

OVERVIEW OF QCM FOR POLLUTION MONITORING SYSTEMS

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Abstract:

Global industrialization and urbanization have increased significantly the concentration of fine particles in the atmosphere. Various methods have been and are being developed for the measurement of fine particles. This paper explored the use of a quartz crystal microbalance (QCM) to measure the mass concentration of combustion particle suspensions and its contribution to air pollution monitoring techniques.

Keywords: Quartz Crystal Microbalance, Air pollution monitoring, QCM Sensors, Combustion particles, Particle suspensions.

1. INTRODUCTION

Air quality, expressed by the concentrations of pollutants in the air, highly varies in time and space. The variation in air quality is caused by the changes in emission rates, large-scale meteorology, local topography and urban effects that modulate the large-scale meteorology; variations in the rates of chemical transformations and deposition; and random fluctuations due to atmospheric turbulence. Furthermore, the concentration of fine particles in the atmosphere has increased significantly with global industrialization and urbanization. In this context, toxicity and epidemiological studies have revealed a correlation between fine particles and health problems, which has raised research interest on airborne fine particles [1,3-5,7-11].

It is therefore a challenging task to obtain representative information on air quality in a geographical domain during a specific time period. For this purpose, several technical tools are used to provide information on the air quality. Key technical tools include: air quality monitoring, air pollution emission inventory, and air quality modeling [4].

The goal of this paper is to present an overview of the use of Quartz Microbalance Sensors in the measurement techniques of fine Particles in the air and consequently measure the air quality or pollution density. We will present the QCM sensors principles and a report of the results of some published works.

2. QCM SENSORS AND INSTRUMENTATION

The QCM sensor is made of a quartz crystal disk, placed between two metal electrodes. The application

of a voltage over the disk will make deformation where the direction depends on the sign of the applied voltage and the crystal cut, as shown in Figure 1.

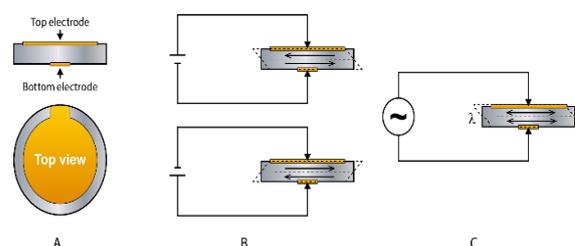


Figure 1: Schematic side and top views of a QCM sensor.

The QCM uses the change in frequency of the quartz crystal to estimate the mass of a sample according to the Sauerbrey equation [2]:

$$\Delta f = -C_f \times \frac{\Delta m}{A} \quad (1)$$

where Δf is the change in the resonance frequency (Hz), Δm is the change in the mass (μg), C_f is the sensitivity factor of the crystal ($56.6 \text{ Hz } \mu\text{g}^{-1} \text{ cm}^2$ for a 5 MHz AT-cut quartz crystal at room temperature), and A is the piezoelectrically active area. The Sauerbrey equation is applicable only if: the mass deposited is small compared to the mass of the quartz crystal; the mass is rigidly deposited; and the mass is evenly distributed over the crystal surface.

For instrumentation design and electrical analysis, the Butterworth van Dyke (BVD) model shown in Figure. 2, is used for electrical analysis and instrumentation. It represents the physical components of the quartz sensor around series resonance according to the change of mass and the type of deposited molecules.

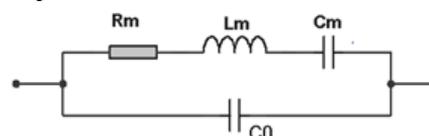


Figure. 2. Butterworth-van Dyke model of Quartz Crystal Resonator.

There are two resonant frequencies: serial and parallel resonant frequencies expressed as follows,

$$F_s = \frac{1}{2\pi\sqrt{L_m C_m}} \quad (2)$$

$$F_p = \frac{1}{2\pi\sqrt{L_m \frac{C_m C_p}{C_m + C_p}}} \quad (3)$$

$$= F_s \sqrt{1 + \frac{C_m}{C_p}}$$

The parasitic capacitance C_p impacts the measurement accuracy in each experience. It represents the sum of the static capacitances of the crystal's electrodes C_0 , holder, and connector capacitance C_0^* as illustrated in Figure. 3.

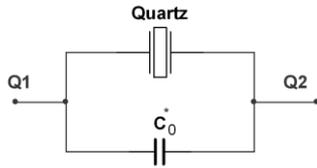


Figure. 3. Quartz with parallel parasitic capacitance.

Then, the compensation of this capacitor is mandatory in any electronic instrumentation in order to detect only the current in the electric motional branch or to enable oscillation conditions in the electronic circuit.

In [6], we have proposed an instrumentation technique based on the injection of an opposite parallel current to compensate for parasitic contribution, instead of using series inductance with a quartz sensor or winding transformer. As shown in Figure.4, we excite the quartz sensor by a sine voltage in the operating range frequencies around the resonant frequency. The compensation devices correspond to analog multiplier K and capacitor C_1 .

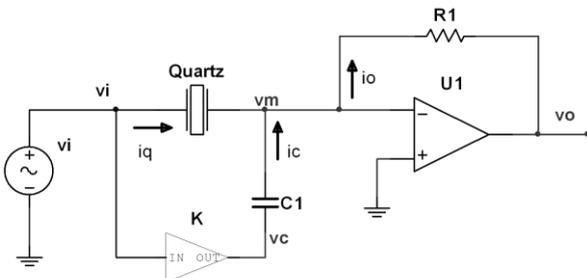


Figure. 4. Parasitic capacitance compensation circuit.

Using the quartz model of Figure 2, and parallel parasitic capacitor of Figure 3, the quartz and compensated currents are,

$$I_q(j\omega) = \left(j\omega C_p + Y_m(j\omega)\right) V_i(j\omega) \quad (4)$$

$$I_c(j\omega) = j\omega C_1 K V_i(j\omega) \quad (5)$$

where $Y_m(j\omega) = R_m + j\left(L_m\omega - \frac{1}{C_m\omega}\right)$. Then the output voltage can be written,

$$V_o(j\omega) = -R_1 \left(j\omega(C_p + KC_1) + Y_m(j\omega)\right) V_i(j\omega) \quad (6)$$

To cancel the contribution of the parasitic capacitance, the condition $C_p + KC_1 = 0$ has to be verified. Therefore, the compensation factor should be programmable as the following expression:

$$K = -\frac{C_p}{C_1} \quad (7)$$

The compensation factor must be updated continuously due to the change of the parasitic capacitance.

3. AIR POLLUTION MONITORING

In this section, we will present two applications of the QCM sensors on the pollution monitoring systems: Optical Particle Counter and Quartz Crystal Microbalance to measure PM10, and Measurement of the Mass Concentration of Combustion Particle Suspensions. Others systems are studied in [1,3-5,7-11]. For example, in [7], a chapter entitled “Air Quality Monitoring with Focus on Wireless Sensor Application and Data Management” provides a review of air quality monitoring techniques ranging from traditional to advanced. It highlights types and measurement principles of sensors for the monitoring of particulate matters and gases with their advantages and shortcomings.

3.1. Measurement of PM10

In the paper “Portable multilateral measurement system employing Optical Particle Counter and one-stage Quartz Crystal Microbalance to measure PM10” [3], a portable system is developed, to measure the number concentration, mass concentration, and effective density of PM10, which are important measures of fine particles. In this study, an Optical Particle Counter (OPC) and a one-stage Quartz Crystal Microbalance (QCM) impactor were used to compose a PM10 multilateral measurement system to calculate the effective density of PM10. As illustrated in Figure 5, OPC is a small device that measures the number concentration of particles, and the QCM impactor measures the mass concentration of particles. A difference of 4.7% and 11% were obtained for mass and number concentrations, respectively. When PM10 was sprayed through the nozzle, particles larger than 300 nm were attached to the QCM surface by inertia. Therefore, the effective density of PM10 was successfully calculated. [3].

Figure 6 shows the results of the experiment, which were used to determine whether the QCM impactor could output a resonant frequency suitable for the experiment [3]. The resonance frequency of 4.997772 MHz was measured without a flow rate for the first 40 s. The QCM impactor was designed to use a flow rate of 1.5 LPM, and the resonance frequency decreased by 22.4 Hz when 1.5 LPM of clean air was blown, at 40 s. The particles were generated using a particle generator at 85 s [3].

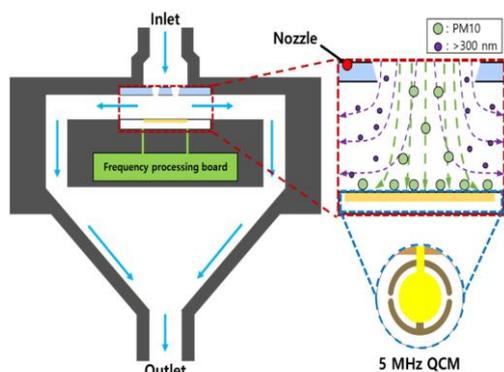


Figure 5: Cross-section view of the laboratory made one-stage QCM impactor.[3]

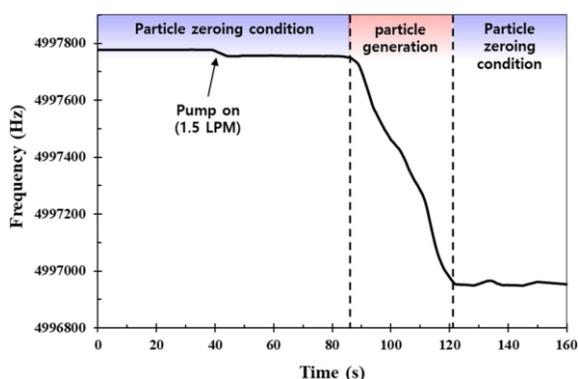


Figure 6: Resonant frequency measurement by the laboratory-made one-stage QCM Impactor. [3]

3.2. Measurement of Particle Suspensions

In the paper “Application of a Quartz Crystal Microbalance to Measure the Mass Concentration of Combustion Particle Suspensions” [1], a comparison between the QCM mass concentration to that estimated by placing a known mass of combustion particles in DI water. It also evaluated the effect of drop volume and combustion particle type on QCM measurements. The study demonstrated that the QCM is a promising technique for accurately estimating the mass concentration of combustion particles in suspensions. The QCM provided accurate and precise estimates of mass concentration for reference diesel PM ($\pm 1.2\%$), flame-generated combustion particles ($\pm 7\%$), coal-fly ash ($\pm 2.6\%$), and silica nanoparticles ($\pm 0.3\%$). The method required a small sample volume (0.5 μL) and

provided rapid results (5 min). Furthermore, the QCM method facilitates the estimation of particle loss (due to interactions with container walls, floating on the surface or due to settling), and coupled with a 20-nm filter, can rapidly estimate the proportion of dissolved organics of a sample [1].

The figure 7 shows the typical characteristics of the crystal frequency signal during the evaporation of a 0.5 μL drop of NIST reference diesel and flame-particle suspensions. The frequency patterns were similar for both the samples, i.e., a sudden drop in frequency when the drop was placed on the crystal, after which the frequency remained somewhat constant followed by a sudden drop before returning to a stable value. The final stable frequency was lower than the original frequency because of the residue left after the drop evaporated [1].

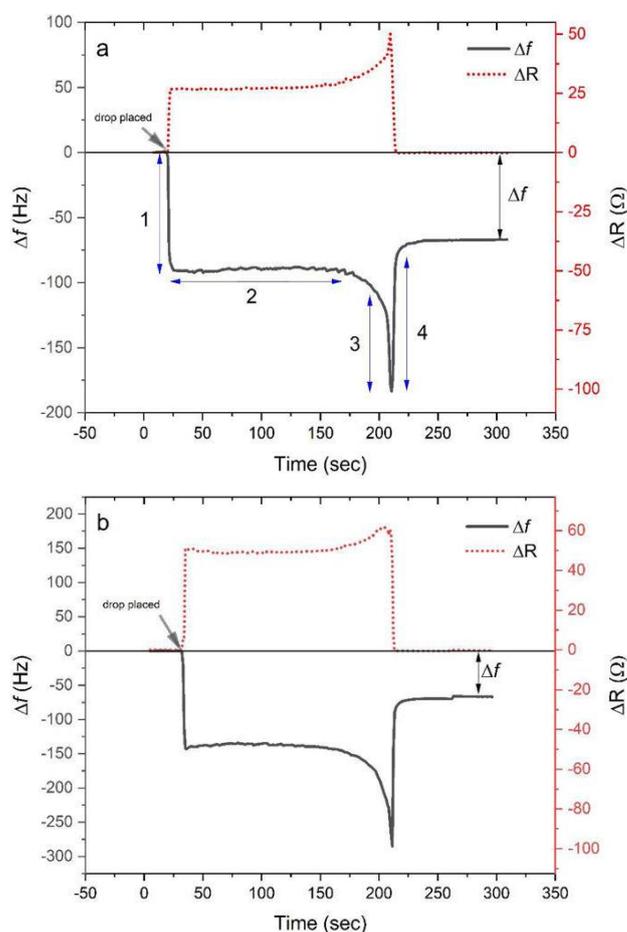


Figure 7: QCM resonance frequency (left axis) and resistance (right axis) versus time for 0.5 μL drops of: a) reference diesel suspension, and b) scraped flame-particle suspension. The numbers show the different stages of drop evaporation.

The change in resonance frequency after the drop fully evaporated was used for mass estimates.

In the paper “Theoretical Modelling of QCM-D Sensors in Environmental Applications” [5], theoretical work on QCM-D based acoustic sensors operated in gases, vapors, and liquids containing dispersed microscopic particles is developed. With

the main goal to provide theoretical support to the sensors for air pollution control, analytical results supplemented with numerical calculations provide a way to quantify measurements taking into account the shear viscosity of liquid as a function of pollutant particles number for the small volume fractions [5].

4. SUMMARY

Based on the published works, the quartz Crystal Microbalance allows precise mass concentration measurements of combustion particle suspensions and the estimation of the dissolved organic fraction of a suspension. The results showed that QCM is a promising direct method for measuring suspended combustion particle mass concentrations and consequently monitoring the air quality in the environment.

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