Configuration of Air Microfluidic Chip for Separating and Grading Respirable Dust

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Abstract: Particulate matter (PM) is a category of airborne pollutants, and fine particles that have a diameter of 2.5 µm (PM2.5) or smaller are especially damaging to human health because of their ability to penetrate deep into our respiratory system. Therefore, Monitoring of PM is very important. In this work, an air micro-fluidic PM sensor based on MEMS was proposed, and numerical model of the sensor was simulated accurately. The sensor was able to separate particles according to their sizes, and then transports and deposits the selected particles using thermophoretic precipitation onto the surface of a microfabricated mass-sensitive film bulk acoustic resonator (FBAR), precisely weighing and providing the concentration of PM. The PM sensor has double stage separation function, and the primary separator can separate the particles with size of less 10 µm from the particles, and the secondary can separate particles with size of less 2.5 µm from the particles.

Keywords: Air microfluidic chip; Film bulk acoustic resonator; Particulate matter; Electrophoretic force

1. Introduction
With the development of industrialization, the living environment of human beings is suffering from the most serious air pollution [1-19], which was seriously affected people's health and normal operation of society. The main composition of fog and haze is sulfur dioxide, nitrogen oxides and particulate matter (Inhalable particles, the aerodynamic equivalent diameter are less than 10µm) [5-15].The inhalable particles can be deposited in the respiratory tract, lung and other parts due to small size. The smaller particle size of the PM is, the deeper the PM entered into the respiratory tract. It is well known that the PM with diameter of 10 µm are deposited in the upper respiratory tract, and the PM with 5 µm diameter can enter into the deep part of the respiratory tract, and the PM with diameter less than 2 µm can be easily penetrated deep into bronchioles and alveoli, which was easy to cause cancer and other diseases. Negative effects of PM on health recently prompted the Beijing Municipal Environmental Protection Bureau to formulate new rules for the safe exposure limits of PM. Therefore, high precision PM monitors are very needed to monitor the total concentration of PM and the concentration of various sizes of PM in real time. Recently, a variety of PM detectors have emerged in the market, some of which are based on light-scattering principles, and some are based on the principle of weighing. Although PM sensors based on light-scattering can collect particle count data and infer the particle concentration based on assumptions about particle density and size distribution, reducing their accuracy and applicability. Therefore, it is of great significance to develop a rapid on-site detection technique for inhalable particles [6], which will be very conducive to understanding of the formation mechanism of
fog and haze. In this work, an air microfluidic PM sensor based was proposed, and the numerical model of the sensor was simulated accurately. The PM sensor has double stage separation function, and the primary separator can separate the particles with size of less 10 µm from the particles, and the secondary can separate particles with size of less 2.5 µm from the particles.

2. Configuration of the air microfluidic chip

Figure 1 shows a configuration of the air microfluidic PM sensor. Air containing PM enters inlet of the microfluidic sensor and immediately flows into an inertial size separator, and fine particles were directed to the thermophoretic deposition region where a temperature gradient induced across the microfluidic channel removes particles from the air stream by thermophoresis. The particles removed from the air stream are deposited on the exposed surface of a mass-sensing film bulk acoustic resonator. The rate of particle deposition, corresponding to the rate of change in the resonant frequency of the FBAR is proportional to the concentration of the particles in the airstream.

![Figure 1](image)

**Figure 1.** Configuration of air microfluidic chip.

It is well known that the inhalable particles can be affected by electrophoretic force at the gas separation port because of temperature gradient induced across the microfluidic channel. Where \( d \) is the particle diameter, \( \eta \) is the dynamic viscosity of the gas, \( \delta T \) is the temperature change, \( \rho \) is the density of particles, \( H \) is the molecular adjustment coefficient.

\[
F = -\frac{9\pi d^2 \eta H \delta T}{2\rho \delta T} \quad \ldots \quad (1)
\]

The smaller the particle size of inhalable particles is, the smaller the inertia is. In the role of electrophoretic force, the small particles turn to both sides of the channel, however, the large particles, directly outflow from the middle channel due to large inertia. Selection of particle size for inhalable particles can be expressed as follows:

\[
d = \frac{9\eta W^2 D_n}{\rho QC} \quad \ldots \quad (2)
\]

Where \( W \) and \( D \) are the channel width and depth of the microfluidic chip, respectively, \( Q \) is the airflow velocity of the inlet and \( C \) the correction factor. The particle size of the PM can be graded by controlling these factors such as \( W \) and \( D \) as well as \( Q \).

3. Experimental Section

3.1. Simulation of PM separation

In order to evaluate the separation performance of the chip, tobacco smoke was acted as the sensor prototype for analyzing the collection efficiency of PM under different flow rates (low flow rate and high flow rate) and different power (low power and high power). In the simulation analysis, the low flow rate is set as 5 ml/min, and high flow rate is set as 15 ml/ min, low loading voltage is set as 5 V, and high loading voltage is set as 15V. Fig. 2 and Fig.3 show the separation of PM (tobacco smoke) with different particle sizes from the air microfluidic chip. The flow rate of the sensor is 15 ml/min and the loading
voltage is 15 V. Fig. 4 shows the collection rate of PM with different particle sizes through the air microfluidic sensor. Fig. 2 and Fig. 3 show the Separation of inhalable particles with different diameter using air microfluidic chip. As we can see that the small particles turn to both sides of the channel, and the large particles, directly outflow the middle channel. The collection rate of PM with 5 microns was more than 90%.

![Figure 2. Separation of tobacco smoke with diameter less than 2.5 µm.](image1)

![Figure 3. Separation of inhalable particles with large diameter of 10 µm.](image2)

![Figure 4. Collection rate of PM for different particle size.](image3)

Fig. 5 show the sensitivity coefficient of PM for tobacco smoke while at two flow rates through the air microfluidic channel and two power settings to the thermophoretic heater. One of the analyses is that the heater of the sensor is loaded with 5V and 15V voltage at low flow rate of 5 ml/min, the heater of the sensor is loaded with 5V and 15V voltage at high flow rate of 10 ml/min, and the heater of the sensor is loaded with 5V and 15V voltage at high flow rate of 15 ml/min, respectively. As we can see from the result, the sensitivity of the PM sensor is dependent of the flow rate and loading voltage. Higher flow-rate and higher loading voltage imply higher sensitivity.
3.2. Double-stage separation sensor

In this work, in order to accurately monitor the concentration of PM with various particle sizes, a miniaturized double stage separator was designed based on the same principle of single stage separator. The separator can separate the PM under 10 µm from the primary separator and get its concentration by FBAR. Then the separated PM in the air was transported into the secondary separator, and the particles of 2.5 µm and below were separated from the particulates below 10 µm by the separator. Finally, the concentration of PM2.5 and the concentration of PM between 10 µm and 2.5 µm were obtained through FBAR, and Fig.6 shows the separation numerical diagram of PM using the double stage separator.

Figure 5. The sensitivity of the sensor exposed to tobacco smoke under low and high power.

Figure 6. Separation numerical diagram of PM using the double stage separator.
4. Conclusion
In this work, an air microfluidic PM sensor based on MEMS for monitoring PM was proposed. The performance of air microfluidic chip was influenced by the flow rate and loading voltage. Furthermore, the performance was also influenced by other factors, such as the location of the heater, the area occupied by the heater, etc. In addition, a miniaturized double stage separator was designed for monitoring the concentration of PM with various particle sizes based on the same principle of single stage separator.

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