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Generation of a Controlled Polluted Atmosphere for Vehicles' Cabins Air Quality Characterization

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Abstract: Air pollution induces significant health risks to individuals exposed to high levels of pollutants concentration. For ground vehicles, pollutants infiltrate the car cabin through the ventilation system, leading to potential health issues. To address this problem, a project was undertaken to develop a protocol for characterizing in-cabin air quality. The study involved a closed chamber (the bubble) where its internal multiphase flow has been optimized to create controlled polluted atmospheres. Experiments were conducted to optimize the positioning of the stirring fan and particle generation source, ensuring a homogeneous distribution of fine and ultrafine particles. This study demonstrated the feasibility of implementing a platform dedicated to characterizing the vehicles' in-cabin air quality under controlled conditions. It allows a better understanding of the dynamics of particle infiltration and the establishment of an optimized protocol for simultaneous measurements of indoor and outdoor concentrations.

Key words: Air pollution chamber, vehicle interior air quality, car cabin, particle infiltration.

1. Introduction

Air quality has become a key issue from both a public health and an economic side. Indeed, globally, it is responsible for the premature death of more than 7 million people per year [1] and the cost related to health expenditure and loss of income is estimated at 225 billion dollars per year [2]. The field of transport is often a source of various and varied pollution, which results in the exposure of people on the move. Numerous studies have shown that exposure to pollutants remains high regardless of the mode of transport (car, bicycle, train, or on foot, etc.) [3]. Recent work by Valentino et al. [4] and Silverman et al. [5] has shown that this pollution is the cause of respiratory and cardiac problems increasing the risk of cancer and even the placental barrier is not sufficient to provide a healthy environment.

In the presence of a closed enclosure, typically the passenger compartment of a vehicle, this exposure may, in certain cases, be greater due to the effect of temporary accumulation of pollutants. This is why many studies have characterized the air quality in the passenger compartment [6]. and have shown that certain ventilation parameters or the age of the vehicle greatly influence VIAQ (vehicle interior air quality).

It has been shown that different parameters such as the inter-vehicle distance, the type (recycled or outdoor air) and the ventilation rate influence the process of pollutant infiltration into the passenger cabin [7, 8]. Knowing that in France the average commuting duration by car is 50 min, the inhabitants of the Paris region having a travel time twice longer than for the small urban centers (68 min against 35 min) [9]. It is therefore important to better control the parameters impacting the motion of pollution in the car cabin to improve the VIAQ and limit passenger exposure.

This work aims to generate a polluted and controlled atmosphere where the vehicle will be introduced in

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order to study the different parameters that influence the rate of pollutants infiltration in the passenger compartment.

2. Methodology

2.1 The Vehicle Interior Air Quality Platform

A closed enclosure called the bubble has been imagined, designed and mounted in our laboratory at the transportation engineering college ESTACA (Figs. 1 and 2) with dimensions: L = 6 m of length, W = 3 m width and H = 2 m height, and has been proposed to study the air quality in a car cabin. This bubble is mainly composed of aluminum structure and plexiglass walls as well as rubber seals to ensure the sealing and it can host a wide range of vehicles with different size.

The bubble's platform is an original experimental bench that allows creating a polluted environment in which atmospheric conditions can be controlled in term of concentration levels, temperature, and humidity. We applied seals to ensure a good tightness so that pollutant concentration could be kept constant in order to create a polluted atmosphere. Several types of gaseous and particulate pollutants can be created at different concentration levels. The bubble is composed of two doors located in the front side and a fan is used to

Fig. 1 Final assembly of the measurement platform (the Estaca's bubble).

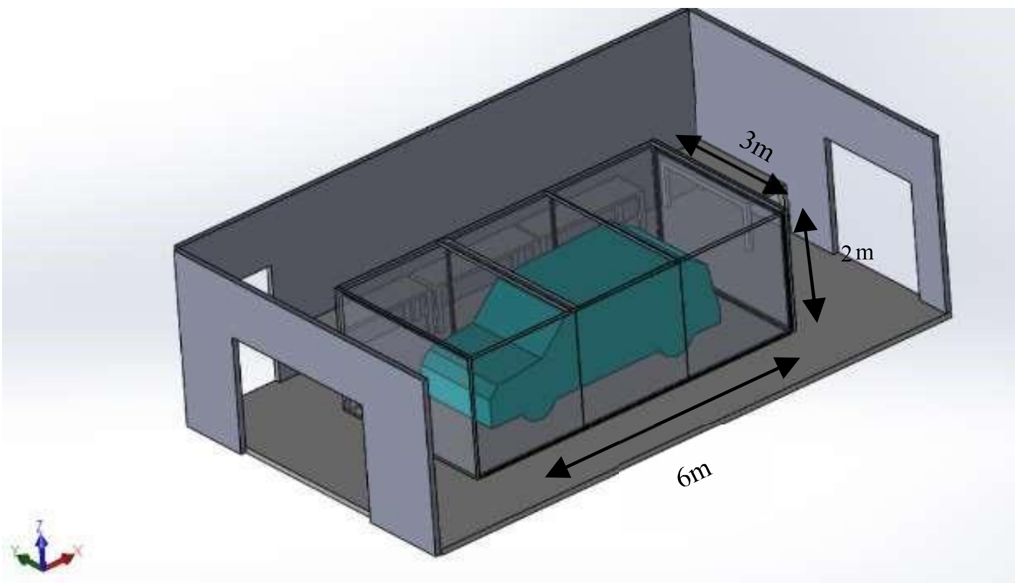

Fig. 2 Representative of the CAD (computer-aided design) of the bubble and measurement room.

Table 1 Measuring instruments.

Name of the instrument	Type of pollutant	Technical characteristics and principles	Representation
TSI Ptrack	Ultrafine particles	• Particle number measurement (optical principle) • Time resolution: 1 s • Concentration value: 0 to 5×10^5 particles/cm^3 • Particle size: 0.02 to 2 µm • Measurement temperature: from 0 to 38 °C • Sampling rate: 100 cc/min	
TSI Dust Trak	fine particles	• Measurement of the mass concentration of particles (mg/m^3) • Time resolution: 1 s • Optical measurement method • Measurement range: 0.001 to 150 mg/m^3 • Particle sizes: 0.1 to 15 µm • Measurement temperature: 0 to 50 °C • Humidity: 0 to 95%	
Grimm MiniWras	Nanoparticles	• Particle size measurement and relative particle concentration • Time resolution: 1 min (for electrical mobility type measurement (ultrafine particles)), and 6 s (for optical type (fine particles)) • Optical measurement technique and electrical mobility • Measurement range: from 10 nm to 35 µm in diameter	
IAQ-CALC™ model 7525	CO_2	• Simultaneously measures CO_2, temperature, humidity, dew point, wet bulb temperature and percentage of outdoor air • Time resolution: 1 s • Measurement range 0 to 5,000 ppm • Acquisition frequency: every 2 min (470 points)	
AGK 2000	Na^+ and Cl^-	• Particle generator powered by nitrogen gas under a pressure of up to 4 bars • Droplet size: 0.01 to 15 µm • Concentration: 10^7 particles/cm^3 • Flow rate: 4 to 12 L/min	

accelerate/homogenize the distribution of pollutants. A fume extractor which is directly linked to the car's exhaust tailpipe, is used when the vehicle's engine is running. This extractor helps to not influence the pollution type and concentration. As temperature inside the bubble needs to be maintained in a constant level when car's engine is on, an air conditioning regulation system is used.

2.2 Instrumentation

As far as the instruments are concerned, they are appropriate for the different types of pollutants most often encountered in the road environment. They varied according to pollutant types, their measurement principles, and characteristics (concentration range, time resolution, etc.). Table 1 summarizes the instrumentation used in this study.

2.2.1 Particle Injection System in the Bubble

The injection system consists of a generator of solid particles: an AGK 2000 (Fig. 3) for fine and ultrafine particle generation. It both needs nitrogen gas, pressure regulator and pipes. Once the whole system is connected, the valve of the nitrogen cylinder is opened so that the nitrogen can pass through the pipes to the particle injector. The particle injector contains a valve which controls the pressure of injection of the aerosol composed of nitrogen and particles. Through this valve we can control the flowrate of the aerosol injected into the bubble. With dedicated instruments positioned in the bubble, we can set the concentration of pollutants inside, allowing us to control the concentration of pollutants with the particle injector pressure valve (Fig. 4).

2.2.2 Exhaust Gas Extraction System

An exhaust gas extraction system (Fig. 5) is used when the vehicle engine is switched on. It consists of a rubber pipe connected to the exhaust tailpipe of the vehicle and a centrifugal pump which sucks up the gases. The extraction system is also connected with the air conditioning system in order to evacuate the hot gases from the air conditioner.

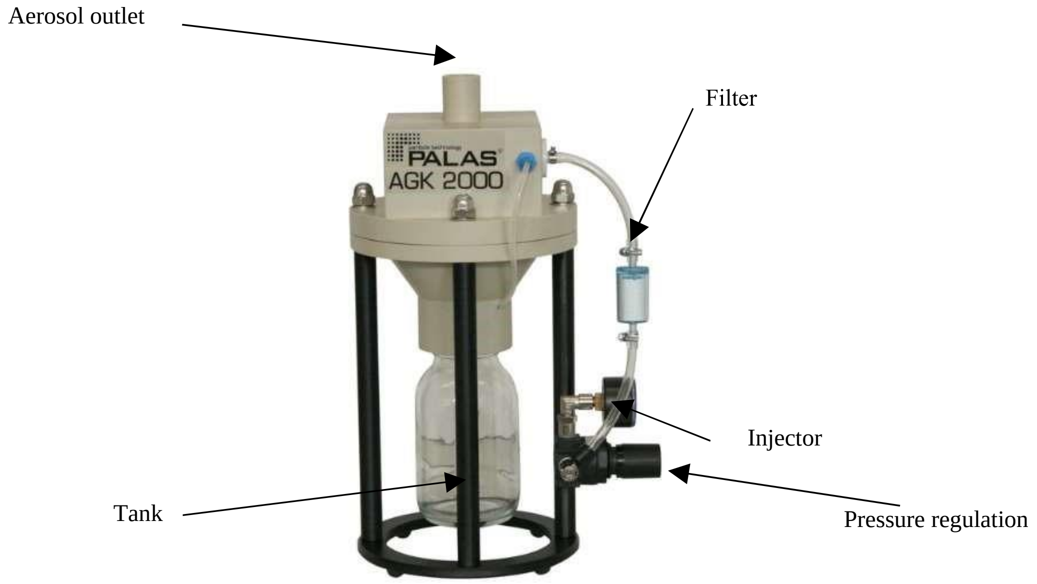

Fig. 3 AGK 2000 particle generator.

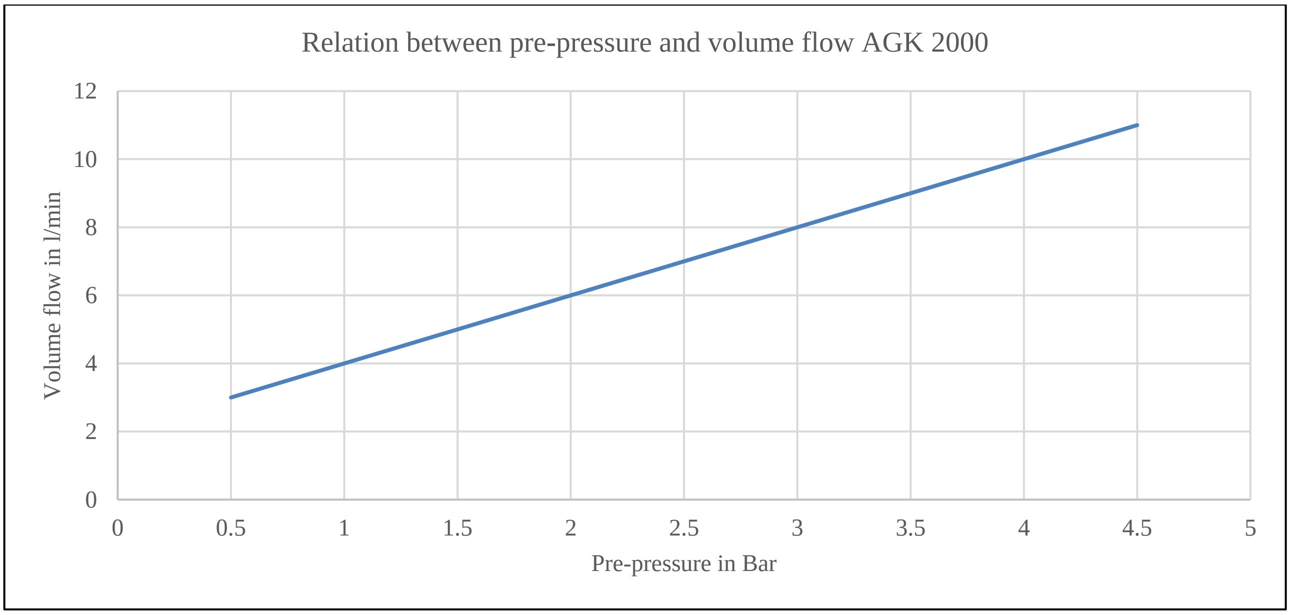

Fig. 4 Variation of the flowrate according to the injection pre-pressure of the AGK 2000.

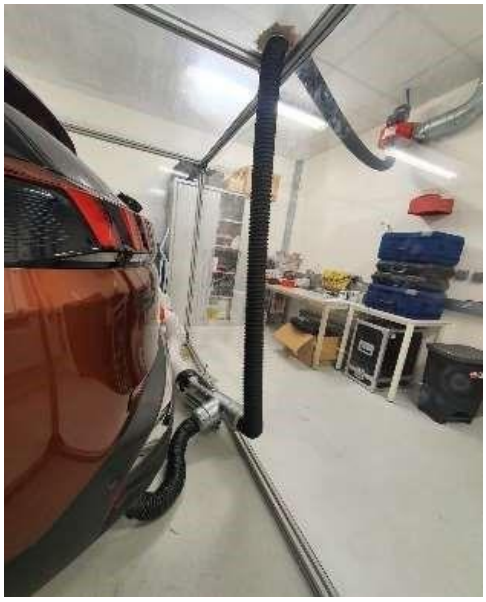

Fig. 5 Gas evacuation system.

3. Results and Discussion

3.1 Background Concentration

The background pollution measurement consists in assessing the concentration of the particles in the bubble without activating the stirring (fan). The value of this concentration is considered as a reference for the beginning of each measurement campaign. The number and mass concentrations of particles were measured.

The measurement of the background pollution is done after the preparation, the zeroing of the measuring instruments and their installation inside the bubble. The instruments used for the measurement of the background noise are the Dust-Trak (for the mass concentration) and the Grimm-Mini-Wras (for the concentration in number). The duration of the background pollution measurement lasts 5 min before the beginning of the measurement campaign.

Tables 2 and 3 represent the concentration of the particles in number/cm^3 and in mass mg/m^3 measured in the empty bubble. We have an initial particle concentration varying between 0.023 mg/m^3 (23 µg/m^3) and 0.029 mg/m^3 (29 µg/m^3), with a total average of 0.025 mg/m^3 (25 µg/m^3). According to WHO data, chronic exposure should not exceed a concentration of 45 µg/m^3 on a daily average for PM_{10} and 15 µg/m^3 for $PM_{2.5}$. Since our bubble is in a closed room most of the time, we assume that the infiltration of pollutants from outside is very low. For the background noise number concentration pollution measurement, we have an initial average concentration of 3,317 particles/cm^3 (calculated from Table 2), a value that will serve as a reference for the rest of the measurements.

3.2 Sealing Test and Particles Dynamics

This test is used to estimate, check, and quantify the potential losses in terms of gas (CO_2) or particle deposition on the walls of the bubble. For the bubble tightness assessment, we injected CO_2 (5,000 ppm) then we followed the time evolution of its concentration using the IAQ-CALC™ model 7525 (Fig. 6). As it is fitted with a polynomial model decrease, the drop coefficient (obtained by smoothing the data) allows us to assess the volumetric exchange coefficient. This coefficient characterizes the tightness of the bubble enclosure. To characterize the particles dynamics, we injected particles in the bubble using the AGK 2000 generator until we obtained a concentration of 120,000 particle/cm^3 (which represents the average concentration of particles in the tunnels). Air quality of tunnels is the most polluted in traffic (influence of road works on the exposure of cyclists to atmospheric pollution Airparif 2008) inside of the bubble. We follow then the evolution of the concentration using the Grimm Mini-Wras. The result is also a polynomial decrease, which is quantified by evaluating this concentration decrease in particles/(cm^3·min).

Fig. 7 represents time evolution of the concentration of CO_2 injected inside the bubble for 15 h. A volume of CO_2 is injected inside the bubble until a concentration of 5,000 ppm is reached and the injection is stopped, then the measurements are launched using IAQ-CALC™ model 7525, the measurement lasts 15 h. The measurement was repeated 2 times. Carbon dioxide is a very volatile gas, it disperses and easily occupies the volume until it reaches equilibrium with the air circulating above.

Table 2 Measurements of background noise concentrations in number/cm^3.

Time (min)	1st measure (particles/cm^3)	2nd measure (particles/cm^3)	3rd measure (particles/cm^3)
0	3,228	3,409	2,126
1	3,328	3,968	2,129
2	3,129	3,191	3,719
3	4,135	3,631	3,720
4	3,129	3,191	3,719

Table 3 Measurements of background noise concentrations in mass/m^3.

Time (min)	1st measure (mg/m^3)	2nd measure (mg/m^3)	3rd measure (mg/m^3)
0	0.029	0.023	0.026
1	0.029	0.023	0.026
2	0.027	0.023	0.025
3	0.027	0.023	0.025
4	0.027	0.023	0.025

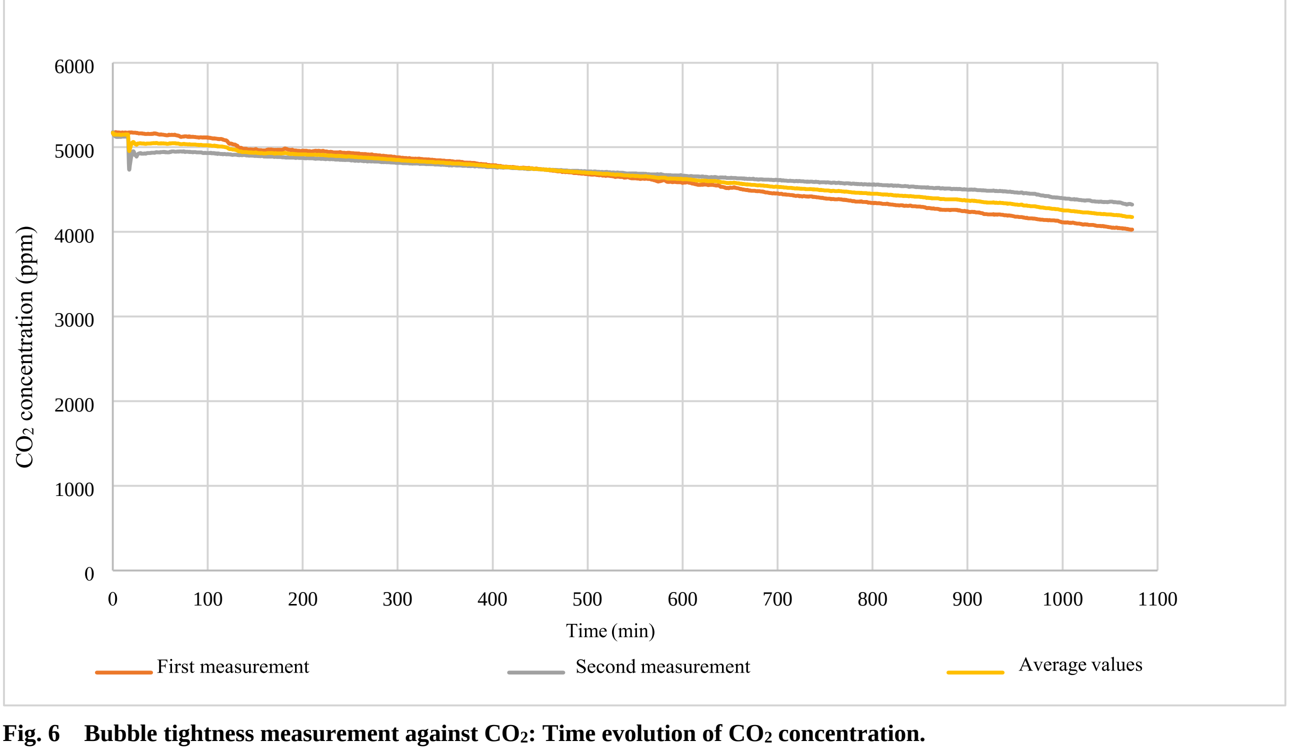

Fig. 6 Bubble tightness measurement against CO_2: Time evolution of CO_2 concentration.

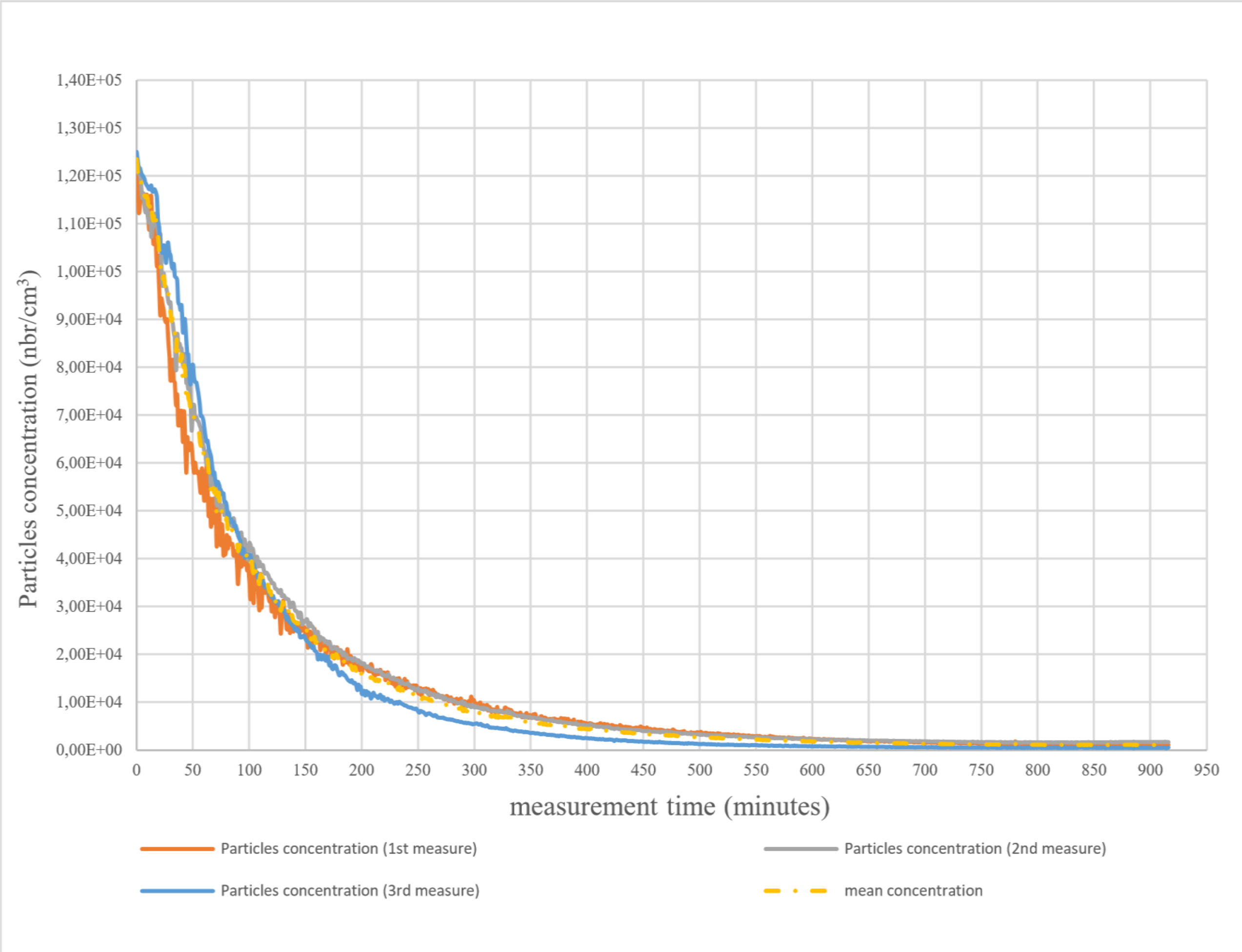

Fig. 7 Particle's dynamics in the bubble.

The only phenomenon responsible for its decrease is exfiltration or exchange by ventilation, hence it is well positioned to use it for airtightness investigation. The drop in CO_2 concentration is quantified for the first measurement of 1.07 ppm/min and the second measurement 0.56 ppm/min. On average, the measuring bubble gas concentration lose is about 0.81 ppm/min which is very weak in comparison to the initial concentration of 5,000 ppm since the total decrease is less than 800 ppm for 15 h.

Fig. 7 represents the time evolution of the concentration of particles in number per cm^3 during the measurement of the tightness of the bubble against the particles, which took 15 h. The process of this measurement is to inject fine and ultrafine particles using the AGK 2000 generator with stirring until reaching a concentration of 120,000 particles/cm^3. Once reaching this concentration, the injection is stopped, we start the measurement with the Grimm-Mini-Wras instrument. We see that the evolution of this concentration is in the form of a decreasing polynomial curve until it reaches the minimum level which corresponds to the level of background noise. This decrease is due to the exfiltration but also to another phenomenon which is the deposition on the walls of the bubble. The deposition can be evidenced because of the formation of fine and white layer on the plexiglass due to the salt particles deposition. The average decrease in particle concentration in number is 420 particles/(cm^3·min).

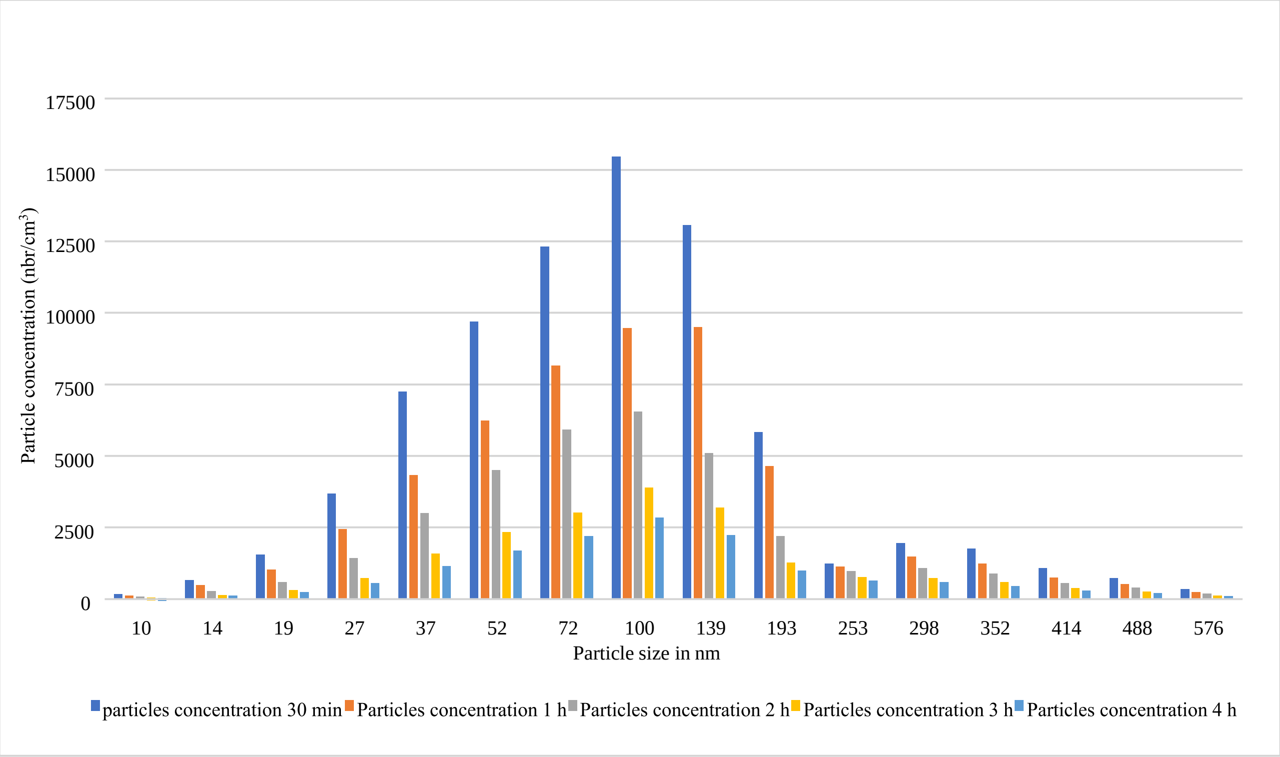

Fig. 8 Time evolution of particles size distribution (first measurement).

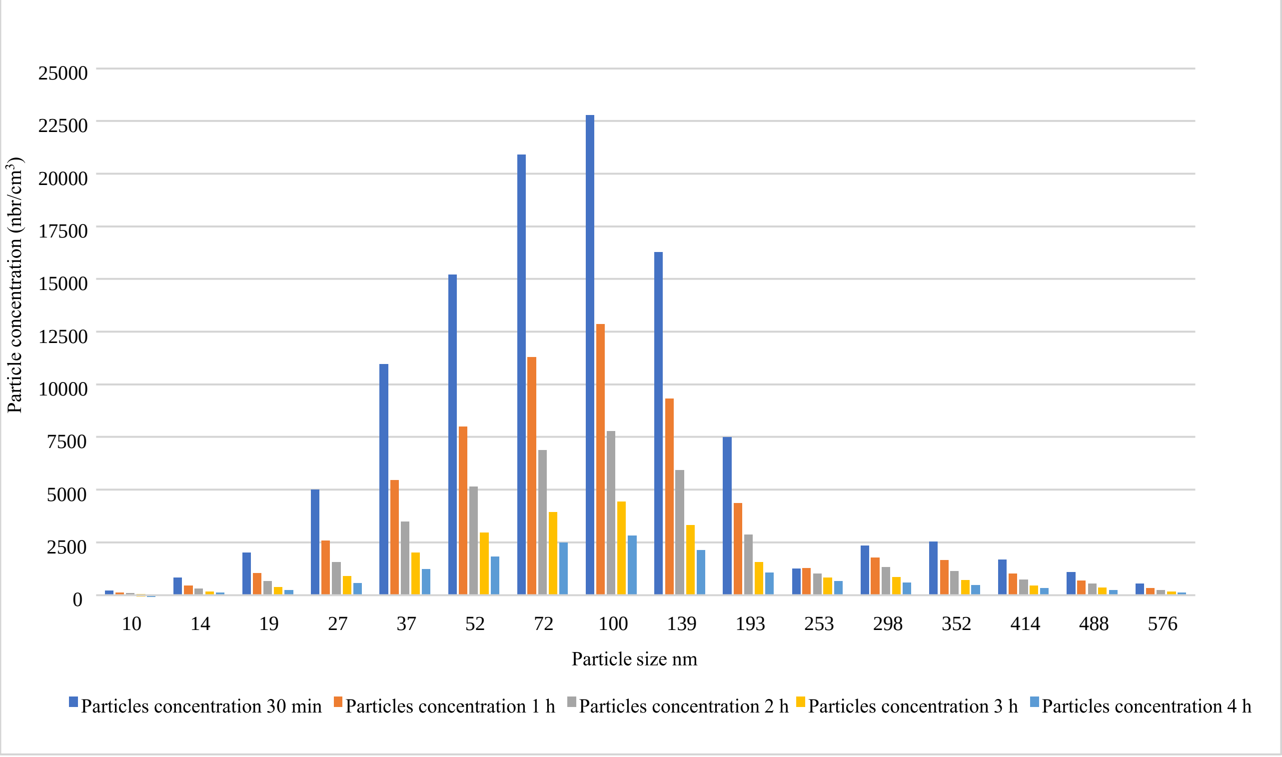

Fig. 9 Time evolution of particles size distribution (second measurement).

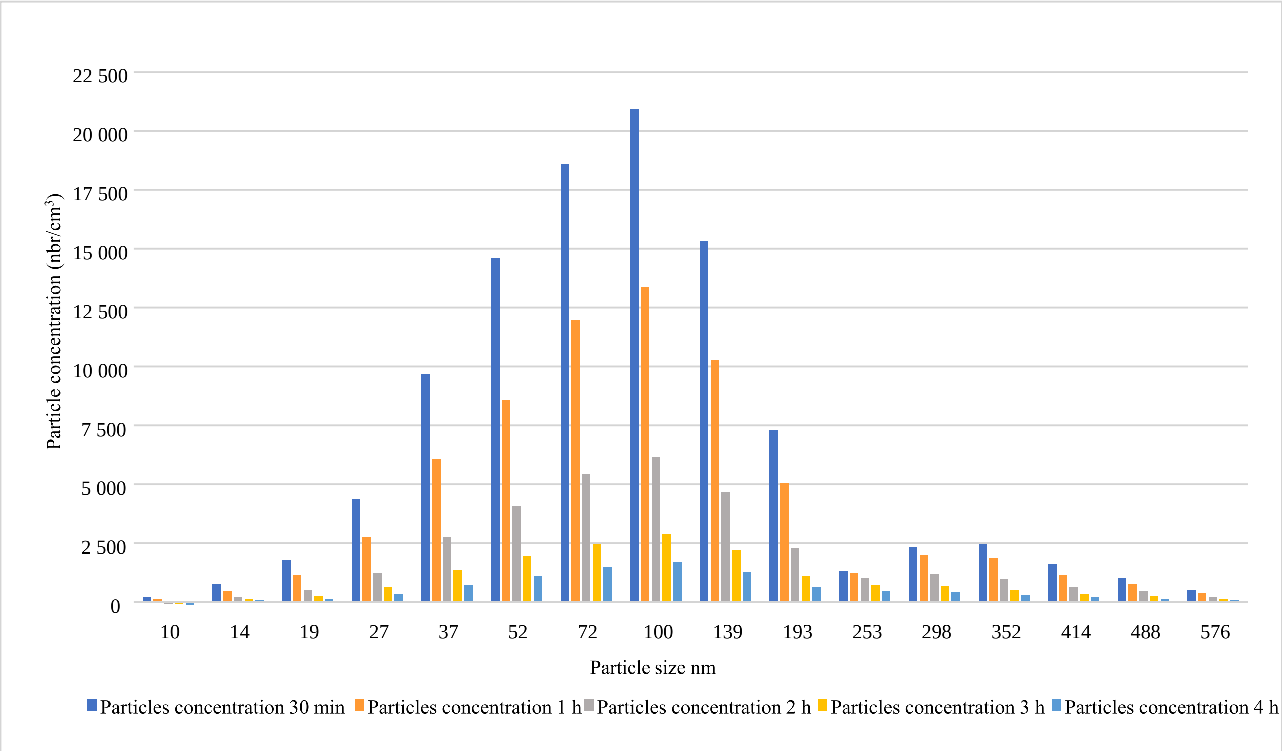

Fig. 10 Time evolution of particles size distribution (third measurement).

Figs. 8-10 represent the time evolution of the particles size distribution injected during the tightness measurement. These measurements are used to understand the dynamics of the particles in the bubble. The concentration drop of particles of size between 37 nm and 139 nm over time is greater than for other particle sizes (e.g. 30% to 40% drop in concentration after 30 min of measurement) mainly due to turbulent and Brownian diffusions. These histograms give us, on one hand, information on the particle size distribution generated by AGK 2000, on the other hand it characterizes the duration for which there is a significant drop in concentration (mostly between 1 h and 2 h of measurement after stopping injection). This kind of information helps to develop protocol for the generation of a constant controlled polluted atmosphere.

3.3 The Homogeneity of Particle Distribution in the Bubble

The purpose of this part of measurement is to study the influence of the injection position and the use of a fan in the bubble to obtain an homogeneous distribution of the particles. We have located 15 points in the bubble; 5 in the right side, 5 in the center and 5 in the left side. These 15 points are positioned along the bubble at mid-height. First, we injected particles through the AGK 2000 to have a concentration of 120,000 particles/cm^3 without using a fan, and we measured the concentration of the particles in the 15 locations (Fig. 11 and 12).

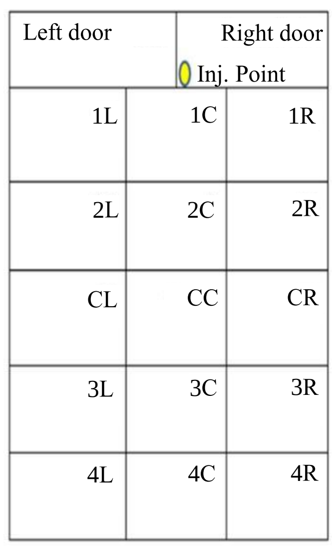

Fig. 11 Homogeneity test measurement positions (top view).

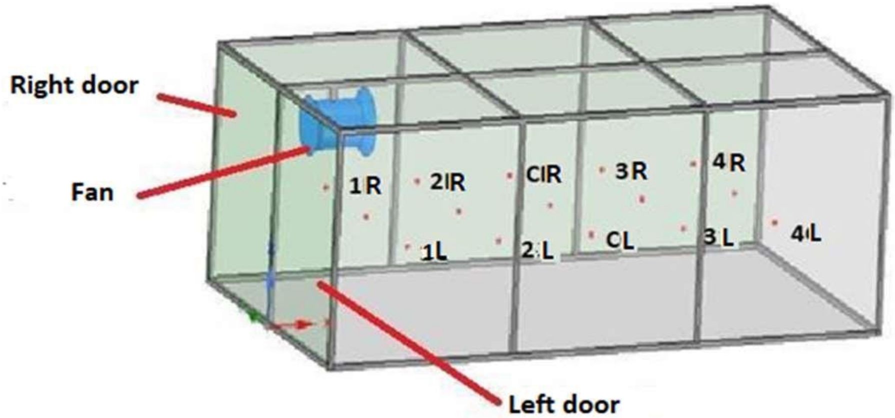

Fig. 12 The measurement's bubble.

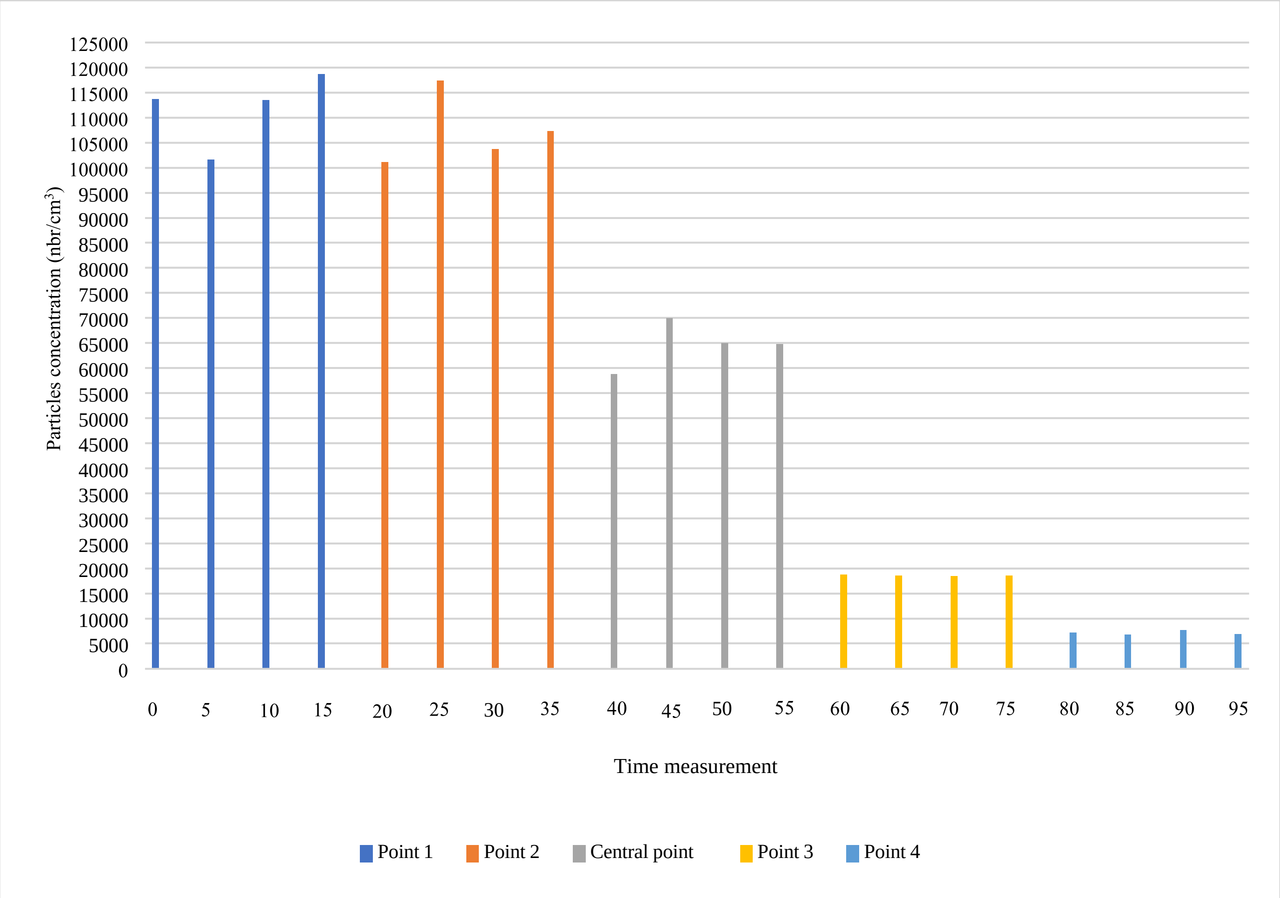

Fig. 13 Distribution of particles in the bubble along the central line (without mixing).

The second measurements achieved with the same procedure but this time we used stirring and we compared the results.

The fan was optimized in term of position and flow rate in order to obtain a good recirculation of the airflow inside the bubble in the presence and without the vehicle. This optimization study was conducted using CFD.

The histograms (Figs. 13-15) represent the number concentration of particles injected into the bubble without activating the ventilation. The distribution of the particles inside the bubble is not at all homogeneous, indeed the particles tend to accumulate in the left sides. We remind that particles are injected in the front of the bubble (next doors) and in the central line. This non-homogeneity in particle distribution is time-independent since the concentration at the same point varies weakly during the measurement duration of 20 min at each point.

When activating the bubble ventilation to stir, we obtain the histograms presented in Figs. 16-18. It also represents the number concentration of particles injected into the bubble. In this case the concentration of the particles is almost homogeneous in all the localized points. And so, mixing is useful to create an homogeneous polluted environment in the bubble for car cabins characterization simulating vehicles in different polluted regions/infrastructures (tunnel…).

3.4 Protocol for Generating an Atmosphere Controlled in Terms of Concentration of Injected Pollutants and Temperature

The objective of the present study is to generate polluted atmosphere in the bubble simulating different environment of pollution that could be encountered by automotive vehicles. One needs to control the injection to stabilize the concentration of the particles generated using the AGK 2000 by controlling the pressure of the nitrogen injected, once having reached a concentration between 110,000 particles/cm^3 and 130,000 particles/cm^3 (which is the concentration rate that we could encounter in situations of traffic congestion in a tunnel) (Fig. 19).

We could see the reproducibility of generating such polluted atmospheres with fine and ultrafine particles with constant concentration levels (Fig. 19).

After the validation of the protocol for generating an atmosphere controlled in terms of pollutants and temperature, the next step will consist of measurements of particle infiltration in the car cabin which is introduced into the bubble beforehand. These infiltration measurements are carried out for different ventilation modes of the in-cabin (recycled mode and non-recycled mode) and with different ventilation rates.

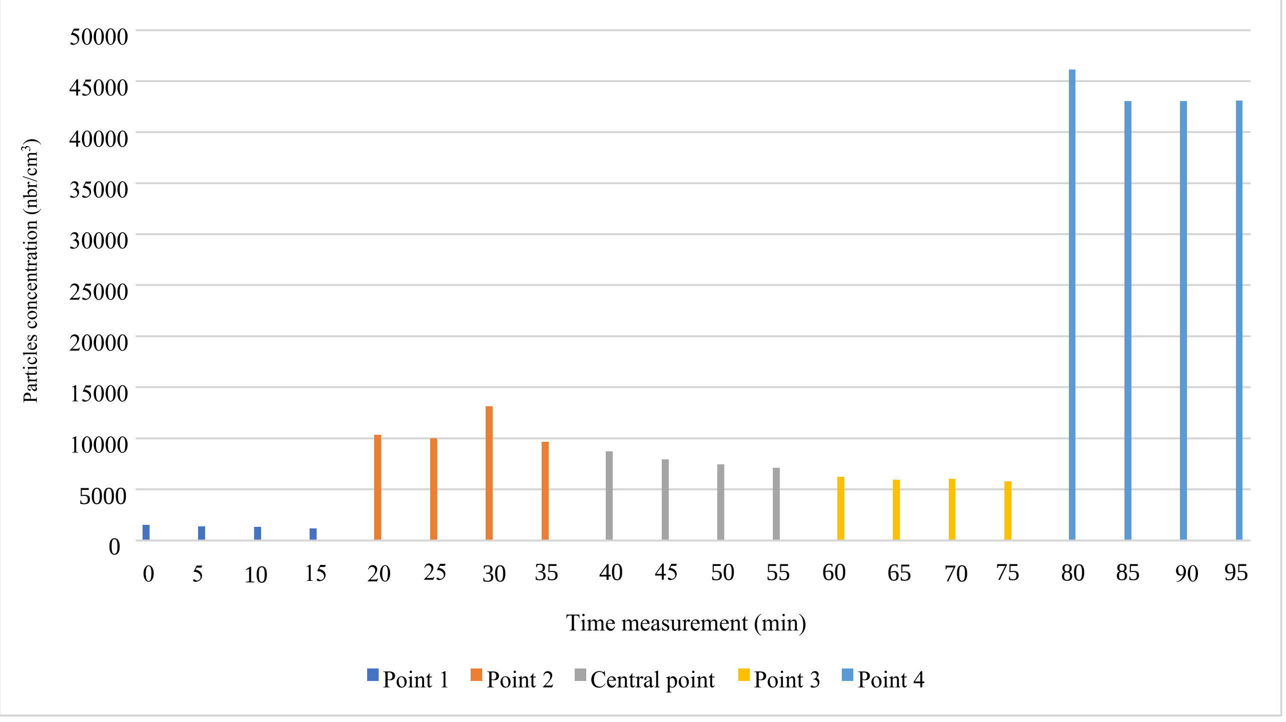

Fig. 14 Distribution of particles in the bubble along the right line (without mixing).

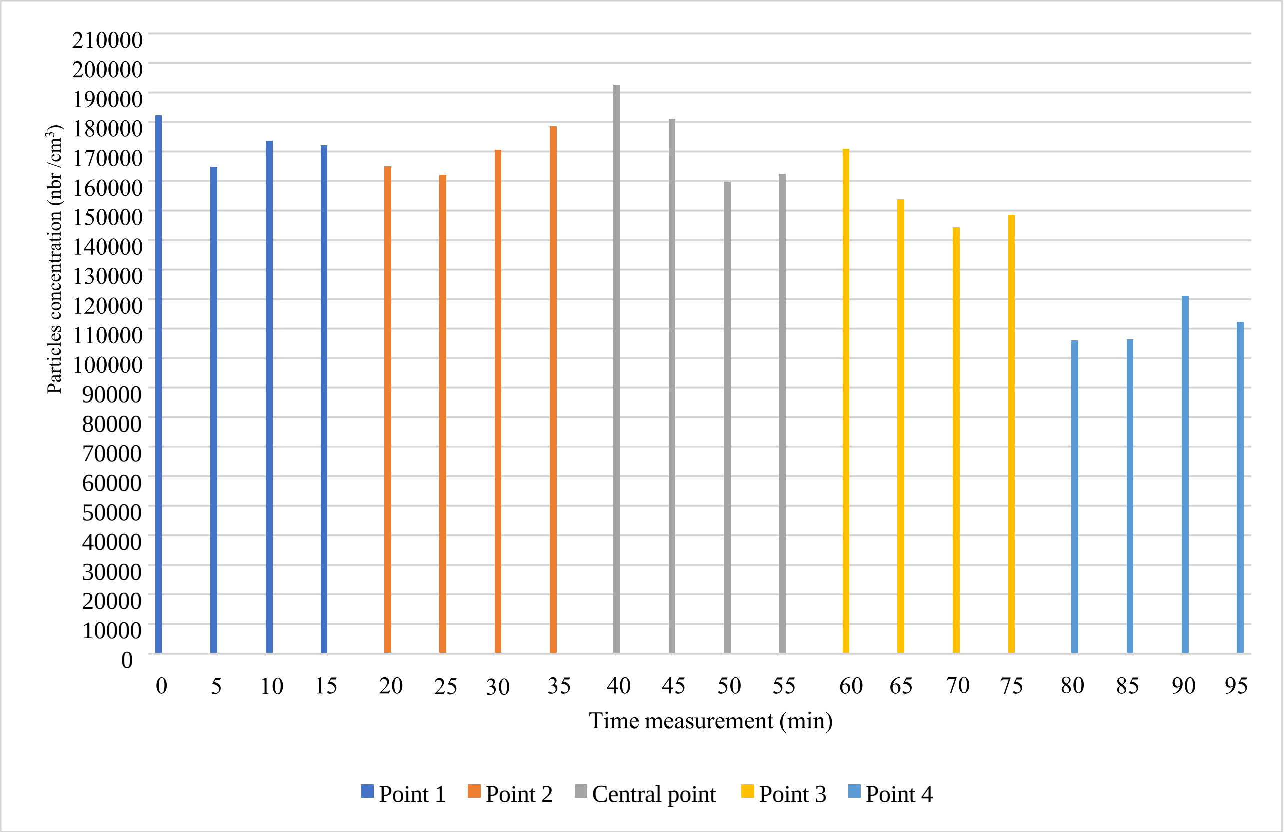

Fig. 15 Distribution of particles in the bubble along the left line (without mixing).

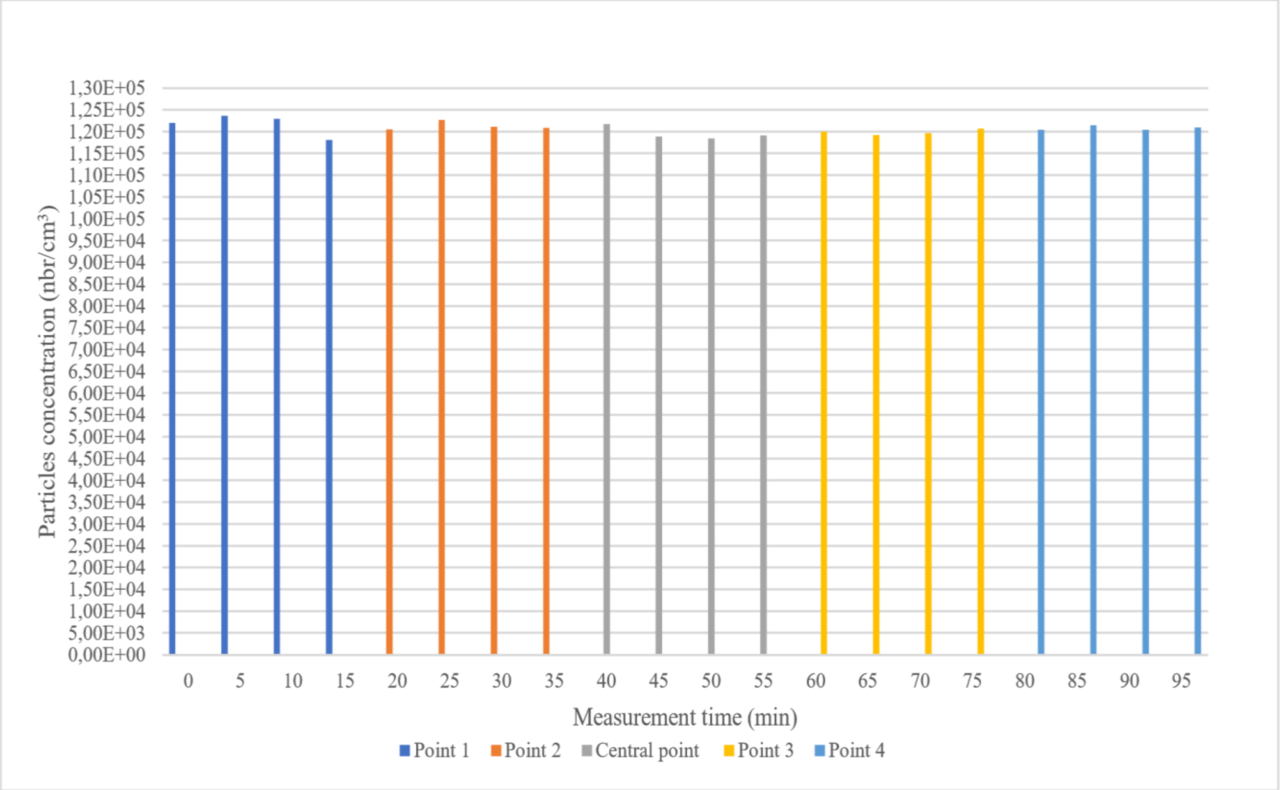

Fig. 16 Distribution of particles in the bubble along the central line (with mixing).

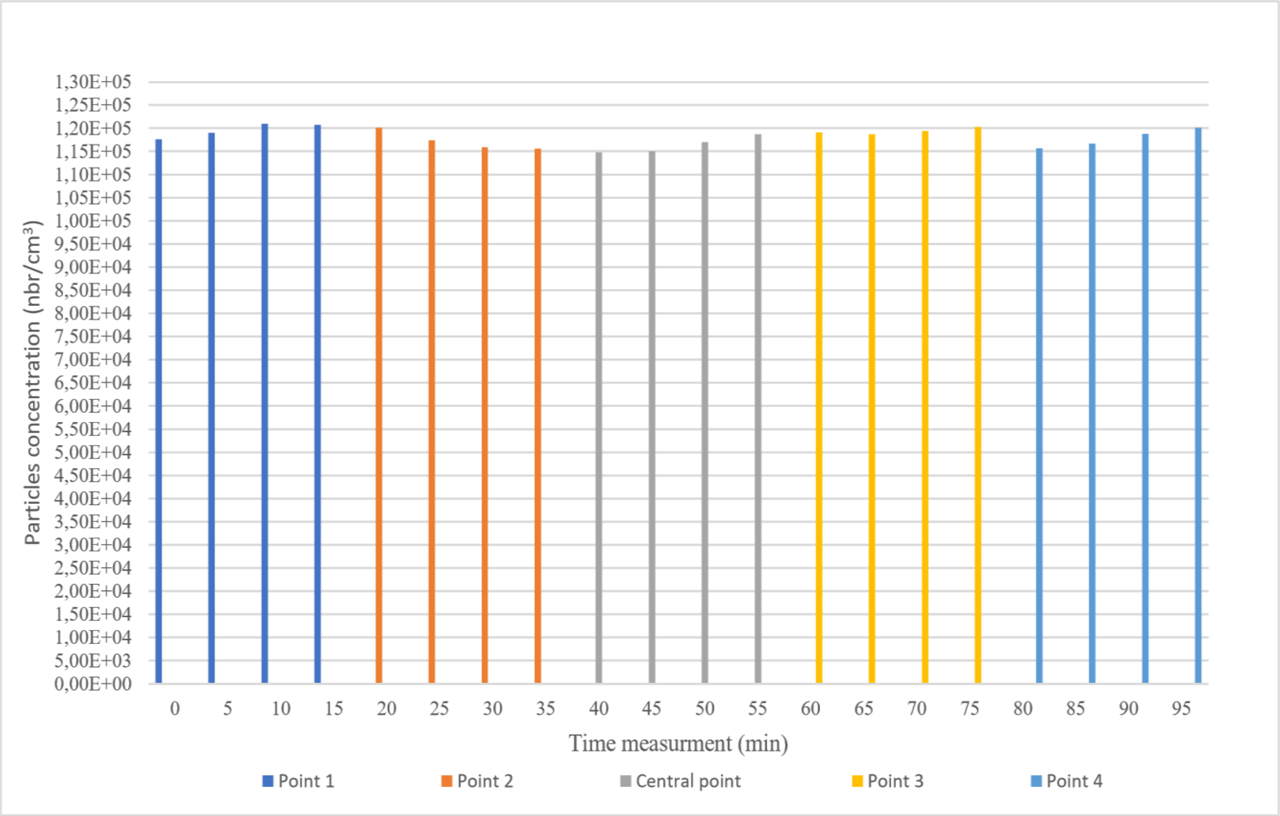

Fig. 17 **Distribution of particles in the bubble along the right line (with mixing).**

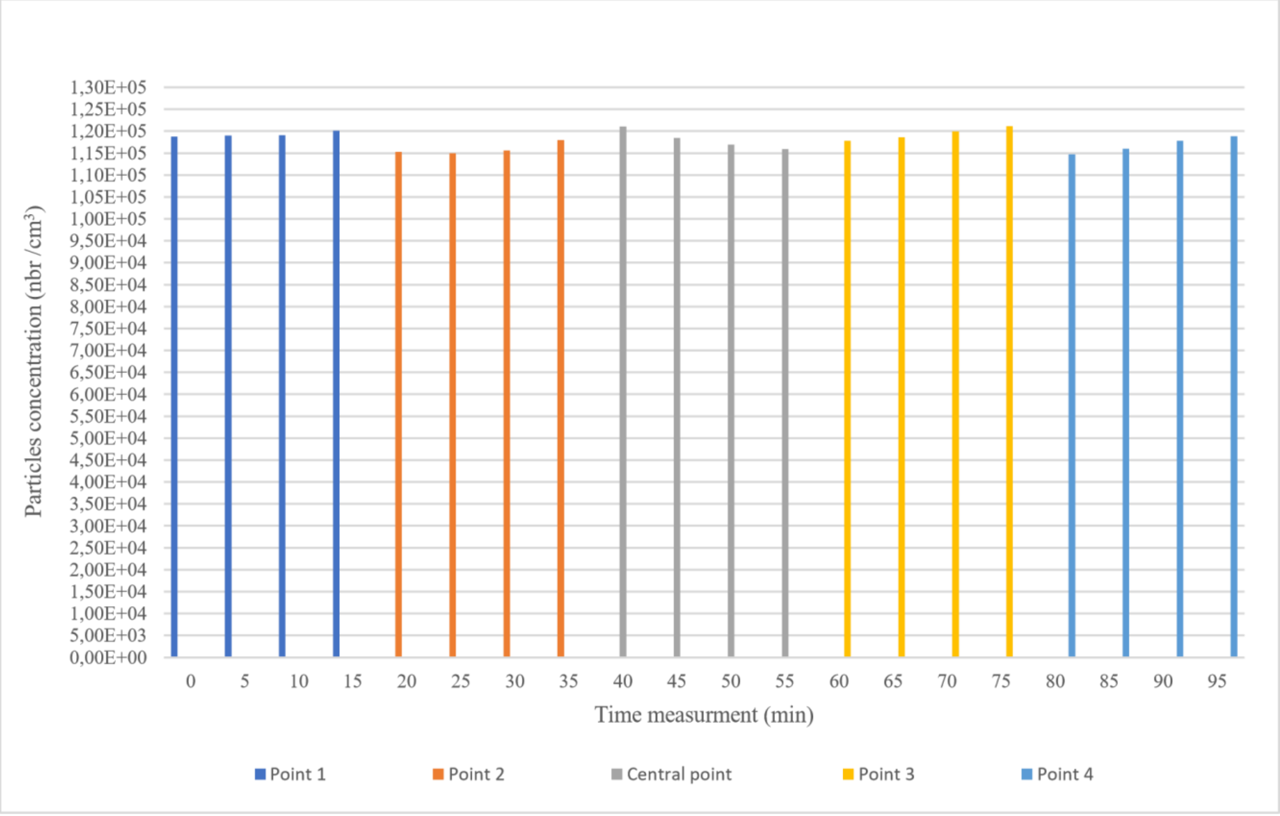

Fig. 18 **Distribution of particles in the bubble along the left line (with mixing).**

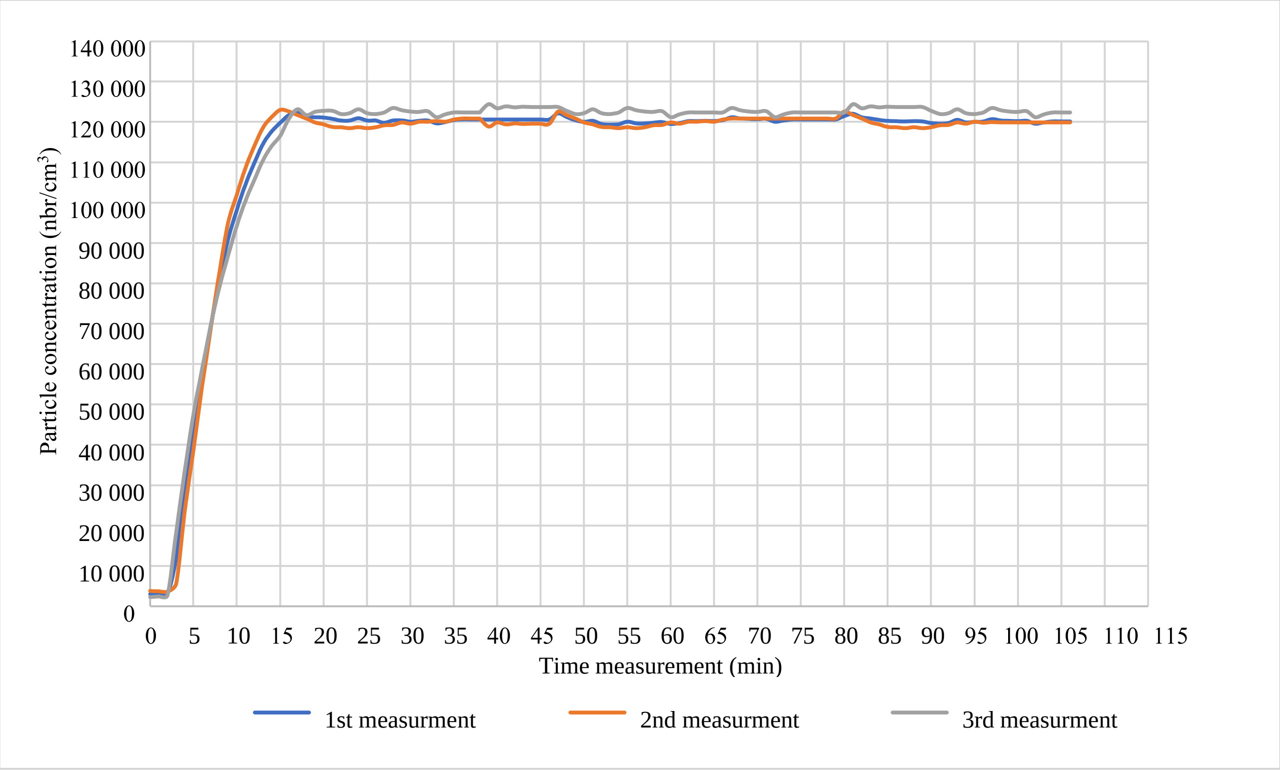

Fig. 19 Time evolution of the concentration of total particles in number in the bubble from the AGK 2000 generator.

4. Conclusion

The present study has focused on an original bench consisting of a closed chamber called the bubble allowing us to generate an atmosphere where we can control the concentration of pollutants injected inside it. We presented the results concerning particles generated using a specific generator (AGK 2000), which injects solid particles of size range from 10 nm up to 15 µm. In order to ensure a homogeneous distribution of the particles inside the bubble, we used an axial fan type positioned at an optimized location in the bubble. It is activated automatically during the injection of the particles. The tightness of the bubble was characterized by several measures: firstly, the tightness against gaseous pollutants was assessed using CO_2. We injected a volume corresponding to a concentration of 5,500 ppm/cm^3 and we quantified the decrease of the concentration for a period of 15 h. Secondly, we investigated the particle dynamics by proceeding to the injection of fine and ultrafine particles until number concentration of 120,000 particles/cm^3 was reached, then we evaluated the decrease of this concentration after 15 h. Finally, we developed a protocol dedicated to the generation of a constant polluted atmosphere without the presence of a vehicle and in the case of the presence of a vehicle in different mode of engine and ventilation settings. The bubble will be intended to conduct measurements of car cabins, it will allow understanding of parameters favoring the infiltration of pollutants but also to develop a protocol for such moving on-road measurements.

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