that these curves are reproductions of profiles with the same name. Nondimensionalized profiles are presented in Figure 13(b). The air speed profiles are repeatable and self-similar.

3.3.3 Repeatability of deposition velocity. Deposition velocities obtained in three experiments are plotted in Figure 14. The variation between the three experiments is lower than 6%. Deposition velocities are considered repeatable.

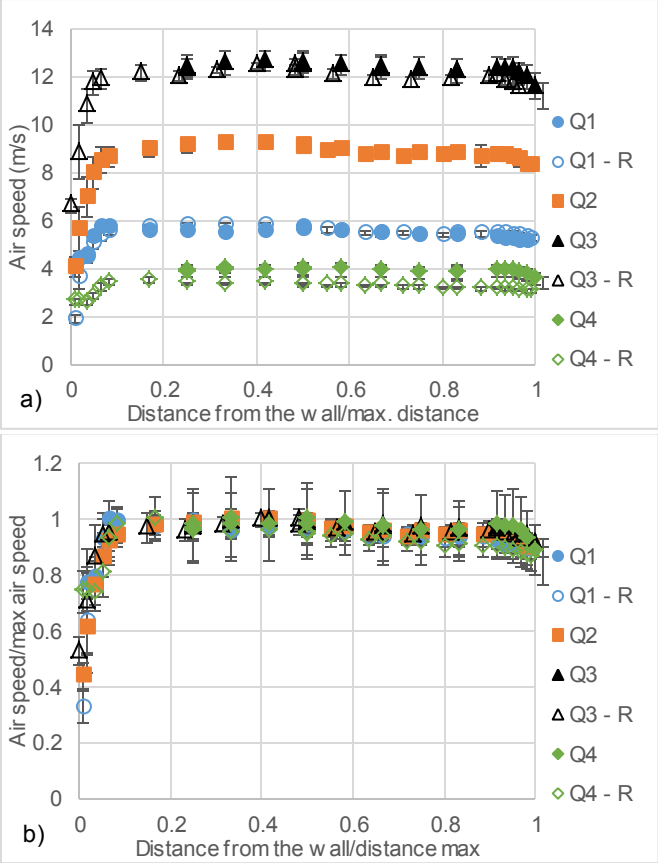

Figure 13. Air speed profiles at different flow rates and their reproduction (a) and nondimensionalized profiles (b)

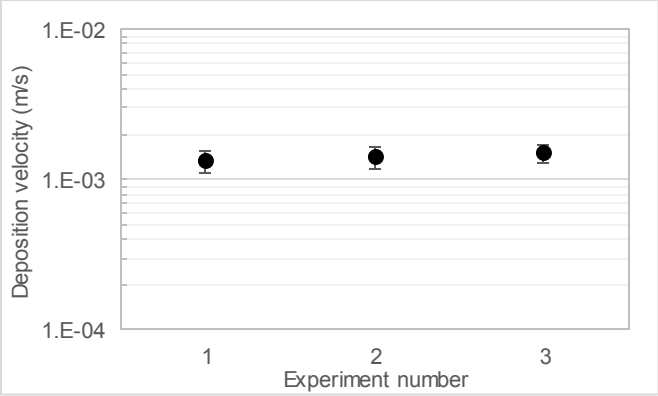

Figure 14. Repeatability of deposition velocities at $5D_h$ after a flow disturbance on duct floor for a 2.7 µm mean MMAD, around 1.4 GSD and air speed around 11 m/s

Validation and outlooks

We apply the calculated uncertainties (Table 2 and Table 4) for the figure presented in this section. It is difficult to compare the results obtained in this study to other experimental studies in the literature, because, on the first hand, the facility used in this study is made of industrial ducts, and thus has industrial surfaces with inhomogeneous roughness. On the other hand, the two studies we compare our work with focus on square galvanized steel ducts (Sippola and Nazaroff's study [11]) and circular stainless steel ducts (Ben Othmane's study [12]), opposed to the rectangular galvanized steel ducts in the test facility (secondary flows appearing in square and rectangular ducts [17–19]). Finally, Sippola and Nazaroff's ducts have D_h = 15.2 cm and Ben Othmane's = 25 cm, which are much smaller than the 48 cm D_h of the test facility ducts. Consequently, the flows are very different from one study to another: turbophoresis deposition mechanism can have a strong influence on deposition, thus showing the importance to have a very detailed measurement protocol. This comparison to two studies allows us to validate the orders of magnitude of the results obtained.

Figure 15 shows the deposition velocities of Sippola and Nazaroff [11], Ben Othmane [12], and this study, for flow velocities from 2 to 12 m/s and, in this study, mean MMADs of 2.70 ± 0.04 µm and 6.30 ± 0.07 µm (i.e. 3 and 6 µm) obtained on floor surface. Sippola and Nazaroff do not specify in their paper if the diameter indicated is a mean MMAD or some other value. Ben Othmane's diameter is the volume equivalent diameter.

The results show close deposition velocities between Sippola and Nazaroff's [11], Ben Othmane's [12] measurements and this study on the floor surface. As the aerosols studied are inertial (mean MMAD higher than 1 µm), the closeness of the different results on the floor surface is consistent as in this case the gravity is the main deposition mechanism.

In all the cases in this study, the results clearly show an increase in deposition velocity with increases in both air speed and particle size. Results are consistent for each flow velocity with an aerosol of 3 µm. For a given speed velocity, doubling particle size in this study's facility induces an increase in deposition velocities by factors from 2.5 to 14.

Deposition velocities increase the most with an increase of air speed for an aerosol of 6 µm from 3.7 to 11 m/s, by factors from 3.7 to 11.

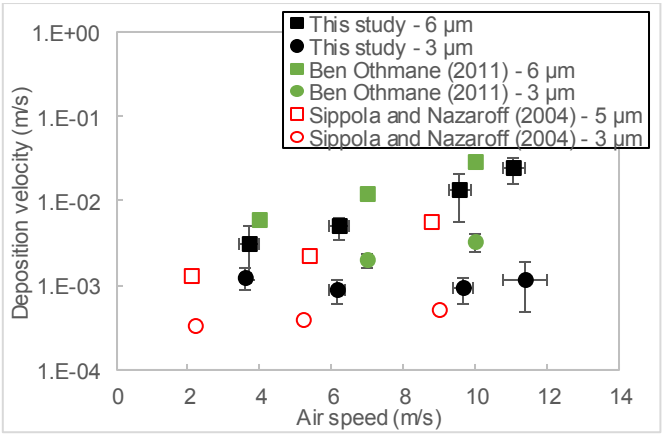

Figure 15. Deposition velocity comparison between this study, [11] and [12] for 2 particle sizes on duct floor

With such a protocol, aerosol deposition can be determined *in situ* on real industrial plants, as it is done for gas tracing for ventilation balancing for example [20]. Indeed, gas tracing provides airflow measurements by injecting helium in industrial ventilation network. In the same way, aerosols could be injected in industrial ventilation ducts by following this method and requirements:

- to have access to the inside of the ducts, through hatches and flanges, for example;
- to stop the network for a few hours for blank measurement and sampling lines installation purposes;
- to switch ventilation on for a few hours for aerosol injection;
- to stop the network a second time after deposition for aerosol deposition collection.

From an aerosol point of view, one would need:

- an aerosol generator;
- magnetic 3D-printed masks adapted to the geometry of the ducts;
- sampling lines.

Conclusion

In this paper, we present the development, validation, and application of an experimental protocol for measuring aerosol deposition on inner surfaces of industrial-sized ventilation ducts with a view to wider application in different ventilation networks. This protocol leads to the determination of aerosol deposition velocity. Fluorescence spectroscopy analysis combined with wiping was chosen as the measurement technique; and the aerosol and injection processes were chosen to be a fluorescent aerosol generated with the most monodisperse size distribution possible and a stable mean MMAD and GSD aerosol generator. This technique provides a local, very sensitive and, especially, non-intrusive measurement of the deposited particles. The last feature has an advantage compared to intrusive techniques regarding the use of the data obtained for the development and use of deposition models. The wiping process was developed and verified to ensure the accuracy and correctness of deposition velocities. Repeatability and validation of the experimental protocol was also checked in an industrial-sized ventilation network.

Compared to other existing protocols for medium-sized ducts, the protocol presented here has the advantage of being easily adaptable to any type of ventilation duct and configuration. With access to the inside of the ducts through hatches, the collection method by wiping can be performed in any case, as 3D-printed masks and stamps can be developed by any operator and their geometries are easily modifiable. Additionally, soda fluorescein does not damage the surfaces of the ducts. Consequently, a method and its requirements were proposed in the previous section to be directly applied in industrial ventilation ducts to measure aerosol deposition.

In other respects, the wiping technique could still be improved. One possibility could be to automate the wiping process to a) save time, as several surfaces could be wiped at the same time and application of the protocol is very time consuming and b) to free up the experimenter during the process. For example, a low-cost automation could be implemented by developing low-cost robots.

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