Particulate Matter Sensor Comparative Tear-Down: Sensirion SEN55 vs. Plantower PMS500s

Introduction

The authors of this document desire only to help the reader choose the best Low-Cost (LC), consumer grade, indoor Air Quality Monitor (iAQM) their budget allows. Data Quality (DC) and Total Cost of Ownership (TCO) are two key metrics for any iAQM purchase. The goal is to maximize DC and minimize TCO.

Insuring adequate DC allows us to make the wisest decisions possible regarding the air we breath. Scientific studies, for good or ill, provide little benefit to the average lay-person. Citizen scientists, as well as commercial and academic scientists, may find it difficult to determine whether an experimental study is designed to produce unbiased, high quality, reproducible, statistically significant data, as well. Many potential iAQM customers simply vest their trust in one or more iAQM vendors using only vendor reputation, frequency or quantity of citations in academic or regulatory reports, difficulty purchasing the product (scarcity bias), or solely based upon total units sold. They choose a metric to which they can comfortably equate DC and move on from there.

We believe that consumers may improve their purchase by filtering the above criteria through the lens of engineering. This white paper is intended to help consumers: evaluate a few of the important, simple design principals used to engineer the sensors used in this class of iAQM; and understand how that engineering, or lack thereof, may impact DC and TCO. For the remainder of this paper, the acronym iAQM will be used as short-hand for Low-Cost, consumer grade, indoor Air Quality Monitor.

Sensors Under Consideration

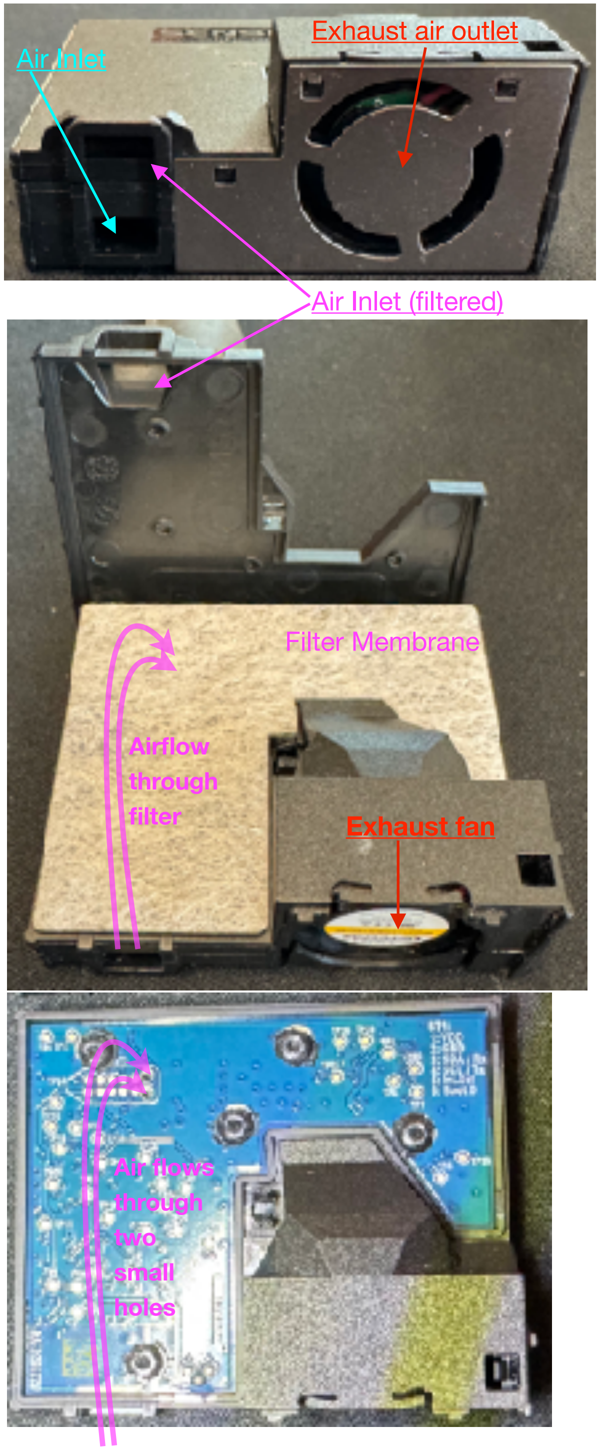
The Plantower PMS5003 and Sensirion SPS30 are two particulate matter (PM) sensor nodes frequently found in laboratory studies and paired in field comparisons. iAQM vendors that use the PMS5003 typically compare their products to the SPS30. However, the SPS30, for all intents and purposes, is no longer used in iAQM; and vendors that base their products on Sensirion, today, incorporate one of the SEN5x sensor nodes, which have been commercially available since 2022. If one is to compare iAQM products from the past three years, the Plantower PMS5003 based products ought to be compared to Sensirion SEN5x based products.

Unfortunately, the research, regulatory, and scientific communities that typically conduct detailed comparative analyses have not appeared to noticed the new line of Sensirion sensors available since 2022. A few tear-downs may be found on the internet that document the Plantower PMS5003 and the aged Sensirion SPS30. However, the authors of this paper have yet to find any tear-down of any Sensirion SEN5x sensor node. This teardown is intended to fill that gap.

Additionally, this teardown will flood that gap by examining a Plantower PMS5003 and comparing it to a Sensirion SEN55. This comparison should allow consumers to evaluate, from an engineering perspective, whether each sensor node is capable of producing quality data, as well as those nodes TCO. Consumers and citizen scientists, alike, should then be able to make more informed use of any available experimental studies and purchase the best iAQM for their needs.

Please note:
- The authors, Larry Greenwald and Tim Vold, declare no competing interests.
- The PMS5003 sensor node was purchased by the authors using personal funds.
- The Sensirion SEN55 sensor was provided by Apollo Automation, free of charge or encumbrances.

Sensirion SEN55



Air Flow Examination

Each sensor node's fan:

- pulls aerosol through the inlet(s),
- across one or more discrete sensors, then
- out the exhaust port.

Both sensor nodes' exhaust fan appears similar in size and capacity.

PMS5003

The PMS5003 has:

- one inlet, of 4 holes; and
- one exhaust port.

All aerosol flows through an internal compartment, across the PCB and surface mount components, into the lower compartment via three holes in the PCB opposite the case inlets, through a sampling chamber, then out the exhaust port. The lower compartment's sample chamber contains the laser and photo detector.

SEN55

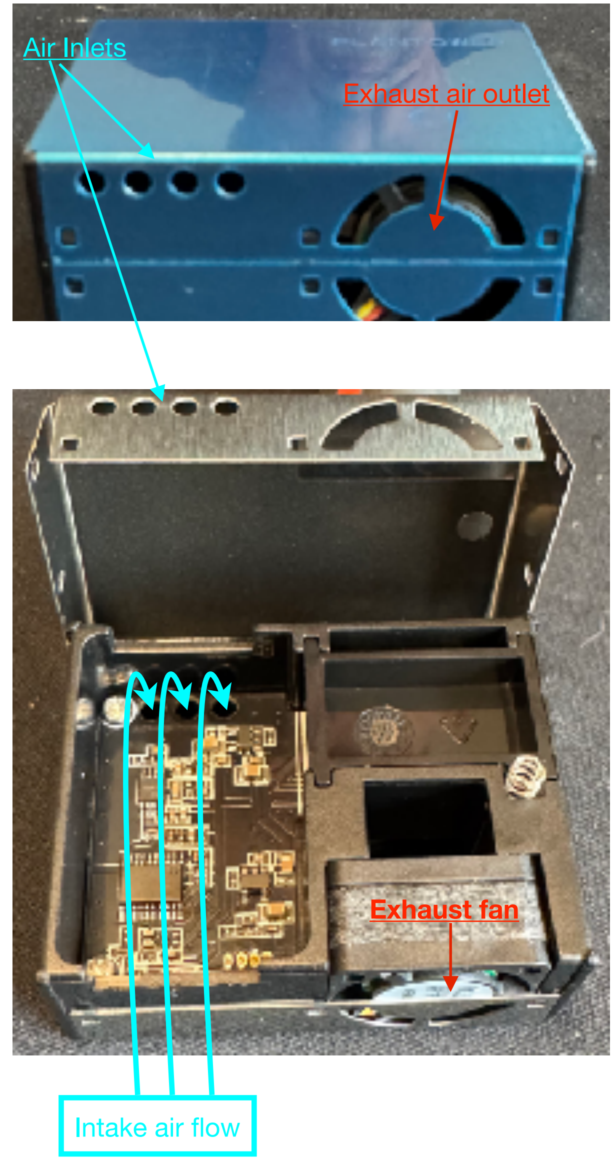
The SEN55 has:

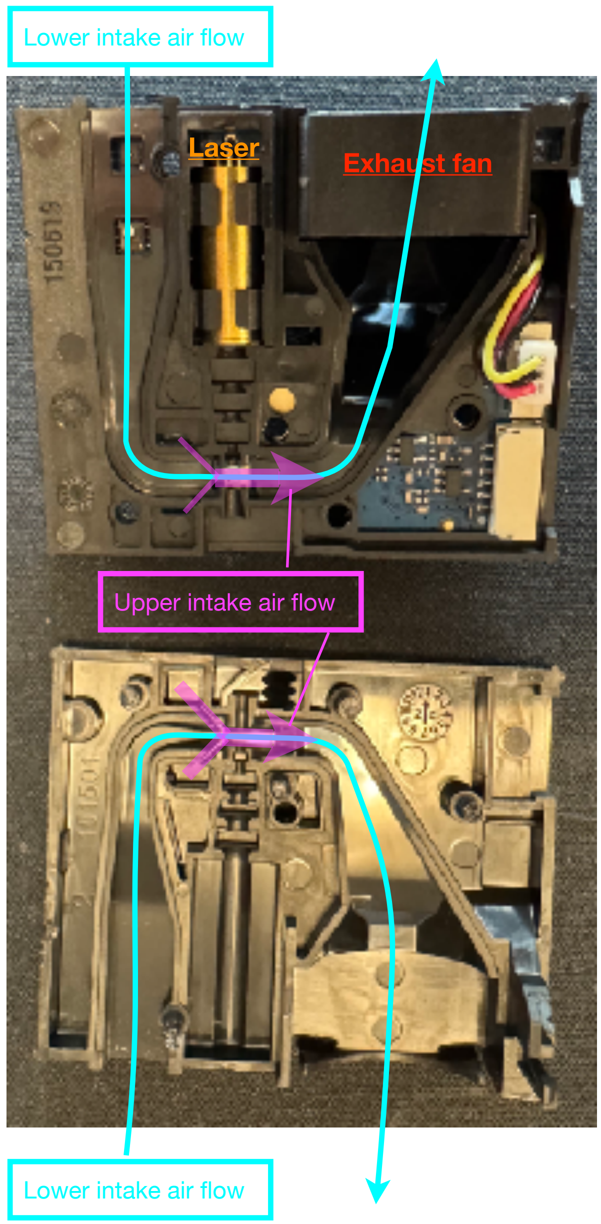
- two discrete aerosol inlets
  - upper inlet;
  - lower inlet; and
- one exhaust port.

The upper inlet aerosol flows through a HEPA filter membrane; then through two small holes in the PCB.

The lower inlet aerosol flows directly into a channel containing two sensor nodes, the laser, photo detector, and exhaust fan.

Plantower PMS5003





Air Flow Examination Cont.

PMS5003

As noted on the preceding page, aerosol flows through the case inlets and upper chamber, across the exposed surface mounted components of the PCB, then through three holes on the opposite side of the PCB.

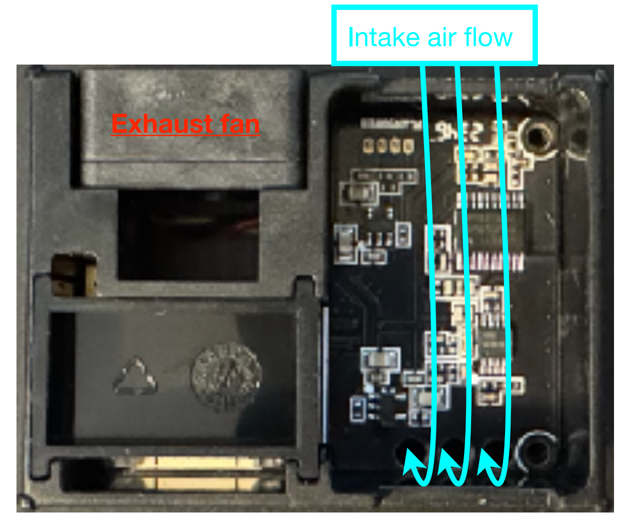
In the other side of the sensor node, the aerosol enters a large empty compartment and is drawn through the sampling channel containing the laser and photo detector. The aerosol flows through the exhaust channel and is expelled by the fan.

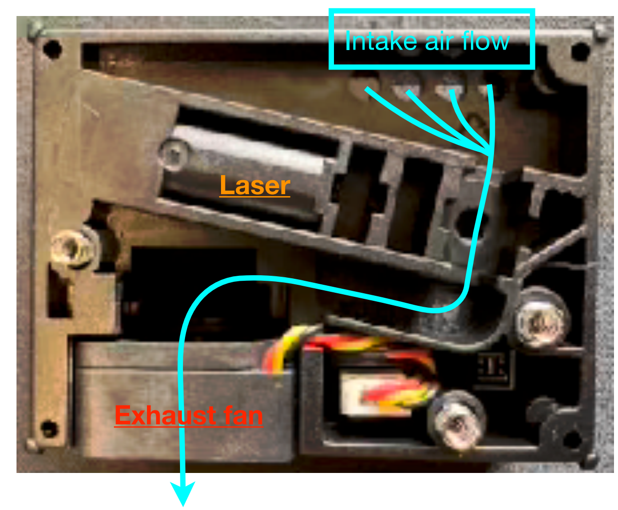
SEN55

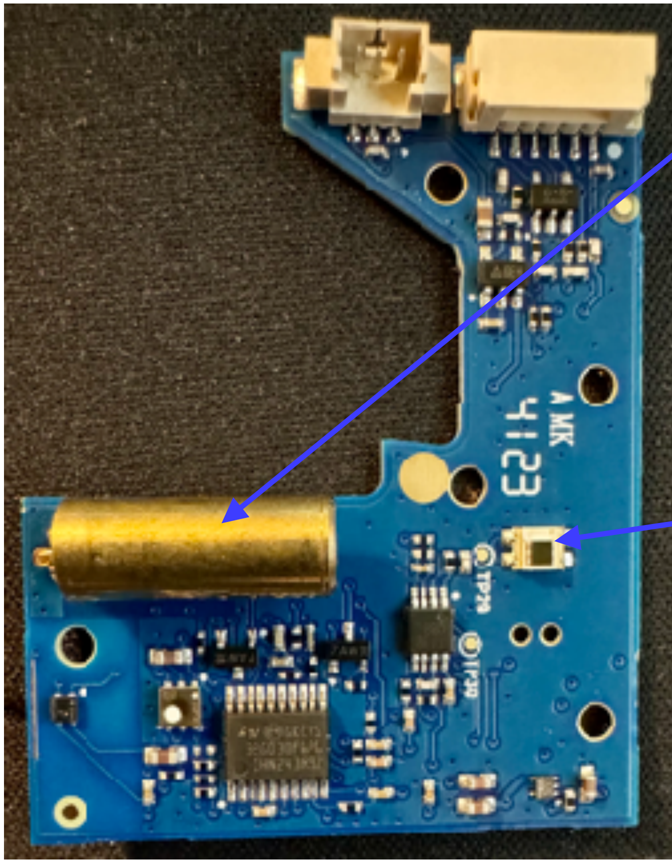
Aerosol is drawn into the lower inlet port, across the SH40 sensor, across the SGP41 sensor, and then constrained to a progressively smaller channel as it approaches the laser and photo detector.

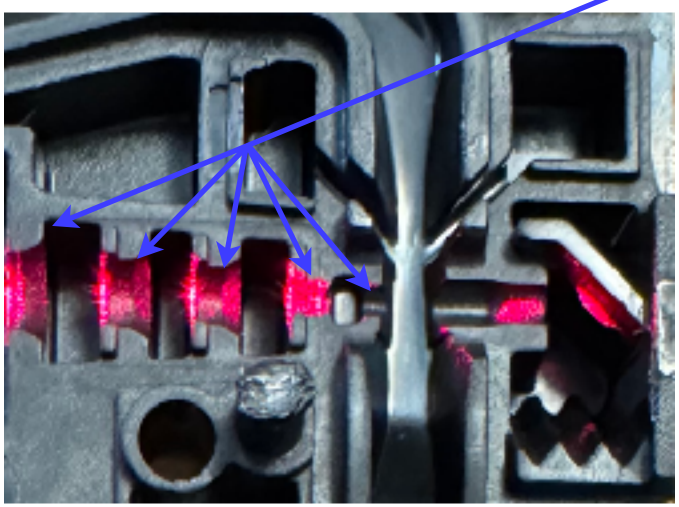
Immediately prior to entering the laser/photo detector cavity, the lower intake aerosol stream is encapsulated by the HEPA-filtered air from the upper intake.

The aerosol stream, *sheathed* in filtered air, passes through the PM sensing chamber, out through a progressively larger exhaust channel, and is expelled by the fan.









Lasers, Photo Detectors, & Baffles

Lasers

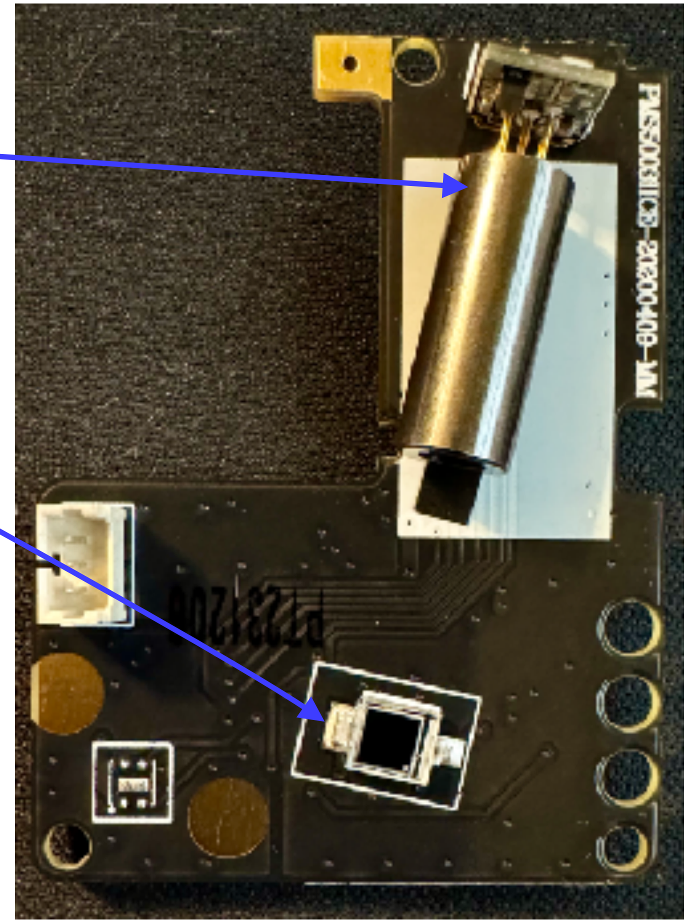
Each of these sensor nodes sports a nondescript, unidentified laser. Technical specifications state that the PMS5003 laser emits 657 nm light and the SEN55 laser emits 660 nm light. No data nor measurements pertaining to either laser's focal length, shape, size, etc. have been acquired.

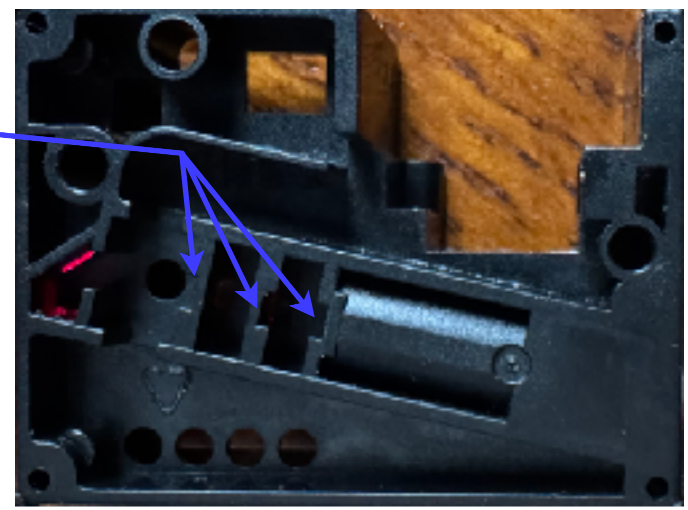
Photo Detector

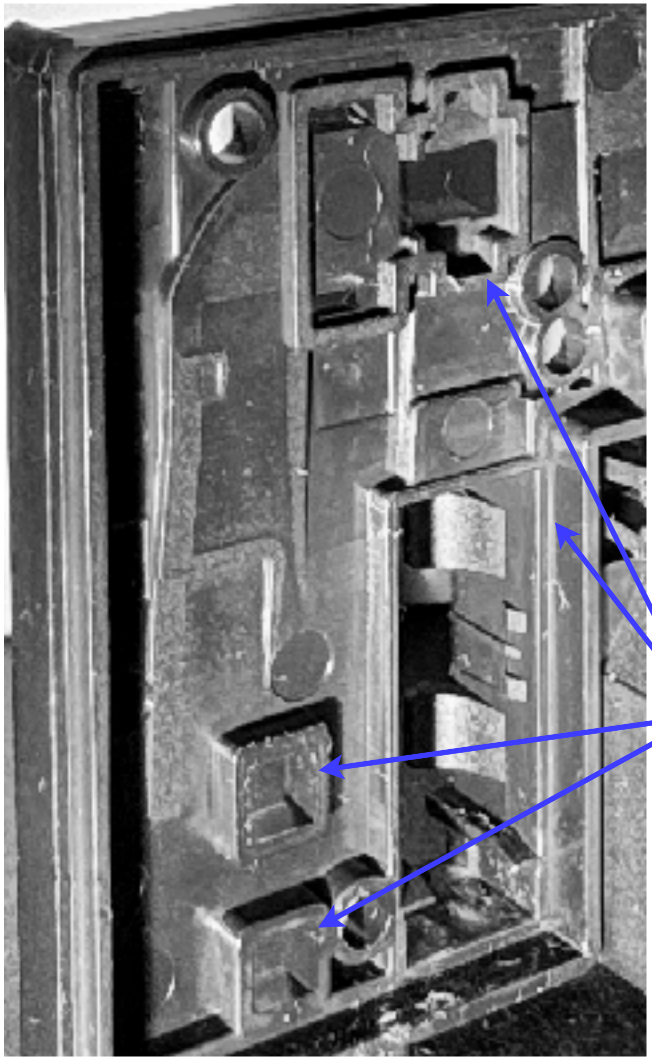
Each of these sensor nodes uses a photo detector to measure incident light scattered from particles that flow through their measurement chambers. It is not known whether these detectors are silicon based or other.

Baffles

Each of these sensor nodes uses a set of baffles to filter off divergent, stray light prior to entrance into the sample chamber. Each sensor node contains a beam dump to preclude light from re-entering the sample chamber where it could strike particles more than once.







Sensor Isolation

Consistent presentation of samples to sensors is key to the precision and accuracy of the raw data those sensors produce. Aerosol volumes and flow rates are critical data used in the calculation of particulate concentration.

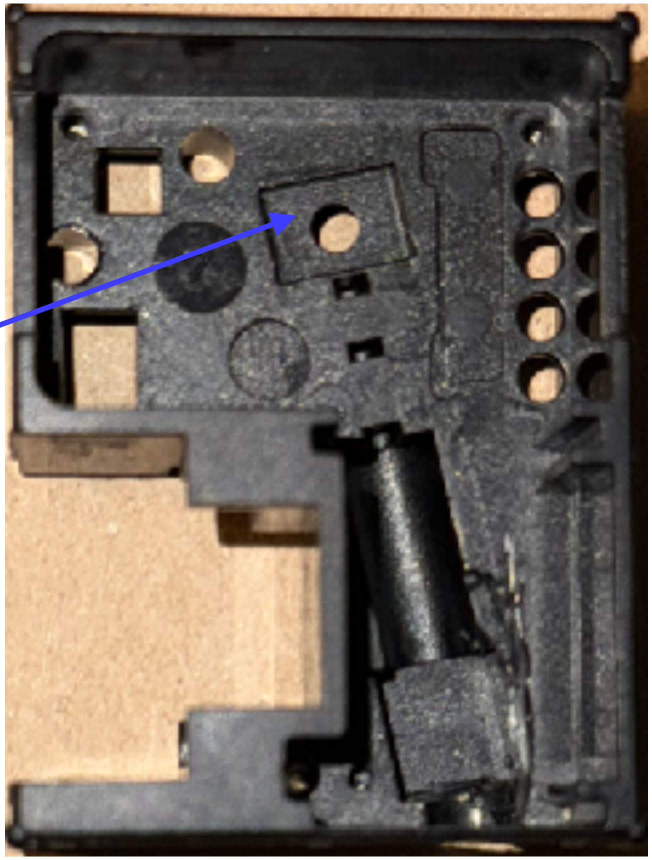
PMS5003

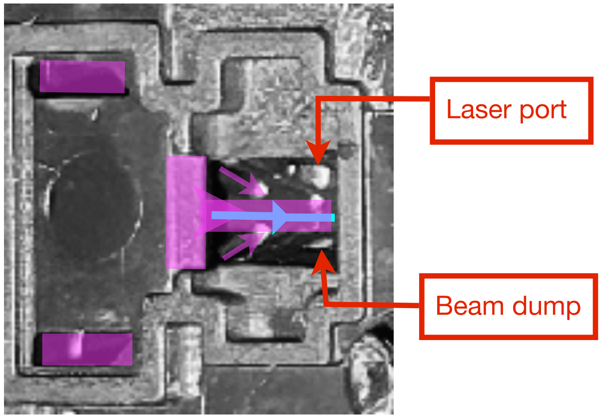
This sensor node's photo detector is seated into a shallow recess that appears capable of preventing stray aerosol from entering the sample chamber from areas other than the designated sample path.

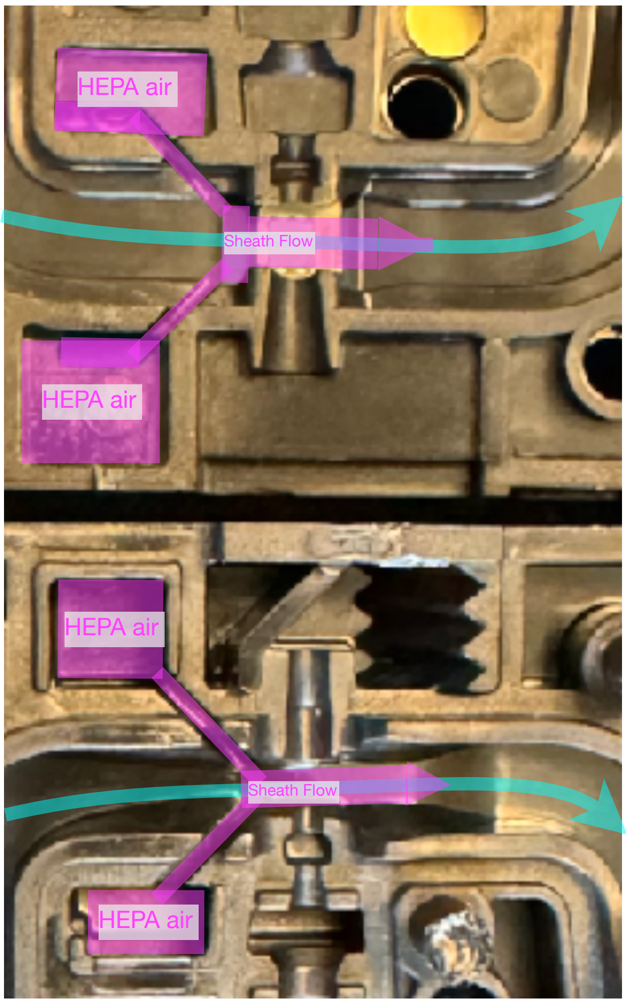
SEN55

SH40 sensor, SGP41 sensor, and laser are enclosed within distinct cavities that are coupled to the aerosol channel path. The cavities are also decoupled from the internal, non-HEPA filtered air flow as well as from the remainder of the sensor node's internal ambient environment.

The photo detector is enclosed within its own compartment. The HEPA-filtered air flows into this area, and then into the aerosol stream channel via several openings.







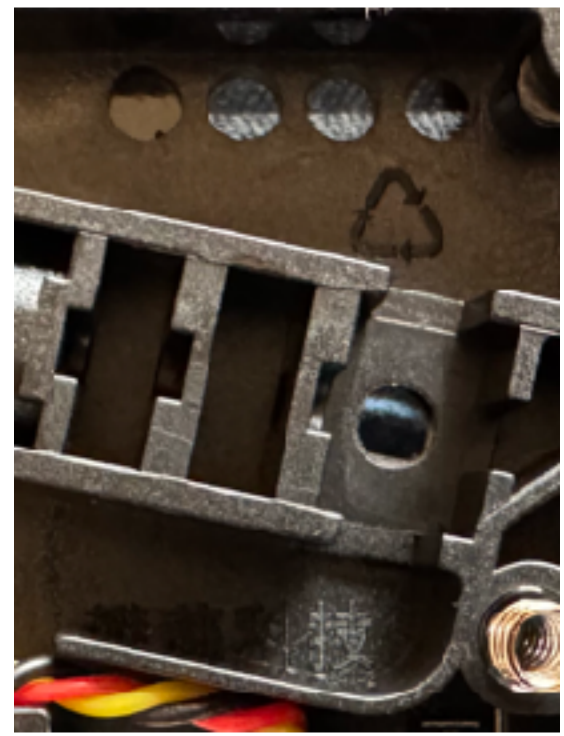
Sheath Air Flow...or lack thereof

PMS5003

There is no sheath flow present in this device.

SEN55

As noted on page 2, air is drawn through the upper intake, through the HEPA filter membrane, through two small holes in the PCB, then into a small cavity. That filtered air is then used to create *sheath air flow*. This sheath air is drawn through two small slots in the photo detector isolation chamber to fill two small reservoirs on the sides of the aerosol stream channel. The sheath air is drawn through a small beveled slot on the windward face the photo sensor, as well as around the lateral edges and leeward side of the photo sensor. All sheath air streams assemble, surround, shape, and position the aerosol stream immediately prior to intersection with the laser's focal path. This constitutes Sensirion's patented implementation of *Sheath* Flow.



Discussion

Computational Fluid Dynamics (CFD)

The data quality (DC) of these iAQM is dependent upon many factors:

1. the quality, consistency, and reliability of components used - lasers, photo detectors, micro controller(s), etc.;
2. the quality and correctness of software, firmware, algorithms, etc.; and
3. the design and engineering of the aerosol delivery mechanism - i.e. how the particulate matter arrives at the sensor to be measured.

To simplify this discussion, we choose to presume items 1 and 2, above are equivalent. Based upon the observations from the preceding pages, item 3 is the differentiator between these iAQM. Without access to a sonic anemometer which could definitively measure the interior air flow within these two iAQM, we must rely upon CFD to inform us whether either device could deliver an aerosol stream to the sensor(s).

Use of an open source CFD product such as OpenFOAM could provide reasonable and comparable estimates as to the nature of the aerosol streams through these iAQM. CFD would show whether the aerosol streams are predominately laminar or turbulent. That is the critical point:

- laminar flow would deliver the external aerosol directly to the sensors without changes to the aerosol's composition in transit.
- turbulent flow would cause changes to the aerosol's composition in transit to the sensors.

Due to the stark design difference between these two iAQM, simple application and discussion of CFD principals is clearly sufficient to our needs.

PMS5003

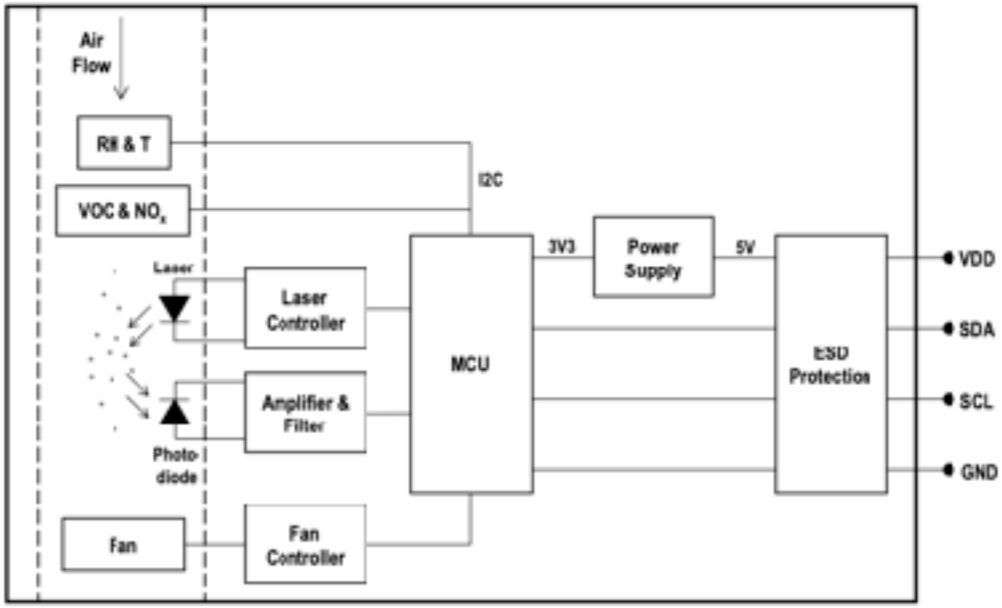
The PMS5003's interior aerosol path appears designed to create turbulence and dead areas. Laminar flow separation occurs at sharp edges, sharp corners, and high angles of attack due to rapid changes in velocity. That separation *is* turbulence, leads to recirculation and dead areas, and will allow particulate matter to leave and re-enter the aerosol stream in indeterminate ways and rates - i.e. the composition and concentration of particulate matter in the aerosol stream entering the device's sample chamber will not be the same as it was when it initially entered the PMS5003. The only area inside the PMS5003 that does not appear to cause turbulence is the short elbow path leading to the exhaust fan and outlet.

The aerosol stream path into and out of the PM sample chamber is smaller than the sample cavity itself. The aerosol sample chamber entrance, the final laser baffle, the beam dump, and aerosol sample chamber exit all have sharp corners that create turbulence within the PM sample cavity. The aerosol stream appears to be unconstrained in any way inside the sample chamber. The turbulence inside the chamber will cause; particles to go undetected; and large particles to scatter light at angles and energies leading to incorrect size - i.e. large particles are likely to be assigned to a smaller bin than their physical size would dictate.

Discussion Continued

SEN55

The SEN55's inlets, by contrast, are unobstructed. The aerosol stream flows through a highly polished channel containing only obtuse angles or changes in direction. The channel is devoid of dead areas, sharp edged surface mounted electronic components, or protrusions into the aerosol stream's path. Each discrete sensor is isolated from the internal, ambient environment of the sensor node; yet directly coupled, in series, to the aerosol stream.



As the aerosol stream approaches the laser and photo detector, the stream volume is progressively reduced and constrained in size and shape by the highly polished channel itself. Immediately prior to the PM detection area within the channel, the HEPA-filtered sheath air flow:

- fully encapsulates the aerosol stream;
- shapes the aerosol stream into a circular pipe whose cross sectional area approximates that of the laser beam and photo detector;
- positions the aerosol stream to optimally intersect the laser's focal path, centered over the photo detector; and
- prevents deposition of particles on the surfaces of the photo detector, laser lens, and channel that could otherwise buildup and contaminate the area.

Conclusions

PMS5003

The PMS5003 appears minimally engineered and cheaply constructed. Plantower provides no data sheet or other documentation for the PMS5003. The only document of any consequence available on the Plantower.com website is for the PMS1003 sensor node. That product specification was created over 10 years ago, remains at version 1.0, and was last updated 4 years ago. There are no other publicly accessible documents, patents, design-in guides, etc.

It may be that Plantower's paying customers are provided adequate documentation once contracts and purchase orders are signed. However, it would appear that such technical, engineering, and other useful documentation and information must be subject to non-disclosure agreements - otherwise, those documents would have been found, disseminated, or cited in countless bibliographies. This inconsiderate and unprofessional behavior by Plantower indicates that they have no consideration for the environmental concerns of their customers. It also implies that Plantower's primary objectives are profits. Plantower's callus and caviler nature easily exemplified by these two statements from their PMS1003 product specification:

> "Only the consistency of all the PM sensors of PLANTOWER is promised and ensured.
> And ***the sensor should not be checked with any third party equipment***."

That first statement means nothing more than that Plantower ensures uniformity across the effectivity of a product line. It *does* not equate to precision nor accuracy. In fact Plantower's second sentence, above, states quite clearly that the data from their sensors "should not be checked" against "any third party equipment." Therefore, the Plantower PMS5003 data can not be correlated or calibrated to **any** reference, regulatory, or research grade sensor; and Plantower does not publish calibration data against international standards for their products.

The only logical conclusions are that:

- the PMS5003 *may or may not* produce usable data for some period of time immediately upon entering field service;
- the PMS5003 may or may not produce data for any appreciable portion of its stated three year lifespan; and
- any iAQM vendor that incorporates a Plantower sensor node into their product does not possess the scientific nor engineering acumen required.

Conclusions Continued

SEN55

The SEN55 is designed, engineered, and built as though people's lives depended on it. They do.

Sensirion produces, updates, and publishes every type of data sheet, application note, guide, certification, product brochure, and patent application that one could want.

Aerosol science, environmental science, physical chemistry, physics - it is all relevant and considered in Sensirion's products, documentation, and patents. The patent applications, themselves, spell out in stark terms the purpose of the designs and reason(s) the sensor node is engineered the way it is.

In-depth study of Sensirion products, careful reading of their documents, and understanding the scientific, real-world ramifications of their designs inevitably leads to an appreciation and admiration of the genius and prowess of Sensirion staff.

They are a commercial company that exemplifies ethical, open, and transparent conduct for no other reason than it is the right way to conduct themselves.

For what it's worth, they do answer email inquiries in a very timely, professional manner; ***and*** they actually follow up when they have more information they know you can use without being prompted to do so.

Final Thoughts

Sensirion SEN55 and Plantower PMS5003 are competitively priced - each costs and average of USD $30.

Sensirion products are insanely well crafted. Plantower products are not.

Sensirion acts as though they care about you and the environment. Plantower does not.

Vendors that incorporate Sensirion sensors can produce high quality iAQM having a rated life time ≥ 10 years. They need only follow some well documented *design-in* engineering guidelines published by Sensirion. They do not have to spend large sums of money on test chambers, staff scientist(s), reference-grade sensors, standards calibrations. These vendors can then pass those savings on to their customers.

Vendors that incorporate Plantower sensors can not produce high quality iAQM - that is a scientific fact that is irrefutable. Cherry-picked data from the numerous, flawed, short term, comparative, experimental studies should not sway you. CEOs whom troll competitors' Discord channels attempting to sow fear, uncertainty, and doubt (FUD) while ignoring their own conservatism bias.

Believe nothing of what you've read in this document. You may trust - provided that you *verify.*
Do your own research, or at least *read* other's research. Wonder. Ask questions. Try to understand the science. Always stay skeptical and keep learning !!!