Design of an air-flow microchamber for microparticles detection

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Abstract A novel device, able to funnel a suspension of micrometric particles in air into a microchamber equipped with a capacitive sensor, has been designed for the detection and characterization of particulate matter (PM) in air. Numerical simulations have been performed to predict the trajectory of the microparticles through the PDMS microchamber where the sensor is located. The feasibility of detecting single PM10 particles has been demonstrated by our experiments, where sequences of single industrial talc particles (average diameter of 8 µm) have been detected and counted by a capacitive sensor. Our results indicate that radical miniaturization of air quality monitors is possible and, therefore, pervasive monitoring of air pollution will be soon feasible.

Keywords: air pollution, atmospheric dust, PM10, microparticles detection

1. Introduction

The effect of pollution on air quality is nowadays a major concern, especially in metropolitan and industrialized areas. Several studies (Gilles, 2001) demonstrated that airborne particulate matter (PM) can be harmful to human health. According to the size, PM can penetrate further into the respiratory system (Matè, 2010): particles smaller than 2.5 µm ($PM_{2.5}$) can reach the bronchioles, while the 2.5-10 µm particles (PM_{10}) are trapped by the cilia from the nose to the bronchi. A few instruments, mainly based on optical detection, are available on the market for monitoring air quality in urban areas and hazardous workplaces (Carminati, 2011). Emerging microelectronic and MEMS technologies could be successfully adopted for designing miniaturized less expensive and bulky devices for personal and pervasive monitoring of single-particles in air. As a proof of concept, we designed a microfluidic device able to capture and deposit fine particulate on top of five differently sized pairs of microelectrodes for the detection and characterization (granulometry) of PM_{10} and

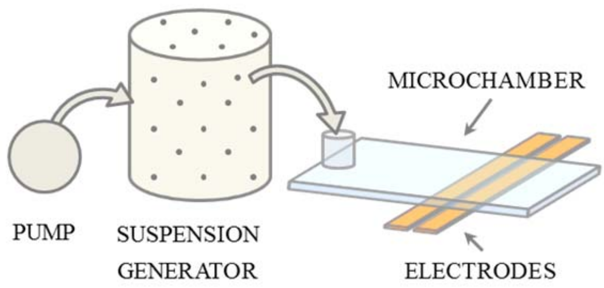

Fig. 1. Sketch of the setup: pump, suspension generator, microchamber and electrodes for impedance measurements.

$PM_{2.5}$ by means of high-sensitivity (aF range) microcapacitance measurements.

2. Design Concept

2.1 System design

The apparatus we devised for the detection and characterization of fine particulate (Fig. 1) consists of a particle suspension generator (of size of a few centimeters) connected to a micro test-chamber (of size of hundreds of microns). Note that the suspension generator plays a crucial role because it is responsible for creating the required particulate suspension and driving the flow into the microchamber. These two tasks can be easily accomplished separately, but are difficult to be coupled together because the same flow has to be optimized to generate the suspension in the macro-chamber and to allow the deposition of particles in the microchamber.

2.2 Settling of particles in suspension

Environmental airborne can be described as a heterogeneous suspension of particles in a gas. In particular, in a gas flow, particles are subjected to external forces such as gravity, buoyancy and centrifugal forces that affect their speed of sedimentation.

For slow gas flows (i.e. Reynolds number $Re = \rho_f\, u\, D/\mu \;< 10^{-3}$, where D is the characteristic dimension of the conduit), the convective forces can be neglected in the Navier-Stokes equation. Therefore, the hydrodynamic force acting on a sphere of radius R settling in a steady Stokes flow is a linear function of the solid-fluid relative velocity u, the size of the particle and the fluid viscosity μ, as follows:

$$F_D = -6\,\pi\,\mu\,R\,u. \tag{1}$$

The associated drag coefficient C_D, obtained by the adimensionalization of F_D, has the form

$$C_D = \frac{F_D}{(^1/_2\,\rho_f\,u^2)(\pi\,R^2)} = \frac{24}{Re}, \tag{2}$$

where ρ_f is the density of the fluid.

For higher Reynolds numbers, the full Navier-Stokes equation should be used. However, in the simple case when the relative velocity of the particle with respect to the fluid is constant and aligned with the gravity and buoyancy forces, the drag force F_D, acting on the particle, exactly balances the sum of the gravity F_G and buoyancy F_B forces as follows:

$$F_D + F_G + F_B = 0. \tag{3}$$

Therefore, for a spherical particle we obtain:

$$F_D = {^4/_3}\,\pi\,R^3\,\Delta\rho\,g, \tag{4}$$

and the associated drag coefficient C_D is:

$$C_D = \frac{8}{3}\,\frac{\Delta\rho\,R\,g}{\rho_f\,u_\infty^2}, \tag{5}$$

where u_∞ is the terminal settling velocity and $\Delta\rho$ is the difference between the density of the particle and the density of the fluid.

2.3 Computational simulations

The analytical expressions for the drag force experienced by a settling particle provide some useful estimates, but are insufficient for accurately describing the flow of the suspension through the microchamber. Therefore, we performed steady-state numerical simulations using a commercial Computational Fluid Dynamics (CFD) software package (ANSYS 15.0) to compute the trajectories of the micrometric particles and gain insights about their distribution and flight time.

A 3D symmetrical model of the microchamber was built using a mixed tetrahedral/hexahedral numerical grid of around 10^6 cells. Flow boundary conditions were imposed at the inlet of the chamber, while atmospheric pressure was set at the outlet. Assuming the problem one-way coupled, because of the micrometric size and mass of the particles, we first solved for the fluid dynamic field. This field was subsequently used to calculate with a Lagrangian method the trajectories of micrometric particles having the same dimensional and compositional properties as the powder used in our experiments. Simulations were considered to have attained convergence when the residuals dropped below the value of 10^{-7}.

Our simulations showed that i) the airborne particles travel along curved trajectories, as the flow bends entering the microchamber and, subsequently, expands in it; ii) the air flow in the micro chamber has a parabolic profile and therefore the particles experience different velocities as they settle toward the bottom of the chamber; iii) the analytical estimates of C_D are only valid for sphere-like shaped particles, an idealized shape far from the innumerable shapes of airborne and dust particles. We leveraged the results of our numerical simulation to design and build a microchamber as described in the next section.

3. Materials and Methods

3.1 Microfabrication

Planar gold electrodes were microfabricated on a glass substrate (forming the bottom of the microchamber) for the detection of particles by electrical impedance measurements. On several Pyrex wafers (525 µm thickness) a resist layer (700 nm) was deposited, UV patterned by means of a Chrome mask (5" Nanofilm SLM 5) and developed. The electrodes were obtained by depositing a 100 nm gold layer on a 20 nm titanium adhesive layer and finalized in a lift-off bath. The PDMS (Sylgard184 DowCorning) top part of the micro chamber was fabricated by established soft lithographic process.

3.2 Experimental setup

The microfluidic device consists of a 10 mm wide, 200 µm high and 15 mm long PDMS micro-chamber mounted on the glass surface, in correspondence to the electrodes. The interdigitated electrodes are placed at the end of the chamber, on the opposite side of the sample inlet, and oriented orthogonally to the direction of flow. A pressure driven air flow (0.45 l/min, generated by a compressor), seeded with micrometric particles, is injected perpendicularly into the chamber through a nozzle-shaped inlet tubing (Fig. 1). The cross section of the chamber perpendicularly to the flow is uniform and the same as that of the outlet (10 mm × 200 µm). As a substitute for airborne PM_{10}, a microtalc powder (Mondo Minerals BV, Amsterdam, ε_r ~2.4) was selected because its particles are characterized by a scale shape and more than 80% in weight showed a characteristic size between 1 µm and 15 µm, with an average of 8 µm.

3.3 Measurements procedure

The loading process relies on the extraction of

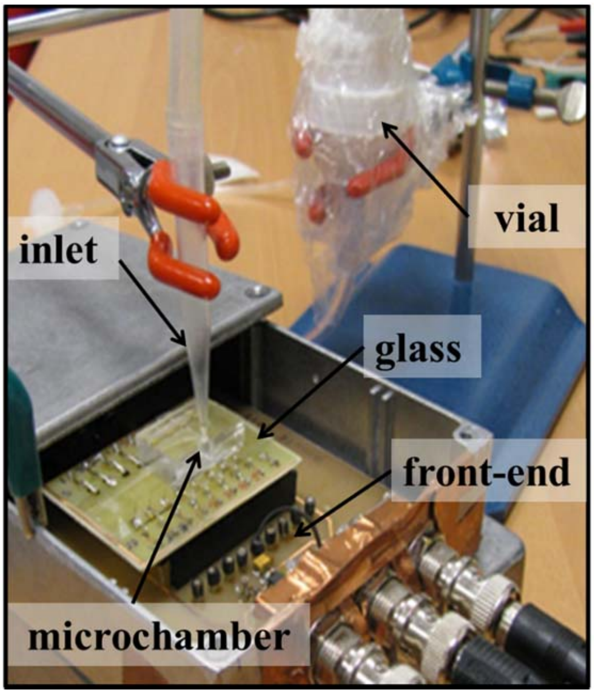

Fig. 2. Picture of the apparatus used in the experiments. It is composed by a vial, a nozzle-shaped inlet, a PDMS micro-chamber, a glass substrate with the electrodes plugged in a low-noise analog front-end.

a small fraction of the suspension created by forcing pure air (HEPA filter 0.2 µm) in a vial containing the selected powder sample. The small fraction of powder suspended in air is then injected perpendicularly into the micro chamber where the fluid dynamic field induces the dispersion of particles into a low density monolayer on the glass surface. Due to the micrometric dimension of the sensitive regions, comparable to the particle sizes, the presence of even a single particle laying on one of these areas produces a capacitance variation that can be clearly detected. This capacitance variation between the planar microelectrodes is measured by applying a sinusoidal signal to one electrode and sensing the current flowing through the mating electrode. The current is then amplified by a custom-designed low-noise front-end and synchronously demodulated by a lock-in amplifier. In optimized operating conditions (1 V applied in the MHz range), the noise floor of the detection system is about 2 aF. Finite element simulations (COMSOL 4.3b) and preliminary static tests with polystyrene microbeads (ε_r ~2.6) demonstrated that the expected capacitance increase due to the deposition of a single PM_{10} spherical particle between a pair of electrodes is of about 25 aF. Thus, the deposition of single particles can be recorded in real-time with an adjustable temporal resolution (from ms to seconds) with a proper signal-to-noise ratio. Experiments were performed by operating the compressor in two different working modes: a continuous and pulsed flow. In the first case the pump was operated for a fixed amount of time of 5, 10 or 30 s, while in the pulsed mode the pump was operated for around 3 s and then switched off. Variations of voltage induced by the deposition of particles on the gap between pairs of electrodes were recorded. Images of the glass bottom of the microchamber were taken with a microscope to visualize the particle distribution within the microchamber.

4. Results and Discussion

Figure 2 shows the configuration of the apparatus designed and used for single particle detection. We tested our apparatus both in continuous and pulsed operating conditions. The results obtained in the continuous case agree with the steady-state CFD simulations (Fig. 3) and show that sedimentation hardly occurs within the microchamber at the high velocities induced by the suspension generator at regime. Smaller particles follow more closely the streamlines than larger particles but, in general, they all flow over the electrodes and out of the microchamber.

As an alternative to the continuous, the pulsed operating conditions have been obtained by switching on and off in time the suspension generator, in order to take advantage of the transient flow generated between the start of the pump and the establishment of the steady-state flow condition. In this operating condition, the creation of the suspension and the deposition of the particles on the electrodes occur both in the first instants of operation of the pump, during the “on” part of the cycle. Operating in the pulsed condition, our apparatus allowed a successful extraction of a particle fraction, suitable for obtaining a

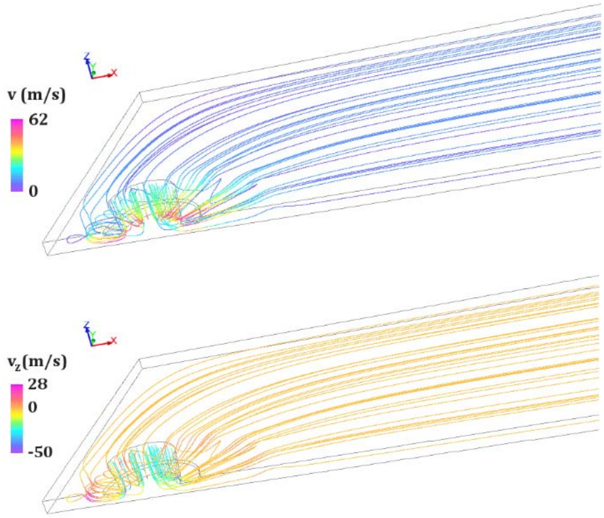

Fig. 3. CFD steady-state simulation of the trajectories of micrometric particles injected through the inlet of the microchamber. The trajectories are colored as a function of the magnitude of their velocity (top) and z-velocity component of it (bottom). Only half of the domain is shown.

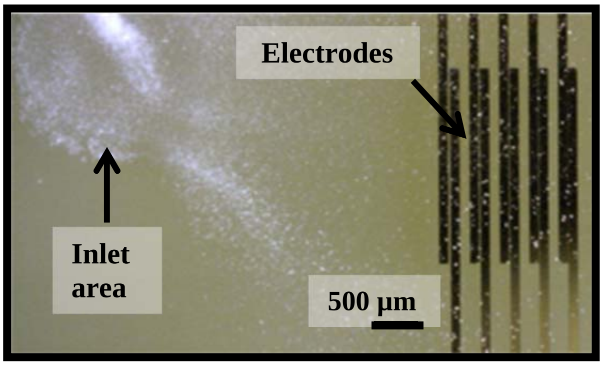

Fig. 4. Picture of the monolayer of micro-particles deposited on the glass substrate hosting the electrodes.

proper dispersed monolayer of particles on the bottom glass surface of the microchamber and, therefore, over the five pairs of straight parallel electrodes (3 mm-long spaced by minimum 4 µm).

Our experiments showed that the deposited monolayer is not homogeneously distributed along the bottom of the chamber: higher surface density can be found in the proximity of the inlet (Fig. 4), gradually decreasing towards the outlet. Therefore, the distance of the electrodes from the inlet is a critical parameter for obtaining a satisfactory deposition of particles over the 4 µm gap

(minimum) separating the electrodes and to perform single particle detection (Fig. 4).
Our experiments also showed (Fig. 5) that in a 2 mm × 2 mm region (over the band electrodes) the particles density - lower than in the inlet area - is sufficiently homogenous. Therefore, we are currently designing a serpentine shaped sensor, formed by arrays of interdigitated electrodes, to create a larger (few mm^2) sensitive area with an aspect ratio closer to one.

5. Conclusion

Since the impact of airborne particulate matter on the air quality and human health is becoming a major concern, we designed, with the insight of numerical simulations, a microfluidic device able to detect and count single micro particles. We tested the performance of our (proof of concept) device using commercial talc powder, as powder sample. Our experimental results showed that a repeatable deposition of a monolayer of particles over five pairs of straight parallel electrodes (3 mm-long spaced by minimum 4 µm) can only be obtained by operating in pulsed conditions our current suspension generator. Continuous operating conditions could be achieved only by simultaneously optimizing the flow in the suspension generator and in the microchamber. This will orient the design of a portable instrument towards pulsed pump operation. Real-time capacitance measurements performed during the deposition of a low density monolayer of particles showed the ability of our device to detect and count the deposition of single talc particles proving that the characterization of PM_{10} can be potentially achieved.
Future work will be aimed at characterizing PM_{10}, and possibly finer particulate, by adapting the current apparatus to sample and characterize environmental air containing real airborne particulate matter. The ultimate purpose of our work is to design and prototype a low cost miniaturized device for pervasive monitoring of environmental air pollution.

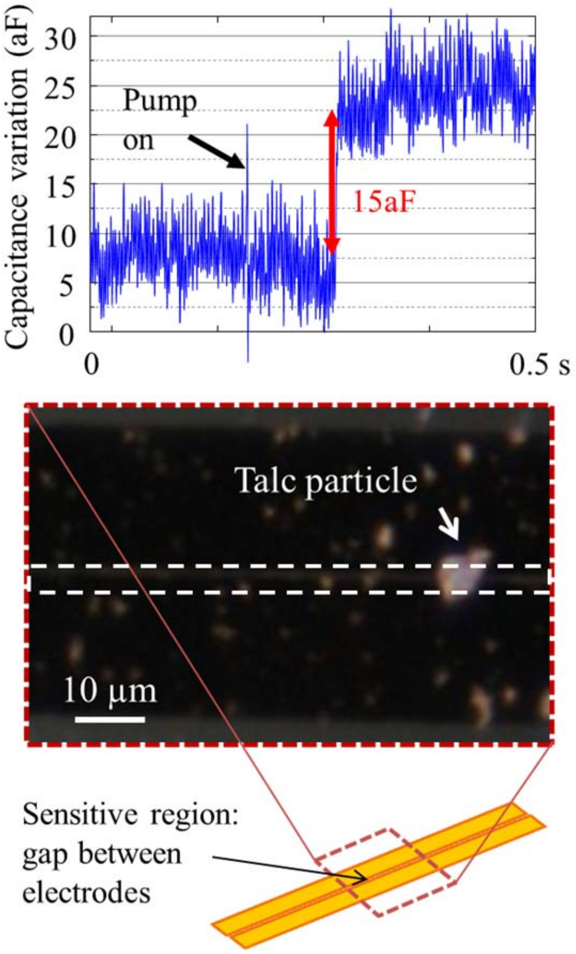

Fig. 5 (a) Real-time capacitance measurement showing the detection of a ~8 µm talc micro-particle on a 4 µm gap, producing a 15 aF increase; (b) Picture of a talc particle deposited on the sensitive region between a pair of electrodes.

6. Acknowledgments

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7. References

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