A Literature Survey on Optical Particle Counter (OPC) Technologies

Mahesh Nikam[1], **Prachi A Deshpande**[2]

[1] M.E.II, Dept. of Electronics & Tele-Communication Engineering, Dhole Patil College of Engineering, Kharadi, Pune, Maharashtra, India.
[2] Professor, Dept. of Electronics & Tele-Communication Engineering, Dhole Patil College of Engineering, Kharadi, Pune, Maharashtra, India.

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Abstract - *The adverse effects of particulate matter (PM) on human health and the environment have led to increased attention on air quality monitoring over the past few decades.[1] In response to this need, mobile, low-cost, and real-time PM detection devices have become more prominent in research and application. Recently, researchers have introduced innovative mobile optical particle counters (OPCs) to meet the growing demand for real-time PM monitoring in both indoor and outdoor environments. However, there remains a scarcity of comprehensive reviews on these new mobile and compact PM measurement technologies. This paper aims to address this gap by reviewing the latest advancements in mobile OPCs for particulate matter detection, with a focus on applications ranging from general air quality monitoring to specific uses like vehicle exhaust analysis.*

Key Words: mobile optical particle counters, particulate matter, air quality monitoring, observation volume, vehicle exhaust.

1.INTRODUCTION

Optical Particle Counters (OPCs) operate on the principle of laser scattering, a technique that allows these devices to detect and estimate the size of airborne particles by measuring how they scatter light. In an OPC, a light source, typically a laser or an LED, emits a focused beam into a chamber through which air is drawn. As particles pass through this light beam, they scatter light in various directions. Detectors positioned around the chamber capture the scattered light, and the intensity of this scattered light correlates with the particle's size: larger particles scatter more light, while smaller particles scatter less.[2]

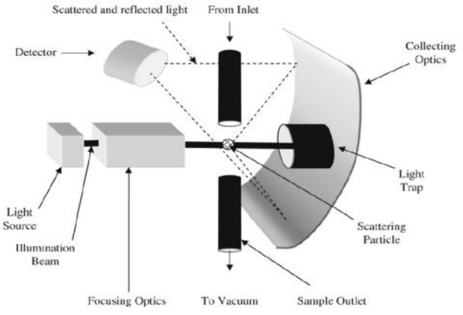


Fig -2: Basic components of the light-scattering optical particle counter. [2]

The underlying scattering phenomenon relies on Mie scattering theory when particle sizes are comparable to the wavelength of the light. Mie theory, a subset of Maxwell's electromagnetic theory, describes how particles within the wavelength range scatter light, allowing for fairly accurate particle sizing. The OPC's detectors capture specific scattering patterns, which are then analysed by the device's processing unit to classify particles into size bins. The result is a size distribution of particles in the sampled air, often represented as PM 1, PM 2.5, or PM10 to indicate particles of specific diameters in micrometres.

In short, when the outside air passes through the light collection chamber the particles in sampled air are scattered by the light beam. The photoelectric conversion unit converts the scattered light signal into a voltage pulse signal, which is pre-amplified and converted into digital signal after AD conversion. The measured number of voltage pulses is the number of particles, and the amplitude of voltage pulses reflects the size of the particle's optically equivalent particle size.

Recent advancements in signal processing and data analysis have further enhanced the accuracy and resolution of OPCs. These improvements allow OPCs not only to measure particle size and concentration but also to provide real-time data, making them valuable tools for air quality monitoring.

1.1 Importance of Air Quality Monitoring

Air quality monitoring is essential because particulate matter (PM) poses a significant threat to human health and the environment. Fine particulate matter, particularly PM 2.5 (particles with a diameter of 2.5 um or less) and PM 10 (particles with a diameter of 10 um or less), can have severe health impacts. Studies have linked PM exposure to respiratory and cardiovascular diseases, aggravated asthma, decreased lung function, and even premature mortality. Additionally, PM plays a major role in environmental degradation, impacting visibility, damaging crops, and contributing to climate change.

Monitoring air quality, specifically particulate levels, is crucial for understanding exposure risks, informing public health decisions, and developing pollution control strategies. However, traditional air quality monitoring methods, such as gravimetric analysis, require stationary infrastructure and involve a time-consuming process of sample collection and laboratory analysis. These limitations have created a demand for more accessible, real-time, and mobile monitoring solutions.

1.2 Current Demand for Mobile, Cost-Effective, and Real-Time PM Monitoring

To address these limitations, there has been a rising demand for mobile, low-cost, and real-time PM monitoring devices that can be deployed flexibly across various settings. Portable OPCs fulfil this need by providing real-time data on particle size and concentration in a compact form. They are now being widely used in both indoor and outdoor environments, allowing individuals, researchers, and organizations to monitor PM levels conveniently. [3] [4] These devices are particularly beneficial in environments that require agile monitoring solutions, such as areas impacted by traffic emissions, construction sites, and even personal exposure tracking in occupational settings.

1.3 Focus of the Review

Despite the advances in mobile OPC technology, there remains a scarcity of comprehensive reviews covering the latest developments in this field. This paper aims to address this gap by reviewing recent advancements in mobile optical particle counters for PM detection.[5] The focus will be on technological innovations, current applications, and emerging trends in OPC technology, with particular attention to improvements in portability, sensitivity, and data connectivity. By consolidating recent findings, this review seeks to provide a valuable resource for researchers and professionals interested in mobile air quality monitoring and the future of optical particle counters in the field.

2. Background of Optical Particle Counters (OPCs)

2.1 Different PM Monitoring Technologies

Particulate Matter (PM) monitoring has evolved through various technologies, each with unique operating principles, advantages, and limitations. The most established method is the Gravimetric and Filter-Based Technique, which involves collecting airborne particles on a filter over a specific duration. These filters are then weighed under controlled laboratory conditions to determine the particle mass concentration. This method is highly accurate and forms the basis of regulatory PM monitoring. However, it is inherently time-consuming, requires stationary infrastructure, and lacks real-time feedback, which limits its utility in dynamic or mobile monitoring scenarios.

Another established method is the Beta Attenuation Monitor (BAM) and Electrostatic techniques. BAM works by measuring the attenuation of beta particles as they pass through particle-laden filters, offering high precision and regulatory-grade data. Electrostatic monitors, on the other hand, use charged plates to attract airborne particles. Both methods offer high sensitivity and reliability but are generally bulky and expensive, making them unsuitable for portable applications.

Optical Particle Counters (OPCs) use light-scattering principles to detect and size particles in real-time. As particles pass through a light beam, the intensity of scattered light—captured by photodetectors—correlates with the particle size. OPCs provide the dual advantage of real-time measurement and particle size distribution, though they can be influenced by ambient humidity or particle refractive index, which may affect accuracy.

To make particle sensing more affordable, Low-Cost OPCs have been developed. These systems mimic the light-scattering principle of standard OPCs but use lower-cost components. While not as accurate, they are ideal for citizen science, community monitoring, and widespread deployment, though their limitations in accuracy and precision must be considered.

Mobile Phone-Based OPCs represent an emerging class of ultra-portable sensors. They utilize the smartphone's camera and LED flash to detect scattered light from particles and then apply image analysis algorithms to estimate concentration levels. These systems are convenient and highly accessible, but their sensitivity and precision are typically lower than dedicated instruments.[6] [7]

Recent research has introduced more sophisticated systems like the Complicated Parabolic Collector (CPC)-Based OPC, which captures scattered light over wide angles to enhance detection of submicron particles without using filters. This setup is highly sensitive but may require precise optical alignment, affecting usability. [8] [9]

Other specialized instruments include Silicon-Based OPCs, which integrate laser diodes and photodiodes into compact, microfabricated silicon chambers. These devices are power-efficient and suitable for wearable technology, although their fabrication is complex and usually targeted at specific applications. [10] [11] [12]

Furthermore, Fresnel Ring Lens-Based OPCs utilize concentric lens structures to focus scattered light onto detectors with high angular precision, improving particle size classification.[13] [14] Similarly, Drilled Lens-Based OPCs enhance light collection efficiency and are optimized for small particle sensitivity, albeit with certain trade-offs in angular collection and beam isolation. [15]

2.2 Key components of OPC

A commercial OPC, regardless of whether it's low-cost or high-end, follows a modular design architecture built around the core principle of light scattering. It begins with a light source, typically a laser or a high-intensity LED. This source emits a narrow, collimated beam of light directed across a flow channel. The wavelength of the light is chosen to optimize the scattering interaction with particles of interest, typically ranging from 400–700 nm.

The particle detection chamber is designed to control the airflow and direct particles through the beam path uniformly. This chamber must ensure laminar flow to prevent turbulence, which could lead to counting errors or signal noise.

When a particle crosses the beam, it scatters light at various angles. This scattered light is captured by the optical collection system, which can include mirrors or lenses that direct the light toward a photodetector. Depending on the particle size and light wavelength, either Mie scattering (for particles ~0.1 to 10 µm) or Rayleigh scattering (for smaller particles) dominates the signal behavior.

The photodetector (usually a photodiode or avalanche photodiode) converts the optical energy into an electrical signal. The strength of this signal correlates with the particle size. This analog signal is then amplified and digitized in the signal processing unit, which assigns each detected event to a particle size bin and counts it accordingly.

To ensure accuracy, particularly in bright or dusty environments, a stray light suppression system—such as optical traps or baffles—is used to block or absorb non-scattered light. This improves the signal-to-noise ratio, ensuring the integrity of the measured data.

2.3 Technological Advancements in Optical Particle Counters (OPCs)

The evolution of Optical Particle Counters (OPCs) spans over a century, beginning with foundational theoretical developments and advancing into today's compact, real-time, and intelligent sensing systems.

In the early beginnings (1900–1950s), the theoretical basis for OPCs was established through the development of light scattering theory. Pioneers like Lord Rayleigh and Gustav Mie formulated the mathematical frameworks for Rayleigh and Mie scattering, respectively. These theories describe how particles scatter light depending on their size relative to the wavelength, laying the groundwork for later particle detection techniques. During this period, early experimental light scattering detectors were developed, although they were rudimentary and used primarily in academic or laboratory settings. These devices demonstrated the feasibility of using light for particle detection, but practical implementation remained limited.

The post-war era (1950s–1970s) witnessed a significant leap with the invention of the laser, which offered a coherent, focused, and stable light source—ideal for precise optical measurements. This innovation drastically improved the sensitivity and resolution of particle detection systems. Consequently, the first commercial OPCs emerged during this phase, primarily targeting applications in clean rooms and industrial quality control where precise monitoring of particulate contamination was essential.

A new wave of innovation followed in the 1980s through the 2000s, characterized by advances in miniaturization and integration. The advent of semiconductor technologies and Micro-Electro-Mechanical Systems (MEMS) enabled the development of smaller, portable OPCs with significantly lower power consumption. In parallel, the introduction of LED-based light sources reduced system costs and extended product lifespan, making OPCs more accessible. The refinement of optical lenses and photo detector designs, coupled with the integration of digital signal processing, further improved the resolution and accuracy of particle measurements. These improvements made it possible to reliably detect finer particulate matter, such as PM2.5, in real time.

The 2000s to 2010s ushered in the digital and low-cost era of OPC technology. During this time, LED-based low-cost OPCs gained traction, facilitating wide-scale deployment for consumer air quality monitors and community-driven environmental sensing networks. Parallel to cost reduction, wireless and IoT integration became common features, enabling OPCs to stream data in real time via mobile and cloud-based platforms. This connectivity allowed for decentralized monitoring and enhanced responsiveness in both urban and rural contexts.

Finally, in the 2020s and beyond, OPCs have undergone remarkable advancements in sensitivity and accuracy. Modern systems now employ advanced optical materials, refined sensor calibration techniques, and AI-powered processing algorithms, bringing the performance of some low-cost OPCs closer to that of reference-grade instruments. Another key development has been the introduction of multi-channel OPCs, which can simultaneously analyze particles across multiple size ranges, thereby providing a more detailed and accurate representation of particulate pollution. In addition, the integration of OPCs into drone and mobile platforms has enabled flexible and high-resolution monitoring of air quality in diverse environments—from urban streets and industrial zones to remote or hazardous locations such as wildfire regions and volcanic sites.

2.4 Applications of Optical Particle Counters (OPCs)

Optical Particle Counters (OPCs) have emerged as indispensable tools across a wide range of domains due to their ability to detect and quantify particulate matter in real-time. Their versatility has led to applications in environmental science, public health, industry, agriculture, aerospace, and transportation.

In the field of environmental monitoring, OPCs are primarily used for air quality assessments in both indoor and outdoor environments. These sensors can measure concentrations of particulate matter such as PM1, PM2.5, and PM10, offering insight into pollutant levels from sources like vehicle emissions, industrial discharge, and natural dust. For ambient air quality monitoring, OPCs provide real-time data crucial for regulatory compliance. Environmental protection agencies and municipalities deploy these sensors to track pollution patterns, enforce emission standards, and inform the public about potential health risks.

Under the umbrella of health and personal exposure monitoring, OPCs are used in two key areas. First, personal air quality monitors equipped with OPCs allow individuals, especially those with asthma, allergies, or respiratory vulnerabilities—to assess the air they breathe throughout the day. These compact, wearable devices have become popular among health-conscious users and researchers studying personal exposure trends. Second, in occupational health settings, such as manufacturing plants or construction sites, OPCs help ensure that workers are not overexposed to harmful particulate matter such as dust, welding fumes, or fibers. These measures support workplace safety regulations and minimize long-term respiratory risks.

In industrial applications, OPCs are integrated into systems for dust monitoring in manufacturing environments. Industries such as cement production, mining, and metallurgy rely on these sensors to maintain dust levels within permissible limits. OPCs also form a key component of Continuous Emissions Monitoring Systems (CEMS) used in factories and power plants. These systems monitor particulate emissions at the stack in real-time, allowing operators to detect anomalies and ensure compliance with air quality regulations.

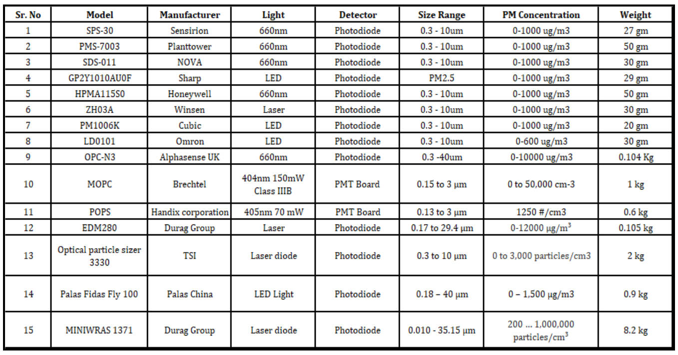
The agricultural sector also benefits from OPC technology. In agricultural air quality monitoring, these sensors track airborne particles generated during activities like plowing, harvesting, and fertilizer or pesticide application. By monitoring the particulate pollution from farming operations, stakeholders can mitigate their impact on nearby communities. Additionally, OPCs are being explored for pest and disease monitoring, where they detect microscopic particles related to fungal spores or pest activity, offering early warnings of crop infestations or plant diseases.

In the realm of aerospace and drone-based environmental sensing, OPCs are mounted on unmanned aerial vehicles (UAVs) to perform aerial monitoring of air quality. This application is especially useful in areas that are difficult to access or potentially hazardous, such as volcanic regions, wildfire zones, or chemical spill sites. Furthermore, researchers use drones with OPCs in weather and environmental research, examining aerosol distribution at various altitudes to understand their influence on cloud formation, radiation balance, and climate dynamics.

Lastly, in the automotive and transportation sector, OPCs are employed in vehicle emissions testing. These devices measure particulate emissions, particularly from diesel engines, to evaluate compliance with environmental regulations. Their real-time capabilities also support innovations in green transportation and pollution control technologies.

2.5 Current All types of OPCs in market

The figure-2 presents a comprehensive comparison of various particulate matter (PM) sensors from different manufacturers, highlighting key parameters such as light source, detection method, particle size range, concentration measurement capability, and weight. Most sensors, such as the SPS-30 by Sensirion, PMS-7003 by Planttower, and SDS-011 by NOVA, use a 660nm light source and photodiode detectors, covering a common particle size range of 0.3 to 10 μm and concentration range up to 1000 $\mu g/m^3$. Notably, advanced sensors like the MOPC from Brechtel and the POPS from Handix Corporation employ high-powered laser sources with PMT (photomultiplier tube) boards, achieving high sensitivity for particles as small as 0.13 μm and measuring in particle number concentration ($\#/cm^3$) instead of mass. On the heavier end of the spectrum, instruments such as the MINIWRAS 1371 from Durag Group weigh over 8 kg and can detect ultrafine particles down to 0.010 μm, making them suitable for high-precision industrial or research applications. Conversely, compact and lightweight models like the PM1006K (20 gm) and SPS-30 (27 gm) are ideal for portable or consumer-grade air quality monitoring. This range of sensors demonstrates the trade-off between sensitivity, measurement capability, and portability, catering to different applications from indoor air quality monitoring to advanced scientific research.



Sr. No	Model	Manufacturer	Light	Detector	Size Range	PM Concentration	Weight
1	SPS-30	Sensirion	660nm	Photodiode	0.3 - 10um	0-1000 ug/m3	27 gm
2	PMS-7003	Planttower	660nm	Photodiode	0.3 - 10um	0-1000 ug/m3	50 gm
3	SDS-011	NOVA	660nm	Photodiode	0.3 - 10um	0-1000 ug/m3	30 gm
4	GP2Y1010AU0F	Sharp	LED	Photodiode	PM2.5	0-1000 ug/m3	29 gm
5	HPMA115S0	Honeywell	660nm	Photodiode	0.3 - 10um	0-1000 ug/m3	50 gm
6	ZH03A	Winsen	Laser	Photodiode	0.3 - 10um	0-1000 ug/m3	30 gm
7	PM1006K	Cubic	LED	Photodiode	0.3 - 10um	0-1000 ug/m3	20 gm
8	LD0101	Omron	LED	Photodiode	0.3 - 10um	0-600 ug/m3	30 gm
9	OPC-N3	Alphasense UK	660nm	Photodiode	0.3 -40um	0-10000 ug/m3	0.104 Kg
10	MOPC	Brechtel	404nm 150mW Class IIIB	PMT Board	0.15 to 3 μm	0 to 50,000 cm-3	1 kg
11	POPS	Handix corporation	405nm 70 mW	PMT Board	0.13 to 3 μm	1250 #/cm3	0.6 kg
12	EDM280	Durag Group	Laser	Photodiode	0.17 to 29.4 μm	0-12000 μg/m^3	0.105 kg
13	Optical particle sizer 3330	TSI	Laser diode	Photodiode	0.3 to 10 μm	0 to 3,000 particles/cm3	2 kg
14	Palas Fidas Fly 100	Palas China	LED Light	Photodiode	0.18 – 40 μm	0 – 1,500 μg/m3	0.9 kg
15	MINIWRAS 1371	Durag Group	Laser diode	Photodiode	0.010 - 35.15 μm	200 ... 1,000,000 particles/cm^3	8.2 kg

Fig -2: Different types of OPC's

Recent advancements in particulate matter (PM) sensing technologies have led to the development of a wide range of low-cost and compact sensors for ambient air quality monitoring. As shown in the sensor comparison, devices such as the SPS-30 (Sensirion) [19] and PMS-7003 (Planttower) utilize 660 nm light sources with photodiode detection to measure particles within the 0.3 to 10 μm range. These sensors are increasingly used in both consumer and research applications due to their affordability and portability. However, challenges such as humidity interference can affect data accuracy; researchers like Andrea Di Antonio et al. [16] have proposed relative humidity correction methods to improve reliability in varying environmental conditions. On the other hand, high-precision instruments like the MOPC (Brechtel) and POPS (Handix), which use photomultiplier tube (PMT) boards and operate at shorter wavelengths, offer greater sensitivity down to 0.13 μm, making them suitable for scientific analysis. As Pope and Dockery [17] emphasize, fine particulate matter (especially PM2.5) poses serious health risks, linking exposure to cardiovascular and respiratory diseases. Consequently, the growing use of IoT-based monitoring systems [21] and open-source air quality initiatives such as AirBeam2 [20] reflects a shift toward more decentralized and community-driven environmental health monitoring. Manufacturers like Alphasense [18] continue to contribute to this evolution by providing sensor components that balance performance and accessibility.

3. CONCLUSIONS

In conclusion, the surge in demand for portable, real-time air quality monitoring systems has catalysed advancements in mobile optical particle counters (OPCs). These devices now enable precise, in-situ measurements of particulate matter (PM1, PM2.5, PM10) by size, mass, and number concentration, making them invaluable tools in industry, regulatory monitoring, and consumer markets. This review has highlighted key technological innovations in OPCs, covering enhanced sensing components, integration techniques, and sensor miniaturization.

The trajectory of OPC development suggests a near future where sensors will become increasingly sensitive, compact, and capable of autonomous, real-time detection across diverse environmental conditions. Emerging trends point toward breakthroughs in miniaturization and advanced detection algorithms, leveraging new materials, photonic integration, and machine learning for more refined data processing. These innovations, driven by the need for accessible and precise air quality data, signal a transformative shift towards OPCs that are not only portable but also highly scalable for widespread use in urban, industrial, and even personal health applications.

ACKNOWLEDGEMENT

The authors may thank Dr. Abhijeet Dandavate Principal DPCOE, Kharadi, Pune.

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