REALIZING THE WORLD'S SMALLEST GRAVIMETRIC SELF-RESETTING PARTICULATE MATTER SENSOR USING MEMS

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ABSTRACT

We introduce a highly compact and low-cost gravimetric-based particulate matter (PM2.5) sensor, with the ability to self-reset, for continuous monitoring of air quality. The complete sensor solution consists of i) a mechanism to segregate the particles based on their aerodynamic size, ii) a mechanism to measure the mass of these separated particles, and iii) a mechanism to reset the sensor after each measurement. To address the barriers of affordability and ease-of-use usually encountered by other existing technologies, we propose here a compact gravimetric particulate matter sensing solution housed in a 20mm × 20mm × 15mm package, including all of the supporting electronics. The experimental results suggest that the solution proposed here is disruptive and has potential to revolutionize the field of gravimetric particulate matter sensing.

KEYWORDS

Particulate Matter (PM), MEMS, Sensors, Thermophoresis, Resonators, Piezoelectric, PiezoMUMPs

INTRODUCTION

Since the rise of the manufacturing industry and the increase in number of automobiles across the globe, the ambient air quality is on a steady decline [1]. The increase in the amount of the airborne particulate pollutants is a rising concern in developed as well as developing countries. These airborne particles consist of natural and man-made sources and their aerodynamic properties determine how far they can get into the human respiratory system [2]. Based on the size of these particles, particulate matter can be divided into two main categories:

- PM10: inhalable particles, with aerodynamic diameters of 10 micrometers and smaller; and
- PM2.5: fine inhalable particles, with aerodynamic diameters that are generally 2.5 micrometers and smaller

The World Health Organization (WHO) has set guideline limits to achieve the lowest concentration of particulate matter to minimize the risk of respiratory and cardiovascular diseases, and these guideline limits are as follows [3]:

Table 1: WHO limits for the annual and 24-hour mean of different particle sizes.

Particle Size	Annual Mean	24-hour mean
PM 2.5	10 μg/m^3	25 μg/m^3
PM 10	20 μg/m^3	50 μg/m^3

The health guidelines from WHO necessitate the need for developing new solutions to accurately measure the amount of particulate matter present in the air. The existing solutions to measure the PM concentration can be classified into two categories: gravimetric based and light scattering based [4, 5]. Gravimetric methods, the gold standard, directly measure the mass of the particles suspended in the air. The particles are collected on a filter over a certain period and are then weighed in a laboratory at the end of this fixed period. These methods are bulky in size, expensive and not suitable for real time sensing [6]. Whereas the sensors based on light scattering principle measure the amount of light scattered by the suspended particles in the air. This outputs the number of particles, which is later converted to mass by assuming the distribution and density of the particles. These assumptions often introduce inaccuracies in the measurements [7].

This work is aimed at designing a highly compact, accurate, low-cost, self-resettable, and easy to use gravimetric-based particulate matter sensor solution for portable applications [8]. Both PM10 and PM2.5 can penetrate deep into the lungs, but PM2.5 can even enter the bloodstream, hence posing severe health risks [2]. Hence, our solution aims at measuring the amount of PM2.5 suspended in the air. The overall system consists of i) a piezoelectric MEMS resonator which exhibits a shift in resonant frequency when mass is loaded on its membrane (reported in [9]), ii) a 3D printed virtual impactor, which is a mechanism that segregates particles based on their sizes (reported in [10]), and iii) a thermophoretic mechanism that helps resetting the sensor for continuous monitoring – a feature that no other MEMS based particulate sensing solution has achieved to date [11]-[13]. The full system design is presented here along with its experimental demonstration.

MATERIAL AND METHODS

This section briefly talks about the design of the different components of the system.

Resonator

A piezo-electric resonator is used to measure the mass of the particulate matter. The transduction principle of the resonator is the mass loading effect, i.e., an addition of a mass to the membrane results in a shift in its resonant frequency. The resonant frequency, f, of the plate can be determined as:

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}} \tag{1}$$

where k_{eff} is the effective spring constant and m_{eff} is the effective mass of the resonator. On addition of Δm on the plate results in Δf shift in the resonant frequency as:

$$\Delta f = -\frac{f}{2m_{eff}} \tag{2}$$

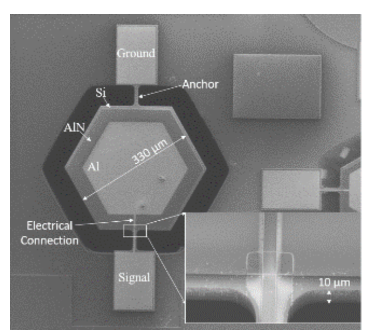

Figure 1: SEM of the resonator

Virtual impactor

The need to segregate the particulate matter based on their aerodynamic sizes arises from the WHO guidelines. The size of the particulate matter largely determines the extent of the damage caused to the environment and to the human health. Since we are targeting PM2.5, we need a mechanism to separate PM2.5 from the stream of particles flowing into the sensor.

A virtual impactor (figure 2) is a device that is used to separate the particles into two streams based on their aerodynamic diameter. Similar in operation to a conventional impactor, virtual impactor replaces the surface for impact with a virtual space of slow moving or almost stagnant air. Particles greater than 2.5 µm in size are collected in the minor flow channel, instead of colliding with the virtual impaction surface. Particles smaller than 2.5 µm (i.e., PM2.5) have smaller inertia because of their small size and are directed towards the major flow channel. By placing the resonator in the major flow channel, we can measure the amount of PM2.5 present in the air.

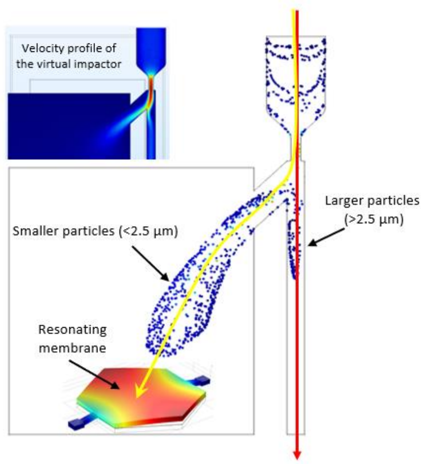

Figure 2: Virtual impactor with yellow streamline representing the trajectory of the particles < 2.5 µm, and the red streamline representing the trajectory of the particles > 2.5 µm.

Thermophoresis

Thermophoresis is the process of movement of colloidal particles or large molecules in a solution in response to thermal gradient. A colloidal particle or large molecule can be forced to move in a liquid or a gas with application of non-uniform thermal gradient. The mass flow rate J_m of these particles in a given fluid, resulting from thermal gradient ∇T, is given as [14]:

$$J_m = -\rho D \nabla c - \rho D_T c(1-c)\nabla T$$

where ρ is the density of the fluid, D is the coefficient of diffusion, D_T is the thermal coefficient of diffusion, and c is the concentration of particles as a mass fraction.

The coefficient of diffusion, D, is given by:

$$D = \frac{kT}{3\pi\eta d}$$

where k is the Boltzmann constant ($k = 1.38 \times 10^{-38}$ J/K), T is the temperature, η is the dynamic viscosity of the fluid and d is the diameter of the particles suspended in the fluid.

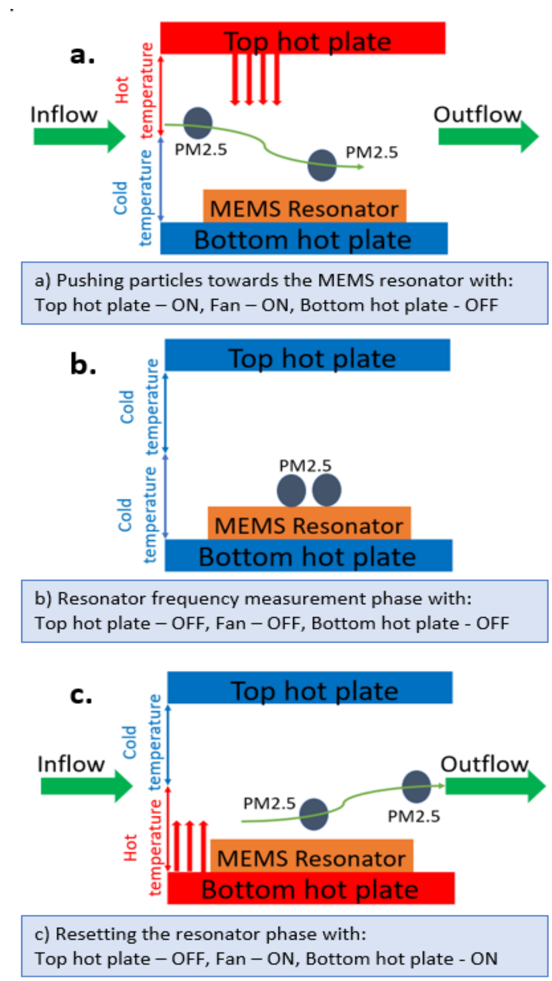

Figure 3: represents the conceptual diagram of our thermophoresis implementation. Both the hot plates, the top hot plate to push particles towards the resonator, and the bottom hot plate to push particles away from the resonator, have been implemented using resistors.

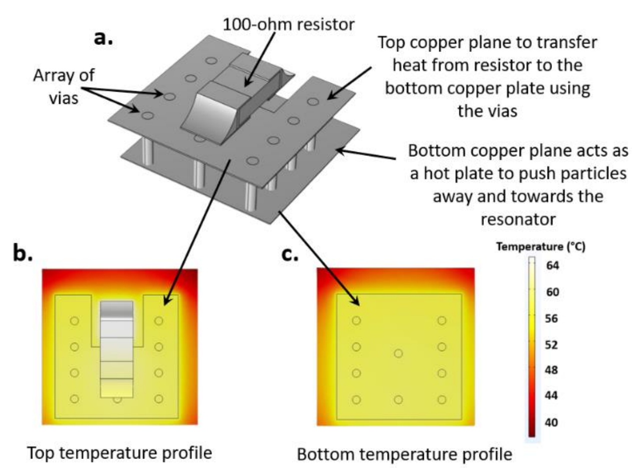

Figure 4: Thermal profile of the resistors and hot plates

Figure 3 represents the conceptual diagram of thermophoresis implementation in our sensor. Here, we use two hot plates, heated using surface mounted resistors, to push particles towards and away from the resonator. Heating the top hot plate pushes air molecules around the plate towards the MEMS resonator. Air molecules moving under the thermal gradient collide with the incoming particles and force them towards the resonator. After measuring the frequency response of the resonator, the resonator can be reset by turning on the bottom hot plate to push the air molecules (hence the particles) away from the resonator.

Figure 4 shows the simulation results from FEM studies carried out using COMSOL Multiphysics. Figure 5a shows the geometrical structure of a single hot plate implementation. Applying electrical power across the resistor heats up the resistor core, which heats up the copper plane which the resistor terminal is soldered to. This heat is transferred to the copper plane on the other side of the PCB using filled through-vias. Figure 5b and 5c present the temperature profile on both sides of the PCB. Such arrangement is used twice to implement the top and the bottom hot plates.

Electronic circuitry

The electronic circuit includes a closed loop oscillation circuit, coupled with a microcontroller circuit that drives the heaters and the fan. The fan is needed to maintain the flow of the particles inside the chamber. The MEMS resonator is combined in a feedback loop with an amplifier to create an oscillator whose frequency variation is then read using a microcontroller. An amplifier is needed to compensate for the motional resistance of the MEMS resonator and create an oscillator. An amplifier with a large gain-bandwidth is used due to the inherently large motional resistance of the MEMS resonator and the need to ensure that the phase shift around the loop is as close to zero as possible.

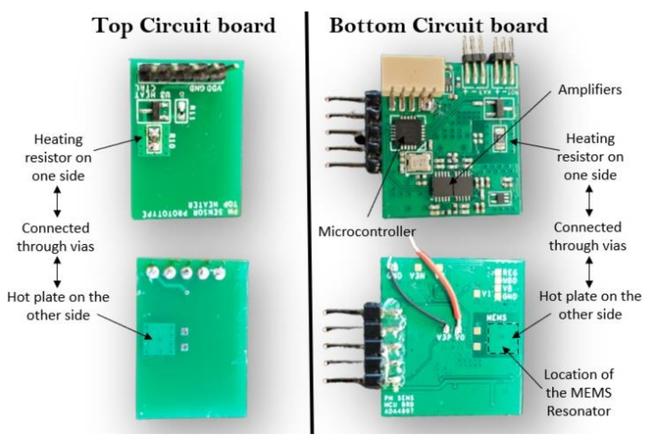

Figure 5: Top and Bottom circuit boards. The top circuit board includes a heating resistor and a transistor to control the operation on one side, and the top hot plate on the other. The bottom circuit board consists of the oscillator circuit and the microcontroller. The other side of the PCB has a designated location for the MEMS die, which is directly wire-bonded over the bottom hot plate area to reset the resonator.

Figure 6 presents a conceptual diagram of the whole solution, with MEMS resonator in a closed oscillation loop, forwarding signal to the microcontroller, which simultaneously controls the top and bottom hot plate and the fan.

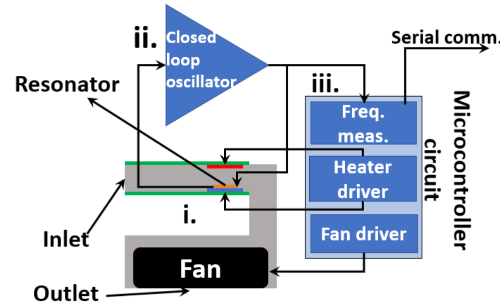

Figure 6: Conceptual diagram of the whole solution (i. 3D printed package that houses the MEMS resonator, ii. The closed loop oscillator and iii. the microcontroller that drives the top hot plate, bottom hot plate, and the fan.

Complete sensing solution

Figure 7 shows the assembled PM sensor solution, which measures 20mm × 20mm × 15mm. The complete solution consists of the 3D printed package with translucent resin, top PCB with the top hot plate and the bottom PCB with bottom hot plate, the oscillator circuit, and the microcontroller circuit. The fan and the top circuit are connected to the microcontroller circuit with wires soldered directly to the circuit (omitted here for clarity).

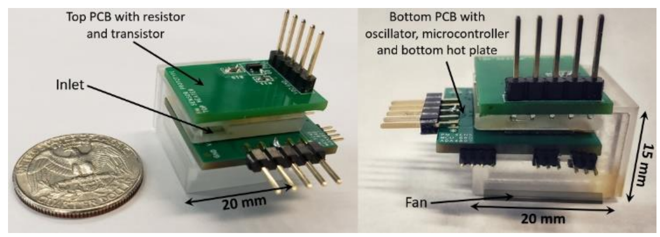

Figure 7: Complete sensor solution next to an American quarter.

TESTING

Incense stick is used as a source for particles to test the PM sensor. The particles in the incense smoke are mostly smaller than 2.5 µm in size (PM2.5) [15]. The incense smoke is introduced into a testing chamber to observe the response of the sensor. However, initial tests show that the incense smoke has a very high moisture content. To eliminate the problem of humidity, a drying column lined with silica gel packs is used to dehydrate the particles before and introduce them into the test chamber.

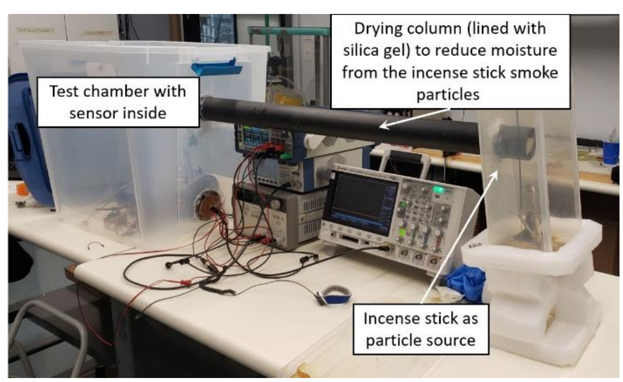

Figure 8: Test setup

The test setup (figure 8) consists of a small container which holds a burning incense stick generating particles, a transporting pipe (the drying column), and a large test chamber where we place our sensor to measure the introduction of particles. Particles travel through the drying column from the small container to the test chamber. And to release the particles, we can simply lift the lid of the test chamber and let the particles escape.

RESULTS

The piezoelectric resonator in the sensor has a resonant frequency of 1539.08 kHz. According to Sauerbrey equation, a mass deposition of incense particles should result in a shift in resonant frequency of the resonator. Introducing the particles into the test chamber results in a negative shift in the frequency, which drops to 1538.82 kHz. We then observe a rise (positive shift) in the resonance frequency on lifting the lid of the chamber slightly, letting some particles escape. This behavior is attributed to the setting and resetting of the resonator. The action is repeated, and we observe a fall in the frequency on closing the lid again as more particles continue to be introduced into the chamber. This resetting behavior is verified by completely removing the lid and letting all of the particle escape. We observe that the sensor resets 100% to its original resonance frequency.

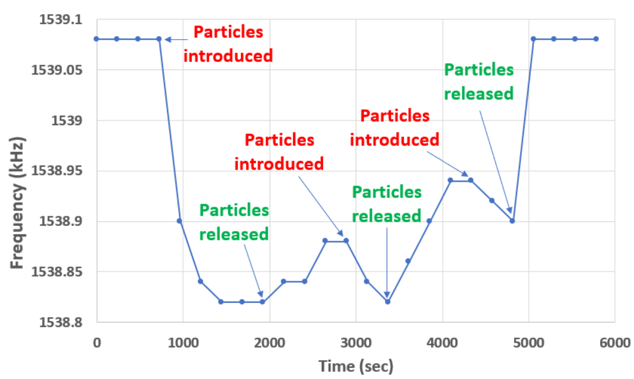

Figure 9: Response of the sensor to introduction and release of the particles from the testing chamber.

CONCLUSION AND FUTURE WORK

We have demonstrated here a fully functional gravimetric particulate matter sensor solution based on MEMS. The sensor is housed in a 20mm × 20mm × 15mm package, including all of the supporting electronics. It is the smallest reported to date, while operating in real-time. Compared to other works, the solution here also includes a novel and efficient mechanism for resetting the sensor automatically after every measurement.

One vital improvement for future developments will include humidity and temperature compensation. By incorporating a temperature and humidity sensor, we can minimize the ambient effects on the sensor measurements. Using an appropriate machine learning model, the sensor can be trained to compensate for these effects.

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