DOE

POTENTIAL DUAL-USE APPLICATIONS OF ATMOSPHERIC MEASUREMENT INSTRUMENTS

June 2022

This project was funded by the Department of Energy, an agency of the United States Government, through a contract for Phase 0 Outreach and Assistance for the Small Business Innovation Research/Small Business Technology Transfer Programs Office.

Prepared by DAWNBREAKER • 2117 Buffalo Road • Rochester, NY • 14624 • (585) 594-0025 • www. dawnbreaker.com

Table of Contents

1.0 Introduction

Participation in the Department of Energy's Small Business Innovation Research (SBIR) and/or Small Business Technology Transfer (STTR) programs provide small business with the opportunity to participate in extramural research and development initiatives that benefit the nation. The **Earth and Environmental Systems Sciences Division Strategic Plan (2018-2013)** presents a set of grand challenges that are critical to DOE's science, environmental and energy missions. The five scientific grand challenges include advancing the understanding of the (1) the integrated water cycle; (2) biogeochemistry; (3) high-latitude components; (4) earth system; and (5) data-model integration.

Small businesses participating in the SBIR/STTR programs are expected not only to apply their creativity to develop break-through technologies, but to find ways to commercialize their solutions using a variety of methods. Most commonly the commercialization strategies used by small business (in no order) include licensing-out their intellectual property; seeking equity investment in their firm to scale up production; strategic partnerships with another entity that possesses complementary skills; delivery of services and/or a combination of the above.

Small business working in specialty fields, often find it wise to consider a dual-use strategy. In other words, to explore commercialization of the technology within the initial market – in this case atmospheric scientific instrumentation/processes – but also to demonstrate the advantage of the new instrument, sensor, or process in another application area.

The purpose of this report is to provide insight into potential dual use applications of instrumentation used for measuring airborne particulate matter, gases, and droplets. The focus is not on the instrumentation, but on the problems that may benefit from the type of solution small businesses that respond to topics under Atmospheric Measurement Technologies develop. Each of these three sections (aerosols, gases, droplets) begins with a brief description of problems that lie outside the scope of what atmospheric researchers typically focus on, but where improvements in measurement capability may be able to address a problem in a different discipline.

Each section of the report will also include information on the market size for related product classes. This is to help you consider market applications and learn about the major players in that field.

The Need for Particle Measurement

2.0 The Need for Particle Measurement

This section provides examples of four problems that could benefit from improvements in particle measurements. These include monitoring of anthropogenic particles, powders used in additive manufacturing, the spread of medical infectious diseases (COVID) and detection of biological agents. The names of vendors that are beginning to address these problems are also included.

2.1 Anthropogenic particles

Airborne particulate matter comes from a wide variety of sources. **Anthropogenic particles** are those which are manufactured or generated incidentally from the degradation and subsequent dissemination of synthetic materials that are released into the environment

> Accelerated industrialization and advances in technology have had wide reaching effects, producing particles which can range from incidental by-products of production and combustion processes (e.g., soot, street dust), to those which are intentionally produced in specific sizes and shapes for targeted applications (e.g., TiO_2 in cosmetics, nano-fertilizers) or generated by the breakdown of larger products over time (e.g., microplastics).[1]

Finding the best analytical methods to monitor the presence of anthropogenic particles … remains a challenge.

Although anthropogenic particles are of interest due to their impact on atmospheric phenomena, they also affect water quality, agriculture, wildlife, and human health. Of most recent interest has been the distribution of microplastics and nanoplastics (MNPs). Finding the best analytical methods to monitor the presence of anthropogenic particles and securing concurrence on the size of particles monitored[2] remains a challenge. "Overall, the number of particles found in the environment increases exponentially as particle size decreases, and it is the smaller size fractions that are more likely to induce adverse effects, owing to their reactivity, ability to pass through biological membranes (e.g. organ tissue), transport behavior, and potential to be mistaken for food by organisms."[3] The 2021 publication by Mattsson et al, provides an overview of the most commonly used analytical techniques for the separation, characterization, and quantitation of anthropogenic microparticles and nanoparticles.[4]

Studies to assess the proliferation and distribution of nanoplastics is increasing. These materials can be airborne or directly enter the water or the ground. A 13-month study of the atmospheric deposition of anthropogenic particles and microplastics in Ontario Canada in remote, pristine environments could be quantified.[5] Another 2021 study using penguins as biological samplers confirmed the presence of microplastics in the food chain (krill) as far away as antarctica.[6] A 2022 publication by Benson et al provides an extensive review of Micro(nano)plastics in aquatic food web interactions.[7]

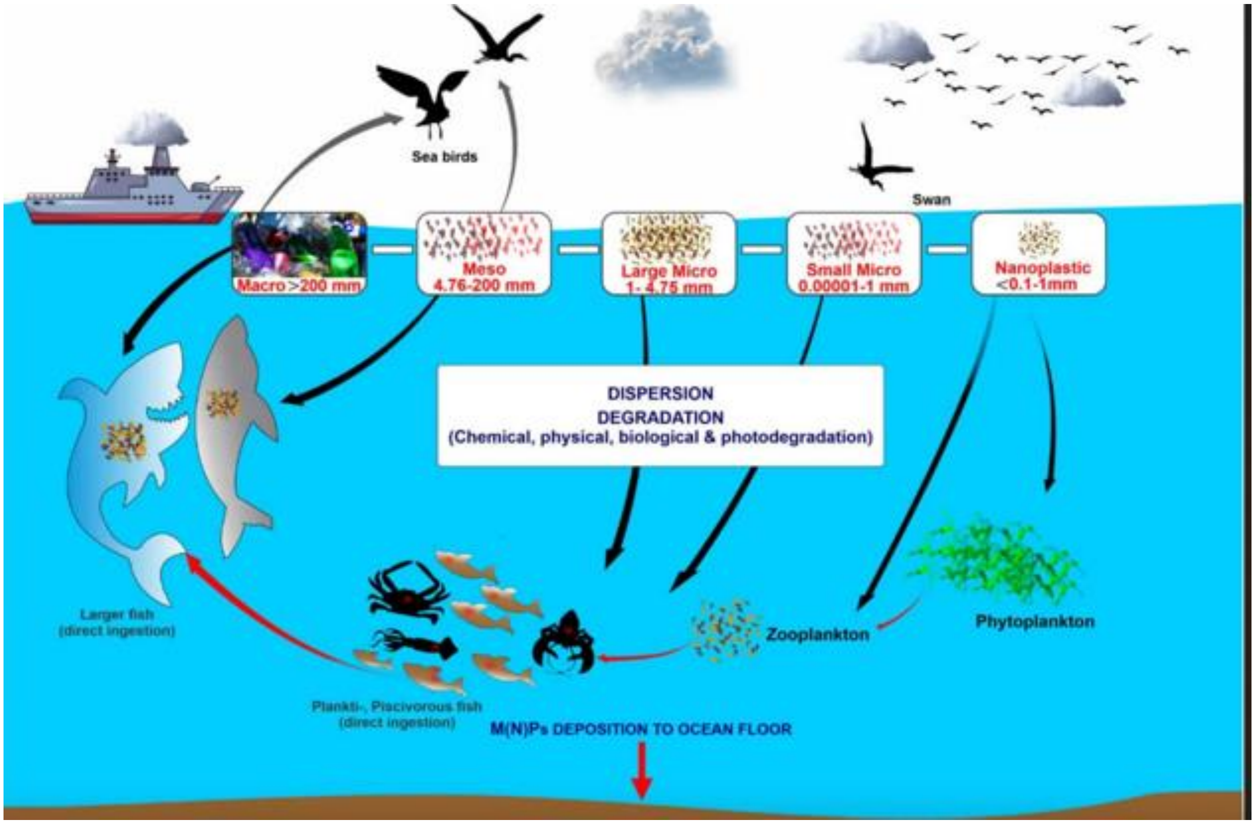


Figure 1: Transport of Microplastics in aquatic environment
Source: Benson, Nsikak et al[8]

Anthropogenic emissions are of particular interest because they can potentially be decreased through[9] regulatory and voluntary actions. Studies which trace the origin of the MNPs to their source may result in better methods to limit pollution at the source.

Some domestic companies providing services or products focused on measurement of anthropogenic particles include: (1) **Rogers Imaging** – which provides nano-material and nano-particle testing; (2) **Advanced Microanalytical** provides nano material and nano-particle testing; (3) **Beckman-Coulter** which provides particle analyzers.

2.2 Occupational Air Quality Issues

The **National Institute for Occupational Safety and Health (NIOSH)** is responsible for conducting research and making recommendations for the prevention of work-related injury and illness. Many occupational illnesses result from poor indoor air quality from exposure to aerosols. Because of the relationship between aerosols and disease, NIOSH has a high interest in the study of aerosols. Occupations of particular note have included:

1. Fire fighters who are exposed to toxic aerosols while performing their duties

2. Construction, stone countertop fabrication, foundries, and other manufacturing settings in which airborne silica dust is created
3. Metal bearing aerosols
4. Nanomaterials having a length of between 1 and 100 nanometers
5. Cooking related fumes

Many of these are more traditional occupations. However new occupations are giving rise to increased concerns about exposure to much smaller particles.

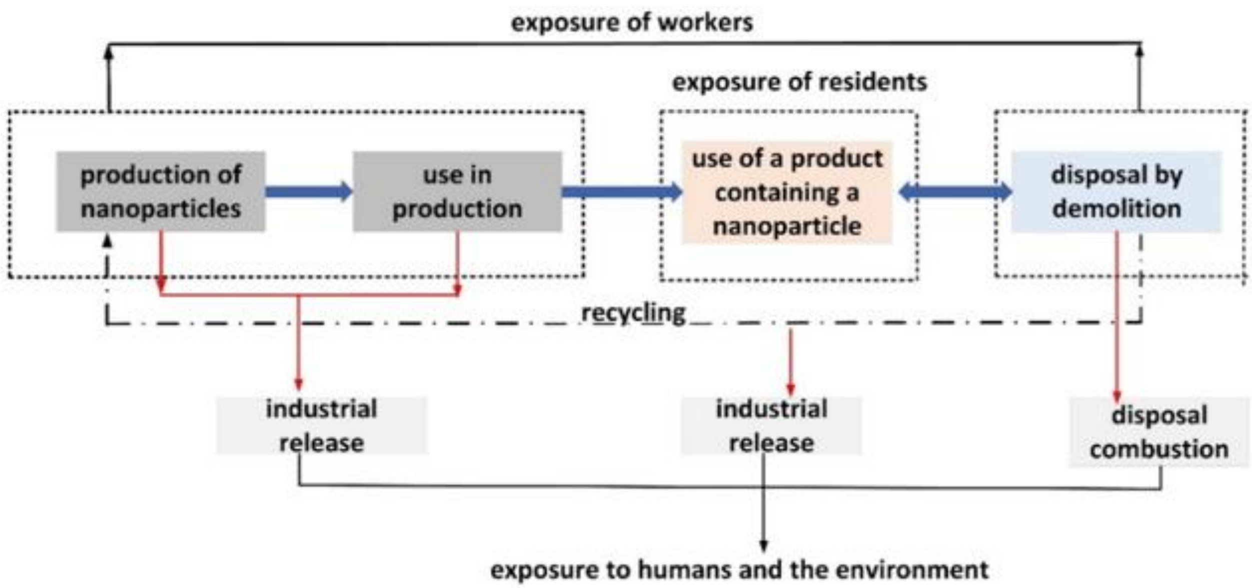


Figure 2: Many innovations use nanoparticles
Source: Renata Wlodarczyk[10]

For example, with additive manufacturing, there is a concern about exposure to aerosols containing the powdered medium. Recent studies have been conducted to understand the extent of exposure during different parts of the additive manufacturing process so that better controls can be exerted.[11, 12]

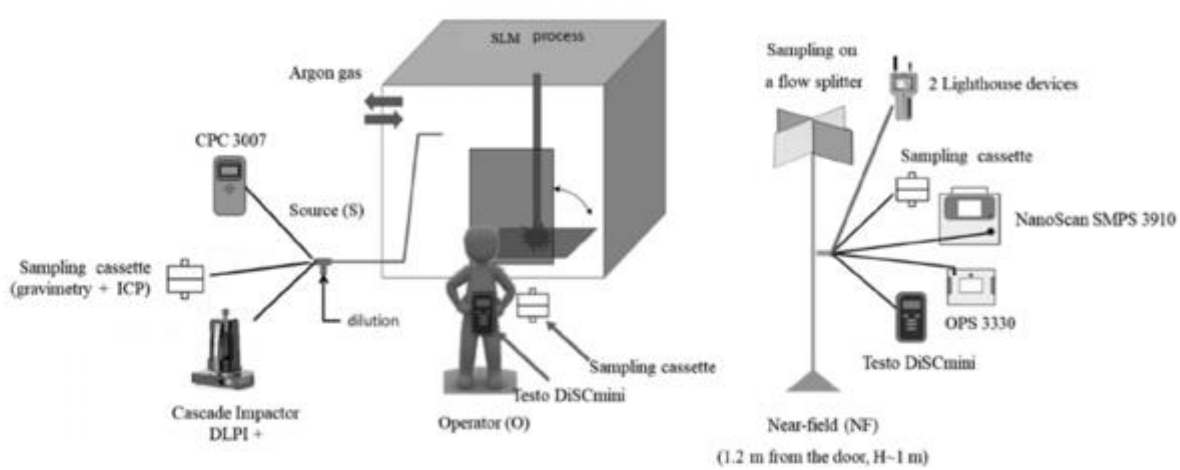


Figure 3: Measuring instruments around the additive manufacturing machine
Source: Azzougagh et al[13]

The cosmetics and medical industries also make extensive use of nanoparticles. Due to lack of regulation concern is being raised about nanoparticles from these sources entering the food chain through the air, water, and soil which could have deleterious effects on health.[14] With respect to cosmetics concern about aerosol exposure is for the consumer who may be exposed to aerosols that penetrate the lungs from using cosmetics in powder form.[15]

A sample of domestic companies providing particle counters for industrial applications include: (1) **TSI Products**; (2) **Particle Measuring Systems**; (3) **ParticlesPlus.**

2.2 Medical Infectious Diseases

The COVID-pandemic gave rise to many studies on the transmission of COVID via aerosols. Before looking at some of the questions asked, it is important to revisit the use of the term's **aerosols** and **droplets** in this body of research. According to a 2021 article published by the Royal Society…

> The CDC did not begin using the words 'airborne' or 'aerosol' to describe transmission [of COVID-19] until October 2020. As we will see, the differentiation between droplets and aerosols by the WHO is based on an arbitrary cut-off in droplet diameter; particles larger than the cut-off are considered 'droplets' and those smaller are considered 'aerosols'.
>
> …" First, droplet and aerosol transmission are currently defined on the basis of size: 'droplets' are considered to be emissions larger than 5 or 10 μm in diameter, whereas those smaller than 5 μm are termed 'aerosols'. Second, droplets are assumed to follow a semi-ballistic trajectory and to settle within 1–2 m from the person who released them. Yet, these thresholds are not consistent with the physics of droplets and aerosols and the exhalation cloud shaping their transport."[16]

After recounting the history of measurement dating back to the late 1800s, the article concluded with the following recommendation:

> Though researchers from multiple (and often disconnected) fields are studying airborne transmission from different perspectives, a move towards consistent conversations and research about airborne transmission—instead of ad hoc conversations that arise only in times of crisis—will give researchers, public health officials and infection control specialists the time needed to collaborate, discuss limitations and ultimately better implement science into policy. We call for a model in which this research is continually advanced, particularly between epidemics and pandemics. We also call for the inclusion of a broader range of expertise in key scientific and decision-making committees.

Many questions were explored by numerous researchers in the past two years regarding the transmission of COVID. As many activities were curtailed due to concern about the airborne transmission of COVID-19, Tehya Stockman et al studied the extent to which singing with a choir, playing a wind instrument with an ensemble and/or participating in theater arts increased the transmission of COVID-19.[17] A variety of methods were used to address this concern, including flow visualization, aerosol and CO_2 measurements, and computational fluid dynamics (CFD) modeling. Participation in sports was also affected by our understanding of aerosol transmission. A study by Coffey, KC et al tracked 109,672 interactions among 1190 football student athletes during a 64-game season using a variety of contact sensors and remote sensing. The authors concluded that playing college football did not contribute to COVID-19 transmission.[18] Others looked at the impact of wind as a vehicle for increasing the likelihood that COVID could be contracted by walking outside.[19] Of great importance was determining how to best protect hospital workers and the best type of personal protective equipment to recommend.

Sample domestic manufacturers providing particle counters focused on medical applications include: (1) **Entegris**; (2) **Fluke**; and (3) **Met One Instruments.**

2.3 Biological Agents

The Army's Modernization Strategy calls for improving the situational awareness of soldiers. One aspect of this is the ability to detect aerosols and specifically biological agents. A current limitation is the ability to detect the morphology of **Coarse Mode Aerosols** or particles sized 1μm or less. At present, particles are often studied in conjunction with ground and satellite data, but more accurate methods are needed in the future, in order to record their exact microphysical characteristics.[20]

HAPI, short for Holographic Aerosol Particle Imager can measure the morphology of coarse mode aerosols.

In response to this need, the Army Research Laboratory in combination with Dr. Gorden Videen and a number of universities have developed **HAPI,** short for **Holographic Aerosol Particle Imager.** HAPI can image and characterize multiple particles from any direction without making physical contact with them.

> "This research is unique because it uses holography to characterize aerosol particles by capturing images of their physical shape," Videen said. "This has not been done before and other researchers have not yet ventured in to this territory. This update is the latest step to miniaturize the instrument, put it onto a drone and fly it around to capture these images in situ. This is a major step and was implemented in a relatively short amount of time."[21]

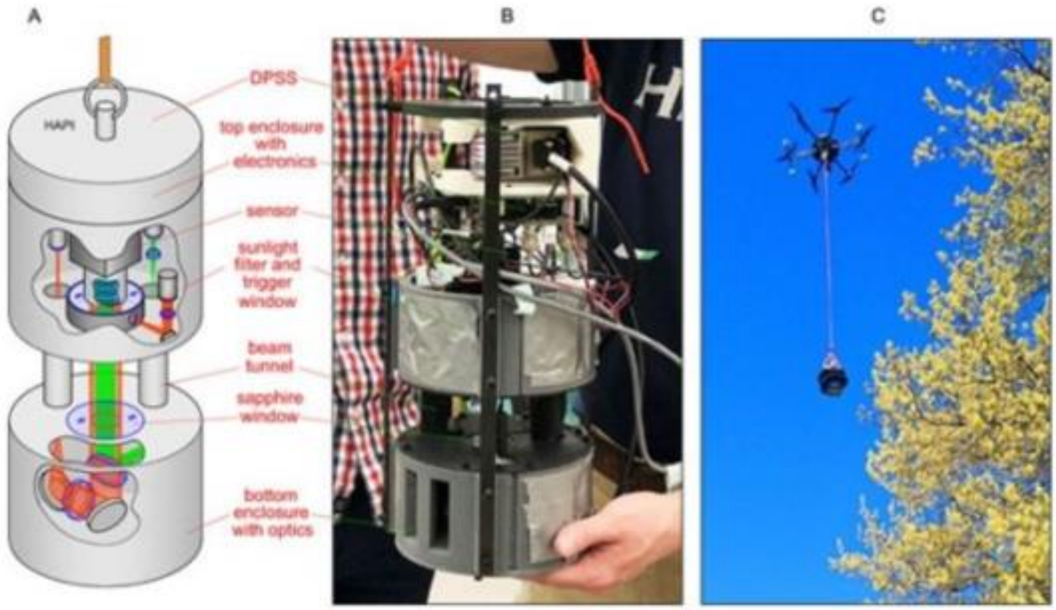


Figure 4: HAPI is deployed by hanging from a UAV
Source: Army Research Laboratory[22]

3.0 Particle Size Analysis and Counting Markets

The purpose of this section is to provide information on the size of the market for particle counting technologies, as well as provide an overview of key players. There are numerous industries where particle counting is important, as particle size significantly affects the stability, appearance, fluidity, and chemical reaction characteristics of the material. Hence, particle size analyzers are extensively used in formulating and manufacturing products across various industries, such as pharmaceutical, chemical, food, cosmetics, petroleum, mining, and coatings industries.[23] In addition to measuring particle size distribution to ensure products are free of contamination, manufacturers can also use measurements to determine compliance with industry standards or regulations and to uncover opportunities for improving production processes.

Particle size influences many properties of particulate materials and is a valuable indicator of quality and performance. For example, particle size analysis plays a key role in the manufacturing of carbon fiber components. Single-wall carbon nanotubes are often subjected to dynamic light scattering technology to assess if the required strength of the material could be drawn from a batch of carbon nanotubes.[24] Demand is particularly high in the automotive industry, as carbon fiber has been replacing metals, such as aluminum and steel, due to its incredible strength and lightweight.[25]

The following provides a quick overview of how particle counting is used in various industries.

- **Paints and coatings** - Typically, paints and coatings are subjected to multiple rounds of particle size analysis, as the particle size of the individual components influences parameters as diverse as tint strength, hiding power, gloss, viscosity, stability and weather resistance.[26]

- **Mining** - The size of materials being processed in an operation is very important.[27] In the mining industry, being able to characterize the material of interest—and check the levels of impurities in the final product is vital to ensuring products meet specifications.[28]

- **Building materials** - In the building industry, the particle size can directly affect the strength of the final material. For example, measuring and controlling the particle size distribution of cement is important both in order to achieve the desired product performance and to control manufacturing costs.[29]

- **Food and beverages industry** - The two process steps where the size of particles in a food product are analyzed are final product sizing and initial product sizing.[30] The optimization of the particle size distribution facilitates the pumping, mixing and transportation of foodstuff. Particle size analysis is usually done with milled food, such as coffee, flour, cocoa powder. Furthermore, in the case of food emulsions, particle size analysis is relevant to predict stability and shelf-life, and optimize homogenization.

- **Biology/pharma**: Particle sizing is a particularly important technique for the characterization of nanoparticles designed for drug delivery, such as vaccines.[31] Particle sizing instruments are part of the quality control process for mRNA vaccines formulated in lipid nanoparticle carriers.[32] Particle size also has an influence on the drugs' overall physical stability. Additionally, the size of the particles can alter the dosage of a drug.[33]

- **Nanomaterials**: In the manufacturing of nanomaterials, particles can stop products from working or cause malfunctions. This can lead to product failures and recalls.[34] Nanoparticles serve various industrial and domestic purposes which is reflected in their steadily increasing production volume. Analytical techniques are, as covered elsewhere, still under development to more efficiently and reliably characterize and quantify nanoparticles.[35]

- Other industries that involve large amounts of glass, such as photography and lens construction, also need to closely monitor particles. If these products are marred by particles, the images will be distorted. In aerospace and defense applications, contamination can have catastrophic effects. For instance, in

NASA's life-detection missions, exceedingly small amounts of target compounds and particles can make or break a mission.[36]

For particles in the lower nanometer to lower micrometer range, dynamic light scattering has now become an industry standard technique. It is also by far the most widely used light scattering technique for particle characterization in the academic world. Other scattering techniques have emerged, such as nanoparticle tracking analysis.

3.1 Particle Size Analysis Market Size

A report from MarketsandMarkets projects the global particle size analysis market to reach $492 million by 2026 up from $371 million in 2021 and growing at a CAGR of 5.8% between 2021 -2026. In 2020, North America commanded the largest share of 31.3% of the particle size analysis market. This share can be attributed to the increasing government support for nanotechnology research and the rising number of regulations pertaining to product quality in the pharmaceutical and food & beverage industries.[37]

Table 1: Particle Size Analysis Market, By Region, 2019-2026 ($ Million)

Region	2019	2020	2021	2022	2023	2024	2025	2026	CAGR (2021–2026)
North America	108.4	111.5	116.1	121.4	127.5	134.5	142.3	151.0	5.4%
Europe	101.5	104.6	109.1	114.2	120.1	126.8	134.3	142.6	5.5%
Asia Pacific	94.9	99.3	105.1	111.8	119.3	127.8	137.4	148.2	7.1%
Latin America	26.2	26.8	27.6	28.7	29.8	31.2	32.7	34.4	4.4%
Middle East & Africa	13.7	13.8	14.1	14.4	14.8	15.3	15.8	16.4	3.1%
Total	**344.8**	**355.9**	**371.9**	**390.5**	**411.6**	**435.5**	**462.5**	**492.6**	**5.8%**

Source: MarketsandMarkets. (2021).[38]

The size of these particles plays a significant role in quality control functions and in formulating the end-use application of materials in various industries, such as the pharmaceutical, mining, minerals, chemical, petroleum, and food & beverage industries.

Table 2: North America: Particle size analysis market, by end user, 2019–2026 ($M)

End user	2019	2020	2021	2022	2023	2024	2025	2026	CAGR (2021–2026)
Healthcare Industry	48.44	50.22	52.71	55.59	58.85	62.54	66.72	71.37	6.2%
Chemicals & Petroleum Industry	23.70	24.25	25.11	26.13	27.30	28.62	30.12	31.79	4.8%
Food & Beverage Industry	16.50	17.01	17.74	18.60	19.58	20.68	21.94	23.33	5.6%
Mining, Minerals, and Cement Industry	9.34	9.47	9.71	10.00	10.34	10.72	11.16	11.64	3.7%
Cosmetic Industry	6.29	6.39	6.56	6.76	7.00	7.27	7.58	7.92	3.9%
Other Industries	4.14	4.17	4.25	4.36	4.48	4.61	4.77	4.95	3.1%
Total	**108.42**	**111.50**	**116.09**	**121.45**	**127.54**	**134.46**	**142.29**	**151.00**	**5.4%**

Source: MarketsandMarkets. (2021).[39]

The most commonly used approaches for particle size analysis include (1) laser diffraction, (2) dynamic light scattering, (3) image analysis, (4) nanoparticle tracking analysis, (5) the Coulter principle-based technology, and (6) sieve analysis.

Many different technologies are used for particle size analysis. The market is segmented into seven major segments, namely,[40] laser diffraction, dynamic light scattering, image analysis, nanoparticle tracking analysis, the Coulter principle-based technology, and sieve analysis. MarketsandMarkets estimates the laser diffraction is the largest technology segment (see table below). The Nanoparticle Tracking Analysis segment is expected to register the highest growth over the forecast among the particle size analysis technologies market over the forecast period. The significant growth of this segment is attributed to advanced applications of these particle size analyzers and growing research activities in the field of nanotechnology. Nanoparticle Tracking Analysis is mainly used in biopharma and biotech applications and with increasing R&D activities in the biopharmaceutical industry.[41]

Table 3: North America: particle size analysis market, by technology, 2019–2026 ($M)

Technology	2019	2020	2021	2022	2023	2024	2025	2026	CAGR (2021–2026)
Laser Diffraction	33.10	33.75	34.83	36.12	37.60	39.28	41.19	43.30	4.4%
Dynamic Light Scattering	28.86	29.90	31.36	33.05	34.97	37.13	39.57	42.29	6.2%
Imaging	13.82	14.49	15.37	16.38	17.51	18.79	20.23	21.83	7.3%
Nanoparticle Tracking Analysis	7.72	8.21	8.83	9.54	10.34	11.24	12.25	13.38	8.7%
Coulter Principle	3.86	3.85	3.89	3.94	4.00	4.07	4.16	4.25	1.8%
Sieve Analysis	3.47	3.47	3.52	3.58	3.66	3.74	3.84	3.96	2.4%
Other Technologies	17.58	17.82	18.28	18.83	19.48	20.21	21.05	21.98	3.8%
Total	**108.42**	**111.50**	**116.09**	**121.45**	**127.54**	**134.46**	**142.29**	**151.00**	**5.4%**

Source: MarketsandMarkets. (2021).[42]

3.1.1 Market Drivers

Market drivers identified by MarketsandMarkets include increasing research activities in the field of nanotechnology, increasing investments in pharmaceutical R&D, and regulatory guidelines for product quality across industries (such as healthcare, food & beverage, and chemical industries).

Ongoing research on nanomaterials and their significance in several industries are stimulating the growth.[43] For example, in March 2022, the **U.S. National Nanotechnology Initiative** published the National Nanotechnology Initiative Supplement to the President's 2023 Budget (Supplement. According to the Supplement, the President's 2023 budget requests more than $1.98 billion for National Nanotechnology Initiative, with an increased investment in the foundational research intended to lead to discoveries that will advance a wide range of areas.[44] Particle technology intersects nanotechnology when scientists need to determine the particle size distribution and zeta potential (surface chemistry) of materials in the nanoscale.[45] Since particle size analyzers play a significant role in the analysis of nanoparticles, one would expect this to be a driver of technology adoption.

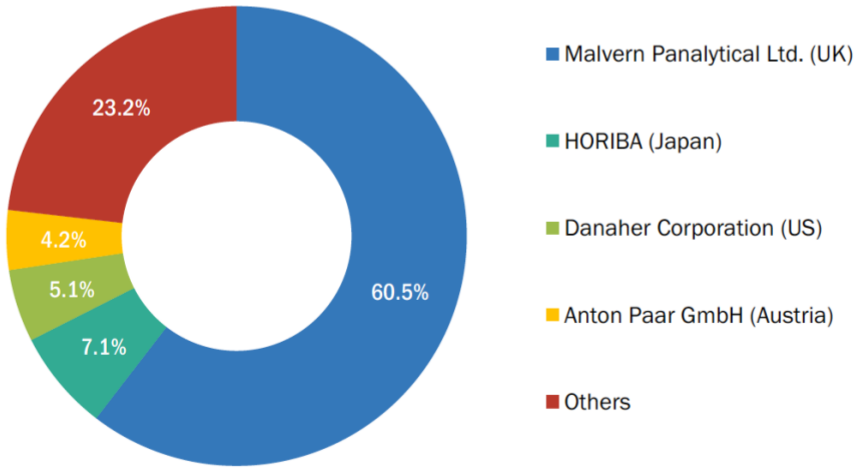
3.1.2 Limitations

One of the limitations pointed out in the secondary literature is technological restraints. Several technologies, such as dynamic light scattering, nanoparticle tracking analysis, resonant mass measurement, and laser diffraction are available for the analysis of nanoparticles. These analytical technologies cover different size ranges. For instance, laser diffraction technology is used to analyze particles ranging from 10 nm up to several millimeters in size, whereas nanoparticle tracking analysis characterizes particles between 30 nm and 1 μm. The resonant mass measurement technology can characterize particles between 50 nm and 5 μm, while dynamic light scattering can analyze materials ranging from below one nm to several micrometers in size. There is no single technology available that can measure all types of nanoparticle properties with the same accuracy and efficiency. In a nutshell, the selection of the analysis technique depends on the size range of the sample and the type of information required.[46]

There is no single technology available that can measure all types of nanoparticle properties with the same accuracy and efficiency.

3.1.3 Particle Size Analysis Instrument Manufacturers

The particle size analysis market is a highly consolidated market, and the market presence of existing players is supported by their large product portfolios, strong brand image & value, strong distribution channels in mature and emerging markets, economies of scale, and significant investment in developing and commercializing innovative products. The vendors operating in the global particle size analysis market include **Malvern Panalytical Ltd**. (UK), **HORIBA** (Japan), **Beckman Coulter, Inc**. (US), **Anton Paar GmbH** (Austria), Aimsizer (China), **Bettersize Instruments Ltd**. (China), **Brookhaven Instruments** (US), **Fritsch GmbH** (Germany), **LS Instruments** (Switzerland), **METLLER TOLEDO** (US), **Micromeritics Instrument Corporation** (US), **Microtrac Retsch GmbH (Germany), Shimadzu Corporation** (Japan), **Sympatec GmbH** (Germany), and TSI (US), among others.[47]



Note: Others include Aimsizer (China), Bettersize Instruments Ltd. (China), Brookhaven Instruments (US), Fritsch GmbH (Germany), LS Instruments (Switzerland), METLLER TOLEDO (US), Micromeritics Instrument Corporation (US), Microtrac Retsch GmbH (Germany), Shimadzu Corporation (Japan), Sympatec GmbH (Germany), TSI (US), Pamas Partikelmess - UND Analysesyteme GmbH (Germany), Jinan Winner Particle Size Instrument Stock Co., Ltd (China), 3P Instruments (Germany), CSC Scientific Company, Inc. (US), IZON Science Ltd. (New Zealand), HAVER & BOECKER OHG (Germany), Sinsil International Pvt. Ltd. (India), Wyatt Technology Corporation (US), Entegris, Inc. (US), and RTI Laboratories (US)

Figure 5: Particle size analysis market share by key player, 2020
Source: MarketsandMarkets. (2021).[48]

Malvern Instruments is the leading player in the global particle size analysis market. The company's broad product portfolio, along with its wide geographic presence across North America, Europe, and the Asia. Horiba and Beckman Coulter are other key players. These three companies have more than 70% share of the market.[49]

The particle analysis market is active with respect to mergers and acquisitions. For instance,

- In August 2020, **VERDER Scientific GmbH & Co. KG (Germany) acquired Porotec GmbH (Germany),** which develops and sells particle and porosity measurement instruments.[50]
- In 2020, **Retsch Technology GmbH (Germany), MicrotracBEL (Japan), and MICROTRAC (US)** merged to form MICROTRAC MRB.[51]
- In January 2019, **HORIBA Instruments** Incorporated (US) acquired MANTA Instruments, Inc. (US) to expand their technology of particle characterization instruments.
- In September 2018, Anton Paar GmbH (Germany) acquired Quantachrome (US). The acquisition expanded Anton's product portfolio in particle characterization. It also provided the firm with a US-based research unit.[52]
- In 2018, **Micromeritics Instrument Corporation** (US) acquired Process Integral Development S.L. (Spain) and Freeman Technology (UK).[53]

3.2 Particle Counting Market

Another related market is particle counting. This section provides an overview of this market.

3.2.1 Need

The Particle Counting Market is distinct from the Particle Size Analysis Market.

Particle counters are monitoring instruments measure the particle concentration in a sample or environment. Particle counters are an indispensable tool for quality assurance and quality control in many industries such as pharmaceutical and biotechnology product testing, semiconductor testing, medical device testing, and food & beverage testing. Particle counters are used as a tool for the contamination monitoring of devices as well as components, the performance of which can be affected by the presence of particles or residues left after manufacturing.[54]

An important part of any machine conditioning program is particle counting. Particle counters also monitor and track the quantity and severity of the contamination, whether it is a result of machine wear or external contamination. The specific application and particle type will usually dictate what the best particle counting method for the job at hand. For example, the continuous cleanliness of a hydraulic system is extremely critical since even very low levels of dirt ingress can clog valves and actuators leading to premature machine failure.[55]

It has been noted that the evolution of automotive improvements through the years has required a higher degree of contamination control throughout the manufacturing process. With the development of VDA 19 and ISO 16232 cleanliness standards, the automotive industry began to set new requirements for the most sensitive components such as antilock braking systems, transmission valve bodies, fuel injection parts and bearings. To meet these requirements, cleanliness analysis equipment including particle counters have become more advanced as testing and reporting particle contamination levels have become more critical.[56]

Within the healthcare industry, the trend of processing technology is for more advanced complex devices integrated in smaller size.[57] Airborne particle counters are an important tool used in the environmental monitoring of pharmaceutical, bio-pharmaceutical and radiopharmaceutical facilities. For example, airborne particle counters perform cleanroom certification testing and the operational process environmental monitoring required within pharmaceutical manufacturing facilities.[1]

[1]Aleksandr Fedotov. "FDA and EU GMP Annex 1 Differences in Cleanroom Specifications." July 22, 2019. https://www.raps.org/news-and-articles/news-articles/2019/7/fda-and-eu-gmp-annex-1-differences-in-cleanroom-sp

Sand, dust, and ash particles have significant detrimental effects on turbine engine performance and durability. Ingestion of particulate materials can cause erosion of the flow path components and particles that reaches the combustor and turbine can adhere to these components, adversely impacting the cooling performance.[58] The degree to which ingested particulate is harmful to a gas turbine is dependent on the particle size, concentration, and composition.[59] Such sensors would record data such as dust composition, particle size distribution, total mass, etc. and have sufficient durability for flight conditions.[60]

3.2.2 Market Size

The particle counter market is projected to grow at a CAGR of 9.9% during the forecast period, from $346 million in 2022 to $554 million by 2031. The North American particle counters market comprises the US and Canada. In 2019, North America accounted for a share of 36.0% of the global particle counters market. This regional segment is projected to reach $205.1 million by 2025 from $125.4 million in 2020, at a CAGR of 10.3% from 2020 to 2025.[61]

Table 4: Particle counters market, by region, 2018–2025 ($ Million)

Region	2018	2019	2020	2025	CAGR (2020–2025)
North America	112.03	121.63	125.43	205.12	10.3%
Europe	94.21	101.43	103.72	162.68	9.4%
Asia Pacific	80.10	87.18	90.12	149.10	10.6%
RoW	25.99	27.38	27.39	38.01	6.8%
Total	**312.33**	**337.62**	**346.66**	**554.90**	**9.9%**

Source: MarketsandMarkets. (2020).[62]

The market is segmented into airborne and liquid particle counters. Airborne particle counters are used to monitor the air quality by counting and sizing the number of particles in the air.[63]

Table 5: North America particle counters market, by type 2018–2025 ($ Million)

Type	2018	2019	2020	2025	CAGR (2020–2025)
Airborne Particle Counters	77.2	83.6	85.8	137.8	9.9%
Liquid Particle Counters	34.8	38.1	39.6	67.3	11.2%
Total	**112.0**	**121.6**	**125.4**	**205.1**	**10.3%**

Source: MarketsandMarkets. (2020).[64]

Key applications for particle counters include cleanroom monitoring and others. Below is an extended list of end users:[65]

- In the pharmaceutical & biotechnology industries, particle counters are mainly used to monitor and evaluate cleanroom conditions in pharmaceutical manufacturing sites as well as in certain aspects of the pharma R&D process. These devices detect significant deviations in air cleanliness from qualified processing classifications. Online particle counters are also used to monitor the production of pharmaceutical products, such as injectables, to ensure that only target ingredients are present in solutions and no insoluble particles, microorganisms, or other impurities are present.
- Particle counters are designed for cleanroom monitoring of air particles in the semiconductor industry according to ISO 14644 (cleanrooms and associated controlled environments) and ISO 21501 (determination of particle size distribution–light-scattering airborne particle counters for clean spaces). Liquid-borne particle counters are used for the contamination monitoring of pure water and chemicals utilized in manufacturing semiconductors.
- In the automotive industry, particle counters are mainly used for the contamination monitoring of devices such as hoses, valves, nozzles, and pumps, as well as components whose performance can be affected by the presence of particles or residues left over after manufacturing.
- The medical device industry is witnessing a considerable increase in the number of miniaturized devices. Such innovations require change in the manufacturing processes. New technologies necessitate the incorporation of advanced manufacturing methods, requiring contained environments, thereby increasing the adoption of particle counters.
- Particle counters find significant applications in the food & beverage industry as part of food safety assurance processes.

The healthcare and pharmaceutical industries also show a high degree of regulatory stringency due to the focus on patient safety and demand for high product quality and has the largest share of the market, followed by the semiconductor industry (see table below). The need to ensure a sterile and contamination-free environment promotes the greater use of cleanrooms and monitored working areas for manufacturing healthcare products. The table below provides a forecast by end users.

Table 6: North America particle counters market, by end user, 2018-2025 ($ Million)

End User	2018	2019	2020	2025	CAGR (2020–2025)
Life Sciences & Medical Device Industry	50.7	55.2	57.1	94.9	10.7%
Semiconductor Industry	23.2	25.2	26.0	42.7	10.4%
Automotive Industry	16.9	18.3	18.9	30.7	10.2%
Aerospace Industry	12.7	13.7	14.0	22.2	9.6%
Food & Beverage Industry	4.6	4.9	5.1	7.9	9.4%
Other End Users	3.9	4.2	4.3	6.6	9.0%
Total	**112.0**	**121.6**	**125.4**	**205.1**	**10.3%**

Source: MarketsandMarkets. (2020).[66]

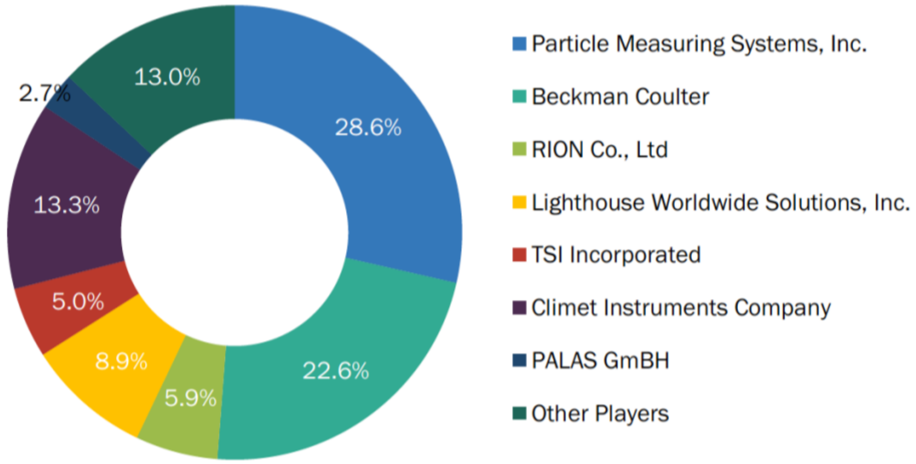
3.2.3 Market Drivers

Favorable conditions and the high adoption of advanced technologies in end use industries such as the automotive, aerospace, energy, and oil & gas industries are driving the market. Specifically,[67]

1. Particle counters are designed for cleanroom monitoring of air particles in the semiconductor industry according to ISO 14644 (cleanrooms and associated controlled environments) and ISO 21501 (determination of particle size distribution–light-scattering airborne particle counters for clean spaces). Furthermore, liquid-borne particle counters have been used for the contamination monitoring of pure water and chemicals utilized in manufacturing semiconductors.
2. Particle counters find applications in the food & beverage industry as part of food safety assurance processes. Particle count data is needed to quantify potential contaminants in the air and determine the quality of air in controlled environments, such as those found in sensitive food industries. The importance of these systems has grown significantly due to the increasing food safety concerns across the globe.
3. Regulatory standards for manufacturing processes and products are another key driver. Quality certifications require products to be processed in a cleanroom environment to ensure minimum possible contamination. The need to ensure a sterile and contamination-free environment promotes the greater use of cleanrooms and monitored working areas for manufacturing healthcare products.

3.2.4 Key Vendors

Particle Measurement Systems, Beckman Coulter, Rion Co., Ltd. (Japan), Lighthouse Worldwide Solutions, TSI, Climate Instruments Company, Met One Instruments, Particle Plus, Setra Systems, PAMAS (Germany), Chemtrack, Hull Technology, Konamax, Veltek Associates, PCE Instruments (UK), GrayWolf Sensing Solutions, Extech Instruments, Palas GmbH (Germany), HYDAC International (Australia), Fluke Corporation. The figure below shows market share of key vendors.



Note: Other players include Met One Instruments, Inc. (US), Particle Plus, Inc. (US), Setra Systems (US), PAMAS (Germany), Chemtrac, Inc. (US), HAL Technology (US), Kanomax USA, Inc. (US), Veltek Associates, Inc. (US), PCE Instruments UK Ltd. (UK), GrayWolf Sensing Solutions (US), Extech Instruments (US), Palas GmbH (Germany), HYDAC International (Australia), and Fluke Corporation (US), among others

Figure 6: Particle counters market share of key vendors
Source: MarketsandMarkets. (2020).[68]

Particle Measuring Systems accounted for the largest share of the particle counters market. The company offers a wide portfolio of particle counters, which cater to the demand from various industries, including pharmaceutical, semiconductor, aerospace, and food & beverage. Beckman Coulter accounted for the second largest market share. Beckman Coulter is a subsidiary of Danaher Corporation, which has been operating in the market for about 50 years. The company's presence in the market is marked by its wide portfolio of airborne and liquid particle counters.

TSI Incorporated is a leading developer of aerosol research instrumentation since 1966. TSI offers a line of particle instruments such as particle scanning spectrometers (see figure below). The company has an extensive catalog of products for sizing, counting, generating, and dispersing aerosol particles. Other specialty instruments include comprehensive solutions to measure ultrafine particles in the atmosphere.[69]

Figure 7: TSI particle scanning spectrometer
Source: TSI Incorporated[70]

TSI also manufactures indoor air quality monitors. In October 2021, TSI introduced the TSI AirAssure Indoor Air Quality Monitor product line that four and six-gas models. AirAssure™ IAQ Monitor caters to many building types ranging from schools, hospitality, office buildings, to manufacturing settings.[71]

The Finnish company, **Dekati** Particle Research Solutions is a manufacturer of fine particle measurement and sampling instrumentation. Dekati also provides calibration and installation services, after-sales support, and hosts user workshops.[72] Dekati product line consists of a variety of real-time measurement instruments for fine particle and aerosol measurements. The products differ in terms of their size classification capability, time resolution, particle size range, and portability such as:[73]

- ELPI®+ for real-time particle concentration and size distribution measurements
- HR-ELPI®+ for detailed particle size distribution measurements
- HT-ELPI®+ for high temperature particle size distribution measurements
- Dekati® eFilter™ for simultaneous real-time and gravimetric PM measurement
- Dekati® MPEC+™ for real-time PEMS/on-board engine exhaust PN measurements

GRIMM Aerosol Technik Ainring GmbH & Co. KG is part of the DURAG GROUP The company, with headquarters in Ainring, Germany, is a manufacturer of instruments for measuring particulates. With respect to nanotechnology, GRIMM offers a wide portfolio of instruments for particle measurements such as:[74]

- Condensation Particle Counters
- SMPS+C
- SMPS+E

Kanomax Japan, Inc. was incorporated in in 1951 and has a location in New Jersey (Kanomax USA). Kanomax is a manufacturer of fine aerosol and particle measurement instruments.

Application of Gas Sensors

4.0 The Need for Gas Sensors

This section provides examples of problems that could benefit from improvements in the measurement of gases. These includes monitoring ammonia from multiple sources (semiconductor manufacturing, agriculture) and greenhouse gas monitoring as urban areas strive to decarbonize.

4.1 Semiconductor Industry

> "The semiconductor industry has a problem. Demand is booming for silicon chips, which are embedded in everything from smartphones and televisions to wind turbines, but it comes at a big cost: a huge carbon footprint."[75]

What do you do when you have two contradictory demands: Improve the domestic supply of semiconductor chips and reduce the carbon footprint? The Chips for America Act proposed $52B for the US semiconductor industry over a five-year period to increase domestic production. But what about pollution? How much pollution are we talking about? Intel's Ocotillo, Arizona campus produced 15,000 tons of waste in the first three months of 2021 – with about 60% being hazardous. According to the same article it consumed 927,000,000 tons of fresh water and used 561,000,000 kilowatt-hours of energy during that same period.[76]

Another article shows emissions sources, as well as the nature of the emissions.[77]

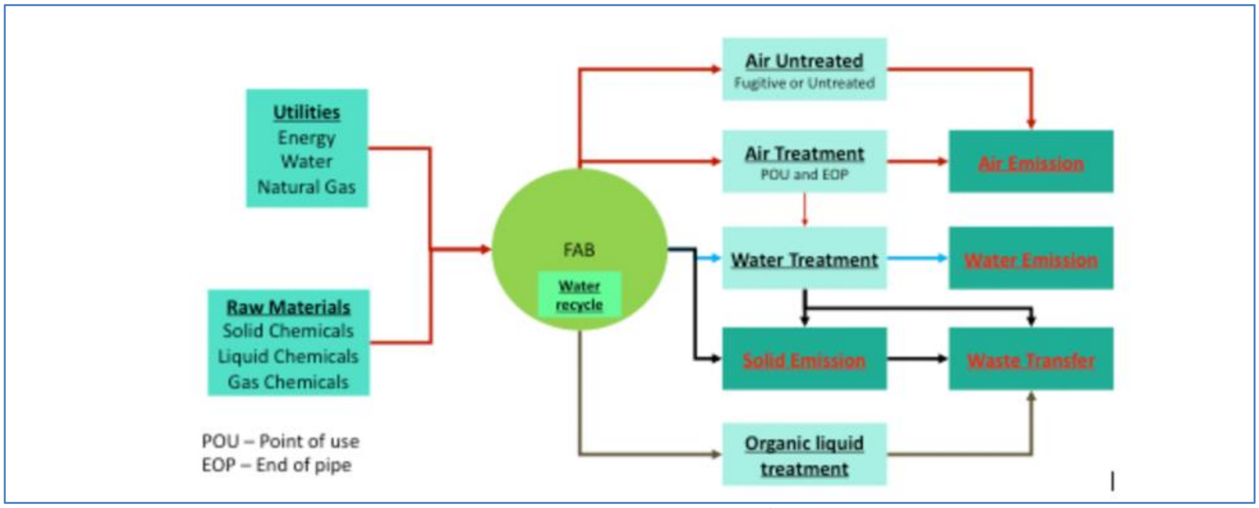


Figure 8: Emission Sources[78]
Source: Shannon

The EPA maintains a [Toxic Release Inventory (TRI)] containing information on toxic chemical releases from various facilities. The following 2020 data are for a different and unnamed semiconductor facility. According to the TRI data, all manufacturing waste was either released to the atmosphere (25%) or transported off-site (75%). The primary components of the 38,000 pounds of compounds released to the air are represented below – with the largest components being ammonia, hydrogen fluoride and sulfuric acid.

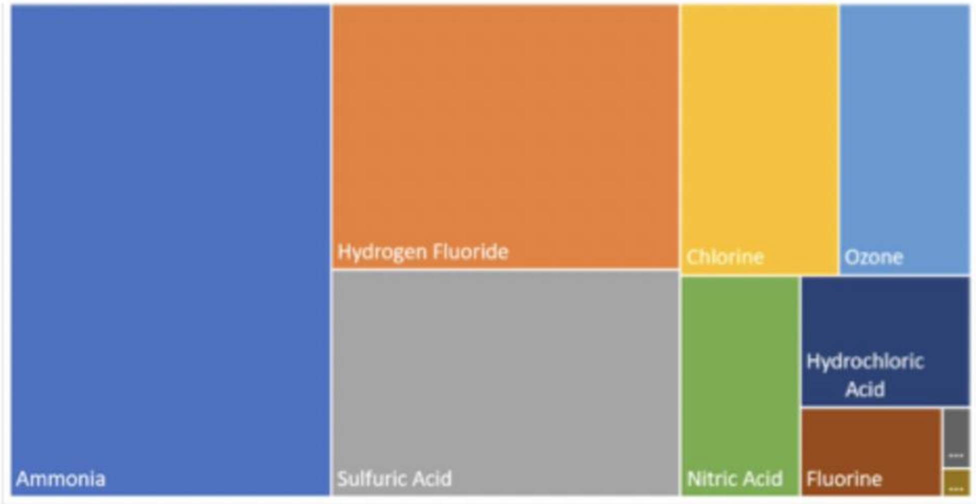


Figure 9: Air emissions from one fab (Area based on 38,000 pounds)
Source: Shannon[79]

5.0 Gas Sensors

Gas sensors detect the concentration of gases, such as Oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), chlorine (Cl), hydrogen sulfide (H_2S), nitrogen oxide (NOx), volatile organic compounds, methane (CH4), hydrocarbons, and hydrogen using electrochemical, metal-oxide-semiconductor, catalytic, infrared, and laser, among other technologies.

5.1 Overview

The overall gas sensors market is expected to grow from through 2026. Gas sensors are applicable to many industries, shown in the following figure.[80]

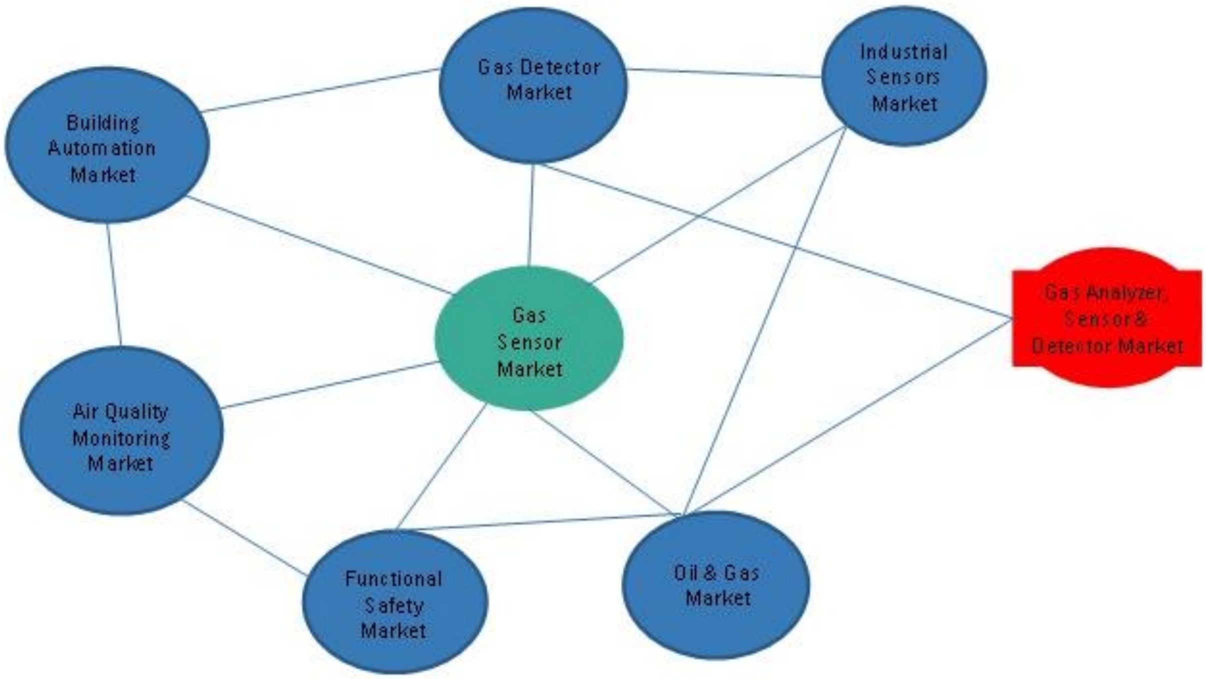
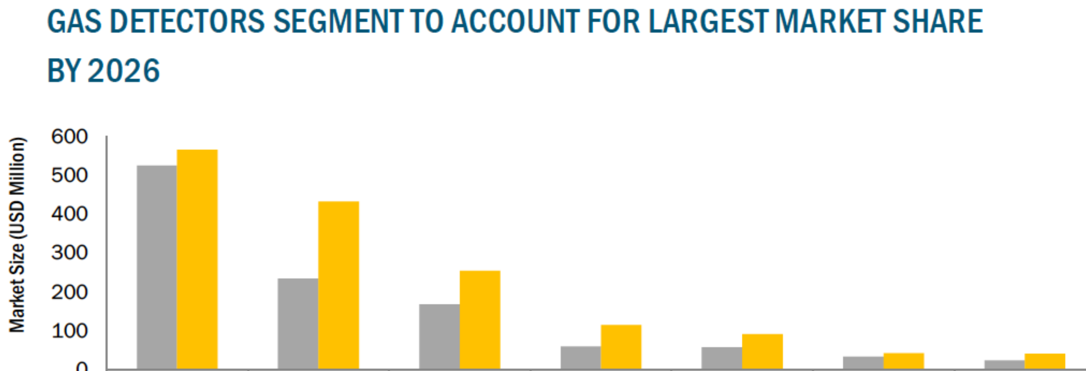


Figure 10: Gas Sensor Markets
Source: MarketsandMarkets. (2021).[81]

Key drivers include the development of miniaturization and wireless capabilities, coupled with the improvement in the communication technologies that enable their integration into various devices and machines to detect toxic gases at a safe distance.[82] Industries such as oil & gas, chemical, mining, and power use gas sensors to detect and monitor the presence of combustible and toxic gases. A large number of gases such as carbon monoxide, carbon dioxide, ammonia, hydrogen sulfide, and hydrocarbons are released into the air by these industries. Moreover, there are some explosive gases such as methane, propane, and butane that might be released by these critical industries. Many regulatory bodies are implementing various regulations to secure the ecosystem from harmful gases.[83]

5.2 Market Size

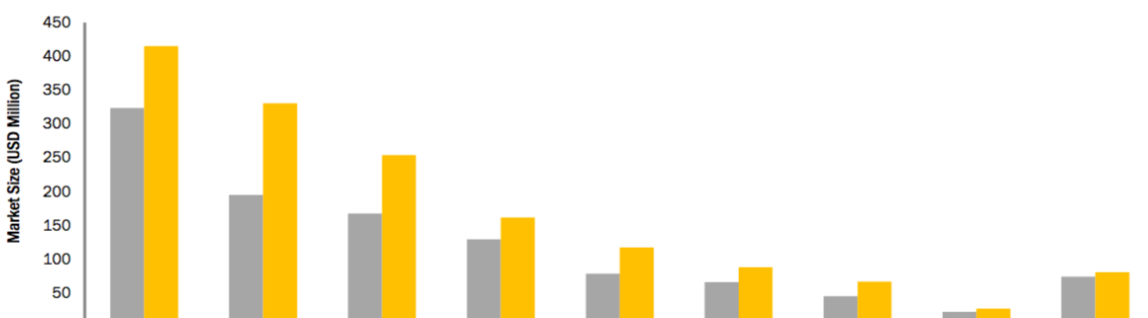
A report from MarketsandMarkets forecasts the global gas sensor market is gaining momentum, to reach $1.5 B revenues in 2026 from 1.1B in 2021 at a CAGR 2021-2026 of 7%. The market is segmented into gas analyzers and monitors, gas detectors, air quality monitors, air purifiers/air cleaners, HVAC, medical equipment, and consumer devices. Due to the adoption of gas sensors in these products, the gas sensor market is expected to grow at a significant rate. The gas sensors segment is expected to account for the largest market share through 2026 and is attributed to the increasing implementation of portable and fixed gas detectors for gas detection in emergency incidents in industrial and residential applications. The consumer market is driving the growth of gas sensors with a CAGR 2020-2026 of 39.4%. The HVAC market, including home air purifiers, is projected to grow to 18% CAGR 20-26. The air comfort for transportation will grow to 15,6% CAGR20-26. It represents another growth opportunity for gas sensors. Other markets like medical, environment, and defense & industrial safety are more conventional and are driven by some niche opportunities.[84]



	Gas Detectors	Air Quality Monitors	Medical Equipment	Consumer Device	HVAC	Gas Analyzers & Monitors	Air Purifiers/Air Cleaners
2021	524	234	167	59	56	32	23
2026	566	432	254	114	91	41	40
CAGR (2021–2026)	1.5%	13.0%	8.7%	14.0%	9.9%	5.1%	11.7%

Figure 11: Global Gas Sensors by Application
Source: MarketsandMarkets. (February 2021).[85]

With respect to technology, electrochemical sensors segment is expected to lead the gas sensor market through 2026, as electrochemical sensors consume less power, are less affected by temperature and pressure, and are used at low concentration ranges. In terms of sensor type, the trend the lack of selectivity of Metal Oxide Semiconductor technologies has slowed down the adoption of MOS.[86]

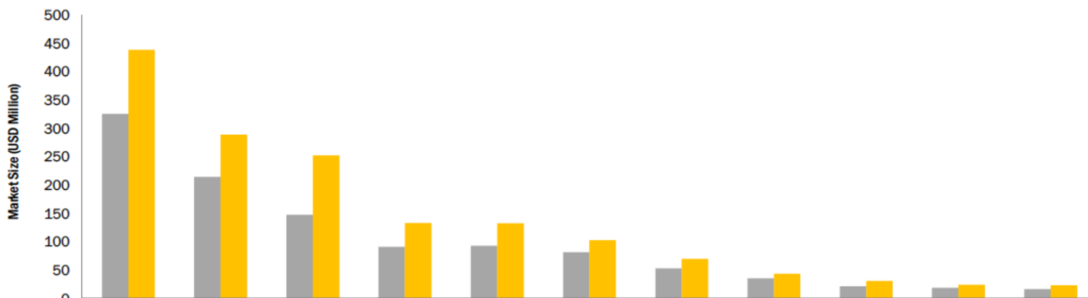


	Electrochemical	Infrared	Solid-State/Metal-Oxide-Semiconductors	Catalytic	Photoionization Detection	Zirconia	Laser	Holographic	Others
2021	323	195	167	129	78	65	44	21	73
2026	415	330	254	161	117	88	66	26	80

Note: "Others" includes paramagnetic, flame ionization detection (FID), chemiluminescence, carbon nanotubes, polymers, and ultraviolet

Figure 12: Global Gas Sensors by Technology
Source: MarketsandMarkets. (February 2021).[87]

The gas sensor market is segmented into types of gases detected: oxygen, carbon monoxide, carbon dioxide, ammonia, chlorine, hydrogen sulfide, nitrogen oxide, volatile organic compounds, hydrocarbons (such as methane, ethane, propane, butane, pentane, hexane, heptane, and octane), and hydrogen. The oxygen sensors segment was valued at $307 million in 2020 and is projected to reach $438 million by 2026. The market for oxygen sensors is expected to lead the gas sensor market during the forecast period, as oxygen detectors, analyzers, and monitors are widely used in the automotive industry, smart cities & building automation, food & beverage industry, and other industrial applications. Medical equipment is another application area of oxygen sensors as they are used in incubators and other hypoxic life science products, anesthesia monitors, respirators, and oxygen concentrators.



	Oxygen	Carbon Dioxide	Volatile Organic Compounds	Nitrogen Oxide	Carbon Monoxide	Methane	Ammonia	Hydrogen sulfide	Hydrocarbons	Chlorine	Hydrogen
2021	325	214	148	91	92	81	53	35	21	19	16
2026	438	289	252	133	132	102	69	43	31	24	23
CAGR (2021-2026)	6.1%	6.2%	11.3%	7.9%	7.4%	4.7%	5.7%	4.3%	7.3%	5.2%	7.1%

Figure 13: Global Gas Sensors by Type of Gas
Source: MarketsandMarkets. (February 2021).[88]

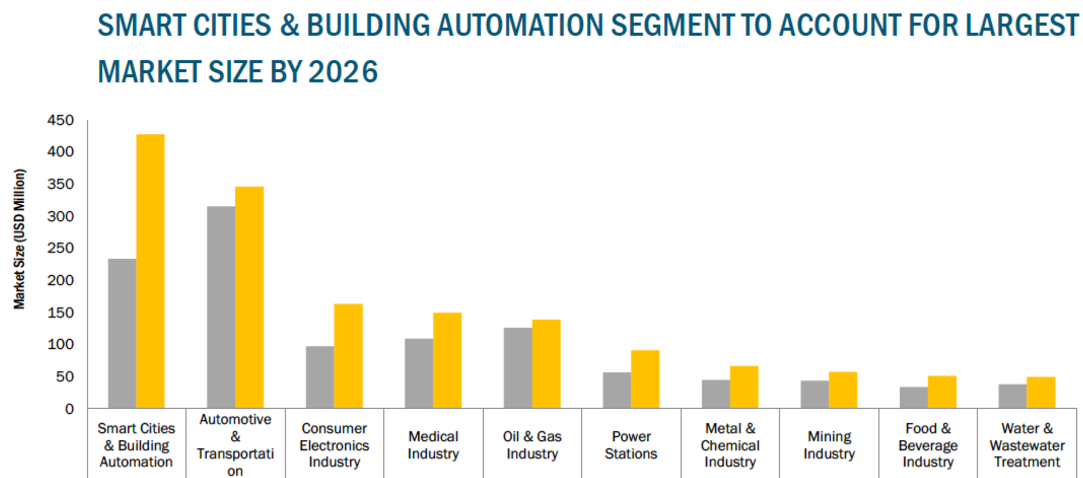
The gas sensor market is segmented into automotive & transportation, smart cities & building automation, oil & gas industry, water & wastewater treatment, food & beverage industry, power stations, medical industry, metal & chemical industry, mining industry, and consumer electronics industry: [89]

- In smart cities, gas sensors can be used for environmental monitoring applications to monitor air quality, which includes weather stations and monitoring of the environment at public places.
- The chemical industry is broadly classified into basic chemicals, specialty chemicals, and consumer chemicals. Basic chemicals include petrochemicals (derived from oils), polymers, and basic inorganics, while specialty chemicals include fertilizers for crop protection, paints, and dyes.
- The power industry releases flue gas into the atmosphere that is generated from the combustion of fossil fuels. Flue gas contains carbon dioxide and water vapor as well as pollutants such as nitrogen oxides and sulfur oxides. It also contains mercury, traces of other metals, and fly ash if it is released from coal-fired plants.
- The environmental sensors, such as gas sensors are more and more interesting in areas of indoor air management. Such products make it possible to monitor both

indoor and outdoor air quality. This is the market where the biggest momentum is expected over the period 2021-2026.

- In the automotive and transportation segment, the development of advanced automotive in-cabin solutions is also an expanding market.

The smart cities and building automation segment are expected to show the largest growth in 2026.



	Smart Cities & Building Automation	Automotive & Transportation	Consumer Electronics Industry	Medical Industry	Oil & Gas Industry	Power Stations	Metal & Chemical Industry	Mining Industry	Food & Beverage Industry	Water & Wastewater Treatment
2021	233	315	97	109	126	56	44	43	33	38
2026	427	346	163	149	138	91	66	57	51	49
CAGR (2021–2026)	12.9%	1.9%	10.9%	6.5%	1.9%	9.9%	8.3%	5.6%	8.7%	5.4%

Figure 14: Global Gas Sensors by End Use
Source: MarketsandMarkets. (February 2021).[90]

Major improvements for gas sensors are miniaturization and low power consumption. According to Yole, the trend is going to more combination sensors (humidity, temperature, pressure with gas sensors) as well as electronic nose developing in parallel for digital olfaction. In addition, there is development towards environmental combination sensors, for example, artificial intelligence is embedded in certain new sensors which could potentially benefit from advances in digital olfactometry to the benefit of applications like food safety or early detection of diseases and even comfort in autonomous and shared transport.[91]

5.3 Key Players

The gas sensor market is dominated by 5 companies, with almost 70% of the total market, in revenue. They are Bosch, Delphi, NGK-NTK, Denso and Honeywell. Beyond this top 5, this industry welcomes a myriad of companies. The particle sensor industry has three main leading companies: Sharp is still leading in shipments and Plantower is leading in revenue at almost $20 million. According to Yole, automotive players remain the main suppliers of gas sensors with more than 55% market share. Bosch is the leader with 22% of the global market share. Key players offering solid-state gas sensor solutions.[92]

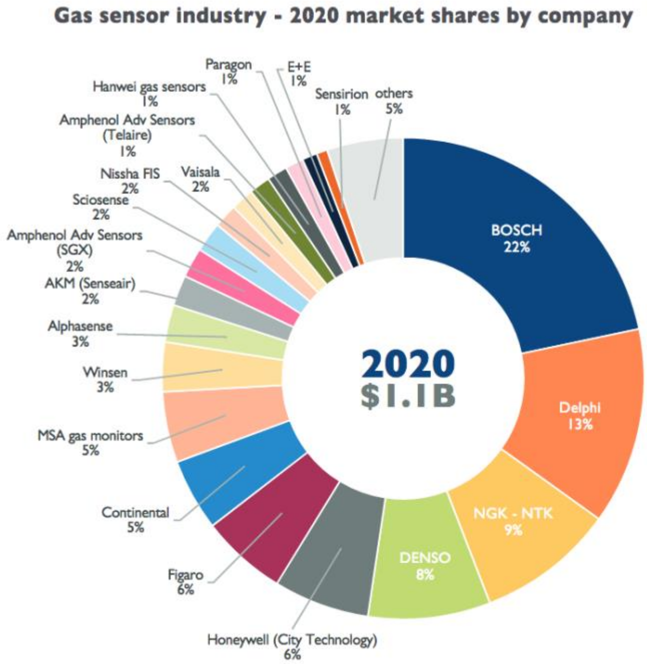


Figure 15: Gas and particle sensors technology
Source: Yole Développement. (June 2021).[93]

Key players are strengthening their technological knowledge or their access to the market via acquisitions, for example:

- In March 2019, Renesas acquired Integrated Device Technology, a supplier of semiconductor solutions and analog mixed-signal products including sensors, connectivity, and wireless power.[94]
- In February 2021, Sensirion acquired the gas analyzer company Qmicro. Qmicro, based in Enschede, The Netherlands, develops, manufactures, and supplies micro gas analyzers based on microelectromechanical (MEMS) gas chromatography (GC) technology. Qmicro's most important application areas include industrial process control as well as natural and biogas characterization.[95]
- In 2019, ams AG re-organized its gas sensor activity via a joint venture creating Sciosense. AMS's units for ultrasound-based flow sensors used in smart metering solutions for utilities and pressure sensors for identifying fluid and gas flows were transferred to the joint venture. The JV's focus is on flow and pressure sensor solutions.[96]

These companies are positioning themselves in these new volume markets of automotive in-cabin comfort, domestic ventilation or even home appliances and consumer devices, for example,

- In 2021, Infineon joined the gas sensor market with its ENSIV™ PAS CO_2 sensor.[97]
- In January 2021, TDK Invensense join the gas sensor market with the commercialization of their MEMS-based CO_2 gas sensor platform or direct and accurate detection of CO2 in home, automotive, IoT, healthcare, and other applications.[98]

Droplet Measurement

6.0 Instrumentation for Measuring Droplets

6.1 Need

The size distribution of droplets is important in many applications across a wide range of industries, from fundamental research and development through to product quality control and batch release testing. One example of current interest is the contribution of droplets to the spread of infectious diseases, such as influenza and severe acute respiratory syndrome and COVID-19. Drop size analyzers collect and record data that is typically in the form of number count per class size. Drop size measurement and characterization is important in many industries. The importance of drop size information has increased considerably during the last decade in many applications involving sprays such as:

- Drug formulation, development and testing of metered dose inhalers, dry-powder inhalers, and nasal sprays.[99]
- Microbial production of biofuels.[100]
- Automotive diesel and fuel injection studies, airbag development.[101]
- Design and optimization of spray nozzles – for the pharmaceutical, food, agriculture, cosmetic, paint, chemical, fire protection, power generation, agriculture, and lubrication industries.[102]
- Research - Simulation of extreme climates.[103]
- The generation, transport, and characterization of supercooled droplets in multiphase wind tunnel-test facilities is of great importance for conducting icing experiments.[104]

Nozzle manufacturer often use droplet size measurement. Accurate drop size information is an important factor in the overall effectiveness of spray nozzle operation. Drop size is especially of interest in applications such as gas cooling, gas conditioning, fire suppression, spray drying, tablet coating, agricultural spraying, and others. In agriculture, aerial spray application offers advantages such as efficiency, speed, and access to constrained areas.[105] Therefore, spray droplet measurement and control system is important to control unintended spray drift. For example, EPA[106] estimates that pesticide drift losses exceed 70 million pounds annually.[107] Drift litigation claims are also a multi-million-dollar annual cost.[108]

In the food and beverages industry,[109] droplet size distribution in emulsions of water in oil (and oil in water) influences the taste, smell, appearance, and microbial stability of foods such as margarine, butter, mayonnaise, salad dressing, and soft cheese.[110] In the cosmetic industry, the droplet size distribution contributes to a better understanding of the relationship between emulsifying process and long-term emulsion stability.[111]

In biofuel production, the exact knowledge of drop size distributions plays a major role in various fields of applications to control and optimize processes as well as reduce waste.

In the microbial production of advanced biofuels, oil droplets are produced under turbulent conditions in an aqueous medium containing many surface-active components, which might hinder the recovery of the product.[112]

Biomedical applications include drug manufacturing and drug delivery, specifically, the metered dose inhalers that deliver fixed mass doses for pulmonary diseases. Aerosolized drugs are prescribed for use in a range of inhaler devices and systems. Delivering drugs by inhalation requires both a formulation that can be successfully aerosolized and a delivery system that produces a useful aerosol of the drug.[113] For example, measuring the change in size of a droplet as it is exposed to changes in humidity, from ambient to the environment of the lung provides vital information for improving the efficacy of inhalation therapies.[114]

6.1.1 Drop Size Analyzers

There are many drop size analyzers available on the market, most of which use optical methods to characterize sprays. Optical methods fall into two main categories: imaging and non-imaging. Imaging includes photography and holography. Non-imaging methods can be subdivided into two classes, those that measure a large number of drops simultaneously and those that count and size individual drops.[115]

Optical imaging analyzers incorporate the spatial measurement technique. These analyzers consist of a light source, camera, and computer. The light is used to illuminate the spray, which is recorded using the camera. An example typical optical imaging analyzer is shown in the figure below.

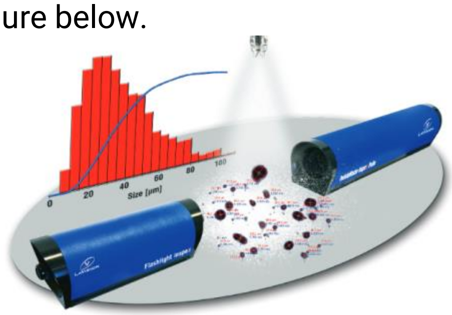


Figure 16: Mastersizer 3000
Source: LaVision.[116]

Laser diffraction analyzers are also spatial sampling devices and consist of a transmitter, receiver, and computer. The technique is based on measuring the scattered light intensity caused by the drops as they pass through the analyzer sampling area.[117] An example of the Malvern analyzer laser diffraction instrument in use today is shown in the figure below.

Figure 17: Mastersizer 3000
Source: Malvern Panalytical.[118]

Optical array probes are flux sampling instruments consist of a light source (low-power laser beam), photo-diode array and computer. Optical array probes are a family of instruments that have been widely used by the cloud physics community. Cloud microphysics is based on in situ measurements made using optical array probes.[119] A schematic of the Optical array probes is shown in the figure below.

Phase Doppler particle analyzers (PDPA) consist of a transmitter, receiver, signal processor and computer. The PDPA measures sizes in the 0.5 to 10,000 μm range using various optical configurations. The PDPA is best suited for two-fluid, hydraulic and flat spray nozzles in every capacity. The phase doppler method is based upon the principles of light scattering interferometry. An example of a PDPA is shown below.

Figure 18: Phase Doppler particle analyzer
Source: TSI[120]

The next figure shows a schematic of a Phase Doppler anemometry analyzer.

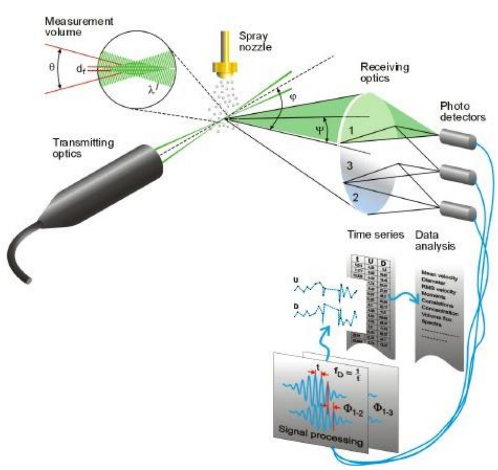


Figure 19: Phase Doppler anemometry
Source: Dantec.[121]

6.1.2 Manufacturers

Optical imaging analyzer instrument manufacturers include:

- Oxford Laser, Inc. Didcot, United Kingdom
  https://www.oxfordlasers.com/laser-imaging/visisize-p15
- LaVision GmbH, Goettingen, Germany
  https://www.lavision.de/en/products/particlemaster/index.php
- MicroTrac MRB (Germany)
- https://www.microtrac.com/products/particle-size-shape-analysis/

Laser diffraction instrument manufacturers include:

- Malvern Panalytical Instruments Ltd., Worcestershire, United Kingdom
  http://www.malvern.co.uk
- Sympatec GmbH, Clausthal-Zellerfeld, Germany
  http://www.sympatec.com
- Particle Measuring Systems, Boulder, CO
  http://www.particlemeasuringsystems.com

There are several manufacturers of Phase Doppler analyzers:

- Artium Technologies, Inc., Sunnyvale, CA
  https://www.artium.com/pdi
- Dantec Dynamics A/S, Skovlunde, Denmark
  https://www.dantecdynamics.com/solutions-applications/solutions/spray-and-particle/
- TSI
- https://tsi.com/products/fluid-mechanics-systems/phase-doppler-particle-analyzer-(pdpa)-systems/

7.0 Conclusion

The purpose of this report was to provide insight into application areas, outside those most commonly addressed by atmospheric researchers where new technology could be applied. The report focused broadly on (1) particle measurement and counting, (2) gas sensors and (3) droplet measurement. The first two application areas are the largest and therefore considerable information was provided on the domestic and global market with data parsed by technology, industry, and region. Key players were also introduced, and insight provided into merger and acquisition activity. Information on the size of the market for spray dispersion analysis equipment was not readily available. However, numerous illustrative examples of applications were provided.

Endnotes

1 Mitrano, Denise Editorial: Biogeochemistry of Anthropogenic Particles. Frontiers in Environmental Science. March 23, 2021
2 Souhail R. Al-Abed. Nanoplastics: adapting existing methods from microplastics and nanotechnology. EPA
3 Mattsson, Karin et al. Monitoring anthropogenic particles in the environment: Recent developments and remaining challenges at the forefront of analytical methods. Current Opinion in Colloid & Interface Science, Vol 56, December 2021
4 IBID
5 Welsh, Brittany et al. Atmospheric deposition of anthropogenic particles and microplastics in south-central Ontario, Canada. Science of the Total Environment, Volume 835, 2022
6 Fragao, et al. Microplastics and other anthropogenic particles in Antarctica: Using penguins as biological samplers. Sci Total Environ, Sept 20,2021
7 Benson, Nsikak. Micro(nano)plastics Prevalence, Food Web Interactions, and Toxicity Assessment in Aquatic Organisms: A Review. Frontiers in Marine Science, March 9, 2022
8 IBID
9 https://www.epa.gov/report-environment/outdoor-air-quality
10 Wlodarczyk, Renata and Kwarciak-Kozlowska, Anna. Nanoparticles from the Cosmetics and Medical Industries in Legal and Environmental Aspects. Sustainability, May 2021
11 Jensen, Alexander et al. Nanoparticle Exposure and Workplace Measurements During Processes Related to 3D Printing of a Metal Object. Frontiers in Public Health,, November 25, 2020
12 Azzougagh, Mohamed Nour et al. Occupational exposure during metal additive manufacturing: A case study of laser powder bed fusion of aluminum alloy. Journal of Occupational and Environmental Hygiene, May 2021
13 IBID
14 Wlodarczyk, Renata and Kwarciak-Kozlowska, Anna. Nanoparticles from the Cosmetics and Medical Industries in Legal and Environmental Aspects. Sustainability, May 2021
15 Hyeon-Ju Oh. Characterization of Inhalable Aerosols from Cosmetic Powders and Sustainability in Cosmetic Products. Sustainability, October 2020
16 Randall et al. How did we get here: what are droplets and aerosols and how far do they go? A historical perspective on the transmission of respiratory infectious disease. The Royal Society. October 12, 2021
17
18 Coffey, KC et al. Preventing transmission of SARS-CoV-2 During College Football Games. JAMA Network Open, January 17, 2020
19 Clouston, Sean A.P. A wind speed threshold for increased outdoor transmission of coronavirus: an ecological study. BMC Infectious Diseases. November 27, 2021
20 Hanaphy, Paul. U.S. Army Research develops "HAPI" 3D Printed Aerosol-Detecting Holography Device. 3D Printing Industry. October 20, 2020
21 IBID
22 Army 3D printed holography device rapidly detects, characterizes aerosols. October 15, 2020
23 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray),

End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026.” November 2021.
24 “Particle Analysis of Carbon Nanotubes.” Horiba. https://www.horiba.com/int/scientific/applications/material-sciences/pages/particle-analysis-of-carbon-nanotubes/
25 MarketsandMarkets. “Carbon Nanotubes (CNT) Market by Type (Single Walled & Multi Walled), End-use Industry (Electronics & Semiconductors, Chemical Materials & Polymers, Structural Composites, Energy & Storage, Medical), Method, and Region - Global Forecast to 2026.” May 2021. https://www.marketsandmarkets.com/Market-Reports/carbon-nanotubes-139.html
26 American Coatings Association. “Analytical Series: Particle Size Distribution, Measurement, and Assessment: Principles, Features, Limitations, and Benefits.” https://www.paint.org/coatingstech-magazine/articles/analytical-series-particle-size-distribution-measurement-and-assessment-principles-features-limitations-and-benefits/
27 Horiba: https://www.horiba.com/int/scientific/applications/metallurgy/pages/particle-analysis-in-mining-and-minerals/
28 Liam Critchley. “Particle Characterization in Mining.” September 6, 2019. https://www.azomining.com/Article.aspx?ArticleID=1506
29 Horiba: https://www.horiba.com/int/scientific/applications/others/pages/particle-size-analysis-of-cement/
30 “Particle Size Analysis Instruments Used in the Food Industry.” https://blog.wstyler.com/particle-analysis/food-industry-particle-size-analysis
31 Gonçalo Farias, Luca Serratore, Sara Pinto, Jagdeep Shur and Robert Price. “Evaluation of Different Setups to Combine Spraytec and Unidose to Assess the Particle Size Distribution of Dry Powder Inhalers.” https://nanopharm.co.uk/wp-content/uploads/2020/08/Farias-2020.pdf
32 Kimberly J. Hassett, Jaclyn Higgins, Angela Woods, Becca Levy, Yan Xia, Chiaowen Joyce Hsiao, Edward Acosta, Örn Almarsson, Melissa J. Moore, Luis A. Brito. “Impact of lipid nanoparticle size on mRNA vaccine immunogenicity.” Journal of Controlled Release, Volume 335, 2021, https://doi.org/10.1016/j.jconrel.2021.05.02
33 Anton Paar. “Particle Size Analysis For The Pharmaceutical Industry.” https://www.pharmaceuticalonline.com/doc/particle-size-analysis-for-the-pharmaceutical-industry-0001
34 Sarah Moore. “How to Measure the Size of Nanoparticles and Why it is Important.” May 6, 2021. https://www.azonano.com/article.aspx?ArticleID=5732
35 Bundschuh, Mirco et al. “Nanoparticles in the environment: where do we come from, where do we go to?” Environmental sciences Europe vol. 30,1 (2018): 6. doi:10.1186/s12302-018-0132-6. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5803285/
36 Eigenbrode Jennifer L., Gold Robert, Canham John S., Schulze Erich, Davila Alfonso F., Seas Antonios, Errigo Therese, Kujawa Faith, Kusnierkiewicz David, Lorentson Charles, McKay Christopher. “Contamination Control for Ultra-Sensitive Life-Detection Missions.” Frontiers in Space Technologies, vol 2 , 2021, https://www.frontiersin.org/article/10.3389/frspt.2021.734423
37 MarketsandMarkets. “Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026.” November 2021.
38 MarketsandMarkets. “Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray),

End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
39 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
40 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
41 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
42 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
43 "Global Nanomaterials Market to Reach $12.1 Billion by 2026." Global Industry Analysts, Inc. March 23, 2022. https://www.prnewswire.com/news-releases/global-nanomaterials-market-to-reach-12-1-billion-by-2026--301506511.html
44 "NNI Supplement to the President's 2022 Budget." March 31, 2022. https://www.nano.gov/2022BudgetSupplement
45 Horiba. "Nanoparticle Analysis." https://www.horiba.com/int/scientific/applications/material-sciences/pages/nanoparticle-analysis/
46 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
47 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
48 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
49 MarketsandMarkets. "Particle Size Analysis Market by Technology (Laser Diffraction, DLS, Imaging, Coulter Principle, Sieving, Nanoparticle Tracking), Dispersion (Wet, Dry, Spray), End-user (Pharma-biotech, Cosmeceutical, Chemicals, Food, Academia) - Global Forecasts to 2026." November 2021.
50 Verder Scientific acquires particle Porotec GmbH. August 13, 2020. https://www.metal-am.com/verder-scientific-acquires-particle-porotec-gmbh/
51 "New Technological Leader in Particle Characterization. January 2020. https://www.verder-scientific.com/news/news/details/news_detail/new-technological-leader-in-particle-characterization
52 "Anton Paar Acquires Quantachrome Instrument. February 2, 2018. https://www.anton-paar.com/us-en/about-us/news/news/detail/anton-paar-acquires-quantachrome-instruments/

53 “Micromeritics Instrument Corp. Acquires Process Integral Development S.L.” August 1, 2018. https://www.pharmaceuticalonline.com/doc/micromeritics-instrument-corp-acquires-process-integral-development-sl-0001
54 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025.” December 2020.
55 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025.” December 2020.
56 Peter Feamster. “Particle Analysis Evolves with Cleanliness Specifications.” November 6, 2020. https://www.productionmachining.com/blog/post/particle-testing-evolves-with-cleanliness-specifications
57 Bin Liu and Shi Liu, "Particle Measurements with Liquid-borne Particle Counters: Effects of Counting Efficiency," Advanced Semiconductor Manufacturing Conference (ASMC), 28th Annual SEMI DOI: 10.1109/ASMC.2017969222, 2017
58 “Particle Sensing in Gas Turbine Inlets Using Optical Measurements and Machine Learning.” https://vtechworks.lib.vt.edu/handle/10919/101969
59 Papadopoulos, G, Bivolaru, D, & Lin, J. "Real Time Gas Turbine Engine Particulate Ingestion Sensor for Particle Size and Composition." Proceedings of the ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition. Volume 6: Ceramics; Controls, Diagnostics, and Instrumentation; Education; Manufacturing Materials and Metallurgy. Oslo, Norway. June 11–15, 2018. V006T05A029. ASME. https://doi.org/10.1115/GT2018-77137
60 Lekki, J., Lyall, E., Guffanti, M., Fisher, J., Erlund, B., Clarkson, R, & van de Wall, A. (2013). Multi-Partner Experiment to Test Volcanic-Ash Ingestion by a Jet Engine. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130013612.pdf
61 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025.” December 2020.
62 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025.” December 2020.
63 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025.” December 2020.
64 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025.” December 2020.
65 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025.” December 2020.
66 MarketsandMarkets. “Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life

Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025." December 2020.

67 MarketsandMarkets. "Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025." December 2020.

68 MarketsandMarkets. "Particle Counter Market by Type (Airborne, Liquid), Application (Cleanroom Monitoring, Contamination Monitoring of Liquids, IAQM), End User (Life Sciences & Medical Devices, Semiconductor, Automotive), Region - Global Forecast to 2025." December 2020.

69 TSI. "TSI Offers Full Solution for Ultrafine Particle Monitoring." September 2021. https://tsi.com/discover-tsi/latest-news/2021/tsi-offers-full-solution-for-ultrafine-particle-monitoring/

70 TSI, Inc. "Particle scanning spectrometer." https://tsi.com/getmedia/b35e42d2-5045-47b1-9522-c0b094d85dbb/Particle_Catalog_Web?ext=.pdf

71 TSI. "TSI Expands Its Offerings for Indoor Air Quality Monitoring."

72 https://www.dekati.com/industries/aerosol-research/

73 Dekati. "Real-time aerosol measurement." https://www.dekati.com/real-time-particle-measurement/

74 GRIMM Aerosol. https://www.grimm-aerosol.com/applications/research/basics/nanotechnology-process-monitoring/

75 Belton, Padraig. The Computer Chip Industry has a dirty climate secret. The Guardian. September 18, 2021

76 IBID

77 Davis, Shannon. Sustainability in Semiconductor manufacturing – A Review of Emissions and Materials Released Off-site. Semiconductor Digest. November 16, 2021

78 Davis, Shannon. Sustainability in Semiconductor manufacturing – A Review of Emissions and Materials Released Off-site. Semiconductor Digest. November 16, 2021

79 IBID

80 MarketsandMarkets. "Gas Sensors Market with COVID-19 Impact Analysis by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography - Global Forecast to 2026." February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html

81 MarketsandMarkets. "Gas Sensors Market with COVID-19 Impact Analysis by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography - Global Forecast to 2026." February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html

82 Grand View Research. "Gas Sensor Market Size, Share & Trends Analysis Report by Product, By Type, By Technology, By End Use, By Region, And Segment Forecasts, 2022 – 2030." April 2022. https://www.grandviewresearch.com/industry-analysis/gas-sensors-market

83 MarketsandMarkets. "Gas Sensors Market with COVID-19 Impact Analysis by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography - Global Forecast to 2026." February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html

84 MarketsandMarkets. "Gas Sensors Market by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology,

Output Type, Product Type, Application, and Geography (2021-2026).” February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html
85 MarketsandMarkets. “Gas Sensors Market by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography (2021-2026).” February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html
86 MarketsandMarkets. “Gas Sensors Market by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography (2021-2026).” February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html
87 MarketsandMarkets. “Gas Sensors Market by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography (2021-2026).” February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html
88 MarketsandMarkets. “Gas Sensors Market by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography (2021-2026).” February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html
89 Yole Développement. “Gas and Particle Sensors - Technology and Market Trends. 2021. Market & Technology Report.” July 2021. https://s3.i-micronews.com/uploads/2021/07/YINTR21178-Gas-and-Particle-Sensors-Technology-and-Market-Trends-2021-Flyer-Yole.pdf
90 MarketsandMarkets. “Gas Sensors Market by Gas Type (Oxygen, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, Hydrocarbons), Technology, Output Type, Product Type, Application, and Geography (2021-2026).” February 2021. https://www.marketsandmarkets.com/Market-Reports/gas-sensor-market-245141093.html
91 Yole Développement. “Gas and Particle Sensors - Technology and Market Trends. 2021. Market & Technology Report.” July 2021. https://s3.i-micronews.com/uploads/2021/07/YINTR21178-Gas-and-Particle-Sensors-Technology-and-Market-Trends-2021-Flyer-Yole.pdf
92 Yole Développement. “Gas and Particle Sensors - Technology and Market Trends. 2021. Market & Technology Report.” July 2021. https://s3.i-micronews.com/uploads/2021/07/YINTR21178-Gas-and-Particle-Sensors-Technology-and-Market-Trends-2021-Flyer-Yole.pdf
93 Yole Développement. “Gas and Particle Sensors - Technology and Market Trends. 2021. Market & Technology Report.” July 2021. https://s3.i-micronews.com/uploads/2021/07/YINTR21178-Gas-and-Particle-Sensors-Technology-and-Market-Trends-2021-Flyer-Yole.pdf
94 “Renesas Completes Acquisition of Integrated Device Technology.” March 29, 2019. https://www.renesas.com/us/en/about/press-room/renesas-completes-acquisition-integrated-device-technology
95 “Sensirion acquires micro gas-analyzer specialist Qmicro.” February 11, 2021. https://sensirion.com/company/investor-relations/ad-hoc-news/article/sensirion-acquires-micro-gas-analyzer-specialist-qmicro/

96 “Apple supplier AMS agrees joint venture for environmental sensor business.” March 19, 2019. https://www.reuters.com/article/us-ams-jointventure-wise-road/apple-supplier-ams-agrees-joint-venture-for-environmental-sensor-business-idUSKCN1R00M2
97 Infineon. https://www.infineon.com/cms/en/product/sensor/co2-sensors/
98 “TDK introduces revolutionary MEMS-based CO2 gas sensor platform.” January 7, 2021. https://invensense.tdk.com/news-media/tdk-introduces-revolutionary-mems-based-sensor-platform-for-detecting-co2/
99 Paul Kippax, Deborah Huck, Carl Levoguer , Anne Virden, Julie Suman. “Characterizing A Nasal Spray Formulation from Droplet to API Particle Size.” February 11, 2011. https://www.pharmtech.com/view/characterizing-nasal-spray-formulation-droplet-api-particle-size
100 Sergios Karatzos and J. Susan van Dyk, et al. “Drop-in biofuel production via conventional (lipid/fatty acid) and advanced (biomass) routes. Part I.” 2016. https://www.osti.gov/servlets/purl/1346341
101 Malvern. “Fuel injectors.” https://www.malvernpanalytical.com/en/industries/automotive-aerospace/fuel-injectors
102 “Measurement of Spray Droplet.” https://www.ikeuchi.us/eng/technology/18/
103 “Climate models miss most of the coarse dust in the atmosphere.” https://www.science.org/doi/10.1126/sciadv.aaz9507
104 Knop, I., Bansmer, S. E., Hahn, V., and Voigt, C.: Comparison of different droplet measurement techniques in the Braunschweig Icing Wind Tunnel, Atmos. Meas. Tech., 14, 1761–1781. 2021. https://amt.copernicus.org/articles/14/1761/2021/
105 Qing TANG, Liping Chen, Ruirui Zhang, Min XU, Gang XU, Tongchuan YI, Bin Zhang. Droplet spectra and high-speed wind tunnel evaluation of air induction nozzles. Front. Agr. Sci. Eng., 2018, 5(4): 442–454 https://doi.org/10.15302/J-FASE-2017169
106 EPA. “About the Drift Reduction Technology Program.” https://19january2017snapshot.epa.gov/reducing-pesticide-drift/about-drift-reduction-technology-program_.html
107 EPA. “Introduction to Pesticide Drift.” https://19january2017snapshot.epa.gov/reducing-pesticide-drift/introduction-pesticide-drift_.html
108 “States Grapple with Dicamba.” September 20,2017. https://www.dtnpf.com/agriculture/web/ag/crops/article/2017/09/20/state-pesticide-regulators-face-2018
109 “Droplet Size Analysis of Mayonnaise.” https://www.entegris.com/content/dam/product-assets/accusizerspossystems/appnote-droplet-size-analysis-of-mayonnaise-10547.pdf
110 Bruker. “minispec Droplet Size Analyzer 2.0.” https://www.bruker.com/en/products-and-solutions/mr/nmr-food-solutions/droplet-size-distribution-of-oil-in-water.html
111 Kim, KM., Oh, H.M. & Lee, J.H. Controlling the emulsion stability of cosmetics through shear mixing process. Korea-Aust. Rheol. J. 32, 243–249. 2020. https://doi.org/10.1007/s13367-020-0023-4
112 Robert P. Panckow, Laura Reinecke, Maria C. Cuellar, Sebastian Maass. Photo-Optical In-Situ Measurement of Drop Size Distributions: Applications in Research and Industry. Oil & Gas Science and Technology - Revue d’IFP Energies nouvelles, Institut Français du Pétrole (IFP), 2017, 72 (3). https://hal.archives-ouvertes.fr/hal-01695273/document
113 American Association for Respiratory Care. “A Guide to Aerosol Delivery Devices for Respiratory Therapists.” 2017. https://www.aarc.org/wp-content/uploads/2015/04/aerosol_guide_rt.pdf
114 MarketsandMarkets. “Pharmaceutical Drug Delivery Market by Route of Administration (Oral, Injectors, Implantable, Syrups, Gels, Pulmonary, Solutions, Tablets, Syringes), Application (Cancer, Diabetes), Facility of Use (Hospitals), COVID-19 Impact - Global

Forecast to (2022 - 2026).” November 2021. https://www.marketsandmarkets.com/Market-Reports/drug-delivery-technologies-market-1085.html?gclid=EAIaIQobChMIoKzcvMHI9wIVw8DICh01CQLIEAMYASAAEgJ_ZPD_BwE
115 R. Sijs, S. Kooij, et al. “Drop size measurement techniques for sprays: Comparison of image analysis, phase Doppler particle analysis, and laser diffraction.” AIP Advances 11, 015315 (2021); https://aip.scitation.org/doi/10.1063/5.0018667?cookieSet=1
116 LaVision: https://www.lavision.de/en/products/particlemaster/particlemaster-inspex/index.php
117 Malvern Panalytical. “A basic guide to particle characterization.” https://www.montana.edu/eal-lres/documents/WP120620BasicGuidePartChar.pdf
118 Malvern Instruments: https://www.malvernpanalytical.com/en/products/product-range/mastersizer-range/mastersizer-3000
119 O'Shea, S., Crosier, J., Dorsey, J., Gallagher, L., Schledewitz, W., Bower, K., Schlenczek, O., Borrmann, S., Cotton, R., Westbrook, C., and Ulanowski, Z.: Characterizing optical array particle imaging probes: implications for small-ice-crystal observations, Atmos. Meas. Tech., 14, 1917–1939. https://amt.copernicus.org/articles/14/1917/2021/
120 TSI: https://tsi.com/products/fluid-mechanics-systems/phase-doppler-particle-analyzer-(pdpa)-systems/itasca-based-pdpa-system/
121 Dantec: https://www.dantecdynamics.com/solutions-applications/solutions/spray-and-particle/phase-doppler-anemometry-pda/measurement-principles-of-pda/