State-Of-The-Art Filter Monitoring

Authors: Andries Bosma (Product Manager / Gas Flow), Manuel Eckstein (Key Account Manager / HVAC)

Where clean air is needed, an air filter is usually not far away. In the last decade, the filtration industry has made tremendous progress in filter technologies. With new materials and designs, advances in nonwoven fabric manufacturing and pleating methods as well as new developments like nanofiber layers and coatings, filters have become more efficient, reliable and compact. Demands on the filtration industry are also changing. It’s no longer solely about filter efficiency and dust-holding capacity; with soaring energy prices and increasing awareness of sustainability, filter media are expected to contribute to lower energy consumption.

Potential and Limits of Air Filtration

Filters are used in numerous industries and applications all around us. Automotive “air induction system” (AIS) filters protect the engine and the mass airflow sensors (MAFS) against contaminants, while cabin air filters provide clean and healthy air for the driver and passengers. In medical technology, filters purify and decontaminate air in respiratory equipment to increase the patient’s safety. Filters also sterilize air in aseptic packaging processes for food and pharmaceuticals and ensure a good indoor environment in the heating, ventilation and air conditioning (HVAC) industry or support clean combustion in gas boiler appliances. Only a few months ago, the World Health Organization (WHO) released a new report on urban ambient air pollution stating that more than 80% of people living in urban areas are exposed to air quality levels that exceed the WHO’s limits. Air filtration technology will play a crucial role in reducing this percentage in the future.

Each filter can only provide good functionality as long as it is undamaged and its pores remain unclogged. Filters should be replaced regularly to ensure economical, safe and adequate operation. Clogged filters can lead to an undersupply of air, substantial loss of energy efficiency, noisy fan operations, reduced filter performance and, eventually, result in damage to the filter itself. Dirty and humid filters can be a breeding ground for mold and bacteria, punctured filters can be outright dangerous in medical respiratory equipment and a clogged filter simply reduces performance and increases the wear and fuel consumption of an automotive engine. It is therefore important to monitor the condition of a filter and replace it in due time.

Condition-Based Maintenance

While air quality management and filter technology have made great progress, filter monitoring has largely remained in stasis. For the most part, filters are still changed according to fixed replacement schedules, as a result of visual inspections by service technicians or based on rudimentary differential pressure switches. The reality is that, in most instances, filters are changed too late, resulting not only in reduced safety, energy efficiency and performance of the application in question, but also in a significant loss of business opportunity for filter manufacturers.
In the last few years, an increasing shift from preventive to condition-based maintenance (CBM) has taken place in the manufacturing industry. Sensors observe the state of different parts and maintenance is only performed when certain indicators show signs of decreasing performance or upcoming failure. This trend will help the filter industry to introduce and commercialize new filter monitoring technologies.

**Technologies Used**

When a filter starts clogging, its resistance to the air flow increases. In systems where the airflow is kept at a constant level, this leads to a rise in the differential pressure across the filter bank. However, fans often begin to propel less air as the filter becomes impeded, so we are really talking about a changing airflow as a filter progresses from a clean to an obstructed state.

To determine the level of filter clogging, various sensor technologies are in use:

- **Traditional differential pressure sensors** measure the deflection of a diaphragm. They work well when the pressure drop across the filter is high enough, but lack sensitivity for very small pressure differences. Membrane fatigue can cause drift issues, which is particularly undesirable in filter monitoring because a sensor drift is difficult to distinguish from slow filter clogging in most cases.

- **Pressure switches** indicate when a certain predefined pressure value is exceeded. They do not measure the actual pressure difference, making trend analysis impossible.

- **Microthermal differential pressure sensors** allow for a small flow of air through the sensor, which is measured in order to determine the pressure difference. With outstanding long-term stability and accuracy around zero flow, they outclass other technologies for most applications and are particularly suitable for filters with low differential pressures. Due to the airflow through the sensor, they cannot be used across the filter bank when safety-critical sterilization is achieved by filtration. Dust-induced failures can be prevented by smart inlet design, sensible positioning of the sensor, a smooth sensor surface and detection algorithms.

- **Flow sensors** measure the air flow and are mostly installed behind the filter. There are cases (as shown in Figure 1) where knowledge of the flow provides higher-resolution information about the state of the filter rather than knowledge of the differential pressure. In many applications, the air flow itself is an important system parameter and measuring it enables the implementation of additional functionality and control. Since an air flow sensor is usually placed behind the filter, precise microthermal technology can be used without the need for additional measures against dust. These are often the same sensor models as used to measure the

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*Figure 1: Graph showing the differential pressure (dp) as a function of the flow for a new and a partially clogged filter as well as a typical dp/flow curve of a centrifugal fan. The intersection points show that the clogging of the filter has a larger effect on the air flow than on the differential pressure in this case.*
differential pressure across the filter bank, but are placed in a bypass setup behind the filter instead.

The most accurate filter monitoring can be achieved when both the pressure drop and the flow are measured in order to determine the changing pressure across the filter in relation to the air flow. We’ll show later that it is imperative to measure both parameters in more complex applications.

Only a few other methods are in use, namely optical systems where the discoloration of the filter is measured and dust load sensors behind the filter that measure the dust concentration based on the triboelectric effect. Both methods are complex and costly and therefore not suitable for high-volume applications.

**Air Flow Circuit**

Let’s have a more detailed look at systems where filtration is used. Basically, all of these applications have a driving source for the air flow (a fan, engine or human breath), a flow restriction (or impedance) given by the filter and another flow restriction given by the rest of the system. This compares nicely to an electrical circuit with a (non-ideal) voltage source and two electrical resistors (see Figure 2).

![Figure 2: Air circuit in a system with a filter compared to an electrical circuit.](image)

In this model, we can compare three different situations:

1. If the impedance of the filter is high and the impedance of the rest of the system is low and constant, a change in filter resistance will predominantly lead to a change in air flow. In this instance, it might be sufficient to monitor the air flow, which can be achieved most simply behind the filter where the air is clean.

2. If the impedance of the filter is low and the impedance of the system is comparatively high but stable, a change in filter resistance will mainly lead to a change in the differential pressure across the filter bank. In this case, it might be sufficient to measure the pressure difference.

For these first two situations, it is also essential that the fan speed is either constant or known so that the air flow or the differential pressure can be assessed in relation to the fan speed.

3. If the impedance of the system is variable or when the speed of the blower is variable and unknown, the air flow and the differential pressure must be known in order to gain enough information to evaluate the filter status. Example applications can be seen in Figure 3.
We can draw different conclusions from this analysis. Firstly, there is no one-size-fits-all solution when it comes to monitoring filtration. Different applications and system complexities ask for different monitoring setups. Secondly, a pressure switch might be sufficient for very simple systems, but it fails as soon as an application gets more complicated, and uses variable fan speeds or has a low or variable resistance to the air flow. Thirdly, measurement of the differential pressure over the filter or the flow of air behind the filter, and the ability to relate this measurement to the changing fan speed are needed for accurate filter monitoring. However, the most accurate statement about the status of a filter can be made when both are known: actual air flow and differential pressure. In complex systems with varying loads and multiple filters, this is the only solution for accurate filter monitoring (see the example of a complex setup in Figure 4).

A benefit of measuring both the differential pressure and the air flow through a system is that no information from the blower (e.g. RPM, current or power) is required to determine the load of the filter. On the contrary, the information from the flow sensor can be used to compensate for deviations in the blower’s performance. The detailed readings from two sensors also create the possibility for fantastic additional functionality. By logging the data over a period of time, trends can be assessed and an estimated date for filter exchange predicted. Detailed and accurate measurements and time series enable the identification of malfunctions like a damaged or missing filter.

### Complex Systems

<table>
<thead>
<tr>
<th>Example use case</th>
<th>Fan</th>
<th>R Filter</th>
<th>R Application</th>
<th>Filter monitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air purifier</td>
<td>RPM data available</td>
<td>High</td>
<td>Low and stable</td>
<td>Only flow sensor is sufficient</td>
</tr>
<tr>
<td>Burner filter</td>
<td>RPM data available</td>
<td>Low</td>
<td>High, but stable</td>
<td>Only DP sensor is sufficient</td>
</tr>
<tr>
<td>Car air conditioning</td>
<td>RPM data available</td>
<td>Medium</td>
<td>Variable, high to low</td>
<td>Both DP and flow sensor required</td>
</tr>
</tbody>
</table>

Figure 3: Examples of different applications and their characteristics.

Figure 4: Example of a more complex system.
filter, or other system failures such as an impaired blower or obstructed flow inlet (see Figure 5). In many cases, the sensor readings can also be used to improve control and increase functionality of the entire system. Flow data in particular often have benefits that go beyond monitoring the filter.

**Pitot Tube Configuration**

Sometimes, there are surprising solutions for a filter monitoring problem. In applications where the velocity of the air is high enough, the differential pressure can be measured between a normal tap upstream of the filter and a pitot tube downstream of the filter. The pressure at the pitot tube port is given by the velocity pressure plus the static pressure and is therefore higher than at the normal port upstream of the filter. This creates an inverted differential pressure reading with the higher pressure at the pitot port (see Figure 6). A clogged filter will lead to a reduction of the measured pressure difference.

![Figure 5: Timeline of the flow through the filter for different scenarios.](image1)

![Figure 6: Inverse pitot tube configuration.](image2)
Sensor Solutions

As precise and adequate sensor solutions become paramount for state-of-the-art filter monitoring, what are the key requirements for such differential pressure and flow sensors?

- Excellent **long-term stability** is key, ensuring that filters are changed when they need to be rather than due to sensor drift.

- A **high dynamic range** is particularly important for systems with variable fan speeds.

- High-tech filters often have a very small pressure drop. Thus, sensors with **high accuracy** at low differential pressures and flows are essential.

- Filter performance and the differential pressure across the filter bank can depend on air temperature and ambient pressure. The ability for **temperature and pressure compensation** will make a filter monitoring system far more accurate.

- **Data acquisition capability** is a plus as it can simplify a trend analysis by the system’s microcontroller.

All of the requirements above are met by microthermal differential pressure sensors like Sensirion’s new SDP800 family. This type of sensor also has the useful benefit that the same model can be used for the differential pressure measurement over the filter bank as well as the flow measurement behind it, using a bypass setup to measure the flow (see further information). Sensirion’s SDP sensors are temperature compensated and can also be programmed to conduct filter- or system-specific temperature compensation.

Microthermal sensors measure the mass flow by default, which is a parameter that should be controlled in most applications. In air conditioning systems, gas heaters, medical respiratory equipment, air induction systems and much more, it is crucial to know the amount of air reaching the application. The measurements gathered by an advanced filter monitoring system can also be used for the application’s control system (or vice versa). Using sensors that are based on mass flow measurements also supersedes the need for ambient pressure compensation as mass flow does not change with varying ambient pressures (unlike volume flow, which does).

Conclusion

Precise filter monitoring adds value to many applications in the HVAC, medical technology, automotive and packaging industries, among others. The detection of the correct moment for a filter change helps to protect humans, animals and equipment by providing clean air and leads to a lower cost, more energy-efficient and sustainable operation of the application. One solution does not meet all demands, but it can be concluded that measuring the flow of air rather than the differential pressure is often a wise choice, and that both readings are required in complex systems. For many filter monitoring applications, microthermal flow and differential pressure sensing is the favorable sensor technology and can provide added value due to its precision and long-term stability.
Further Information

Bypass Flow Measurement and Bernoulli Ring

An economical and precise way of measuring the gas flow is by placing a microthermal flow or differential pressure sensor over a flow restrictor. The technology to do this is well understood and documented and further information can be found on Sensirion’s website. The Bernoulli ring is a very specific but cost-effective setup developed to measure the air flow induced by a centrifugal fan. A simple ring is attached to the side of the blower, tapping the pressure on the inside and outside of the rotating impellers. The pressure drop can then be measured with a differential pressure sensor, leading to an accurate flow reading.

Proven and Improved – Differential Pressure Sensors SDP800 Series

Differential pressure sensors of the SDP800 series are the reliable solution for precise air flow measurement in most demanding, but cost sensitive HVAC applications, such as filter monitoring, VAV controllers, burners and heat recovery systems. The SDP800 sensor is the result of more than 15 years of experience in measuring the air flow in millions of HVAC systems, car engines and medical equipment. It utilizes the successful mechanical features of the SDP600 series and can easily be integrated, due to its proven form factor. The next generation sensor chip offers extended functionality, smart averaging functions and multiple measurement modes. The sensor measures with speed up to 2 kHz, and provides a configurable analog voltage output or a digital I2C interface. Where the SDP800 is intended for a direct threaded connection to a pressure manifold via O-ring sealing, the SDP810 is designed for a tube connection.

Like all Sensirion differential pressure sensors, the SDP800 series come with outstanding accuracy and long-term stability, together with no zero-point drift.

About Sensirion – Experts for Environmental and Flow Sensor Solutions

Sensirion AG, headquartered in Staefa, Switzerland, is a leading manufacturer of digital microsensors and systems. The product range includes gas and liquid flow sensors, differential pressure sensors and environmental sensors for the measurement of humidity and temperature, volatile organic compounds (VOC), carbon dioxide (CO2) and particulate matter (PM2.5). An international network with sales offices in the US, Europe, China, Taiwan, Japan and Korea supplies international customers with standard and custom sensor system solutions for a vast range of applications. Sensirion sensors can commonly be found in the medical, industrial and automotive sectors, analytical instruments, consumer goods and HVAC products.

One of the hallmark features of Sensirion products is the use of its patented CMOSens® Technology, which permits intelligent system integration of the sensor element, logic, calibration data and a digital interface on a single chip. Sensirion's credentials as a reliable supplier are underscored by its loyal customers, quality reputation (ISO/TS 16949) and top customer pedigree.

Contact: www.sensirion.com, info@sensirion.com, Tel. +41 44 306 40 00, Fax +41 44 306 40 30