ADVANCES IN A DEVELOPED SURFACE ACOUSTIC WAVE BASED PARTICULATE MATTER 2.5 MONITOR

Wen-chang HAO[1], Zhong NIE[2], Jiu-ling LIU[1,*], Ming-hua LIU[1], Shi-tang HE[1]

[1]Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China
[2]University of Science and Technology Beijing, Beijing 100083, China
[*]Corresponding author, E-mail: liujiuling@mail.ioa.ac.cn; Tel.: 86-010-82547805.

This paper presented a surface acoustic wave (SAW) based particulate matter (PM) 2.5 monitor, which consisted of a SAW dual-resonator oscillator, a thermophoresis unit and a virtual impactor. The structure optimization for improving the performance of the sensor by considering the particle distribution deposited by thermophoresis on the SAW detector was analyzed and verified in experiments. The size of thermophoresis microchannel was obtained by Talbot formula and the movement of particles to the surface of the SAW detector was simulated by using the finite element method (FEM). Based on the theoretical results, the microchannel was fabricated and the thermophoresis distribution was observed under an optical microscope. The optimal monitoring structure of the SAW based $PM_{2.5}$ monitor was established theoretically.

Keywords: Particulate matter (PM); Surface Acoustic Wave; Thermophoresis; Deposition distribution; Mass sensitivity

1. INTRODUCTION

Atmospheric particulate matter (PM) is the sum of solid and liquid particles suspended in air. The complex mixture originates from a variety of sources such as salt, soot, metals and fly ash. $PM_{2.5}$, also known as fine particle, refers to particles with a nominal aerodynamic diameter less than or equal to 2.5 μm, which has adverse impact on air environment. Exposure to such air pollution may carry a risk of epidemic disease and the atmospheric visibility is degraded [1,2]. To control the $PM_{2.5}$ pollution, the monitoring work, especially extensive area monitoring, is indispensable. At present, the main methods for $PM_{2.5}$ monitoring are gravimetric, β-ray decay and tapered element oscillating microbalance (TEOM) methods, which suffer from large volume and expensive. For potable purpose, the light scattering and the micro electro mechanical systems (MEMS) device were reported recently. The light scattering method output depends highly on particle composition and size, which leads to low accuracy [3]. The MEMS device based on a film bulk acoustic resonator (FBAR) mass sensor owns a sensitivity of 2 $\mu g/m^3$ with 10 min testing time, but the fabrication is complex [4]. To further reduce the manufacturing complexity of the MEMS device and to obtain high sensitivity, a novel $PM_{2.5}$ monitor based on a surface acoustic wave (SAW) detector was developed, which consists of a SAW dual-resonator oscillator, a thermophoresis unit and a virtual impactor.

In this SAW based $PM_{2.5}$ monitor, the mass sensitivity is a key parameter, which is closely related to the operation frequency of the SAW detector, the thermophoresis collection efficiency and the SAW velocity shift caused by the deposited particles [5]. Obviously, to increase the SAW velocity shift, the particle deposition distribution on the SAW detector surface should be highly regarded, which eventually improves the performance of the sensor. In 2011, Thayer et al. used a scanning electron microscope (SEM) to analyze the airborne nanoparticles distribution in a plate-to-plate thermophoretic sampler with the flow rate of 5 mL/min, indicating the nonuniform particle deposition distribution on the collection plate [6]. Furthermore, in our previous work, it is proven that the mass sensitivity of a SAW sensor with a resonator configuration varies strongly across the device surface and the optimal sensitive area lies towards the center of the device [7]. Thus, in this contribution, an optimal structure of the $PM_{2.5}$ monitor by considering the particle deposition distribution was presented.

2. SYSTEM OVERVIEW

The schematic of the SAW based $PM_{2.5}$ monitor is shown in Fig. 1.

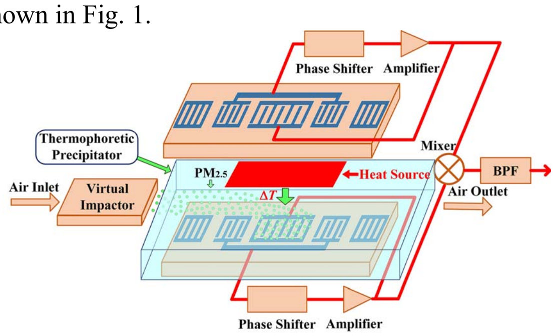

Figure 1. The schematic of the SAW based $PM_{2.5}$ monitor.

The sensor contains an air current microchannel, which is composed of a SAW dual-resonator oscillator,

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a thermophoresis unit and a virtual impactor. When the airborne particles are separated by size in the virtual impactor, the $PM_{2.5}$ is transferred to the plate-to-plate thermophoretic precipitator. By the thermophoresis effect, the mass loading from the $PM_{2.5}$ deposited results in the SAW velocity shift, and accordingly, the change of the oscillation frequency is utilized to $PM_{2.5}$ evaluation. The concept of the monitor and the corresponding threshold detection limit under the 100% thermophoresis collection efficiency condition was given in Ref. [8].

Based on the thermophoretic deposition efficiency formula for a laminar flow profile in a plate-to-plate precipitator given by Tsai *et al.* [9], a thermophoretic precipitator dimensions for particle diameter of 2.5 μm under 100% collection efficiency condition is shown in Fig. 2. Besides, considering the surface size of a SAW device, the dimensions of the thermophoretic precipitator is 200 μm × 3.6 mm × 6.3 mm.

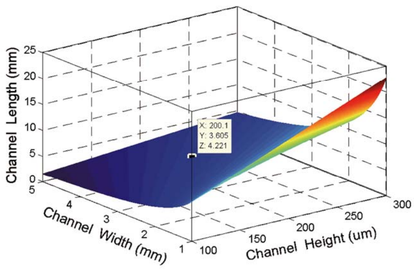

Figure 2. Thermophoretic precipitator dimensions for particle diameter of 2.5 μm under 100% collection efficiency condition.

3. THEORETICAL ANALYSIS

3.1. Particle Deposition Distribution in the Original Prototype

The heat source and the air current microchannel below it with a SAW device embedded in form the plate-to-plate thermophoretic precipitator. When particles move through that temperature gradient, they will experience a force in the direction of decreasing temperature. The force is called thermophoretic force. To describe the movement of the particles to the surface of SAW detector, a 3-dimensional FEM with the commercial software COMSOL MULTIPHYSICS was used to model the structure, shown in Fig. 3.

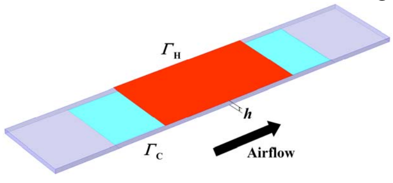

Figure 3. The schematic of the original plate-to-plate thermophoretic precipitator.

The temperature of the hot plate (Γ_H) in red color is 393.15 K and that of the cold plate (Γ_C) in light blue color is 303.15 K, where the SAW device was embedded in the center. The height of the precipitator (h) is 200 μm. The thermophoretic force, F_{th}, is assumed to be

$$F_{th} = \frac{6\pi d_p \mu^2 C_s \left(\kappa_a / \kappa_p\right)}{\rho\left[2\left(\kappa_a/\kappa_p\right)+1\right]} \cdot \frac{\nabla T}{T}. \qquad (1)$$

where d_p is the particle diameter, κ_a and κ_p are the thermal conductivity of air and particles, ρ is the air density, μ is the air dynamic viscosity, C_s is the Cunningham coefficient, ∇T is the temperature difference and T is the mean gas temperature [10]. By using the Non-Isothermal Flow and the Particle Tracing for Fluid Flow packages with the flow rate of 6 mL/min, the deposition distribution of particles with d_p = 2.5 μm was obtained, shown in Fig. 4. It is shown that particles were high-density distributed at the entrance and along the centerline of the collection plate. And the distribution exhibits parabolic. Besides, it was proven before that the optimal sensitive area lies towards the center of the SAW detector with a resonator configuration [7].

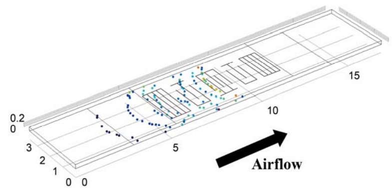

Figure 4. The deposition distribution of particles with d_p = 2.5 μm in the plate-to-plate thermophoretic precipitator shown in Fig. 3.

3.2. Particle Deposition Distribution in the Optimal Prototype

To optimize the original structure, the position of the heat source was moved to the right to guarantee the particles high-density distributed area corresponds with the optimal sensitive area of the SAW sensor, namely the center of the cold plate. Figure 5 exhibits the optimal structure of the thermophoretic precipitator. The corresponding deposition distribution of particles with d_p = 2.5 μm was shown in Fig. 6.

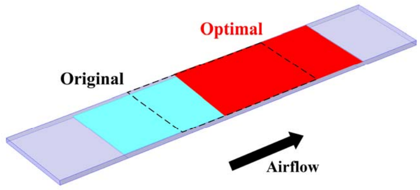

Figure 5. The schematic of the optimal plate-to-plate thermophoretic precipitator.

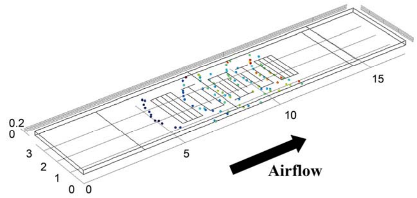

Figure 6. The deposition distribution of particles with d_p = 2.5 μm in the plate-to-plate thermophoretic precipitator shown in Fig. 5.

4. EXPERIMENTS

Based on the theory, a thermophoretic precipitator configuring the original structure was manufactured. With the help of an air sample, a low flow rate (6 mL/min) was formed in the thermophoretic field (∇T = 90 K). When the airborne smoke particles (a cigarette was lit and collected in the particle chamber) passed through the precipitator, the particles were deposited on the surface of the SAW device. A photograph taken by an optical microscope of the surface of the prototype exposed to high concentration of tobacco smoke is shown in Fig. 7. The particles distributed densely at the entrance of the thermophoretic precipitator shown in a yellow circle, which is in accord with the theoretical result in Fig. 4. The preparation of the optimal $PM_{2.5}$ monitor is ongoing, and the corresponding experiments will be carried out in the future work.

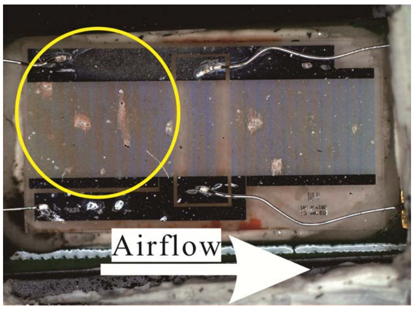

Figure 7. Optical micrograph of the surface of an original prototype exposed to high concentration of tobacco smoke.

5. CONCLUSION

This paper presented a SAW based $PM_{2.5}$ monitor. The particle distribution deposited by thermophoresis was simulated by the finite element method and verified by experiments. By changing the microchannel structure, the particles will be deposited on the optimal sensitive area of the SAW detector. And the performance improvement of the sensor by configuring the optimal structure will be achieved.

ACKNOWLEDGEMENTS

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