Deposition characteristics of bioaerosols by inertial impaction

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DEPOSITION CHARACTERISTICS OF BIOAEROSOLS BY INERTIAL IMPACTION

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TITLE

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ABSTRACT

The objective of this study is to elaborate a micro sampling method that can possibly be combined with inertial mass sensors such as silicon-based MEMS. In this context, a multiple round nozzle single-stage bio-impactor has been designed, fabricated, and characterized based on classical impactor design criteria. The latter, various type and size of bioaerosols and aerosol test particles have been impacted on silicon (smooth) and nanostructured silicon surfaces in order to investigate the deposition characteristics. The empirical results show that the size of airborne particles determines the deposition characteristic by the mechanism of rebound and re-entrainment (i.e. bounce effect). The local collection efficiency in the primary impaction zone has been estimated. Furthermore, nanostructured silicon surface has enabled to reduce the bouncing effect of micron size particles due to its sharp pillars by breaking the particles into fragments, which result in a confined deposition pattern under the nozzle. This localized pattern can be easily aligned with the micro sensor. Therefore, this study envisages that nanostructured silicon-based inertial MEMS mass sensors are favorable for the detection of micron size particles.

KEYWORDS: Bioaerosols, deposition characteristics, Real-time detection, Microbalance, Microelectromechanical systems (MEMS)

1. INTRODUCTION

Over the last decades, exposure to airborne biological particles such as pollen, viruses, bacteria, and fungal spores has been one of the main concerns due to their adverse health effects on human being. Nowadays, clear evidence for bioaerosols exposure-related health issues have been widely recognized and the exposures have been associated with contagious infectious diseases, acute toxic effects, allergies, and cancer (Douwes, Thorne, Pearce, & Heederik, 2003) (Fiegel, Clarke, & Edwards, 2006) (Bush & Portnoy, 2001) (Lindsley et al., 2010). However, lack of quantitative bioaerosol exposure assessment methods leads difficulties to define exposure limits. For accurate quantitative characterization of the particles, bioaerosol sampling methods should be accompanied by a real-time detection method that would enable rapid mass concentration measurements.

Collection of the reliable and representative amount of bioaerosols has been realized by traditional aerosol sampling methods, including gravitational sedimentation, inertial impaction, centrifugation, electrostatic precipitation, and filtration. The latter, detection techniques such as polymerase chain reaction (PCR) (Pyankov et al., 2007), enzyme-linked immunosorbent assay (ELISA) (Speight, Hallis, Bennett, & Benbough, 1997), traditional colony counting (Han et al., 2018), optics or spectroscopy (e.g. Fluorescence, Raman) (Jonsson, Olofsson, & Tjärnhage, 2014) have been used for qualitative and quantitative analysis of the collected bioaerosols. Most of the efforts have been recently given to real-time fluorescence-based optical systems either using microfluidic approaches (Choi, Kang, & Jung, 2015) or integrating it with a sampling method (Choi, Kang, Hong, Bae, & Jung, 2017). Although some of the proposed systems achieved real-time detection, none of them have demonstrated a miniature, integrable, low-cost, and real-time mass concentration measurement system. As discussed earlier, the integration of silicon-based high-performance inertial MEMS mass sensors to a micro sampling method can pave the way for the reliable real-time mass concentration measurements of airborne particles (Soysal et al., 2017). But, small active surface area (1 mm^2) of MEMS should be applicable to the size and shape of the deposition patterns. There have been only a few studies discussing the underlying mechanism for the deposit shapes, but it hasn't been achieved a consensus. Usually, the halo-shaped, ring-shaped or only primary deposits (underneath the nozzle) have been observed in the impaction studies. This study presents a lab-made multiple nozzle bio-impactor based on classical impactor design criteria and investigates the deposition characteristics by impaction on smooth silicon and nanostructured silicon surfaces.

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2. ELABORATION OF A LAB-MADE BIO-IMPACTOR

A single stage multiple nozzle inertial bio-impactor has been designed and elaborated. The bio-impactor consists of a probe connection where the impactor have attached to the homogenization sphere to extract particles from the controlled ambient, nozzle plate where 10 round nozzles each of 500 µm diameter located circularly, micro impaction chamber where is partially vacuumed during the operation and exhibit a 500 µm separation between the nozzles and silicon/black silicon samples which are located on the impaction plate. This lab-made single-stage impactor exhibits the calculated cut-off diameter of 0.39 µm and experimental cut-off diameter of ~ 0.8 µm while Reynolds (Re) number has been kept below 3000 that maintains a laminar flow. The operating flow rate is 10 LPM, therefore each nozzle delivers 1 LPM to each sample. Thereby, 10 nozzles are meant to be aligned with 10 individual silicon/nanostructured silicon samples. On the other hand, the major issue in inertial impactors is the bouncing particles off the impaction plate. To overcome this issue, silicon surface has been nanostructured thanks to microfabrication methods which are adaptable to development of MEMS mass sensors unlike the common practices such as using of sticky materials like oil/grease.

Following that, various sizes of monodispersed ($\sigma_g < 1.2$) particles are generated between 0.9 µm to 4 µm mean median aerodynamic diameter (MMAD) of fluorescence test particles by using vibrating orifice aerosol generator (VOAG), Aspergillus niger spores with MMAD of (3.04 ± 0.05)µm by dry generation, Staphylococcus epidermidis, and Pseudomonas fluorescens with MMAD of (0.70 ± 0.02)µm, and (0.66 ± 0.01)µm, respectively by Collison nebulizer method. These particles have been impacted on silicon (smooth surface) and nanostructured silicon (black silicon) as impaction plates of the bio-impactor.

3. RESULTS AND CONCLUSION

Although the properties of the biological and non-biological test particles used in this study are different, their deposition characteristics show similarities and the deposition patterns correlated with the size of each type of particles. The results show that the halo-shaped, ring-shaped or only primary deposits (underneath the nozzle) have been observed. A halo type pattern consists of a primary deposit in the center that is surrounded by a secondary deposit. A ring-shaped pattern forms a particle-free area underneath the nozzles, thus the deposit encloses this area.

This study shows that the collection efficiency of the primary impaction zone is the particle of size-dependent due to the bounce effect. In the case of smooth silicon impaction surface, the local collection efficiency at the primary impaction zone was estimated as low as three times as that of the global efficiency for the sub-µm particles. This local collection efficiency at the primary impaction zone has been found to be less than 1% for the impaction of particles of MMAD>1µm size.

In the present study, the black silicon surface has been used as an impaction plate to overcome the bounce effect by its surface properties. It has not significantly changed the deposition characteristics of sub-µm particles. However, preliminary experiments have shown that the black silicon enables to reduce the bounce effect of particles of MMAD>1µm size and provide a confined circular deposition spot by breaking these particles into fragments. This study suggests that nanostructured inertial MEMS mass sensors can be favorable for the detection of micron size particles.

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