ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DEVELOPMENT OF QCM SENSORS FOR MEASURING PARTICULATE MATTER CONCENTRATION

Ph.D. THESIS

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Department of Mechanical Engineering

Mechanical Engineering Programme

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

QCM SENSÖRLERİNİN PARTİKÜL MADDE KONSANTRASYONUNU ÖLÇMEK İÇİN GELİŞTİRİLMESİ

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Majid JAVADZADEHKALKHORAN, a Ph.D. student of ITU Graduate School student ID 503182013, successfully defended the thesis entitled "DEVELOPMENT OF QCM SENSORS FOR MEASURING PARTICULATE MATTER CONCENTRATION", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 17 May 2024
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To my family,

FOREWORD

Completing a PhD is a profound journey of intellectual exploration, perseverance, and personal growth. This thesis is the culmination of years of dedicated research, countless hours of study, and the unwavering support of many individuals who have contributed to this scholarly endeavor.

First and foremost, I am deeply grateful to my supervisor, Prof. Dr. Levent TRABZON whose guidance, expertise, and encouragement have been invaluable throughout this process. His insightful feedback and unwavering belief in my research have pushed me to refine my ideas and achieve a higher standard of academic excellence.

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This thesis is not just a product of my efforts; it is a testament to the collective support and encouragement of a wonderful network of people. As I present this work, I am filled with gratitude for the guidance, collaboration, and love that have made this achievement possible. It is my hope that this research contributes meaningfully to the field of particulate matter sensors and inspires future scholars to pursue their passions with the same vigor and determination.

May 2024

Majid
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TABLE OF CONTENTS

Page

ABBREVIATIONS

AQI	**:** Air Quality Index
BAM	**:** Beta Attenuation Monitor
COPD	**:** Chronic Obstructive Pulmonary Disease
DLP	**:** Digital Light Projection
HEPA	**:** High-Efficiency Particulate Air
HRV	: Heart Rate Variability
PM	**:** Particulate Matter
PWM	**:** Pulse Width Modulation
RH	**:** Relative Humidity
SEM	**:** Scanning Electron Microscopy
T	**:** Temperature
TEC	**:** Thermo Electric Cooler
UFP	**:** Ultra Fine Particle

SYMBOLS

A	**:** Area
C_f	**:** Frequency Constant
Δf	**:** Frequency Shift
Δm	**:** Mass Change
f_o	**:** Quartz Fundamental Resonance Frequency
μ_q	**:** Quartz Dynamic Viscosity
µm	**:** Micrometer
ρ_q	**:** Quartz Density
T	**:** Temperature
W	**:** Weight

LIST OF TABLES

Page

LIST OF FIGURES

Page

DEVELOPMENT OF QCM SENSORS FOR MEASURING PARTICULATE MATTER CONCENTRATION

SUMMARY

Particulate matter (PM) refers to a mixture of tiny solid particles and liquid droplets suspended in the air. These particles come in various sizes and compositions, and they can be made up of different substances including dust, dirt, soot, smoke, and liquid droplets. PM is typically categorized by size: PM10 includes particles with diameters that are 10 micrometers and smaller, while PM2.5 encompasses those with diameters that are 2.5 micrometers and smaller. These fine particles are of particular concern because they can penetrate deep into the lungs and even enter the bloodstream, posing significant health risks. PM1 is ultrafine particle (UFP), with a diameter of 1 µm or less. This is roughly 70-100 times smaller than the width of a human hair. PM1 particles can bypass the body's natural defenses much easier than PM2.5.

Exposure to PM poses several significant health risks, primarily due to its ability to penetrate deep into the respiratory system and even enter the bloodstream. PM can irritate the respiratory tract, leading to conditions such as asthma, bronchitis, and other chronic respiratory diseases. Fine particles (PM2.5) can reach the alveoli in the lungs, causing inflammation and aggravating existing lung conditions. Long-term exposure to PM is linked to heart diseases, including heart attacks, arrhythmias, and hypertension. The particles can cause systemic inflammation and oxidative stress, which contribute to the development and progression of cardiovascular conditions. Studies have shown a correlation between PM exposure and premature mortality. People with pre-existing health conditions, the elderly, and children are particularly vulnerable to the harmful effects of PM. The severity of these health risks depends on several factors, including the concentration and composition of the particulate matter, the duration of exposure, and individual susceptibility. Reducing PM emissions through regulatory measures and personal protection strategies is crucial for mitigating these health risks.

PM originates from a variety of sources, both natural and human-made. Key sources include combustion processes like emissions from vehicles, industrial facilities, power plants, residential heating or burning of biomass; construction activities such as dust from construction sites, demolition or road dust from vehicles traveling on unpaved roads; and natural sources like windblown dust, volcanic eruptions, and wildfires.

Public awareness regarding air quality and the detrimental effects of particulate matter exposure has significantly increased in recent years. This has led to a surge in demand for reliable and accurate PM sensors for various applications, including indoor air quality monitoring, environmental monitoring, and occupational safety assessments. To ensure the effectiveness of these sensors, robust testing and evaluation procedures

are crucial. However, conventional PM test setups often pose significant barriers due to their inherent limitations.

Traditional PM test setups typically rely on large, complex equipment such as Scanning Mobility Particle Sizers (SMPS) and Aerosol Mass Spectrometers (AMS). While these instruments offer exceptional accuracy and detailed PM characterization, their high cost, operational complexity, and significant maintenance requirements make them inaccessible for many potential users. This limited accessibility hinders the widespread deployment and adoption of PM sensor technology, particularly for applications requiring real-time monitoring or deployment in resource-constrained settings.

This thesis proposes a novel approach to address the challenges associated with conventional PM test setups. We introduce a cost-effective experimental setup specifically designed for PM sensor testing. This compact design prioritizes affordability and ease of use by leveraging readily available and commercially obtainable components. The core of the setup lies in a custom-made PM generator capable of producing PM from diverse sources, including dry powder, liquid suspension, and combustion. This versatility allows for a comprehensive evaluation of sensor performance under a wide range of PM types, simulating real-world scenarios encountered in various environments.

A key innovation of this study lies in the combined use of Quartz Crystal Microbalance (QCM) and laser sensors within the test setup. Laser sensors are well-established for detecting larger PM due to their ability to measure particle size and number concentration based on light scattering principles. However, their sensitivity diminishes for ultra-fine PM, particularly those resembling smoke particles. By incorporating a QCM sensor, the setup gains the ability to effectively detect these smaller particles through mass accumulation on the sensor surface. This combined approach provides a more complete picture of PM concentration across a broader size spectrum, offering valuable insights into air quality.

The subsequent sections of this thesis will delve into the details of the proposed experimental setup, including the design considerations for the PM generator and the selection criteria for the chosen sensor technologies. We will then present the findings from a comprehensive investigation into the performance of the QCM sensor under various PM sources and ambient conditions.

In this thesis, an automatic aerosol generation setup was developed to maintain a stable PM concentration during experiments. This setup incorporates three different techniques for generating PM to investigate their effects on sensor response. In first technique the aerosol is generated from PM suspended in water. Dry chemical powders are initially mixed with water, and the mixture is then evaporated using a nebulizer. This aerosol passes through a custom-made PM dryer, which consists of a network of pipes running through a cylinder filled with silica gel grains. Moisture is removed from the mixture through diffusion as it travels through these pipes. The dried aerosols are then expelled from the PM chamber by an air pump. The second method is considered for creating dry aerosol from chemical powders. The powder is dispersed in a cylinder using pressurized air. Inside the cylinder, two small fans keep the particles suspended, creating a homogeneous mixture. The aerosol is then pushed out by a piston, which is controlled by a stepper motor and threaded bar. The third technique is used for smoke aerosol generation. Particles are produced by burning an incense stick and are collected in a smoke chamber. Similar to the method, the PM mixture exits the chamber via an air pump. All pumps and the stepper motor are controlled by a microcontroller connected to a computer.

QCM is a compelling technology with potential applications in PM measurement, offering a unique approach that complements other established techniques. QCM technology holds promise for PM detection due to its distinct capabilities. Central to a QCM is a precisely crafted AT-cut quartz crystal, celebrated for its exceptional piezoelectric properties. These properties enable the crystal to convert mechanical stress into a measurable electrical signal, and conversely, an electrical voltage can cause the crystal to vibrate at a specific frequency. This characteristic frequency serves as a unique identifier, determined by the crystal's size, shape, and, most importantly, its mass.

Continuously operating the QCM and implemented pump provides real-time resonance frequency data but does not directly indicate the rate of change in this frequency. To overcome this limitation and streamline the measurement process, this study introduces a novel method using pulsed pump operation. The pump delivers air intermittently, with brief idle periods in between. Each time the pump stops, the QCM's resonance frequency is recorded and compared to the frequency measured at the previous stop.

To increase the sticking efficiency of particles, the surface of the QCM has been coated with a layer of grease. Applying this coating proved to be an effective strategy for enhancing sensor response, particularly for dry particles. The coating significantly improved particle adhesion, resulting in a stronger overall response. Furthermore, it reduced variations in sensor response due to differences in particle characteristics, ensuring more consistent performance across a wider range of PM types.

The results will highlight the influence of factors such as PM composition, size, relative humidity (RH), and temperature on the sensor response. Finally, the study will discuss the complementary nature of QCM and laser sensors in PM detection, paving the way for the development of more robust and cost-effective PM monitoring systems. By offering a cost-effective and user-friendly alternative to existing test setups, this study has the potential to democratize PM sensor testing and accelerate the development of advanced air quality monitoring solutions.

Variations in PM composition and size have a significant effect on the QCM response. Additionally, relative humidity (RH) can alter the sensor response by up to 22%. Although temperature changes in the airflow have minimal impact on the bare QCM response, increasing the temperature from 25°C to 30°C results in a 12% change in response for the grease-coated sensor. Notably, the QCM sensor performs best with small-sized smoke PMs, showing the least sensitivity to ambient conditions.

Finally, the study will discuss the complementary nature of QCM and laser sensors in PM detection, paving the way for the development of more robust and cost-effective PM monitoring systems. By offering a cost-effective and user-friendly alternative to existing test setups, this study has the potential to democratize PM sensor testing and accelerate the development of advanced air quality monitoring solutions.

QCM SENSÖRLERİNİN PARTİKÜL MADDE KONSANTRASYONUNU ÖLÇMEK İÇİN GELİŞTİRİLMESİ

ÖZET

Partikül maddesi (PM), havada asılı duran küçük katı parçacıklar ve sıvı damlacıklardan oluşmaktadır. Bu parçacıklar çeşitli boyutlarda ve bileşimlere sahip olup ve toz, kir, kurum, duman ve sıvı damlacıkları gibi farklı maddelerden oluşabilir. PM genellikle boyutuna göre sınıflandırılır: PM10, çapı 10 mikrometre ve daha küçük olan parçacıkları içerirken, PM2.5 çapı 2.5 mikrometre ve daha küçük olanları kapsar. Bu parçacıklar akciğerlerin derinliklerine nüfuz edebilir ve hatta kan dolaşımına girebilir ve ciddi sağlık riskleri oluşturabilirler ve özellikle önemlidi . PM1, çapı 1 µm veya daha küçük olan ultra ince parçacıktır (UFP). Bu, insan saçının kalınlığından yaklaşık 70-100 kat daha küçüktür. PM1 parçacıkları, vücudun doğal savunma mekanizmalarını PM2.5'ten çok daha kolay aşabilirler.

Partikül maddeye maruz kalmak, partiküllerin solunum sisteminin derinliklerine nüfuz edebilme ve hatta kan dolaşımına girmesinden dolayı birçok önemli sağlık riskine yol açar. PM, solunum yollarını tahriş edebilir, astım, bronşit ve diğer kronik solunum yolu hastalıkları gibi durumlara yol açabilir. PM2.5 akciğerlerdeki alveollere ulaşarak iltihaplanmaya neden olabilir ve olası mevcut akciğer rahatsızlıklarını kötüleştirebilir. PM'ye uzun süre maruz kalmak, kalp krizleri, aritmiler ve hipertansiyon gibi kalp hastalıkları ile ilişkilendirilmiştir. Parçacıklar, sistemik iltihaplanma ve oksidatif strese neden olarak kardiyovasküler koşulların gelişimine ve ilerlemesine katkıda bulunur. Araştırmalar, PM maruziyeti ile erken ölüm arasında bir ilişki olduğunu göstermiştir. Mevcut sağlık koşulları olan kişiler, yaşlılar ve çocuklar PM'nin zararlı etkilerine karşı savunmasızdır. Bu sağlık risklerinin ciddiyeti, partikül maddenin yoğunluğu ve bileşimi, maruz kalma süresi ve bireysel duyarlılık gibi birkaç faktöre bağlıdır. PM emisyonlarının düzenleyici önlemler ve kişisel koruma stratejileri yoluyla azaltılması, bu sağlık risklerini hafifletmek için kritik öneme sahiptir.

Partikül maddeler, hem doğal hem de insan kaynaklı çeşitli kaynaklardan ortaya çıkar. Temel PM kaynakları arasında araç emisyonları, endüstriyel tesisler, elektrik santralleri, evsel ısıtma veya biyokütle yakma gibi yanma süreçleri; inşaat faaliyetleri, inşaat sahalarından gelen toz, yıkım veya araçların toprak yollarda seyahat etmesiyle oluşan yol tozu; ve rüzgarla savrulan toz, volkanik patlamalar ve orman yangınları gibi doğal kaynaklar bulunur.

Kamu bilinci, son yıllarda hava kalitesi ve partikül madde maruziyetinin zararlı etkileri konusunda önemli ölçüde artmıştır. Bu durum, iç mekan hava kalitesini izleme, çevresel izleme ve iş güvenliği değerlendirmeleri gibi çeşitli uygulamalar için güvenilir ve doğru PM sensörlerine olan talebi artırmıştır. Bu sensörlerin etkinliğini sağlamak için sağlam test ve değerlendirme prosedürleri hayati öneme sahiptir. Ancak, geleneksel PM test kurulumları, doğası gereği sahip olduğu birçok sınırlama nedeniyle önemli engeller yaratmaktalar.

Geleneksel PM test kurulumların çalışma şekli genellikle Taramalı Hareketlilik Parçacık Boyutlandırıcıları (SMPS) ve Aerosol Kütle Spektrometreleri (AMS) gibi büyük, karmaşık ekipmanlara dayanır. Bu cihazlar olağanüstü doğruluk ve ayrıntılı PM karakterizasyonu sunarken, yüksek maliyetleri, operasyonel karmaşıklıkları ve önemli bakım gereksinimleri nedeniyle birçok kullanıcı için erişilemez hale gelmişler. Bu sınırlı erişim, gerçek zamanlı izleme veya kaynak kısıtlı ortamlarda konuşlandırma gerektiren uygulamalar için PM sensör teknolojisinin yaygın dağıtımını ve benimsenmesini engeller.

Bu tezde, geleneksel PM test kurulumlarıyla ilişkili zorlukları gidermek için yenilikçi bir yaklaşım önerilir. Özellikle PM sensör testleri için tasarlanmış az maliyetli bir deneysel kurulum sunmaktadır. Bu kompakt tasarım, kolay temin edilebilen ve ticari olarak bulunabilen bileşenlerden yararlanarak uygun fiyatlılık ve kullanım kolaylığına öncelik verir. Kurulumun içerisinde, kuru toz, sıvı süspansiyon ve yanma dahil olmak üzere çeşitli kaynaklardan PM üretebilen özel yapım bir PM jeneratörü yer almaktadır. PM jeneratörünün bu çok yönlülüğü, çeşitli çevrelerde karşılaşılan gerçek dünya senaryolarını simüle ederek sensör performansının kapsamlı bir değerlendirmesine olanak tanır.

Bu çalışmanın önemli bir yeniliği, test kurulumunda Kuvars Kristal Mikrobalans (QCM) ve lazer sensörlerin birlikte kullanılmasıdır. Lazer sensörler, ışık saçılımı prensiplerine dayanarak parçacık boyutunu ve sayı yoğunluğunu ölçme yetenekleri nedeniyle daha büyük PM'yi iyi bir şekilde tespit ederler. Ancak hassasiyetleri, duman gibi ultra ince PM için önemli ölcüde azalmaktadır. Bu kurulum, bir QCM sensörünün dahil edilmesiyle ultra ince parçacıkları etkin bir şekilde tespit etme yeteneği kazanır. Bu birleşik yaklaşım, PM konsantrasyonun olçmesine dair daha geniş bir boyut spektrumunda eksiksiz bir tablo sunar ve hava kalitesi hakkında değerli bilgiler sağlar.

Bir sonraki bölümde, PM jeneratörünün tasarımında dikkate alınan kriterler ve seçilen QCM yeönteminin detayları incelenmektedir. Ardından, QCM sensörünün performansı çeşitli PM kaynakları ve ortam koşulları altında incelenip ve bulgular sunulacaktır.

Bu tezde, deneylerde istikrarlı bir PM konsantrasyonu elde etmek için, otomatik çalışan bir aerosol jeneratörü geliştirilmiştir. Bu jeneratör, üç farklı PM üretim yönteminden yararlanmaktadır. İlk yöntemde, aerosol, PM içeren su suspansiyonundan üretilir. İlk olarak kuru kimyasal tozlar suyla karıştırılır ve karışım bir nebülizatör vasıtasıyla buharlaştırılır. Bu aerosol, silika jel taneleriyle dolu bir silindir ve delikli borulardan oluşan özel yapım bir PM kurutucudan geçer. Karışım bu borulardan geçerken difüzyon yoluyla nemden arındırılır. İkinci yöntemde, kimyasal tozlardan kuru aerosol elde edilir. Kimiyasal toz, basınçlı hava kullanılarak bir silindir içinde dağıtılır. Sonra, üretilen aerosoller bir piston vasıtasıyla dışarı itilir. Üçüncü yöntemde, aerosoller duman üretimi ile elde ediler. Partiküller, bir tütsü çubuğu yakılarak üretilir ve bir haznede toplanır. Bu karışım, bir hava pompası ile hazneden dışarı çıkar. Tüm pompalar ve pistonun hareketi, bir mikrodenetleyici tarafından ve bilgisayar üzerinden kontrol edilir.

QCM, PM ölçümleri için yüksek potansiyele sahip olan bir teknolojidir ve diğer mevcut ölçüm teknikleri tamamlayan benzersiz bir yaklaşım sunmaktadır. QCM teknolojisi, kendine özgü yetenekleri nedeniyle PM tespiti için umut vaat etmektedir. Bir QCM, piezoelektrik özellikleri tanınan AT-kesim kuvars kristalinden oluşmaktadır. Bu özellikler, kristalin mekanik stresi ölçülebilir bir elektrik sinyaline dönüştürmesini sağlar ve tersine, bir elektrik voltajı, kristalin belirli bir frekansta titreşmesine neden olur. Bu karakteristik frekans, kristalin boyutu, şekli ve en önemlisi, kütlesi tarafından belirlenen benzersiz bir kimlik görevi görür.

QCM ve hava akışını sağlayan pompanın sürekli çalıştırılmasından, gerçek zamanlı rezonans frekansı elde edilir, ancak bu frekanstaki değişim hızını doğrudan göstermez. Bu problemi aşmak ve ölçüm sürecini basitleştirmek için, pompa aralıklı olarak çalıştırılır. Pompanın durduğu her seferde, QCM'nin rezonans frekansı kaydedilir ve önceki duraklamada ölçülen frekansla karşılaştırılır.

Partiküllerin yapışma verimini arttırmak için, QCM yüzeyine bir katman gres kaplama uygulanmıştır. Bu uygulama, sensör verimini özellikle kuru parçacıklarda olumlu olarak etkilemiştir. Bu kaplama, parçacık yapışmasını önemli ölçüde artırarak daha tutarlı sonuçlar elde etmeyi sağlamıştır. Ayrıca, partikül özelliklerindeki farklılıklar nedeniyle sensör tepkisindeki varyasyonları azaltarak, QCM için daha geniş bir PM türü yelpazesi boyunca tutarlı bir performans sağlar.

Sonuçlar, PM'nin bileşimi, boyutu, bağıl nem (RH) ve sıcaklık gibi faktörlerin sensör tepkisini etkilediğini. Bağıl nem, sensör yanıtını %22'ye kadar değiştirebilir. Hava akışındaki sıcaklık değişiklikleri, kaplamasız QCM yanıtını etkilemezken, sıcaklığın 25°C'den 30°C'ye çıkarılması, gres kaplı sensör için yanıtın %12 oranında değişmesine neden olur. QCM sensörü küçük boyutlu duman PM'lerinde, çevre koşullarından en az etkilenerek, en iyi performansı sağlamaktadır.

Son olarak bu çalışma, QCM ve lazer sensörlerinin PM algılamada birbirini tamamlayan bir yapıya sahip olduklarini ve bu şekilde daha uygun maliyetli olmanın yanısıra, daha kararlı sonuçlar veren bir PM gözleme sistemi sağladıklarını göstermektedir. Bu çalışma, mevcut olan konvansiyonel PM test kurulumlarına, daha uygun fiyatlı ve kullanışlı bir alternatif sunarak, hava kalitesini gözleme sistemlerinin geliştirilmesini hızlandırma potansiyeline sahiptir.

1. INTRODUCTION

1.1 Particulate Matter:

Particulate matter (PM), also known as particle pollution, is a complex mixture of microscopic solid and liquid droplets suspended in the air. These particles vary in size, composition, and origin, posing a significant threat to human health and environmental quality.

1.1.1 Multitude of sources

PM originates from various sources, both natural and anthropogenic (human-induced). Differentiating these sources is crucial for developing effective mitigation strategies.

1.1.1.1 Natural sources

Windblown dust from deserts, wildfires, volcanic eruptions, and sea spray can all contribute to natural PM production. These events can be episodic like forest fires and wildfires that release large amounts of PM into the atmosphere; or can be continuous like windblown dust arising from deserts, exposed soil, and agricultural activities.

1.1.1.2 Anthropogenic Sources

Combustion processes like vehicle exhaust, industrial emissions, and power generation are significant sources of human-made PM. Construction activities and cooking with solid fuels further contribute to localized PM pollution, particularly in urban environments.

1.1.2 The granular threat: classifying pm by size and health impact

The size of a PM particle is a critical determinant of its health effects. Figure 1.1 differentiates PM size categories to show their health impact.

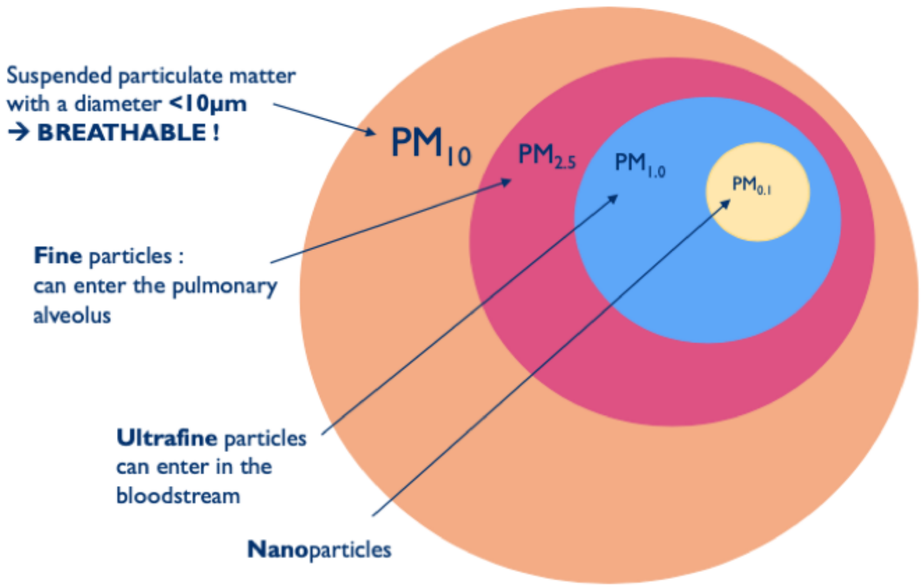

Figure 1.1 : PM size categorization (Technologies, 2021).

PM is typically classified into three key categories:

1.1.2.1 PM10

These are inhalable coarse particles with a diameter of 10 micrometers (µm) or less. While PM10 can irritate the eyes, nose, and throat, the body's natural defenses typically trap them in the upper airways.

1.1.2.2 PM2.5

These are fine inhalable particles, with a diameter of 2.5 µm or less. Due to their minute size, PM2.5 can bypass the body's defenses and penetrate deep into the lungs, even reaching the pulmonary alveolus. This deep penetration is the reason why PM2.5 poses a greater health risk.

1.1.2.3 PM1

These are ultrafine particles (UFP), with a diameter of 1 µm or less. This is roughly 70-100 times smaller than the width of a human hair. PM1 particles can bypass the body's natural defenses much easier than PM2.5. They can enter the bloodstream, potentially causing significant health problems. The health risks associated with PM1 are likely similar to, or even greater than, those of PM2.5. Figure 1.2 compares the PM size with human hair.

Figure 1.2 : Comparison of PM and human hair in size (Benes, 1984).

1.1.3 Health impact of PM

Exposure to PM, especially the small ones, has been linked to various adverse health outcomes, including:

1.1.4 Respiratory issues

PM inhalation can irritate the airways, triggering asthma attacks, bronchitis, and chronic obstructive pulmonary disease (COPD).

1.1.4.1 Cardiovascular disease

Fine particles can damage blood vessels and promote inflammation throughout the body, increasing the risk of heart disease and stroke.

1.1.4.2 Lung cancer

Long-term PM exposure is classified as a carcinogen by the World Health Organization, particularly linked to lung cancer development.

1.1.5 Strategies to combat PM and breathe easier

Air quality monitoring stations track PM levels, and many countries have air quality index (AQI) systems that report daily air quality conditions. By staying informed about AQI levels, individuals can take steps to protect themselves, such as limiting outdoor activity when PM levels are high.

On a broader scale, advocating for policies that reduce air pollution from human-made sources is crucial. These policies may include stricter emission standards for vehicles and industries, along with promoting the adoption of cleaner energy sources like solar and wind power.

Furthermore, investment in green infrastructure projects like urban tree planting and the development of sustainable transportation systems can significantly reduce PM concentrations, particularly in densely populated areas.

By implementing a multi-pronged approach that addresses both monitoring and mitigation, we can work towards a healthier environment for all. This collaborative effort involving individuals, policymakers, and industries is vital to reducing PM levels and safeguarding public health.

1.1.6 PM filtering

PM filtering refers to the process of removing PM from the air. There are various types of air filters with varying degrees of PM capture efficiency. Furnance filters are the basic filters typically used in heating and ventilation systems. They capture larger particles like dust and pollen but are less effective against finer PM. Passive electrostatic filters attract particles using an electrostatic charge. They offer some improvement over furnace filters in capturing finer PM, but their efficiency is still limited. Pleated filters have a pleated design that increases their surface area and improves dust capture compared to basic furnace filters. Some pleated filters may be treated with a dust-holding spray to enhance their effectiveness against PM2.5. High-Efficiency Particulate Air (HEPA) filters are the gold standard for PM filtration. They can capture at least 99.97% of airborne particles as small as 0.3 microns, which includes most PM2.5 and even some ultrafine particles (PM0.1).

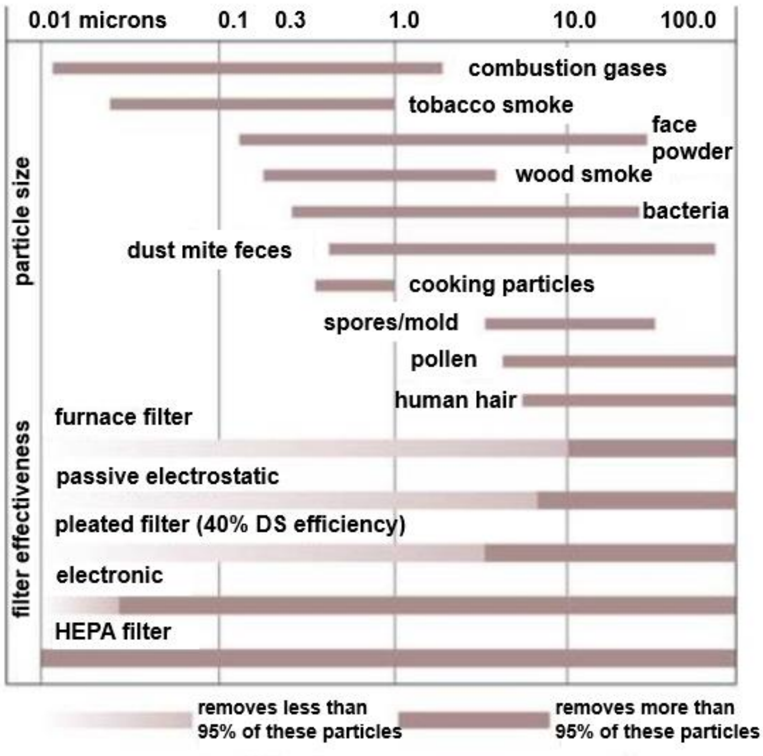

Figure 1.3 : Efficiency comparison of different air filters at capturing particles (Technologies, 2021).

The choice of PM filter depends on various factors, including air quality in the area, health concerns and cost. Figure 1.3 depicts how well different air filters perform at removing various airborne particles.

1.2 Purpose of Thesis

PM monitoring safeguards health and guides policy. It allows us to warn individuals about risky air quality and track pollution trends. This data informs policies to curb PM sources and evaluate their effectiveness. By pinpointing PM origins, we can target interventions and track pollution movement across regions. Public awareness of PM levels empowers individuals and communities to advocate for cleaner air. The purpose of this thesis is firstly to design and construct an experimental setup for particulate matter sensing, comprising a PM generator with various sources, an ambient condition controller, and a monitoring system. Secondly, to develop a MEMS-based PM sensor and evaluate it under various environmental conditions and PM concentrations.

1.3 Literature Review

1.3.1 PM concentration and health

Air pollutants, both gaseous and solid, can damage the endothelium, the lining of blood vessels, contributing to cardiovascular diseases. These pollutants disrupt endothelial function, potentially through direct harm or inflammation (Münzel et al., 2018). Figure 1.4 shows the number of deaths attributable to PM2.5 in recent years.

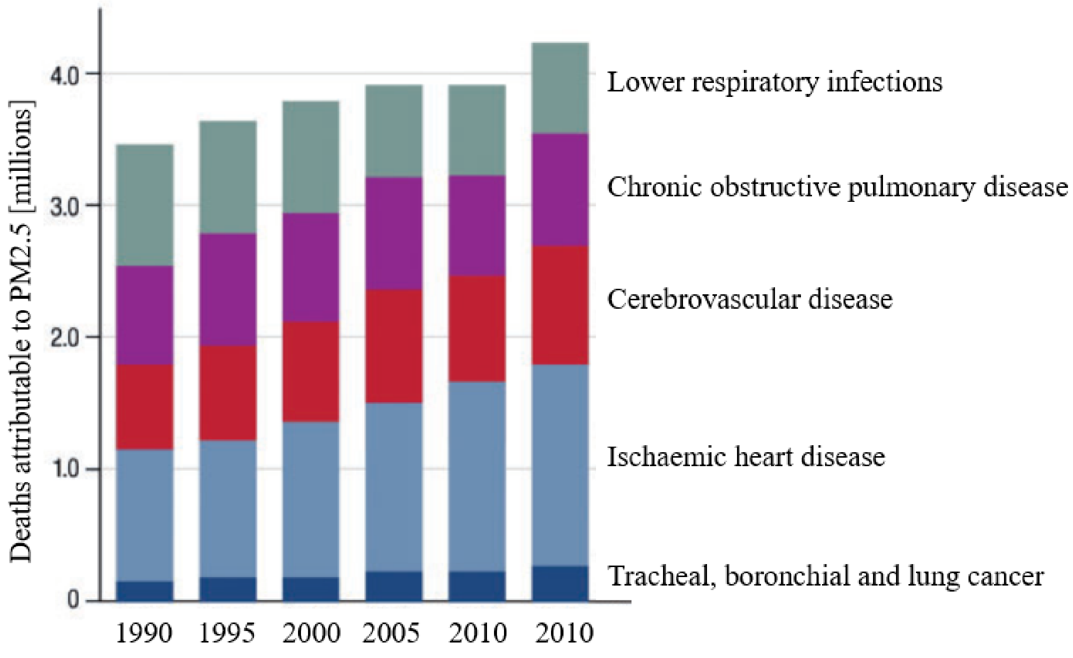

Figure 1.4 : Increasing number of deaths attributed to PM2.5 in recent years (Münzel et al., 2018).

Hemmingsen et al. examined the effects of short-term exposure to traffic-related PM on cardiovascular health in overweight, middle-aged and older adults (Weichenthal, 2012). Participants were exposed to filtered air or air containing real-world levels of PM from a busy street. After exposure, researchers measured vasodilation (blood vessel widening) and heart rate variability (HRV), both indicators of heart health. The findings showed reduced vasodilation and HRV following PM exposure, suggesting that even brief exposure to urban air pollution can negatively impact cardiovascular function in this at-risk population.

Another review article examines the potential link between UFPs, a type of air pollutant linked to vehicle emissions, and increased risk of cardiovascular problems (Hemmingsen et al., 2015). UFPs are especially concerning due to their deep penetration into the lungs. The paper explores how these tiny particles might influence the body in ways that contribute to acute cardiovascular events. The physiological effects discussed likely involve mechanisms such as inflammation and oxidative stress, both of which can negatively impact heart health. Understanding how UFPs affect the cardiovascular system is crucial for developing strategies to reduce air pollution's role in heart disease and related illnesses.

Antonini et al. found that welding fumes, a complex mixture arising from welding processes, can trigger respiratory problems in welders (Antonini et al., 2004). This study investigates how the specific metals present in welding fumes influence lung health. Research suggests the composition of the metal significantly impacts the harm caused. Fumes from stainless steel, rich in nickel and chromium, appear to induce more lung inflammation and injury compared to fumes from mild steel, which primarily contains iron. Additionally, these stainless-steel fumes linger in the lungs for longer periods. The study highlights the role of metal constituents in determining the lung's response to welding fumes, suggesting a need for considering material composition in workplace safety measure.

Another study quantifies the health burden of PM2.5 air pollution in China. By employing an ensemble modeling approach, the research attributes 1.3 million premature deaths in 2013 to PM2.5 exposure (Hu et al., 2017). Source apportionment analysis identifies industrial and residential sources as the primary contributors, followed by secondary particulate matter formation. Figure 1.4 demonstrates the contribution of each PM sources in premature mortality. The study further explores potential mitigation strategies. Achieving a 30% reduction in PM2.5-related mortality necessitates a nationwide 50% decrease in PM2.5 concentrations. The analysis emphasizes the need for stricter air quality standards exceeding current levels to achieve substantial public health improvements.

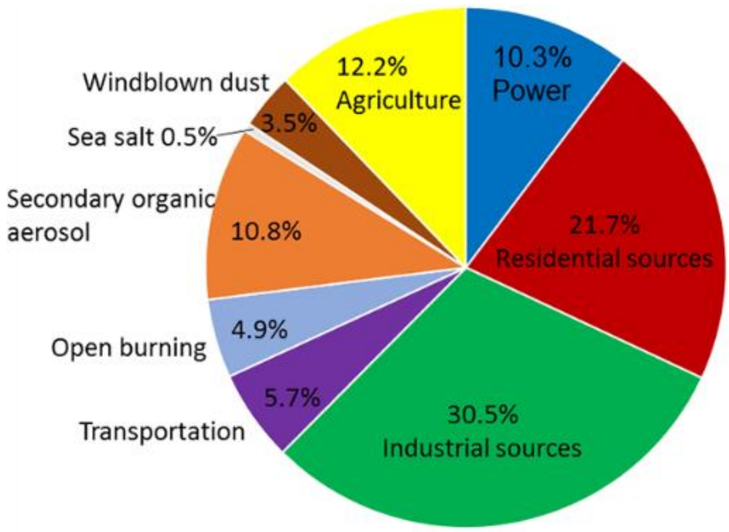

Figure 1.5 : Contribution of each PM sources premature mortality (Hu et al., 2017).

In recent years, public consciousness regarding air pollution and its associated health detriments for both adults and children has demonstrably heightened. This heightened awareness can be attributed, in part, to targeted local and national campaigns undertaken by non-governmental organizations (NGOs) and amplified by media coverage. Furthermore, in some countries, citizen groups, often bolstered by NGO support, have successfully pursued legal action against authorities over air quality issues. These legal challenges have, in several instances, resulted in court rulings upholding the fundamental right to clean air (European Environment Agency, 2019).

1.3.2 PM measurement techniques

Accurately measuring PM concentration is crucial for developing effective mitigation strategies. There are couple of key techniques employed to quantify this invisible threat explored here.

1.3.2.1 Light scattering techniques

These methods leverage the interaction of PM with light. Instruments like nephelometers and photometers measure how PM scatters light. Imagine tossing pebbles into a still pond and observing the ripples spreading outwards. Similarly, when light hits PM, it gets scattered in various directions. The intensity of the scattered light is then used to estimate PM concentration. Light scattering techniques offer several advantages: portability makes them suitable for personal use, and real-time data allows individuals to track air quality fluctuations in their immediate surroundings. These

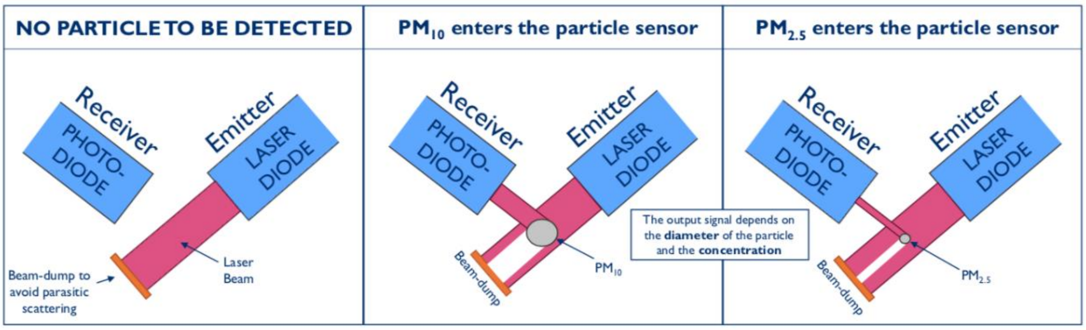

Figure 1.6 : Light scattering method in PM concentration measurement (Technologies, 2021).

portable monitors can be a handy tool for people who are particularly sensitive to air pollution or who live in areas with high PM levels.

Figure 1.6 illustrates the principle of light scattering. As light interacts with particles, the photodetector registers spikes in its output voltage. The magnitude of these spikes corresponds to the size of the particles. This signal is then processed and converted into concentration values for each PM size.

There are two types of Light Scattering Instruments. The first is nephelometers, which measure the overall amount of light scattered by PM particles at a specific angle, typically 90 degrees from the incident light source. Higher scattered light intensity indicates a greater concentration of PM. The second is photometers, which measure the total amount of light scattered by PM particles across a wider range of angles. Analyzing the scattering pattern at different angles can provide some information about the size and shape of the PM particles.

Light scattering techniques has couple of advantages. These instruments are often smaller and lighter than other PM monitors, making them suitable for personal use and field measurements. They also can provide readings in real-time, allowing users to track air quality fluctuations in their immediate surroundings. Compared to some advanced techniques, light scattering instruments tend to be more affordable.

In spite of their advantages, these devices also have limitations. The accuracy of the light scattering method can be affected by the size, shape, and composition of the particles. Different particles scatter light differently, and the method may not accurately reflect the true concentration or distribution of particles, especially for non-spherical particles or those with varied refractive indices. Environmental factors such as humidity and temperature can affect light scattering measurements. Light scattering methods may have limitations in detecting very small (ultrafine) or very large particles accurately. This can result in a biased representation of the PM size distribution. Instruments using light scattering need frequent calibration against reference methods to ensure accuracy. Calibration can be complex and time-consuming, often requiring comparisons with gravimetric methods, which are more accurate but less convenient for real-time monitoring. The presence of gases in the sampling environment can interfere with the measurement process, leading to inaccurate readings. Certain gases can scatter light similarly to particles, causing errors in PM concentration estimates. The optical components of light scattering instruments require regular maintenance and cleaning to ensure consistent performance. This can add to the operational costs and complexity of using these devices for continuous monitoring.

In terms of applications of this technique, these instruments can be helpful for individuals who are particularly sensitive to air pollution or who live in areas with high PM levels. While not a substitute for regulatory-grade PM monitors, light scattering devices can provide a general sense of air quality fluctuations. In conjunction with other techniques, light scattering data can be used to understand trends in PM concentration and its potential sources.

Overall, light scattering techniques offer a valuable tool for personal and indicative air quality monitoring. Their portability and real-time data capabilities make them a convenient option for individuals to stay informed about the air they breathe. However, it's important to remember that these techniques might not provide the most accurate mass concentration measurements compared to other methods like gravimetric analysis.

1.3.2.2 Gravimetric analysis

Gravimetric analysis remains the gold standard for PM measurement. In this method a clean, pre-weighed filter (typically made of Teflon or quartz) is placed in a special holder designed to capture airborne particles. A known volume of air is drawn through the filter using a pump at a constant flow rate. Particles suspended in the air become trapped on the filter, while clean air passes through. After sampling, the filter with its captured PM is carefully removed from the holder and meticulously weighed again using a high-precision analytical balance. The difference between the final weight (filter with PM) and the initial weight (clean filter) represents the mass of PM collected from the sampled air volume. This value, divided by the volume of air sampled, provides the PM concentration expressed in units like micrograms per cubic meter (μg/m³).

Gravimetric analysis offers several advantages. This method offers the most accurate and reliable determination of PM mass concentration, particularly when performed meticulously. Beyond its high accuracy, the technique boasts wide applicability, measuring PM of various sizes, from coarse particles to fine PM2.5. However, some limitations also exist. This method requires careful handling of filters, precise weighing procedures, and controlled laboratory conditions, making it time-consuming and labor-intensive. Gravimetric analysis is not suitable for real-time monitoring as it necessitates post-sampling analysis in a laboratory setting.

Although gravimetric analysis and filter-based methods require more expertise and time compared to newer real-time techniques, they remain essential tools for accurate PM measurement. The high accuracy of gravimetric analysis establishes a benchmark for other methods, while filter-based techniques provide valuable insights into PM composition alongside gravimetric data. These methods continue to play a crucial role in research efforts aimed at understanding PM pollution and developing strategies to combat it.

1.3.2.3 Beta attenuation monitors

Beta attenuation monitor (BAM) is a widely used technique for continuously measuring the mass concentration of PM in ambient air. BAMs employ the principle of beta radiation attenuation. Imagine shining a light through a dusty window. The more dust there is, the dimmer the light becomes on the other side. BAMs operate in a similar way, but instead of light, they use beta radiation and instead of dust, they measure PM concentration.

Components of a BAMs are a beta radiation source, filter tape and beta radiation detectors. When no filter tape is present, or the air is clean, the beta radiation source emits a stream of beta particles. These particles freely pass through the sampling area and are detected by both detectors on the other side with minimal loss of intensity. As air containing PM is drawn through the system, particles get trapped on the filter tape. This creates a barrier for the beta radiation, causing some particles to be absorbed or scattered before reaching the detectors. The detectors measure a decrease in the intensity of beta radiation compared to the unobstructed case. The greater the decrease in intensity, the more PM is present on the filter tape. By analyzing the difference in radiation intensity, BAMs can calculate the mass concentration of PM in the sampled air.

The advantages of BAMs are continuous monitoring, relatively simple operation, widely used standard. However, they are sensitive to volatile components, provide limited information on particle composition and also require regular calibration.

1.3.2.4 Quartz Crystal Microbalance

Quartz Crystal Microbalance (QCM) emerges as a fascinating technology with potential applications in the realm of PM measurement. While not the undisputed champion in this arena, QCMs offer a unique approach that complements other established techniques. QCM technology offers a promising approach to PM detection, complementing established techniques with its unique capabilities.

At the heart of a QCM lies a meticulously crafted AT-cut quartz crystal, renowned for its remarkable piezoelectric property, meaning they generate an electric charge in response to mechanical stress and vice versa. The AT-cut orientation ensures optimal piezoelectric performance for frequency control and sensing applications. The term "AT-cut" refers to the specific orientation of the quartz crystal relative to its crystallographic axes. In an AT-cut crystal, the quartz wafer is cut at an angle of approximately 35 degrees 15 minutes (35°15') to the Z-axis (optic axis) of the quartz crystal. This orientation is chosen to optimize the crystal's performance in terms of frequency response. The AT-cut quartz crystal poses unique properties, make it ideal for use in a variety of precision applications, including oscillators, frequency control devices, and sensors like Quartz Crystal Microbalances (QCM). This property allows the crystal to convert mechanical stress into a measurable electrical signal, and conversely, an electrical voltage can induce the crystal to vibrate at a specific frequency. This characteristic frequency acts as a fingerprint, uniquely determined by the crystal's size, shape, and most importantly, its mass. As shown in Figure 1.7, a thin layer of metal electrodes is deposited on opposing faces of the disc. These electrodes allow for applying the voltage needed to induce vibrations and measuring the electrical signal generated by the disc.

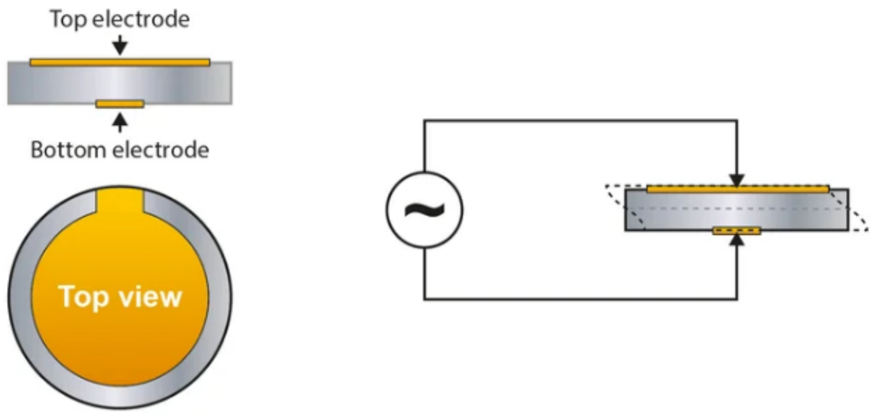

Figure 1.7 : QCM structure (Malin Edvardsson, n.d.).

The quartz crystal is adorned with a specially chosen film, designed to act as a highly selective and efficient trap for PM. As PM accumulates on this coated surface, the mass of the crystal increases ever so slightly. This minute mass change, though seemingly insignificant, has a measurable effect – it alters the natural vibration frequency of the crystal as shown in Figure 1.8. The QCM system functions with unwavering precision, meticulously monitoring the crystal's oscillation frequency. When PM accumulates, the frequency dips ever so slightly, and this decrease is directly proportional to the mass of PM captured on the coated surface. By precisely measuring this frequency shift, QCMs can indirectly estimate the amount of PM present in the air sample.

The frequency shift can be monitored in real-time to determine the amount of adsorbed mass. This can be calculated using the Sauerbrey equation (a core principle of QCM theory) (Sauerbrey, 1959):

$$\Delta f = -\frac{2 f_0^2 \Delta m}{A\sqrt{\rho_q \mu_q}} \tag{1.1}$$

Here, Δf represents the change in frequency, f_0 is the fundamental frequency of the crystal, Δm is the amount of adsorbed mass, A is the area under the electrode surface, ρ_q is the density of quartz, and μ_q is the shear modulus of quartz. The parameters f_0, ρ_q and μ_q are constants for a given crystal. By combining these constants into a single constant, C_f, the equation can be simplified as follows:

$$\Delta f = -C_f . \frac{\Delta m}{A} \tag{1.2}$$

Where C_f = 56.6 for a 5 MHz AT cut quartz crystal at 25 °C.

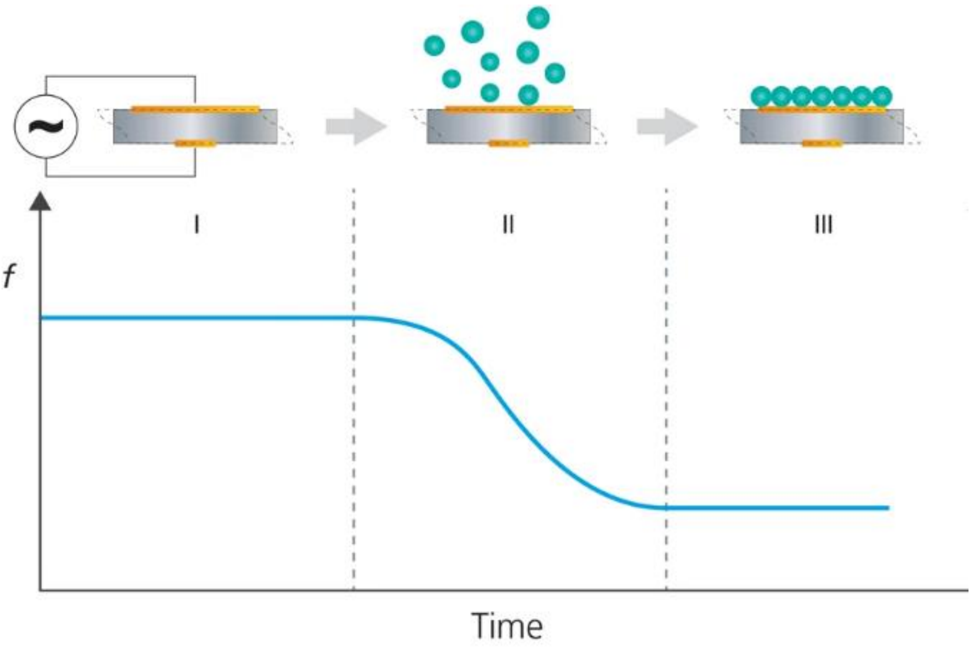

Figure 1.8 : Frequency shift due to mass change in QCM (Malin Edvardsson, n.d.).

QCMs offer distinct advantages that make them a valuable tool in the professional realm of PM detection. QCMs can provide continuous data on PM concentration, making them suitable for real-time air quality monitoring applications. This real-time aspect is crucial for environmental agencies and researchers to track PM fluctuations throughout a designated period, providing valuable insights into air quality dynamics. Unlike some bulkier PM measurement instruments, QCMs are generally smaller and lighter. This portability makes them potentially more suitable for field measurements, allowing researchers to take QCMs directly to the source of potential PM pollution for on-site analysis. QCMs can be used in conjunction with other techniques to study the interaction of PM with different materials or coatings. This information can be invaluable for developing improved filters or air purification technologies that can more effectively capture PM of various sizes and compositions.

While the scientific principles behind QCMs are intriguing, a professional assessment necessitates acknowledging their limitations in PM detection. Compared to highly accurate but time-consuming gravimetric analysis, QCMs might exhibit lower sensitivity. This translates to limitations in detecting extremely low PM concentrations, particularly in pristine environments. However, in areas with significant air pollution, QCMs can still provide valuable real-time data on PM trends.

Similar to BAMs, QCMs typically only measure the total mass of PM. They lack the ability to differentiate between various particle types, such as those originating from traffic emissions, industrial processes, or dust storms. This limitation can be a drawback if understanding the specific composition of PM is crucial for regulatory or research purposes. The effectiveness of QCMs for PM measurement hinges on the chosen coating material. An ideal coating should function like a highly efficient PM interceptor, attracting and capturing particles with minimal interference. However, factors like water vapor adsorption can also influence the crystal's frequency. Researchers must meticulously select a coating that minimizes these unwanted effects to ensure accurate PM detection.

Overall, QCMs offer a promising avenue for PM detection, particularly in research settings or for continuous monitoring applications where real-time data is essential. While their sensitivity limitations and inability to differentiate particle types necessitate careful consideration, QCMs can play a valuable role in the fight for cleaner air by providing real-time data on PM concentration and aiding researchers in developing improved PM capture technologies. As research and development continue, QCMs have the potential to become even more sensitive and versatile tools in the ongoing battle against air pollution.

1.3.3 Selected method

By employing any of these mentioned techniques, we can gain valuable insights into PM concentration levels across various environments. However, each of them has its own advantages and limitations. As a part of this study, the QCM method was selected for PM concentration sensing.

Haung et al. highlighted the importance of optimizing QCM mass sensitivity for PM detection and explores strategies to achieve this goal (Huang et al., 2018). The research explores various factors that influence the mass sensitivity of QCMs. The size, thickness, and material of the electrodes deposited on the QCM disc can affect its sensitivity. As shown in Figure 1.9, various electrode designs have been made on crystal surface and devided into four groups. The study found that the group C with 6.13 Hz/ng has the highest mass sensitivity compared to other groups.

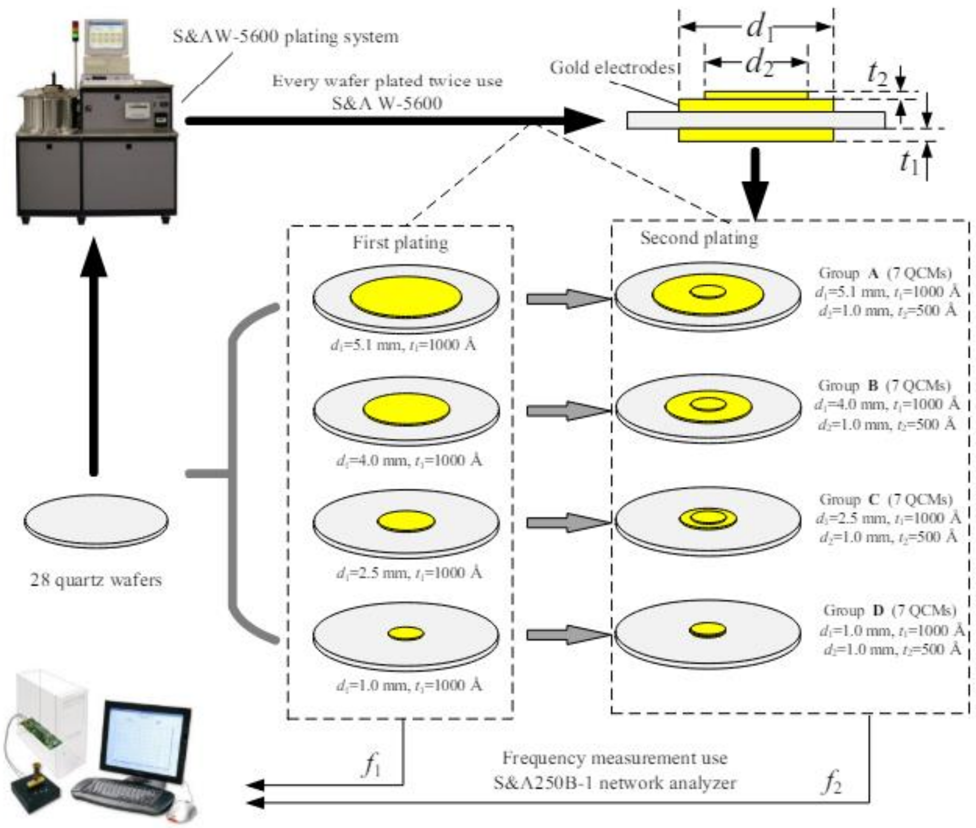

Figure 1.9 : Mass sensitivity of QCM sensor with various electrode types (Huang et al., 2018).

Palomba et al. explored the use of QCMs, typically employed for measuring mass changes, as a potential tool for collecting cosmic dust (Palomba et al., 2001). This paper likely focuses on a method for collecting these tiny particles, specifically those smaller than one micrometer. The research here investigated how effectively the crystal surface can capture these sub-micron sized dust particles. A critical aspect of this research is the concept of "sticking efficiency". This refers to the probability of a dust grain colliding with the QCM crystal and adhering to its surface. The study explores factors affecting this efficiency, such as grain properties, crystal surface, impact velocity. The size, composition, and surface texture of the dust grains could influence how well they stick to the quartz crystal. The cleanliness, roughness, and potential coatings on the QCM crystal surface might also play a role in capturing dust particles. The speed at which dust grains collide with the crystal could affect their sticking probability.

A unique technique also has been implemented in this study for dust generation as shown in Figure 1.10. Upon contact with the cogwheel, the dust clumps break apart (de-agglomerate), and the individual grains (accelerate) towards their destination in the center of the image.

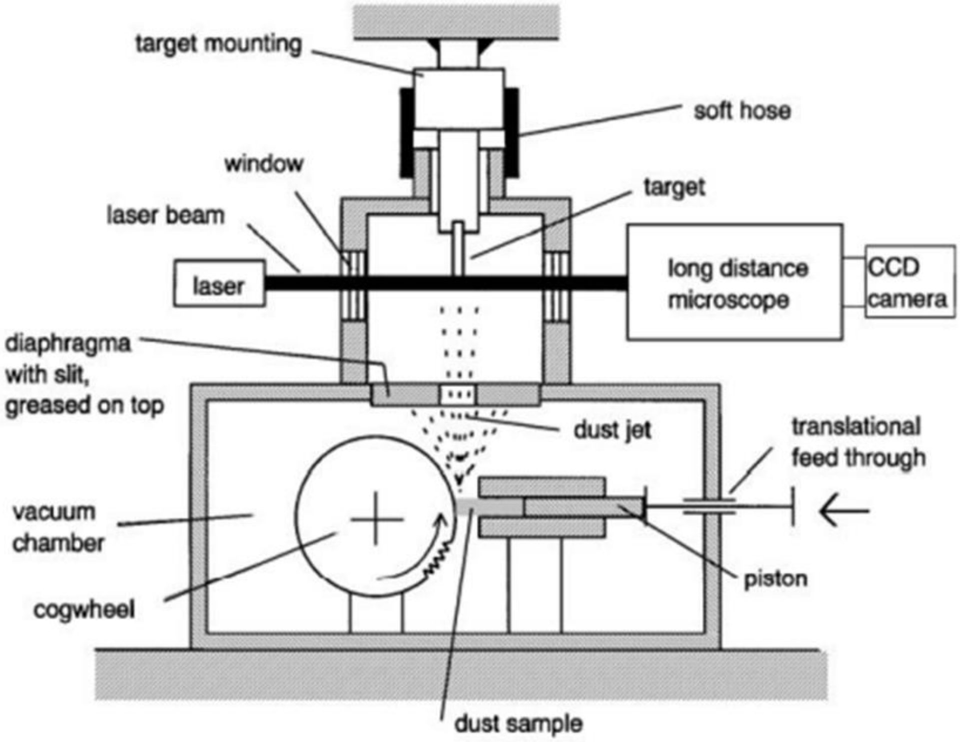

Figure 1.10 : An example of dust generator. Cited from (Palomba et al., 2001).

In this study, the researchers used Apiezon-L grease as a coating for the QCM surface (Figure 1.11). They compared the performance of the sensors using scanning electron microscopy (SEM). The results showed an increase in the number of PMs captured by the sensor with the Apiezon-L grease coating.

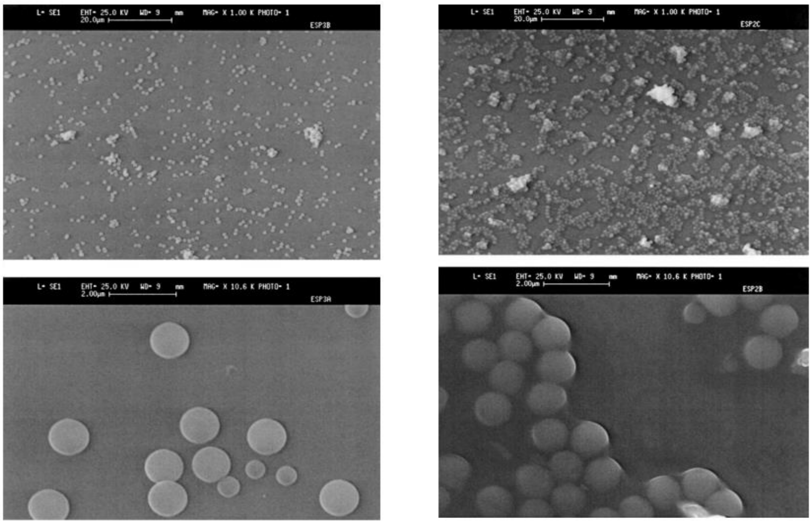

Figure 1.11 : SEM images of un-coated (left) and coated (right) QCM sensors after using with sub-micron particles. Cited from (Palomba et al., 2001).

Figure 1.12 shows the results of experiments where 1.2 micrometer silica spheres were impacted onto three different surfaces: a C1 electrode-coated quartz crystal, a mm-sized C1 chip, and a C1 chip covered with Apiezon-L. The graph shows that the impact behavior of silica spheres on C1 surfaces is affected by the presence of an electrode coating and a covering of Apiezon-L. A tick at the top of the graph indicates that the particle stuck, and a tick at the bottom indicates that the particle bounced.

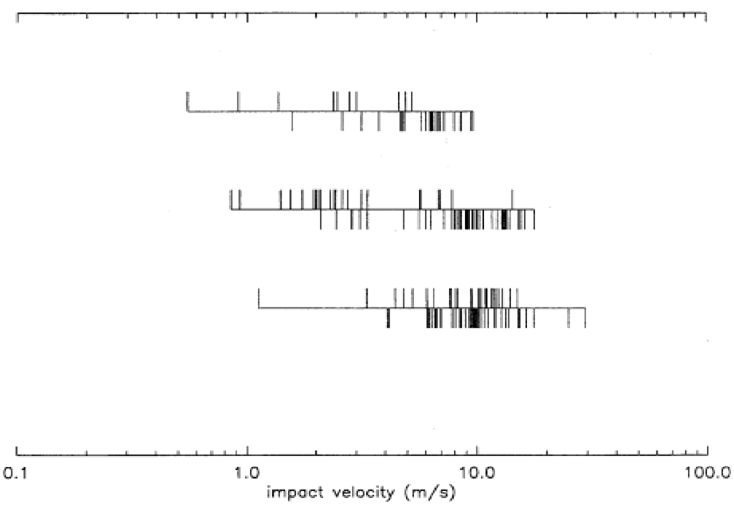

Figure 1.12 : The capture velocity of PMs with coated and un-coated QCMs (Palomba et al., 2001).

The top plot shows the results for the C1 electrode-coated quartz crystal. At low impact velocities, the silica spheres stick to the surface. At higher impact velocities, the silica spheres bounce off the surface. The middle plot shows the results for the mm-sized C1 chip. The behavior is similar to the top plot, but the impact velocity at which the spheres start to bounce is lower. The bottom plot shows the results for the C1 chip covered with Apiezon-L. The silica spheres stick to the surface at all impact velocities shown in the graph. The spheres are more likely to stick to the surface at lower impact velocities and more likely to bounce off the surface at higher impact velocities.

Another study dives into the intricate world of how tiny particles interact with QCMs. Understanding these interactions is crucial for improving QCM performance in air quality monitoring (Vittorias et al., 2010). The study unveils the interplay between several factors that govern particle adhesion to the QCM crystal. Particle characteristics like size, shape, and surface chemistry play a significant role, influencing how effectively a particle sticks upon contact. The QCM crystal itself is not a passive participant; its surface topography (smoothness) and cleanliness can significantly influence particle adhesion. The surface of QCM was coated with polystyrene film and then annealed to increase the adhesion of particles. Furthermore, the impact velocity determines whether it sticks or bounces off.

Kaur et al. explores the potential of QCMs for quantifying the mass concentration of particles derived from combustion processes (Kaur et al., 2019). This research holds significance as it investigates a potentially more direct approach compared to traditional methods. While gravimetric analysis remains the gold standard for PM measurement, its time-consuming nature necessitates alternative approaches. However, the hydrophobic character of combustion particles makes it challenging to create well-suspended mixtures for this technique. Using polystyrene containers for sample collection can lead to substantial particle losses, skewing the final concentration measurement. QCMs offer a potentially direct method for measuring the mass concentration of suspended particles. As particles accumulate on the QCM crystal surface, the crystal's oscillation frequency dips due to the increased mass. This shift in frequency can be correlated to the mass concentration of the particles. The inherent properties of QCMs might be more compatible with hydrophobic particles compared to traditional methods relying on aqueous suspensions. The research explores factors influencing the effectiveness of QCMs for combustion particle measurement. The volume of the liquid droplet containing the suspended particles might influence the accuracy of the measurement. Researchers might investigate the optimal volume for efficient particle capture and reliable mass concentration determination. The specific type of combustion particle (e.g., soot from diesel engines vs. smoke from burning wood) might affect its interaction with the QCM surface and the resulting frequency shift. Similar to other PM measurement instruments, QCMs likely require periodic calibration using established methods like gravimetric analysis to ensure accurate mass concentration translation from the measured frequency shift. While QCMs can quantify the total mass concentration, they might not provide information about the specific composition of the combustion particles. This limitation might be crucial depending on the research or regulatory needs. Figure 1.13 demonstrates a droplet evaporation process on QCM surface. This process indicates the necessity of humidity existance in PM measurements for QCM. Before the droplet completely evaporated, the particles migrated towards its edges. This increased the combined effect of density and viscosity around the crystal.

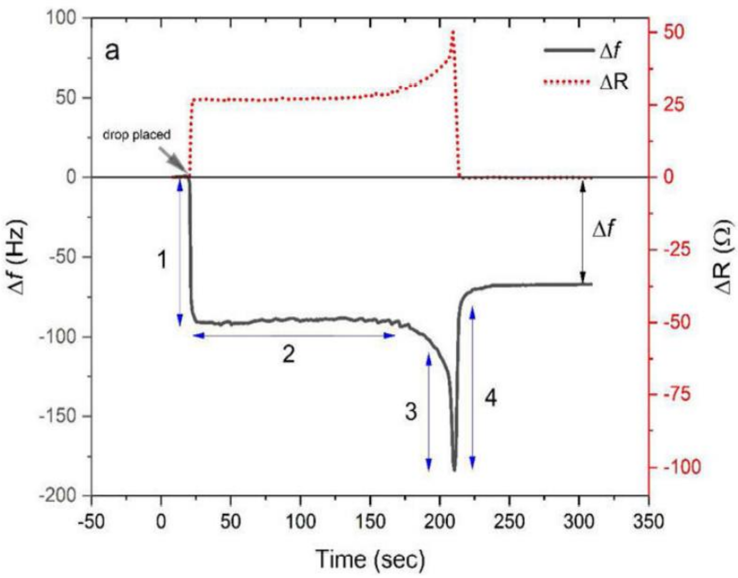

Figure 1.13 : Process of evaporation of a droplet containing combustion particles on QCM surface (Kaur et al., 2019).

As a result, as shown in Fig. 1.13 the crystal's oscillation became dampened at point 3, causing a sudden decrease in frequency and an increase in resistance. It's important to note that at this point, the particles were not yet firmly attached to the crystal surface because of a thin layer of water remaining between them. As soon as all the water evaporated, the frequency increases at point 4. This research concludes that QCMs hold promise as a direct method for measuring the mass concentration of combustion particle suspensions. This approach offers advantages like potentially overcoming the challenges associated with traditional techniques and enabling a more streamlined measurement process.

Another study introduces a groundbreaking instrument – a novel quartz crystal cascade impactor for real-time aerosol mass distribution measurement (Chen et al., 2016). It tackles the crucial task of quantifying airborne particles (aerosols) not just in terms of total concentration, but also by size. This size distribution is vital for understanding the health risks and environmental impact of aerosols. The QCM is cleverly integrated into a cascade impactor system. This system separates aerosols into distinct size fractions as they flow through the instrument. Imagine a series of filters with progressively smaller pores, each capturing a specific size range of particles as shown in Figure 1.14. Unlike traditional methods, the QCM cascade impactor provides continuous data on the mass of particles in different size ranges. This real-time aspect

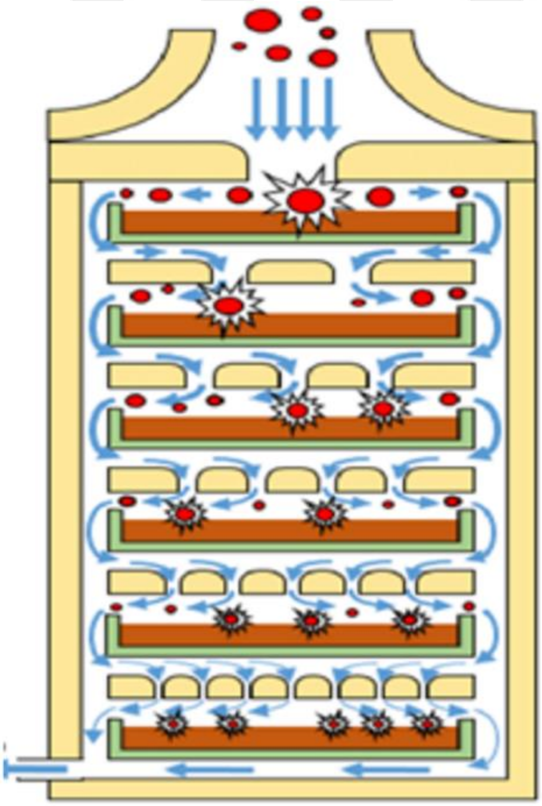

Figure 1.14 : Cascade impactor to differentiate the particles (Nayak et al., 2020).

allows researchers and environmental agencies to track fluctuations in aerosol concentrations throughout the day, week, or even year.

The cascade impactor separates aerosols into distinct size fractions. The QCM then measures the mass of particles collected in each size range. This detailed information is invaluable for understanding the health risks associated with different sized particles. For instance, PM2.5 particles, finer than 2.5 micrometers, can penetrate deep into the lungs, posing a more significant health threat than larger particles. Fluctuations in relative humidity can affect the mass of particles collected, potentially influencing the measurements (Figure 1.15). The research might discuss strategies for mitigating the impact of humidity on the instrument's performance.

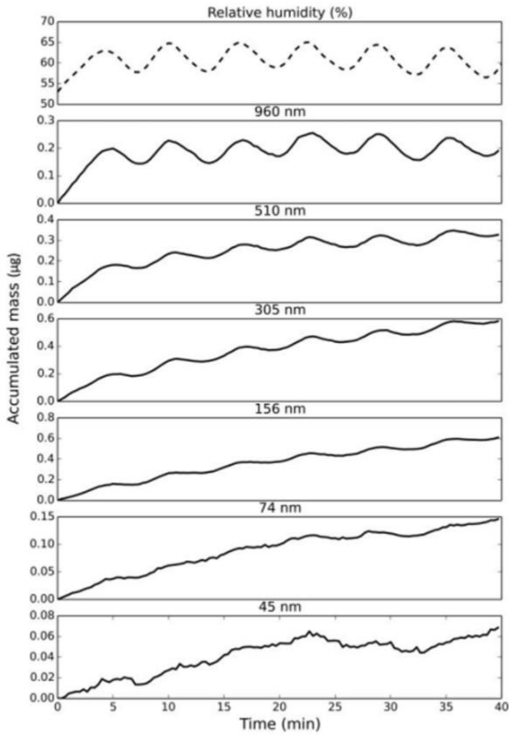

Figure 1.15 : Effect of humidity on accumulated mass on QCM surface (Chen et al., 2016).

Zempetti et al. explore a novel approach to improve the performance of QCM sensors for measuring PM (Zampetti et al., 2017). This innovation integrates a tiny heater directly onto the QCM as shown in Figure 1.16, potentially leading to more accurate and versatile PM detection. The research investigates the potential benefits of incorporating a microheater directly onto the QCM sensor. This microheater offers exciting possibilities such as desorption of volatile components and improved water vapor management. By carefully heating the QCM surface, the microheater can potentially desorb (release) volatile components present within the collected PM. This could be crucial for differentiating between volatile and non-volatile components of the PM, providing valuable insights into its composition. Controlled heating can potentially help evaporate water vapor adsorbed on the QCM crystal, minimizing its interference with the measurement of PM mass. This could lead to more accurate mass determination, especially in humid environments.

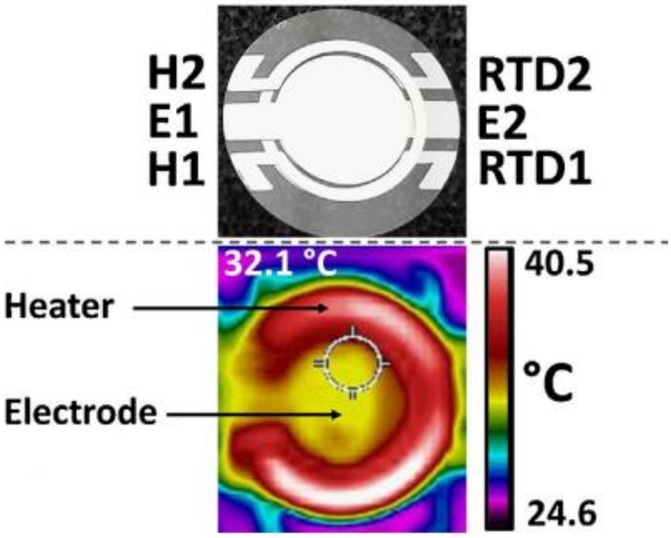

Figure 1.16 : CM sensor with integrated microheater. E1 and E2 stand for electrode, H1 and H2 for heater, RTD1 and RTD2 for temperature sensor poles (Zampetti et al., 2017).

Determining the ideal heating profile temperature and duration is crucial. Excessive heat could damage the QCM crystal or alter the properties of the PM itself. Similar to traditional QCMs, this new approach requires calibration using established methods like gravimetric analysis. This ensures accurate interpretation of the frequency shifts associated with PM mass and desorption events. While the microheater might offer insights into PM composition, it might not provide the same level of details as dedicated chemical analysis techniques. This study also positions the microheater-integrated QCM as a promising avenue for advancing PM measurement capabilities. By enabling the desorption of volatile components, the microheater could offer valuable clues about the chemical makeup of PM, complementing traditional mass measurements. Controlled heating can potentially minimize water vapor interference, leading to more accurate PM mass determination, especially in humid conditions. Further research might explore the potential of using the microheater for analyzing the size distribution of PM particles.

Figure 1.17 demonstrates how the microheater increased the QCM sensitivity.

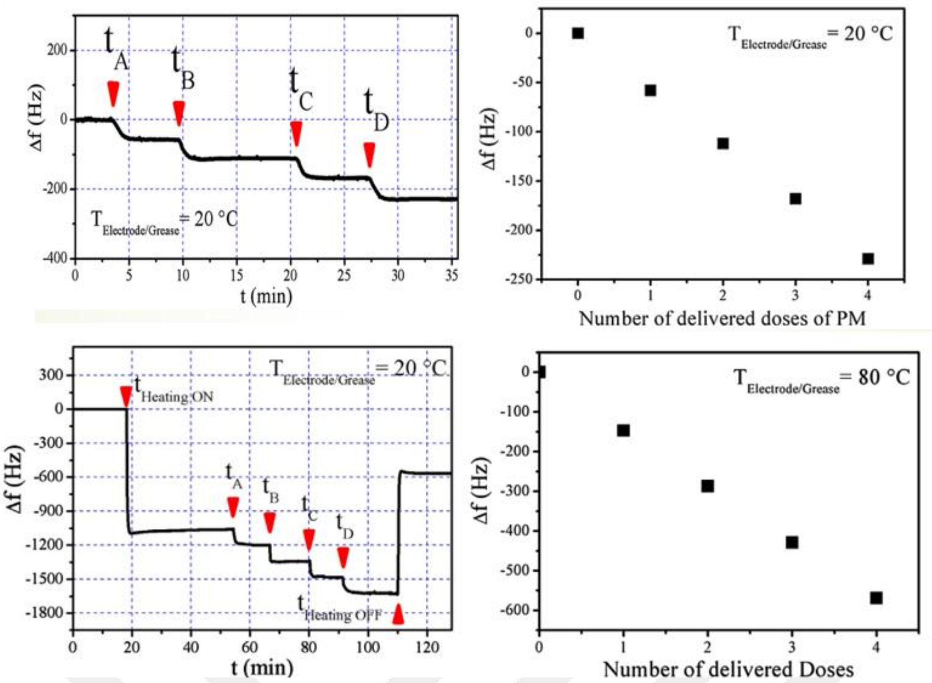

Figure 1.17 : The sensitivity of QCM without microheater (top) and with microheater turned on (bottom) (Zampetti et al., 2017).

Another study details a three-pronged strategy for PM detection using the MEMS-based resonant membrane (Singh et al., 2022). As shown in Figure 1.18, miniature version of a virtual impactor technology was employed to pre-concentrate larger PM particles before they reach the sensor membrane. This pre-concentration step enhances the sensor's sensitivity to detect smaller PM fractions.

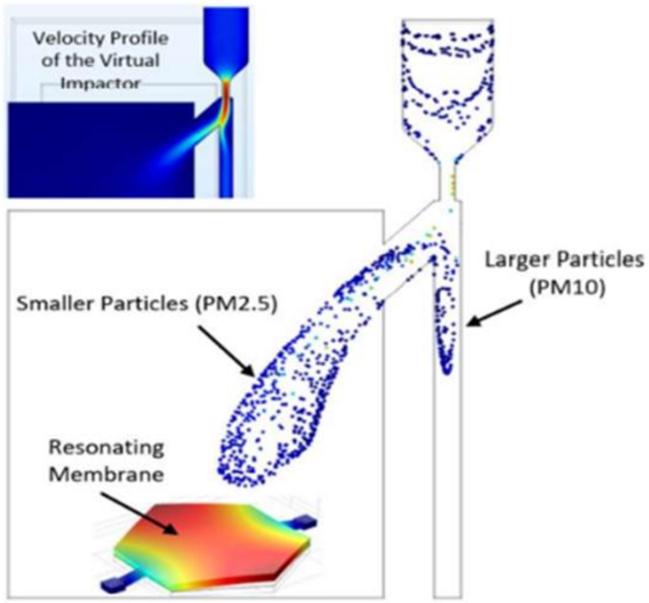

Figure 1.18 : Virtual impactor to separate lager PMs from PM2.5 (Singh et al., 2022).

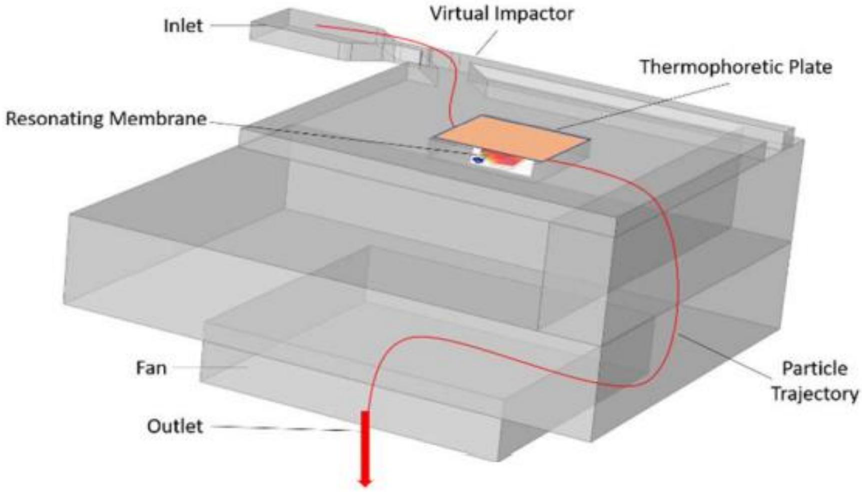

Figure 1.19 : Resonating membrane with implemented thermophoretic plate (Singh et al., 2022).

In this study also a strategically placed thermophoretic plate utilizes a temperature gradient to attract PM particles towards the sensor membrane, a further enhancement to the capture efficiency of the sensor (Figure 1.19).

Thermophoretic plates are a common method for enhancing PM collection efficiency. Studies have shown that increasing the temperature gradient (∇T) can significantly improve capture efficiency. For example, Figure 1.20 demonstrates that increasing the temperature gradient can result in a significant increase in PM collection efficiency.

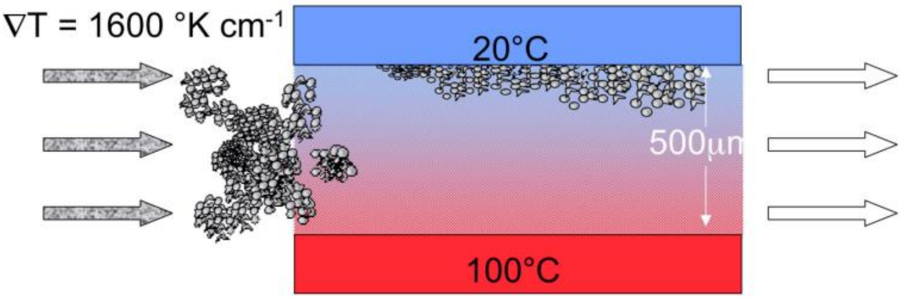

Figure 1.20 : Usage of thermophoretic plate for increasing the PM collection efficiency (Singh et al., 2022).

In terms of experimental setup for PM measurments, Byrne et al. focuses on using stable tracer aerosols to investigate how airborne particles deposit on surfaces within a controlled environment (Byrne et al., 1995). The research describes the design and functionalities of a test chamber used for the experiments. The paper discusses the size, material (e.g., aluminum), and air exchange rate of the test chamber. These factors influence how aerosols behave and deposit within the chamber. The research describes methods employed to ensure a uniform distribution of tracer aerosols throughout the chamber. This homogenous mixing is crucial for obtaining reliable data on deposition patterns. The paper mentions the specific types of surfaces (e.g., aluminum, wallpaper, polyethylene sheet) used within the chamber to represent various real-world scenarios.

Another describes the development and use of a specialized chamber designed to evaluate and calibrate instruments used for measuring airborne particles (Marple & Rubow, 1983). The research introduces an aerosol chamber as a more efficient and versatile alternative for instrument evaluation and calibration. The chamber design allows for the simultaneous evaluation of several instruments, optimizing testing efficiency. The chamber is designed to accommodate various types of aerosols, enabling researchers to evaluate instruments for measuring diverse particle characteristics. The size of the chamber can influence the types of instruments that can be accommodated and the scale of experiments that can be conducted. The study discusses strategies for ensuring uniform distribution throughout the chamber and temporal stability (consistent concentration over time) of the generated aerosols. This is crucial for reliable instrument evaluation. As shown in Figure 1.21, the setup has a turntable where the sensors are placed. This will allow to deliver more uniform flux to the sensors.

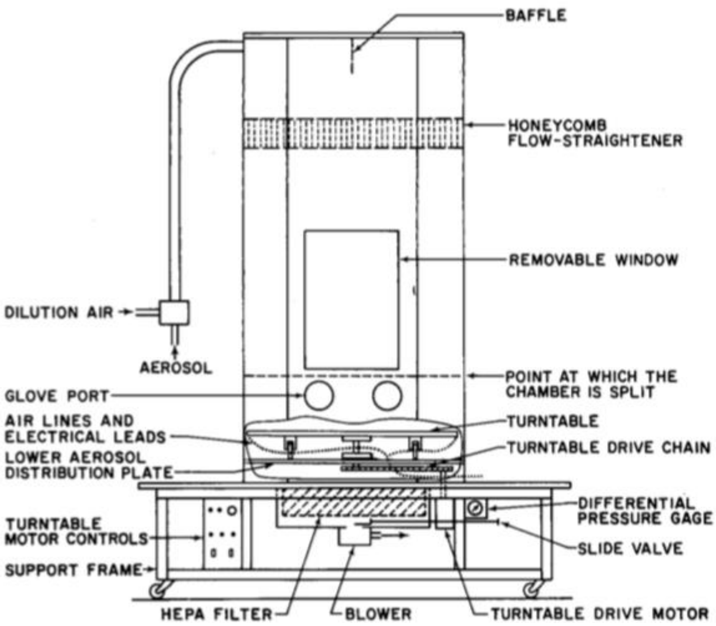

Figure 1.21 : Experimental setup to evaluate PM sensor tests (Marple & Rubow, 1983).

The research describes the methods used to generate aerosols within the chamber. These methods could involve atomization of liquid solutions, dispersion of dry powders, or combustion processes, depending on the desired particle characteristics.

Another study focuses on characterizing a specialized chamber designed to mimic real-world conditions for testing these sensors (Hapidin et al., 2019). This research explores the development and characterization of an aerosol chamber specifically designed for PM sensor evaluation. The chamber allows for generating aerosols with specific PM concentrations and size distributions, mimicking real-world scenarios. The controlled environment ensures consistent test conditions, enabling repeatable sensor evaluations. The whole experimental setup in this study is shown in Figure 1.22.

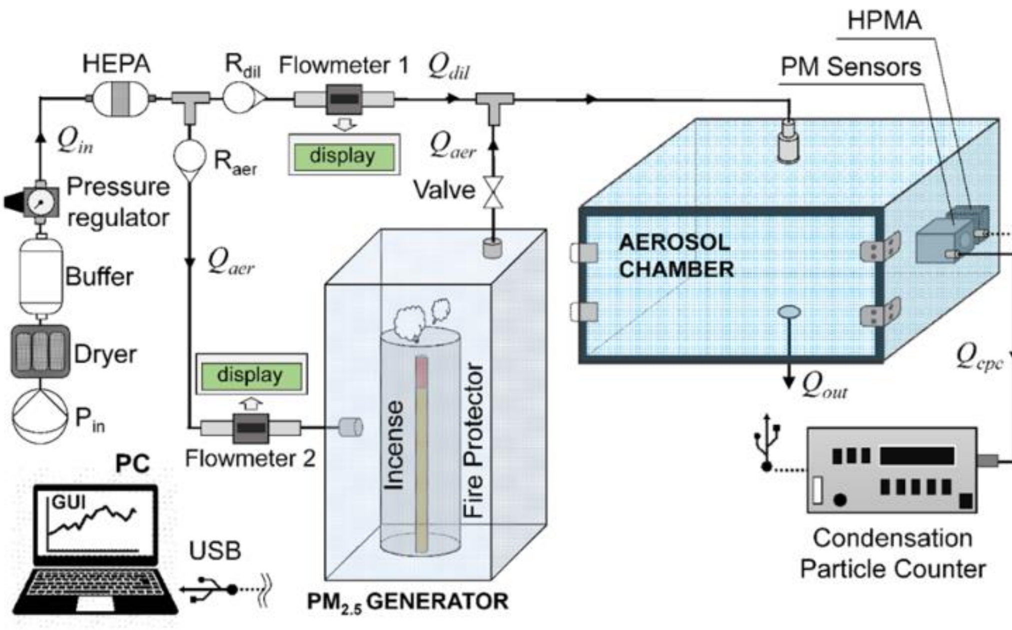

Figure 1.22 : Experimental setup to characterize the PM chamber (Hapidin et al., 2019).

The research describes how the PM concentration within the chamber decreases over time due to factors like settling and wall deposition. Understanding this decay profile is essential for designing test protocols with appropriate durations. The paper might explore methods for ensuring a uniform distribution of PM throughout the chamber. This uniformity is crucial for accurate evaluation, as any spatial variations could lead to skewed sensor readings.

1.4 Hypothesis

Developing and optimizing an experimental setup that incorporates features like controlled airflow velocity, particle size fractionation, generation of PM from various sources, controlling the temperature and relative humidity (RH) and real-time monitoring capabilities will significantly improve the sensitivity and accuracy of QCM-based PM sensor measurements compared to existing methods. This enhanced setup will allow for a more realistic simulation of real-world PM exposure scenarios, leading to a better understanding of the sensor's performance under varying environmental conditions. Additionally, the ability to fractionate particles by size will enable the QCM sensor to be evaluated for its effectiveness in detecting specific PM categories, such as the highly concerning PM1.

Changes in ambient temperature and relative humidity will affect the mass collection efficiency, resonant frequency response, and consequently, the accuracy of PM concentration measurements obtained using a QCM-based PM sensor. This thesis delves deeper by proposing a quantitative relationship between these environmental factors and the observed measurement uncertainties. The research will involve characterizing the sensor's response across a controlled range of temperatures and humidity levels. By establishing this relationship, researchers can develop correction algorithms or environmental compensation techniques to improve the reliability of PM concentration data obtained from QCM sensors in real-world deployments.

Coating the QCM sensor surface with a thin layer of a specifically chosen grease will enhance its PM capture efficiency, particularly for larger particles, while minimizing negative effects on sensor sensitivity compared to uncoated QCM sensors. This thesis can be further strengthened by proposing a specific mechanism by which the grease coating improves capture efficiency. For example, the research might explore the possibility of the grease acting as a size-selective filter, allowing smaller PM2.5 particles to adhere more effectively while minimizing the capture of larger particles that could dampen the sensor's response. Additionally, the research can investigate the optimal properties of the grease coating, such as viscosity and thickness, to achieve the desired balance between capture efficiency and sensitivity.

2. METHOD AND MATERIAL

2.1 Experimental Setup

To address the significant cost of commercially available equipment, this thesis presents a novel, custom-designed experimental setup for PM generation and sensing. Table 2.1 provides a summarize for common PM experimental setup device and their high costs.

Table 2.1 : Common devices used in PM test setup and prices.

Device	Description	Price(€)
TSI 3410U	Dry PM generator	40,000
TSI 3073	Smoke generator	12,000
TSI 8026	Wet PM generator	6,000
TSI APS 3321	PM analyzer	40,000
TSI 3062	PM diffusion dryer	3,000

In here we describe a cost-effective approach to PM experimental setups. To achieve this, we designed and manufactured a setup with low-cost devices. A breakdown of the components used in this custom design; is provided in Table 2.2. This table allows for a direct comparison with commercially available alternatives.

Table 2.2 : List of the parts that are used in PM experimental setup.

Device	Description
Sensirion SPS30	Laser PM sensor
Cubic PM2008	Laser PM sensor
SHT40	Temperature and RH sensor
FS1015	Airspeed sensor
OpenQCM Q-1	QCM Driver
OpenQCM sensor	5 MHz QCM sensors
Peltier 1276	For controling the temperature
ST7735(x2) LCD	To display PM data
0.96 OLED (x3)	To display RH and temperature
Omron Nubulizer	For wet PM generation
DC pump (x4)	To create flow in

Stepper motor	To push the piston
Servo motor (2)	To control valves
Fan (x5)	For PM dispersion
Plexiglass	Pipe and plate for manufactring
Filament	For 3D printing

2.1.1 PM generator

The designed setup consists of a PM generation part that can produce PM in three different ways mentioned in the coming sections.

2.1.1.1 Dry PM generator

This method generates PMs from dry powder. As illustrated in Figure 2.1, the generator consists of a piston moving inside a cylinder.

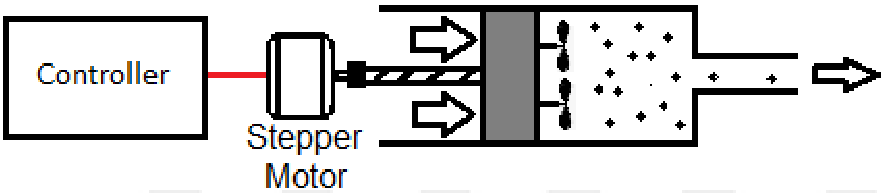

Figure 2.1 : Schematic diagram of the dry PM generator.

First, pressurized air disperses the dry powder throughout the cylinder. Two small fans ensure a uniform mixture within the cylinder. A stepper motor drives the piston forward via a threaded rod. As the piston moves, it pushes the particles out of the cylinder. The stepper motor speed controls the rate at which the piston displaces the particles. Figure 2.2 shows a real picture of the PM generator.

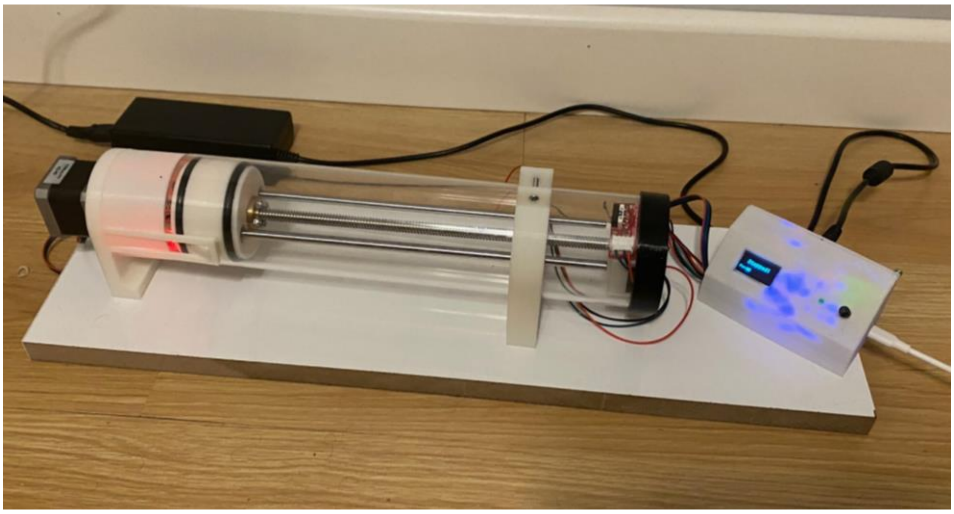

Figure 2.2 : Dry PM generator.

2.1.1.2 Wet PM generator

This system generates an aerosol containing PM originally suspended in water. First, dry chemical powders are mixed with water. As demonstrated in Figure 2.3, a nebulizer then evaporates the water from the mixture, creating a mist.

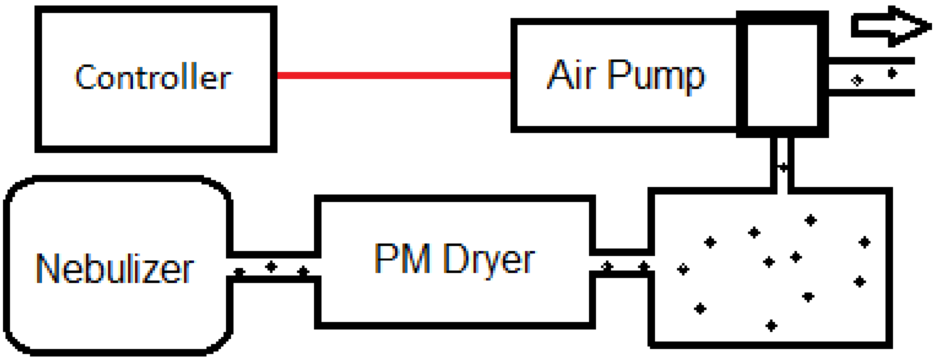

Figure 2.3 : Schematic diagram of the wet PM generator.

Nebulizer

A nebulizer (Figure 2.4) is a medical device that turns liquid medication into a fine mist that can be inhaled directly into the lungs. It uses compressed air to break up the medication into a mist. Here, the nebulizer breaks up the PM-water mixture into a fine mist.

Figure 2.4 : The nebulizer used in the wet PM generator system.

PM dryer

The mist travels through a specially designed PM dryer. The dryer consists of a network of pipes (Figure 2.5) that wind through a cylinder filled with silica gel beads. These pipes are made via digital light projection (DLP) 3D printer with photopolymer resin.

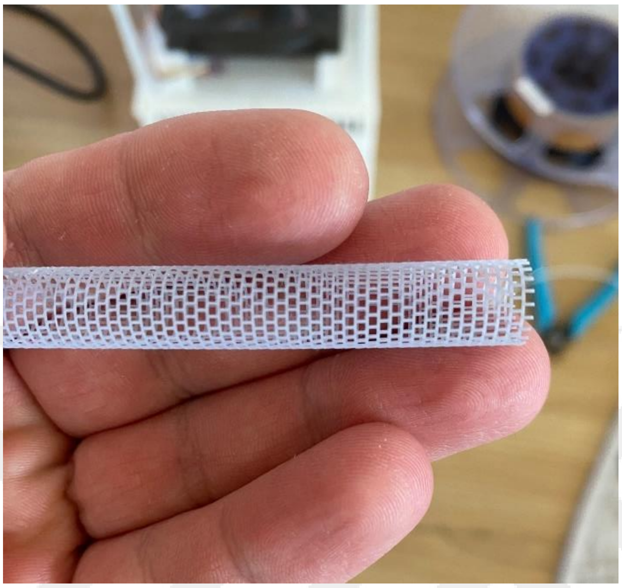

Figure 2.5 : 3D printed network pipe.

As the mist passes through these pipes, moisture diffuses from the mist to the silica gel, drying the particles. The design of this drying process is based on techniques used in commercially available devices. Figure 2.6 illustrates the final product of this device

Figure 2.6 : PM dryer.

Following the drying stage, a vacuum pump is used to extract the flux from the chamber.

2.1.1.3 Smoke generator

The third section focuses on generating smoke aerosols. As shown in Figure 2.7, this is achieved by burning an incense stick or cigarette within a dedicated smoke chamber, where the resulting smoke particles accumulate. Similar to the wet PM generator, an air pump draws the PM mixture out of the chamber.

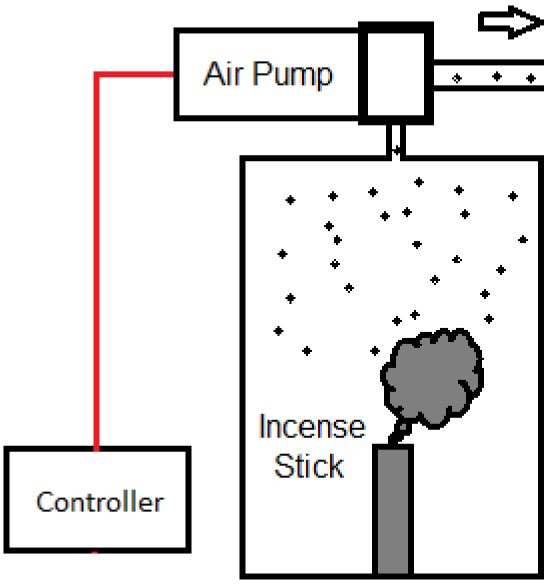

Figure 2.7 : Schematic diagram of the smoke generator.

Figure 2.8 shows the actual picture of the smoke Generator.

Figure 2.8 : Smoke generator.

Figure 2.9 portrays the entire PM generation unit within the experimental setup. Each PM generation parts are connected to a central microcontroller. This microcontroller governs the system's operation by selecting which PM generation method to activate and controlling its generation rate. Furthermore, the microcontroller connects to a PC for external control through a user interface.

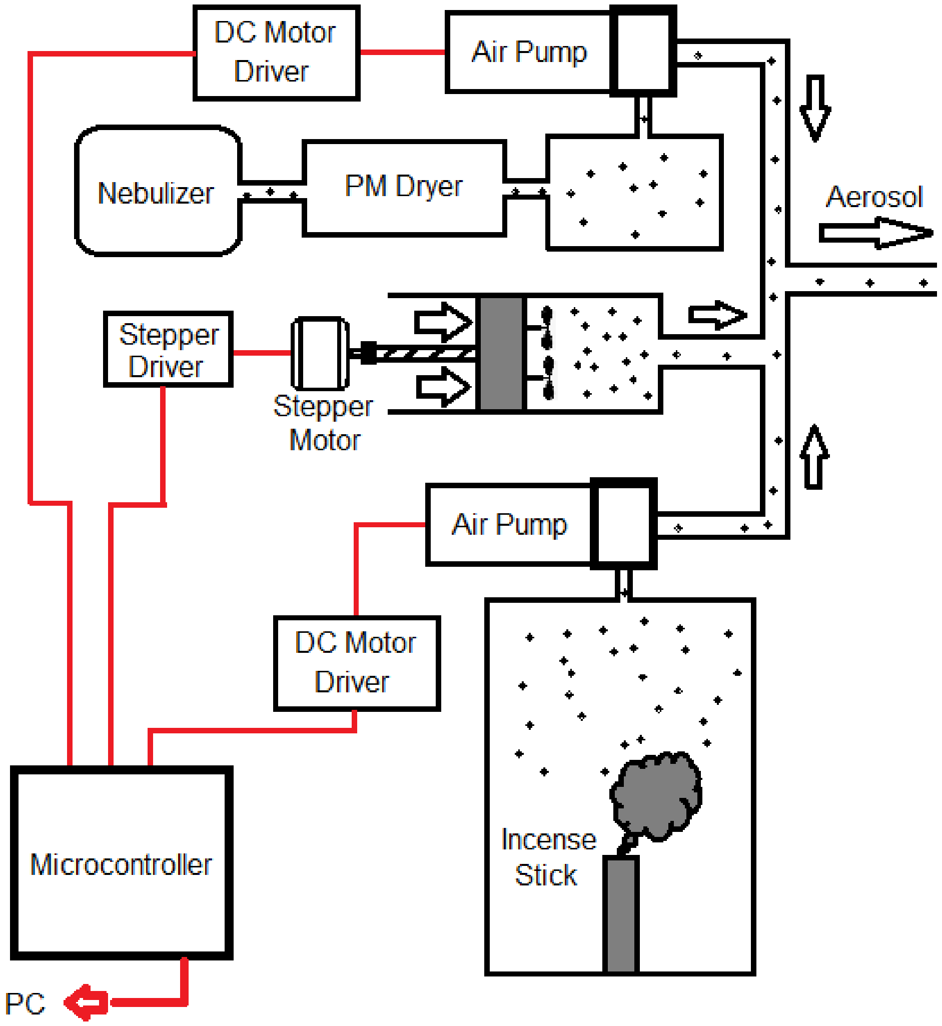

Figure 2.9 : Schematic diagram of the PM generation unit.

1.1.1 Mixing chamber

Following its generation, the PM mixture is directed to a dedicated mixing chamber, as illustrated in Figure 2.10 This chamber plays a critical role in conditioning the mixture by precisely controlling its temperature and relative humidity.

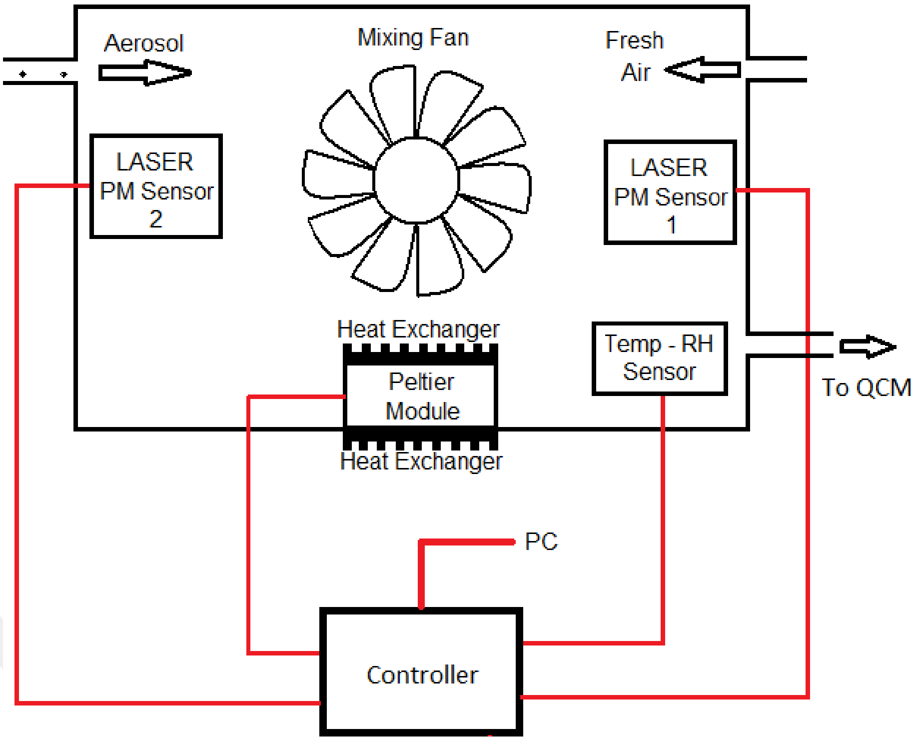

Figure 2.10 : Schematic diagram of the mixing chamber.

A Peltier module, a solid-state heat pump, resides within the chamber. This module can either heat or cool the mixture based on user-defined settings, ensuring optimal conditions for the experiment. A crucial component in maintaining these conditions is the continuous monitoring of internal temperature and RH. This task is handled by a Sensirion SHT30 sensor, which provides real-time data to the central microcontroller. As shown in Figure 2.11, to achieve the desired RH level, an electrically controlled mixing valve comes into play.

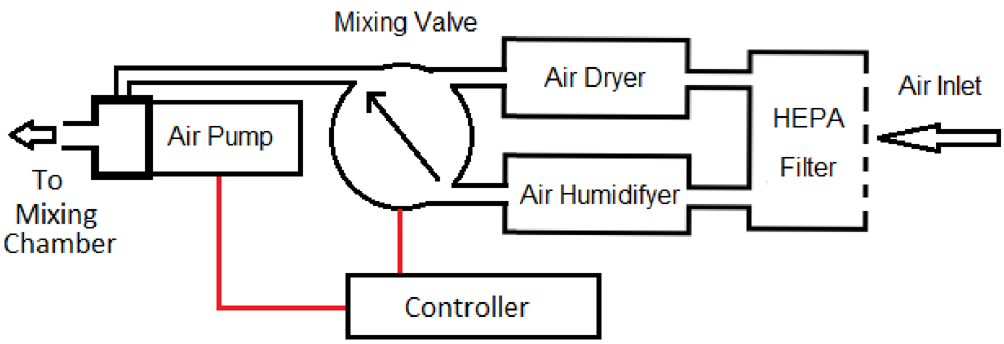

Figure 2.11 : Humidity control system.

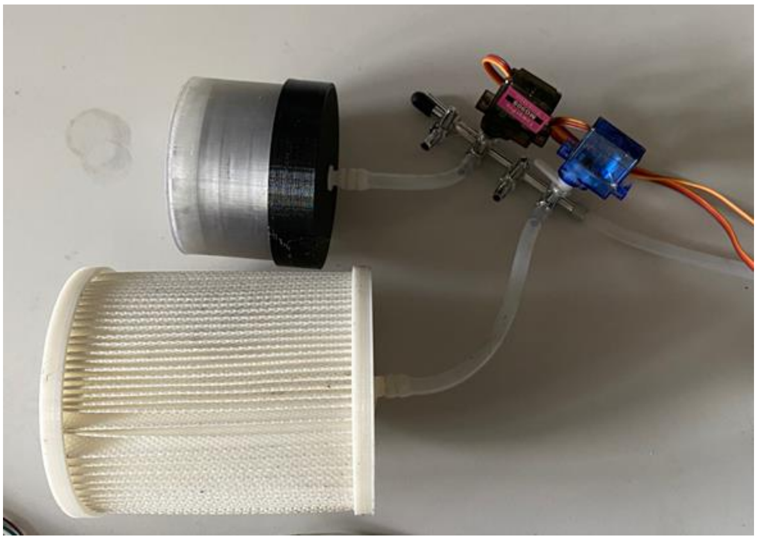

Figure 2.12 : The mixing valve system.

The mixing valve strategically regulates the flow of fresh air entering the chamber. As depicted in Figure 2.12, two connected servo motors precisely control the operation of this mixing valve. The source of this air can be either a HEPA-filtered humidifier or a dryer filled with silica gel desiccant. The humidifier, containing wet cotton, introduces moisture to the air stream, while the dryer efficiently removes moisture using the desiccant properties of silica gel. This allows for precise adjustments to the RH within the chamber.

Two laser-based PM sensors, the Sensirion SPS30 and the Cubic PM2008, are strategically positioned within the chamber. These sensors play a vital role in measuring the concentration of PM in the conditioned mixture. The collected PM concentration data is then transmitted to the QCM for further analysis.

The central microcontroller serves as the brain of this entire operation. It orchestrates the control of the Peltier module and the mixing valve, ensuring that the temperature and RH within the chamber are maintained at user-defined setpoints. Furthermore, the microcontroller acts as a data acquisition hub, collecting readings from all the sensors (PM concentration, temperature, and RH) and transmitting them to a computer for real-time monitoring and control. This comprehensive data allows researchers to not only monitor the entire process but also fine-tune various parameters to achieve the desired experimental conditions. Figure 2.13 illustrates the physical mixing chamber. It features two LCD displays prominently positioned to present real-time data acquired from the laser sensors monitoring PM concentration. Additionally, an OLED display

Figure 2.13 : Mixing chamber.

is integrated into the chamber, specifically dedicated to displaying real-time temperature and relative humidity (RH) readings obtained from the dedicated sensor.

2.1.2 QCM driver

This study utilizes a Q-1 QCM model and its corresponding driver unit, both obtained from OpenQCM, Italy. The employed QCM sensors are 5 MHz AT-cut crystals, also purchased from OpenQCM. Each sensor features a diameter of 13.95 mm and a thickness of 270 µm. A thin layer of gold (200 nm thick) serves as electrodes on both sides of the crystal.

Figure 2.14 : OpenQCM driver (left) and QCM sensor (right).

The standard top cover of the QCM is designed for liquid measurements, with the inlet and outlet positioned away from the sensor's center (most sensitive area (Huang et al., 2018)). However, for PM measurements, a modified top cover was implemented. This modified design, as detailed in Figure 2.15, places the inlet at the center for optimal sensitivity, surrounded by three strategically positioned outlets.

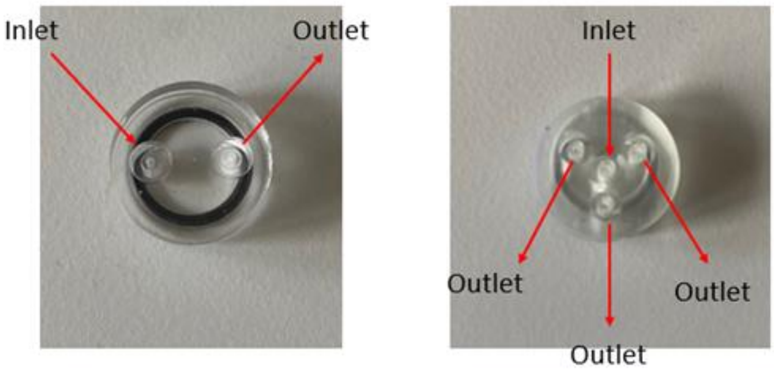

Figure 2.15 : QCM original top cover (left) and modified (right).

2.1.3 Suction pump

To maintain a stable flow of air through the QCM cell, a separate pump and controller unit are situated downstream at the cell's outlet as shown in Figure 2.16. This setup actively draws in air. An airspeed sensor, the Renesas FS1015, precisely measures the actual airflow rate. The microcontroller acts as a feedback loop, continuously monitoring the sensor data. By comparing the measured airflow rate to the desired setpoint, the microcontroller can adjust the pump speed to ensure the optimal flow rate for the experiment.

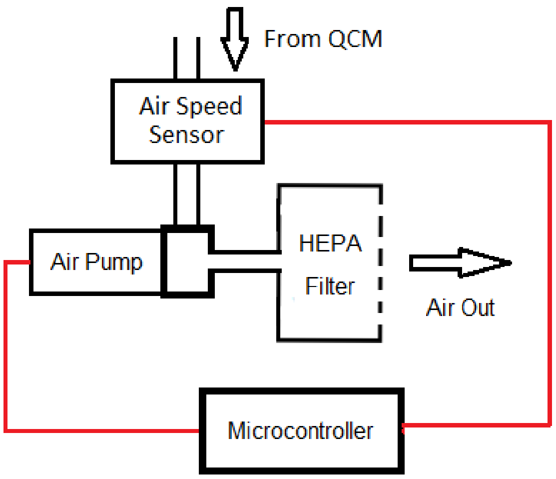

Figure 2.16 : Schematic diagram of suction pump.

The pump's flow rate was then meticulously calibrated using a manometer, as depicted in Figure 2.17.

Figure 2.17: Suction pump.

Figure 2.18 presents a comprehensive schematic diagram of the entire sensing system.

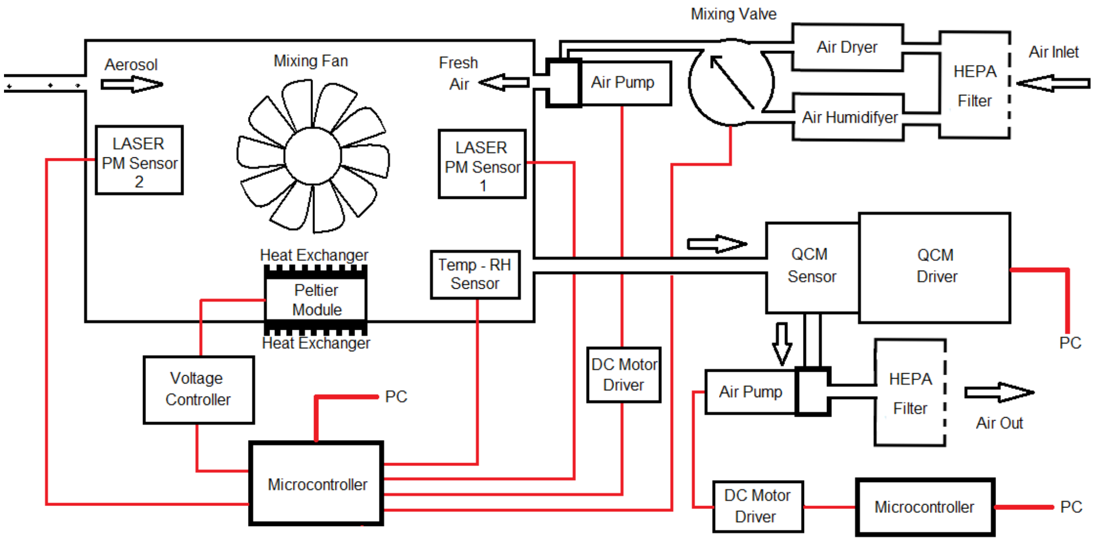

Figure 2.18 : Schematic diagram of sensing system.

2.1.4 QCM Coating

Several studies have explored coating techniques to enhance the sensitivity of QCM sensors for PM detection [Olsson et al., 2013; Palomba et al., 2001; Zampetti et al., 2017]. The primary objective of these coatings is to prevent particles from bouncing off the sensor surface, thereby improving their adhesion.

In this experiment, Apiezon-L grease was chosen as the coating material for the QCM sensors. To achieve a thin and uniform layer, the grease was first diluted with toluene in a 1:10 mass ratio. This diluted solution was then carefully sprayed onto the QCM surface using an airbrush as shown in Figure 2.19. Subsequently, the sensor underwent heating at 45°C within a vacuum chamber to ensure complete evaporation of the toluene solvent. The final coating thickness, measured using an optical profilometer, was approximately 1.2 µm. This coating resulted in a decrease of about 5 kHz in the baseline resonance frequency of the QCM. To assess the effectiveness of the coating, the sensor's performance was evaluated in both uncoated and coated states.

Figure 2.19 : QCM get coated via airbrush.

2.1.5 Electronic circuits

This section delves into the schematic diagrams of the electronic devices and circuits employed within the experimental setup. All of the microcontrollers that are used in this setup are STM32 F103 series microcontrollers.

Starting with temperature controller, as previously mentioned, the temperature control system utilizes a Peltier module to regulate the temperature of the air within the chamber. This module functions by either heating or cooling the air, depending on the desired settings. A Peltier module, also known as a thermoelectric cooler (TEC), is a solid-state device that uses electricity to create a heating or cooling effect. It works based on the thermoelectric effect, which is the conversion of heat into electricity and vice versa.

The Peltier module requires polarity reversal to switch between heating and cooling functions. To achieve this, as shown in Figure 2.20, one H-bridge transistor circuit, controlled by the microcontroller, is implemented. Due to limitations in controlling the Peltier's power using pulse width modulation (PWM), a buck converter is employed. This buck converter, also controlled by the microcontroller, regulates the Peltier's voltage and consequently its power output.

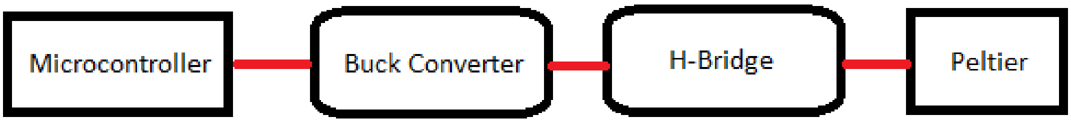

Figure 2.20 : Schematic diagram of temperature controller.

Individual DC motor drivers are employed to control each air pump. These drivers, in turn, receive control signals from the microcontroller, as illustrated in Figure 2.21.

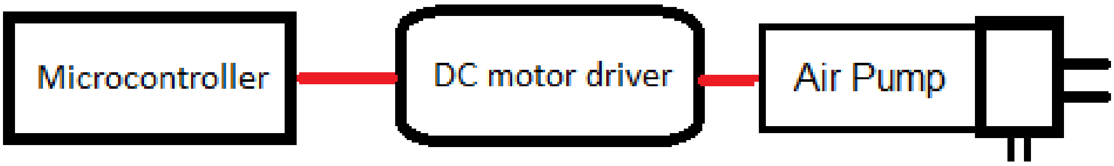

Figure 2.21 : Schematic diagram of air pump controller.

Consistent with the other devices, the stepper motor utilized in the dry PM generator is controlled by a microcontroller. A stepper motor driver acts as the intermediary, facilitating communication between the microcontroller and the motor, as detailed in Figure 2.22.

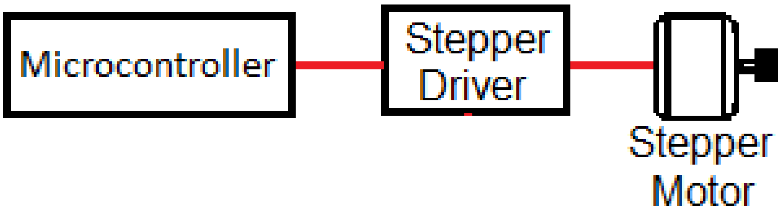

Figure 2.22 : Schematic diagram of the stepper motor controller.

2.1.6 Software interfaces

To facilitate data acquisition and control of the experimental setup, several software interfaces were created using Visual Studio. Figures 2.23 and 2.24 show the interfaces specifically designed for collecting data from the laser sensors.

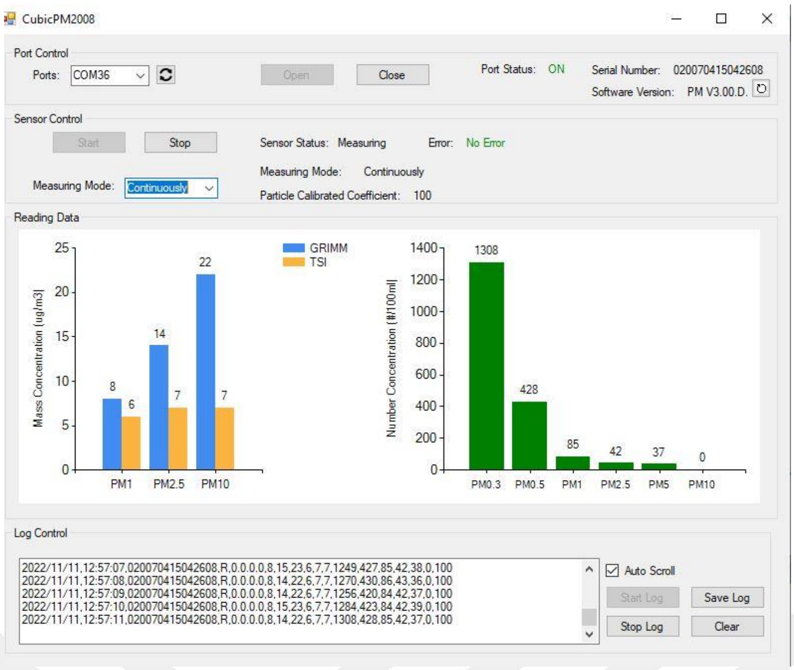

Figure 2.23 : Cubic PM2008 user interface.

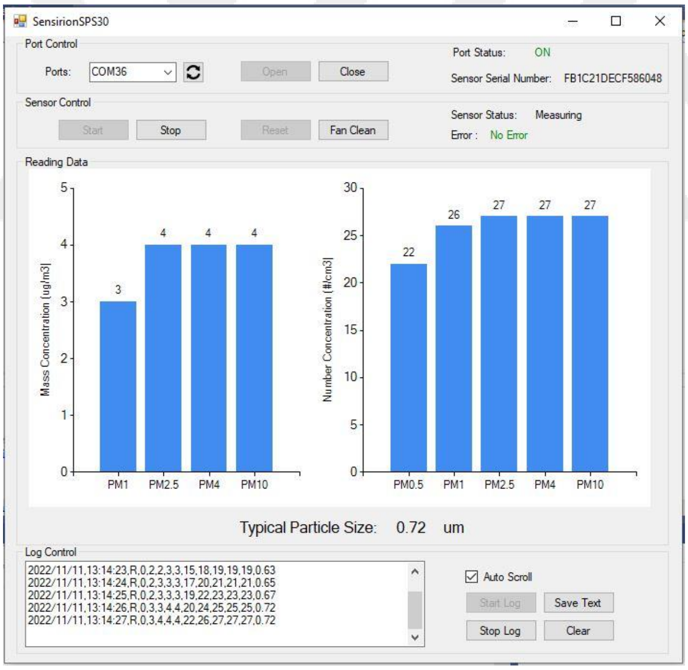

Figure 2.24 : Sensirion SPS30 user interface.

Similarly, Figure 2.25 presents the interface designed for controlling temperature and relative humidity, along with functionalities for real-time data acquisition of these parameters.

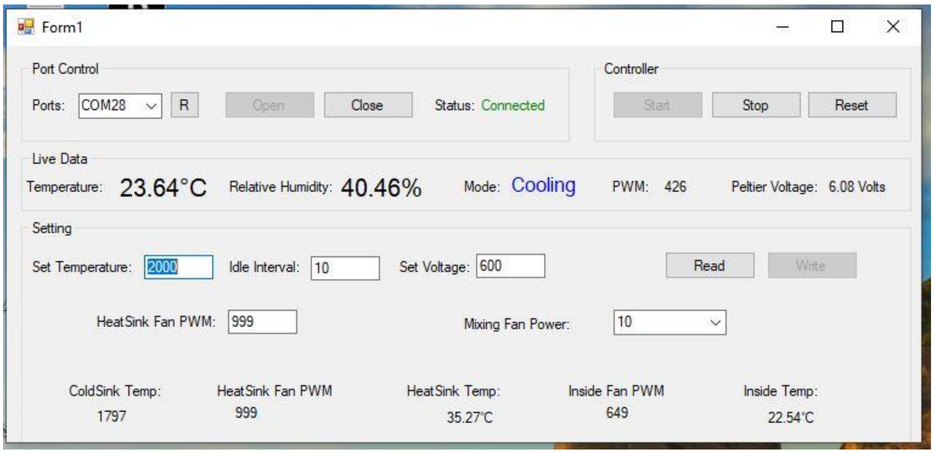

Figure 2.25 : Temperature and humidity controller interface.

2.2 Materials

Table 2.3 details the various materials employed for PM generation in this experiment. The investigation aimed to explore the influence of both particle size and material composition on sensor response. To achieve this, materials of identical composition were utilized in different sizes, and conversely, materials of varying compositions were employed in the same size range.

Table 2.3 : List of the materials used for PM generation.

Material	Formula	Size
Graphite	C	1 µm
Graphite	C	1 – 5 µm
Silicon carbide	SiC	1 µm
Boron carbide	B_4C	1 – 3 µm
Aluminum oxide	Al_2O_3	< 1 µm
Insence stick	-	< 1 µm

3. RESULTS AND DISCUSSION

Following the meticulous configuration of all experimental components and the completion of preliminary testing, the first experiment was conducted using smoke PM (the standard ambient condition for the tests was 25°C and 50% RH, except for cases examining temperature and RH effects). The corresponding response of the QCM sensor is illustrated in Figure 3.1.

The QCM sensor exhibited a high degree of sensitivity to temperature variations during testing. To mitigate this effect and ensure accurate measurements, a thermal equilibration period was implemented before commencing each test. This period allows the temperature of the QCM sensor to reach equilibrium with the incoming airflow.

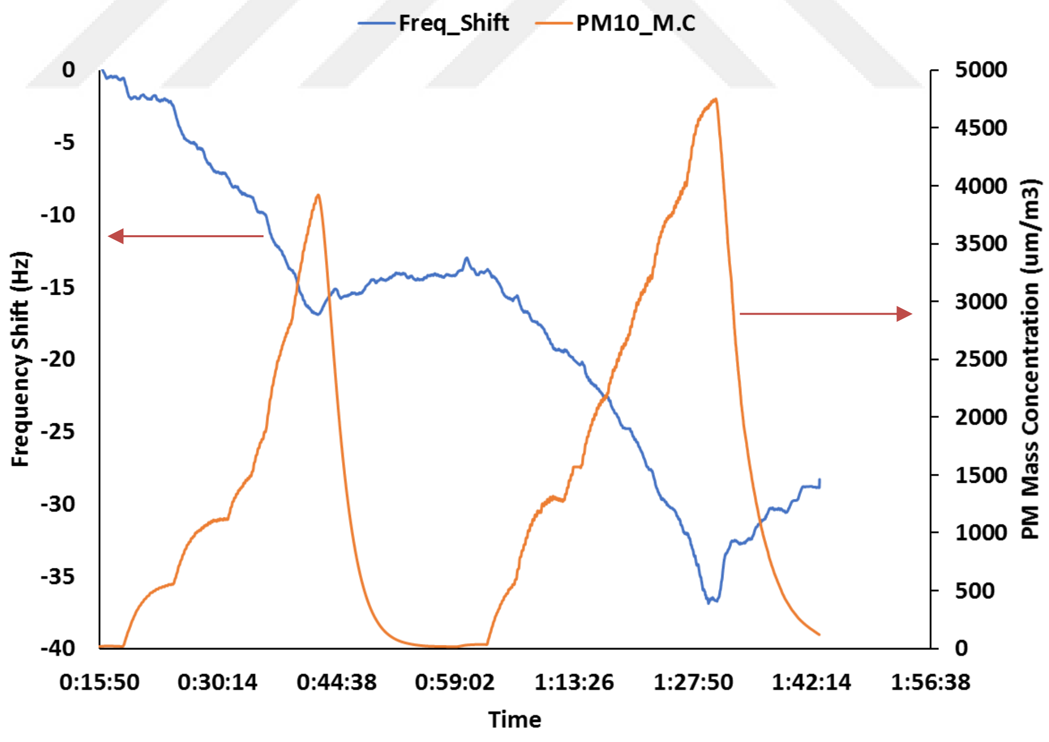

Figure 3.1 : QCM response to smoke PM.

While continuously running the QCM and pump provides real-time resonance frequency data, it doesn't directly reveal the rate of change in this frequency. To address this limitation and simplify the measurement process, this study introduces a novel method.

This method involves pulsed operation of the pump. The pump delivers air intermittently, with short idle periods in between. Each time the pump stops, the QCM's resonance frequency is recorded and compared to the value measured at the previous stop point. It's important to note that airflow itself can cause a slight shift in frequency, even without the presence of PM, as illustrated in Figure 3.2. This shift is temporary, and the frequency returns to its baseline value when the pump stops because no particles are deposited on the sensor surface.

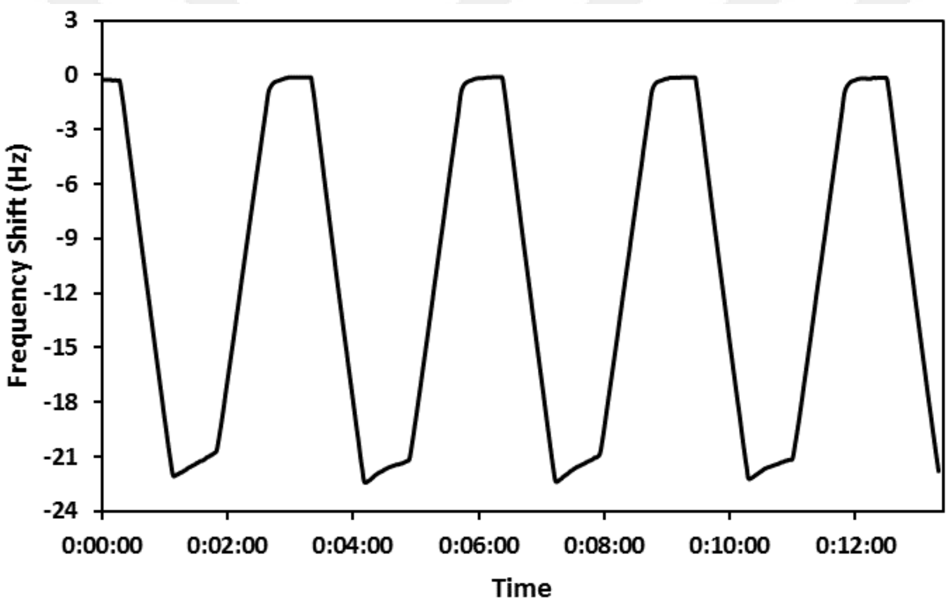

Figure 3.2 : Intermittent work of the pump and QCM response.

However, when PM is introduced into the airflow, as shown in Figure 3.3, the frequency at each stop point shows a decrease compared to the previous cycle. The magnitude of this decrease is directly related to the concentration of PM in the air. The PM mass concentration values indicated in the chart correspond to PM10, which encompasses all particles with a diameter less than 10 microns, as measured by the laser sensors.

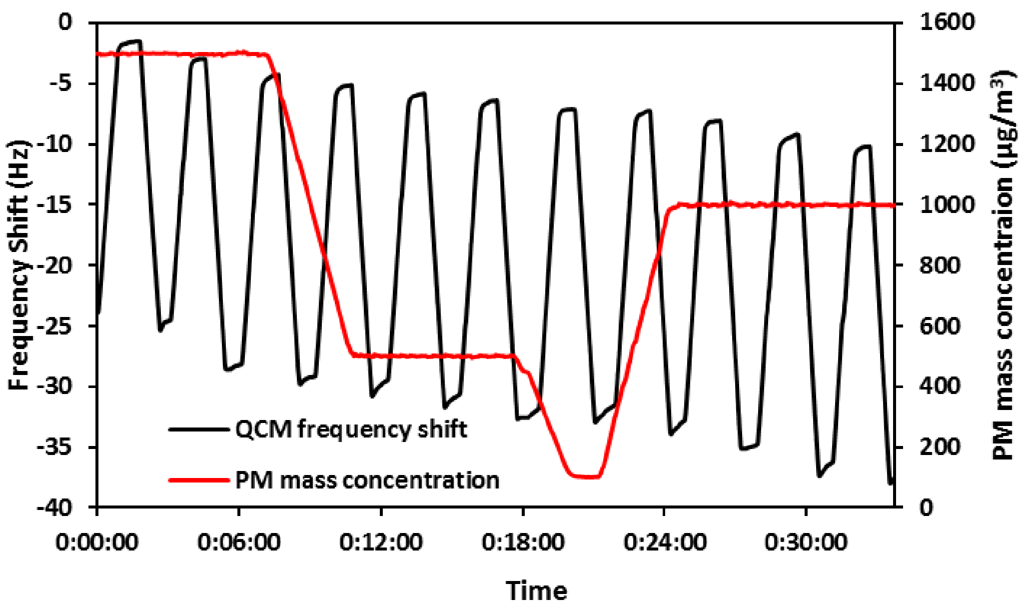

Figure 3.3 : Intermittent work of the pump with introduced some PM.

The optimal duration of the working and idle cycles can vary depending on the experimental conditions. These durations need to be carefully chosen to minimize any temperature fluctuations on the QCM surface while allowing sufficient time for a measurable amount of PM to deposit for an accurate response. In this study, the optimal values were found to be 1 minute for the working cycle and 1 minute for the idle cycle. Figure 3.4 demonstrates the sensor's response to varying concentrations of smoke particles using this optimized pulsed-pump method.

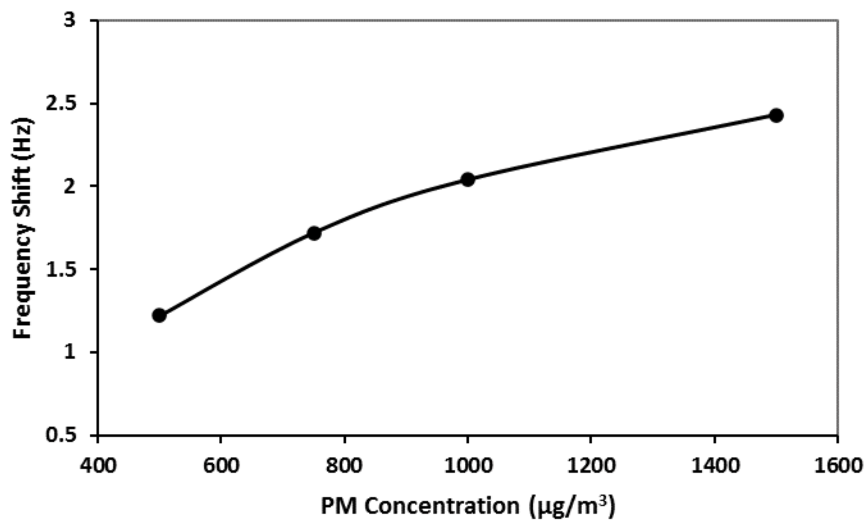

Figure 3.4 : Bare QCM response to smoke particles at various concentrations.

The airflow rate supplying the QCM was initially set at 1 liter per minute (lt/min) to optimize sticking efficiency for ultra-fine particles, as supported by Palomba et al (Palomba et al., 2001). However, to comprehensively evaluate the QCM's performance across a wider range of particle sizes, this study also investigated a reduced flow rate of 0.5 lit/min for tests involving larger particles. This lower flow rate helped mitigate particle bouncing from the sensor surface.

Experiments were conducted using a variety of materials listed in Table 2.3. The QCM frequency shift for each material, measured using the established intermittent method, is shown in Figure 3.5. From these results we can investigate the effect of particle size on the response of the QCM. Graphite particles of two sizes were used;1 µm diameter and a range of 1-5 µm in diameter. As shown in Figure 3.5, increasing the graphite particle size led to a 25% decrease in the bare QCM response when the particles were generated using the dry method. This could be explained by the impact value formula, which relates the force of an impact to the mass (m) and velocity (V) of the particle:

$$\vec{I} = m.\vec{V} \tag{3.1}$$

Larger particles typically exhibited higher impact forces during their interaction with the sensor surface. These stronger impacts often resulted in the particles bouncing off the surface rather than adhering to it, leading to a minimal QCM response.

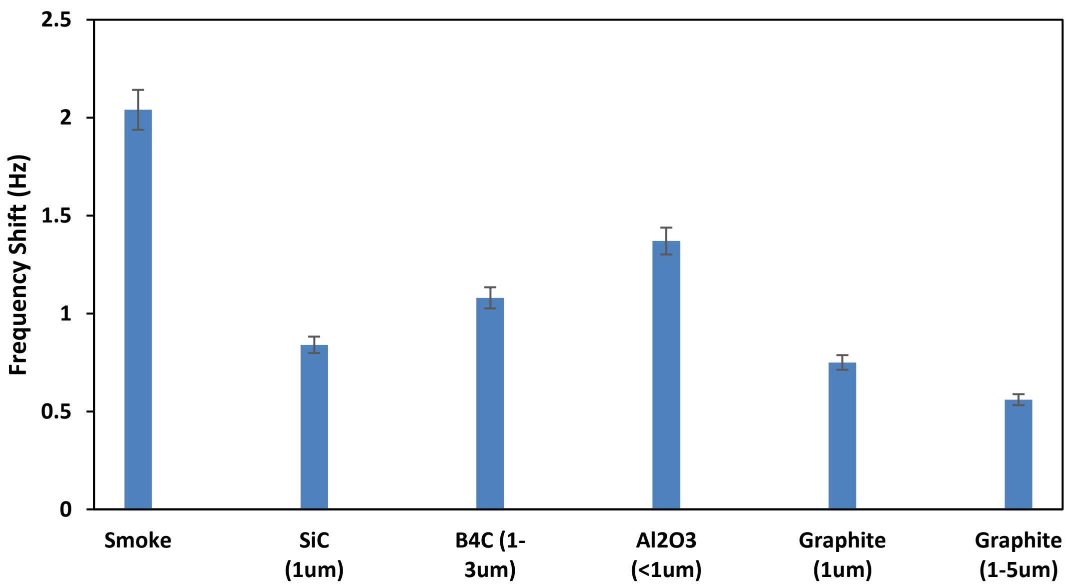

Figure 3.5 : QCM response to dry PM’s.

To address this challenge and improve the adsorption of larger dry particles, the airflow rate was strategically reduced from 1 lit/min to 0.5 lit/min. This effectively decreased the particle velocity, allowing for lower impact value and also more time and a gentler interaction with the sensor surface, thereby promoting their adhesion. To ensure a consistent sampling volume despite the reduced flow rate, the pump operation time at 0.5 lpm was doubled compared to the 1 lpm setting. As Figure 3.6 clearly demonstrates, this approach demonstrably enhanced the QCM response for larger particles. Notably, the effect on fine PM was minimal, suggesting that the original flow rate of 1 lpm was already sufficient for efficient capture of these smaller particles.

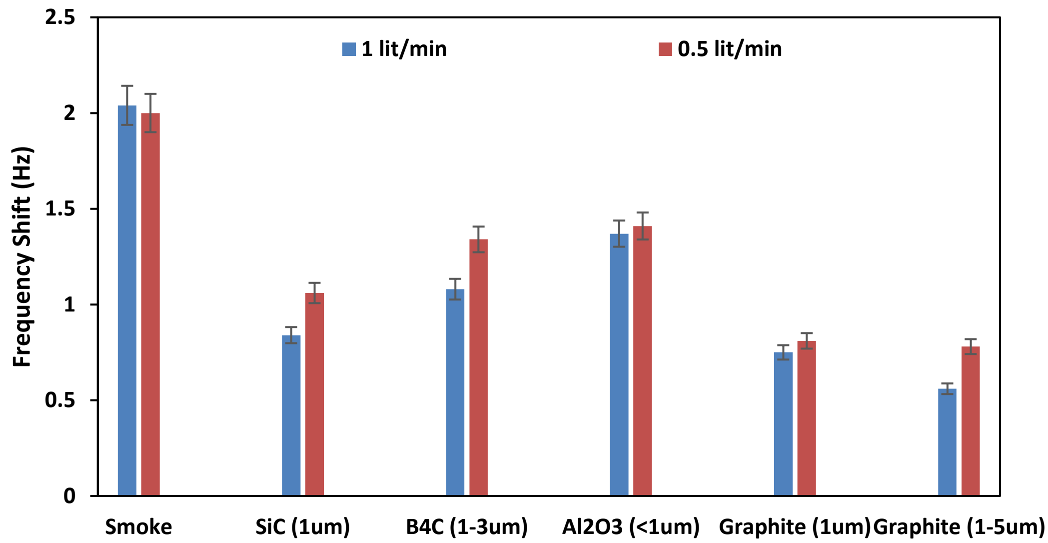

Figure 3.6 : Comparison of QCM response to dry PM's with different speeds.

Comparing the QCM response to silicon carbide and graphite, both of which have a 1 μm diameter, we observe that silicon carbide exhibits a 10% higher response than graphite. This indicates that particle size is not the only factor influencing the QCM response; particle composition also plays a significant role. Several factors may determine this effect, including particle elasticity, which reduces bounce from the QCM surface; electrostatic forces, which cause particles to stick to the QCM surface; and covalent bond forces, which help gather particles together on the QCM surface.

Another approach investigated in this study involved generating the same particles using the wet method. This method yielded an average of 11% improvement in the QCM response compared to the dry method as illustrated in Figure 3.7. The presence of a small amount of residual moisture on the particles from the wet generation process increased their adhesion coefficient to the sensor surface.

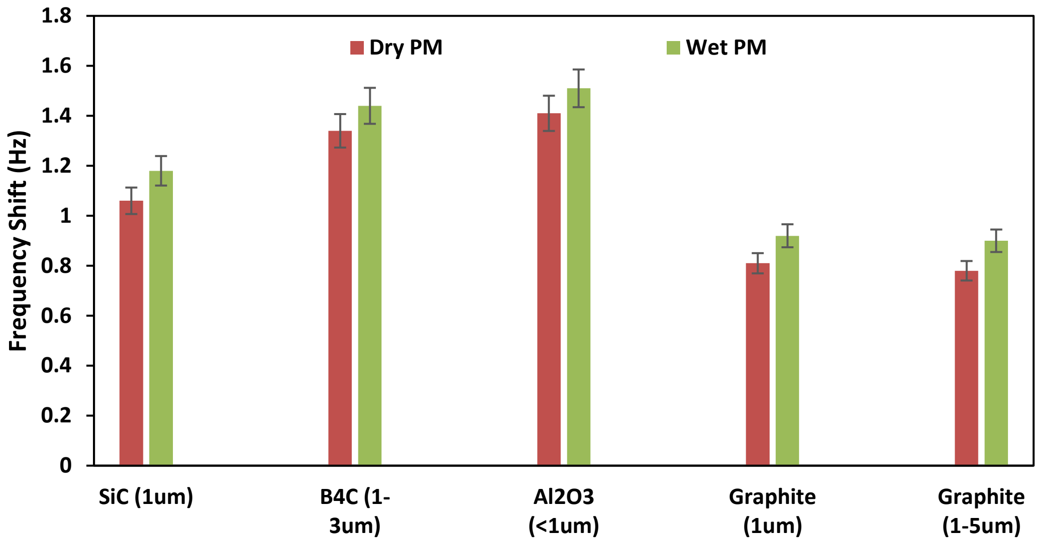

Figure 3.7 : Comparison of QCM response to dry and wet PM’s.

These findings highlight that not only the physical size of the particle but also its material composition plays a significant role in sensor response. The variation in response observed for different materials can be attributed to the differences in their intrinsic properties, such as elasticity and surface characteristics that influence electrostatic forces. These forces can either attract or repel particles depending on the materials involved.

The implemented coating significantly improved sensor response by minimizing particle bounce and maximizing sticking efficiency, particularly for larger particles, as shown in Figure 3.8. This improvement can be attributed to the fact that the coating creates a softer, more compliant surface that dampens the impact of incoming particles, allowing for better adhesion. Additionally, the coating helps reduce discrepancies in sensor response caused by variations in particle size and material composition. This is likely because the coating provides a more uniform interaction surface for all particles, regardless of their inherent properties. However, it is important to note that the influence of temperature on sensor response becomes more pronounced when using a coating. This is likely due to changes in the viscoelastic properties of the coating material (Apiezon-L grease) at elevated temperatures. As the temperature increases, the grease may become softer and more fluid, potentially affecting its ability to effectively capture particles and leading to variations in the sensor response.

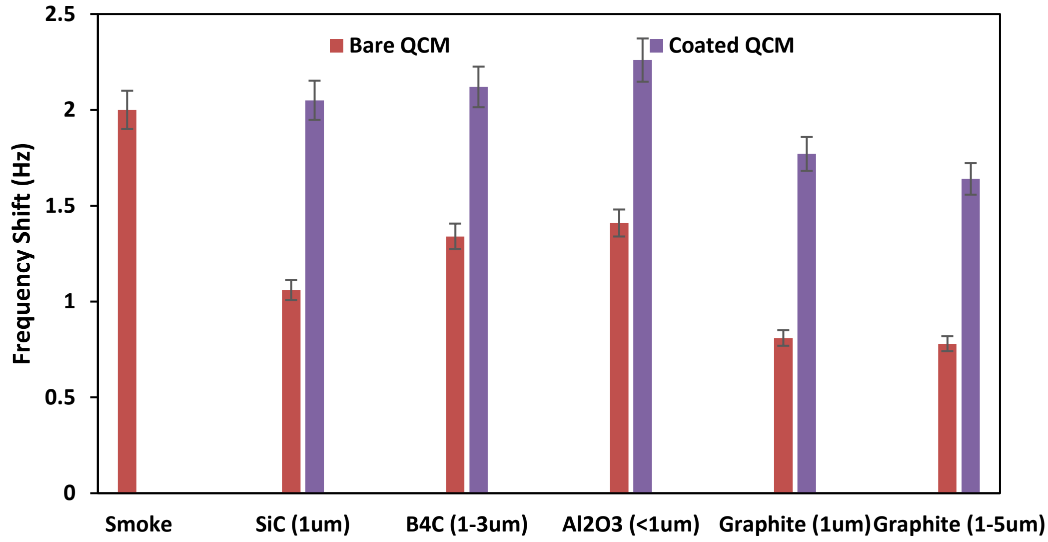

Figure 3.8 : Comparison of the results for bare and coated QCM.

To provide a comprehensive comparison of all the tests and methods applied, the complete results are presented in Figure 3.9.

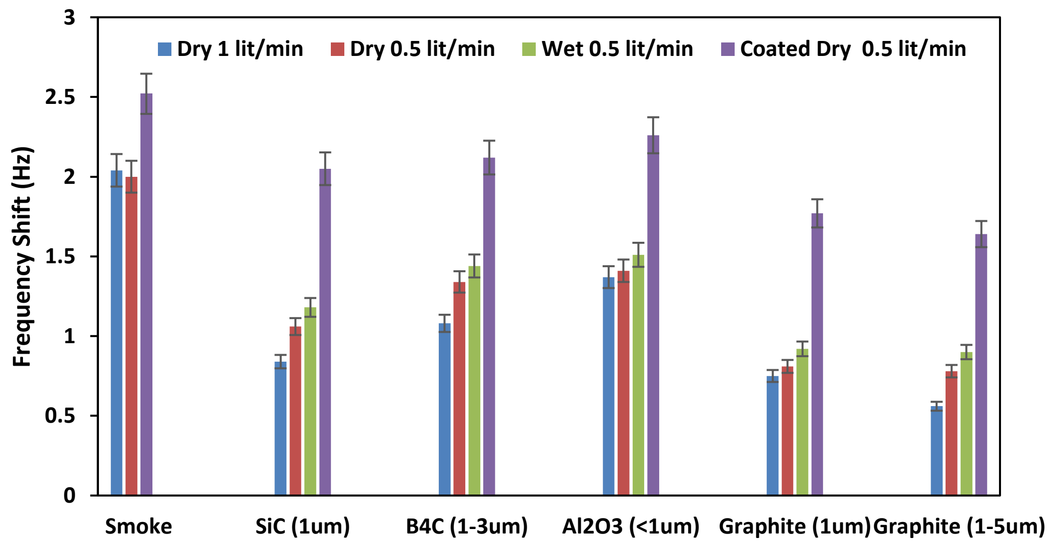

Figure 3.9 : QCM response to different PMs in various condition.

Figure 3.10 explores the QCM sensor's response to dry and smoke particles under varying humidity conditions. The standard test condition employed a base RH of 50%, with experiments conducted at both higher and lower RH values for comparison. The results clearly reveal that the sensor response is indeed influenced by changes in RH, with this effect being more pronounced for dry particles. This can be attributed to the fact that dry particles have a greater tendency to form water vapor bonds with the sensor surface when exposed to increased humidity. These bonds enhance particle adhesion, leading to a stronger sensor response. Smoke particles, on the other hand, possess an inherent oiliness that facilitates their adhesion to the sensor surface. Consequently, the presence or absence of moisture has a less significant impact on the response for smoke particles compared to dry ones.

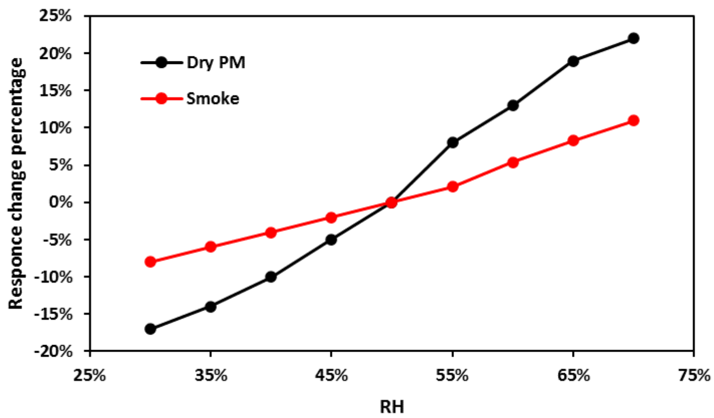

Figure 3.10 : Effect of humidity on the QCM response.

The influence of temperature on sensor response was also investigated, as shown in Figure 3.11. For bare sensors (without coating), temperature changes within the investigated range (25°C to 30°C) did not produce significant variations in the sensor response. This is because the primary mechanism of particle adhesion remains unaffected by moderate temperature fluctuations. However, for sensors coated with Apiezon-L grease, temperature plays a more prominent role, with the response increasing up to 12% as the temperature rises from 25°C to 30°C. This can be explained by the changes in the viscoelastic properties of the grease at elevated temperatures. As the temperature increases, the grease may become softer and more fluid, potentially altering its ability to capture particles effectively. This can lead to variations in the sensor response, particularly for larger particles that might experience a weaker adhesion force on a softer coating surface.

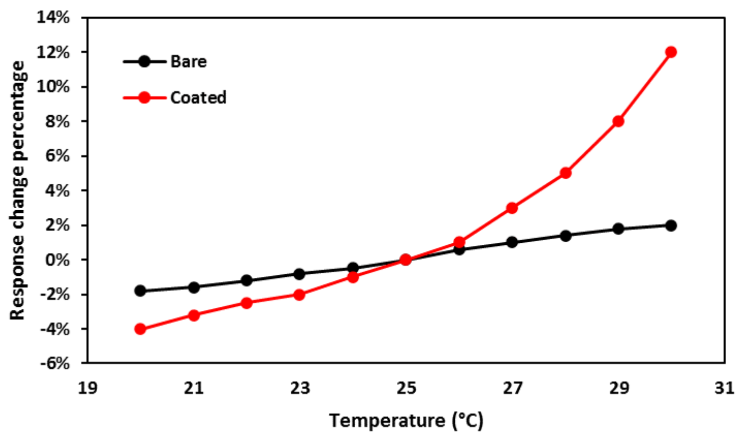

Figure 3.11 : Effect of temperature on the QCM response.

The experimental results demonstrate the complex interplay between particle size, material composition, airflow rate, and the presence of a coating in influencing the QCM sensor response. By carefully considering these factors and implementing appropriate strategies such as optimizing airflow rate and using a coating, the sensitivity of the QCM sensor for PM detection can be significantly enhanced. These findings highlight the importance of considering both particle properties (size and composition) and environmental conditions (RH and temperature) when interpreting QCM sensor responses for PM detection. The interplay between these factors can significantly influence the sensor's performance.

4. CONCLUSION

This study has comprehensively evaluated the performance of a QCM sensor for aerosol concentration sensing under various conditions. The investigation explored the sensor's response to different particulate matters with varying sizes and compositions, along with the influence of environmental factors such as relative humidity and temperature. The findings highlight the interplay between these elements and their impact on the QCM's suitability for PM detection.

A key takeaway is the significant influence of particle size and composition on the sensor response. The QCM exhibited greater sensitivity towards smaller particles, particularly those generated by smoke, compared to larger PM. This suggests the sensor's potential for applications where fine particle detection is crucial, such as monitoring indoor air quality or occupational exposure to airborne particulates.

The implementation of a grease coating on the QCM surface emerged as a successful strategy to improve sensor response, especially for dry particles. The coating demonstrably enhanced particle adhesion, leading to a stronger overall signal. Additionally, the coating helped mitigate variations in response caused by differences in particle characteristics, promoting more consistent sensor performance across a wider range of PM types.

Furthermore, the study examined the effect of environmental conditions on the QCM response. Increased RH values were found to enhance the sticking efficiency of dry particles on the sensor surface, leading to a more pronounced response. This highlights the importance of considering environmental humidity when interpreting QCM data, particularly in applications where ambient humidity levels can fluctuate. Conversely, the influence of temperature variations within the investigated range was found to be negligible for bare QCM sensors. However, coated sensors exhibited a heightened response to temperature changes due to alterations in the viscoelastic properties of the coating material. This finding underscores the need for careful calibration and potential temperature control measures when using coated QCM sensors in environments with significant temperature variations.

The study also acknowledges the complementary strengths and limitations of QCM and laser-based PM sensors. While laser sensors excel at detecting the number and size of larger particles, QCMs demonstrate a clear advantage in detecting smaller, smoke-like particles where lasers have limitations. This complementary nature suggests that combining these two techniques in an array could create a more powerful PM monitoring device. A synergistic system that leverages the strengths of both laser sensors (effective detection of large particles) and QCM sensors (superior sensitivity to ultra-fine particles) has the potential to provide a more comprehensive and informative characterization of PM concentrations in various environments. This combined approach holds promise for the development of robust and advanced PM monitoring systems capable of capturing the complexities of real-world aerosol environments.

Environmental factors and particle characteristics significantly influence QCM sensor response. Variations in PM size and composition can substantially alter the sensor's signal. For instance, relative humidity can increase the response by up to 22%. While temperature fluctuations in the airflow have minimal impact on bare QCM sensors, coated sensors exhibit a 12% response increase when temperature rises from 25°C to 30°C. Interestingly, the QCM demonstrates its best performance with small-sized smoke PM, exhibiting minimal influence from ambient conditions like humidity and temperature.

Enhancing selectivity and specificity could be the potential areas for future studies in PM sensing with QCM technology. Develop new QCM coatings that can selectively bind to specific PM types (e.g., differentiate between organic and inorganic particles, or even identify types of pollutants based on chemical signatures). This would allow for more detailed air quality analysis. Miniaturization and integration of QCM in portable devices for real-time air quality monitoring in various environments, both indoors and outdoors, would enable more widespread air quality data collection. As a high-tech step, machine learning and data analysis for PM identification by utilizing algorithms to analyze the QCM response data to identify specific PM types or sources could lead to more automated and intelligent PM monitoring systems.

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2012-2013 Haftan Consulting Engineers Co., Ardabil, Iran Design and execution of building utility projects. Position: Junior Consultant. This was my first working experience; me and my teammates job was to design the air conditioning systems of buildings.

2013-2014 Ghazal Goldsmith, Tehran, Iran. Position: CNC machine operator. In here my job was to draw the desired designs in AutoCAD and convert them to G-Codes for working with CNC machines.

2016-2017 TAI – ITU Very Light Aircraft Project, Powertrain Group. (Part time work)

2016-2020 Istanbul Technical University Automotive laboratory, Istanbul, Turkey. I started to work in here when I was M.Sc. student. I did lots of experiments with internal combustion engines and electric motors and also accomplished my M.Sc. thesis about Internal Combustion Engine. I have also designed a new engine control unit (ECU) and published a paper about it. I also worked with electric motor used in the fully electric cars and their control units and did lots of tests about power consumption efficiency of them. I also was a scholarship student in a TUBITAK supported project during this time and gained lots of experience in engine/electric motor testing setups.

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- **Javadzadehkalkhoran, M., Trabzon, L**. Preparation and Characterization of Affordable Experimental Setup for Particulate Matter Sensing. Sens Imaging 25, 29 (2024). https://doi.org/10.1007/s11220-024-00479-0

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