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1 May 2005

Scintillation Technology Bests NIST

By Ting-I Wang and Donn Williams

Optical technology has sensor external to the process and behind windows.

Airflow sensing in an industrial environment such as a stack or duct is a difficult challenge.

Flare stack and combustion airflow are two applications that provide some of the greatest challenges because of high temperatures, wide range of flow rates, particulate loading, confined installation space, and concerns over the measurement location's suitability for accurate monitoring.

The accuracy of flow monitoring in these kinds of applications can have a great influence on both combustion efficiencies and safety. Existing technologies such as ultrasonic and Pitot tubes require significant maintenance and installation effort and can suffer from inaccuracies leading to a misreporting of flow. For example, Pitot tube devices only measure at one point and may under or over report the true flow. Recent Environmental Protection Research Institute (EPRI) studies indicate Pitot tube flow monitors over report flow from 2% to 5%. Ultrasonic devices install at two levels on the stack, requiring two access platforms. In addition, both ultrasonic and Pitot devices are intrusive to the media and may quickly become clogged or corroded leading to inaccurate measurements and high maintenance costs.

The optical anemometer using a non-intrusive atmospheric scintillation technology solves these problems. Optical flow sensing won approval in 1998 as an equivalent Method 14 technology for compliance with the U.S. Environmental Protection Agency (EPA) Maximum Achievable Control Technology (MACT) rules. A number of Optical Anemometers are working at primary aluminum producers around the world. The optical flow sensor, based on the same measurement technology, measures flow in the relatively small diameters (0.2- 10m) of stacks and ducts. This path-averaged measurement technology has undergone thorough testing at the U.S. National Institute of Science and Technology (NIST) wind tunnel and by numerous industry case studies and reference method comparisons.

This sensor uses many powerful features to enhance its performance. These include: (1) the measurement technology of scintillation such that the flow velocity measurement is completely independent of temperature, pressure, humidity, and opacity and is path-length averaged across the duct with minimal installation limitations; (2) the use of advanced digital signal processing measurement algorithms to yield a wide dynamic measurement range, even with cold air; (3) the use of built-in self test and diagnostics to monitor sensor calibration and performance; (4) the use of both standard current loop and digital/RS232 interface formats for ease of interfacing to a wide variety of PC, PLC (mainframe), continuous emissions monitoring (CEM), or other data collection devices. The result is a sensor technology that is inexpensive to install and operate and can offer improved performance as compared to traditional sensors in measuring true flow data, even in the most challenging applications.

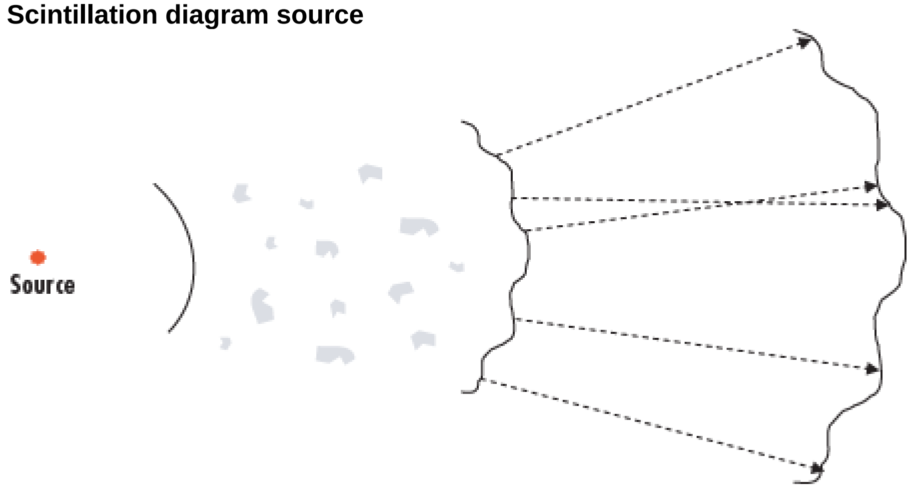
Atmospheric turbulence

The optical flow sensor (OFS) and its predecessor, the long-baseline optical anemometer (LOA—a sensor which uses the same technology as the OFS but measures along much longer path lengths, 100m to 10 km), use optical scintillation as the detection method.

Scintillation is a general term, which describes changes in the apparent position or brightness of an object when viewed through the atmosphere. A common example of this phenomenon is the twinkling of starlight.

These fluctuations occur as light passes through pockets of air with differing temperature and density, causing the refraction and scattering of the light through the non-homogenous air. By detecting the speed of movement of this scintillation, the OFS can measure air velocity in a stack or duct.

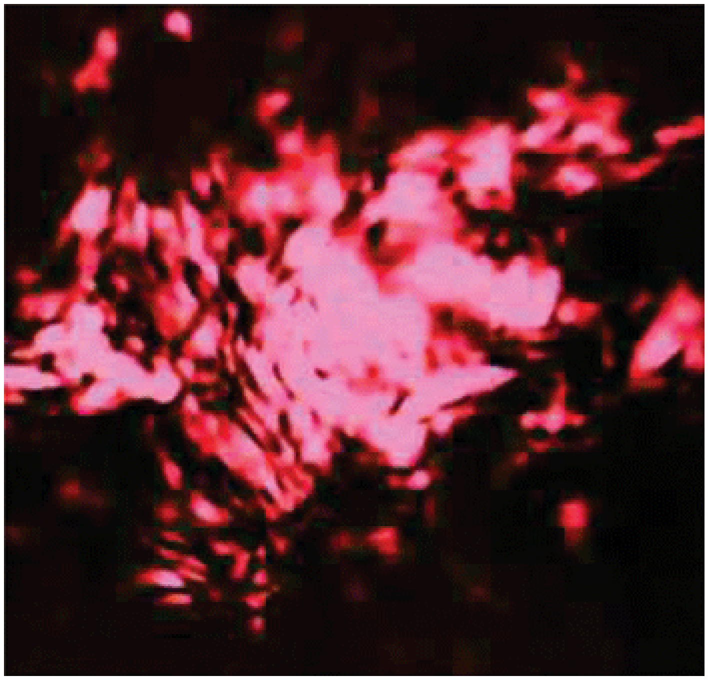
Scintillation diagram source



Photographs readily show the effect of scintillation or optical turbulence on a laser beam after traveling through the atmosphere. Instead of a uniform round disc, the beam is broken up and distorted by the turbulence. The strength of the atmospheric turbulence translates as a refractive index structure constant.

The LOA transmitter emits a modulated beam of infrared light, while the OFS uses a visible red beam (for ease of alignment). The LOA or OFS receiver detects this beam and reconverts it to an electronic signal. Intensity variations of the detected signals caused by the scintillating air parcels provide the basis of the turbulence measurement for the LOA. The amplitude of the scintillation varies as the strength of the turbulence. The twin photodiode modules in the receivers furnish the capability of measuring crosswind by detecting the temporal correlation between the two signals as the air parcels move across the beam path (covariance). The movement of the scintillation from one receiver to the next relates to the wind speed or flow rate.

Optical scintillation has a proven record of accomplishment and history. It has worked for nearly 30 years to measure crosswind outdoors. This same technology, after modification, works well for industrial airflow monitoring in the aluminum industry. The LOA measures the air velocity along a smelting-pot-room roof vent that is typically 200-1000 meters long. This is a very challenging flow field to measure. There is tremendous flow variability in these vast buildings from dead zones to cyclonic to sometimes even negative flow depending on the wind patterns outside.



Effects of scintillation of optical turbulence on a laser beam is around here.

The LOA has proven itself very capable in measuring even such complex fields, which led to the EPA approving the LOA for Method 14 (as an equivalent method in emissions airflow monitoring compliance rule for the aluminum smelting industry.). The optical anemometer is widely used in the aluminum industry for air velocity monitoring to comply with EPA regulations. Most of the aluminum smelters in the U.S. rely on this technology to provide air velocity measurements. The EPA has also acquired LOA and used them for airflow measurements in chloralkali applications, which are similar to the aluminum smelters. The EPA has considered the optical anemometer technology for other environmental airflow applications including outdoor fence line monitoring for agriculture.

After approving the optical scintillation instrument for Method 14 equivalency, EPA officials suggested the optical anemometer should also apply to smokestacks for Part 60 and 75 and similar stack emissions flow sensing. As a result, the OFS was developed. The OFS uses the same technology as the optical anemometer. The primary difference is the OFS uses smaller optics to measure across the shorter path lengths (stack diameters). Due to the technology's versatility and non-intrusiveness, the OFS applies a wide variety of industries and applications. Any smokestack, duct, or pipe with a minimum inner diameter of 0.2 meter, which requires an air velocity measurement, is a possible site for the OFS.

Now, most facilities satisfy their Part 60 and Part 75 airflow measurements via two predominant methods: Pitot tube and ultrasonic sensors. Both methods have their own strengths and weaknesses. The Pitot tube is a point measurement. Installation of the Pitot tube is simple, but non-uniform flow such as cyclonic or swirling is a problem for this technology. The ultrasonic sensor provides a more representative path-averaged measurement. However, the instrument requires a very costly angled installation and a path angle correction, which might suffer if there's non-uniform flow. Both instruments need a purge air or blowers. Both methods are also problematic due to their intrusive nature, especially in the frequently harsh conditions.

The OFS provides a technological solution that offers several advantages over more traditional methods. It is necessary to discuss these advantages as well as the nature of the technology and provide evidence that the OFS is a viable alternative to the existing methods. In addition, the aspects revealed about optical flow technology will demonstrate the sensor meets the high standards of Part 60 and 75 flow requirements and can be used for a wide range of other demanding applications, industries, and site conditions. The instrument can cover everything from environmental airflow compliance in power plants to the monitoring of flow rates in flare lines and stacks in the petroleum industry to flow based process control in ducts in combustion applications.

Path-averaged result

The OFS consists of a transmitter, receiver, and control box. The transmitter and receiver install on standard 4-inch pipe flanges on opposite sides of the stack perpendicular to flow direction. The transmitter contains a red LED, which emits a beam of light to the receiver. The receiver houses two photo detectors, which detect and send the signals to the control box. The box contains the digital signal processor (DSP) and other electronics for processing and user interface. The data output is sent to the user's data collection unit via serial RS-232 and/or 4-20 ma current loop output, or optionally over serial RS-422, RS-485, or fiber optics.

Alignment of the instrument is straightforward. After installation on flanges, the user moves two adjustment dials (one left and right, the other up and down) on the back of the transmitter optical emitter mount. The red beam is clearly visible on the receiver due to reflectors on the receiver face that help highlight the beam. Once the transmit beam is adjusted, the receiver optics assembly is similarly adjusted for proper signal strength in the two detectors. One person can do the whole process in 15 minutes or less. Unlike laser-based sensors, alignment is easy and non-critical. Quite often, optical adjustments are not even required after bolting the transmitter and receiver heads in place. The control electronics enclosure that connects to the receiver is typically near the receiver though it can be in a control room up to 300 feet away.

The optical technology allows the sensor to be located external to the stack and behind windows, "looking" through the stack chamber (or duct or pipe). No part of the instrument exposes to or contacts the direct flow of the media in the stack. Avoiding direct exposure to stack effluent helps reduce maintenance and increase durability. Pitot tubes must be located directly in the stack environment where aggressive conditions (such as excessive heat, acidic gases, particulate, etc.) can degrade performance or damage the unit irreparably. Ultrasonic sensors whose transducers touch the direct flow face the same issue. In addition, unlike these two technologies, the optical flow sensor does not affect the flow field because of its non-intrusive nature. Additionally, thanks to high performance automatic gain circuits in the receiver, dust and dirt buildup on the optical windows does not adversely affect performance unless the buildup becomes so heavy that virtually no light can pass through.

The path-averaged result of the OFS provides a more representative reading of the flow characteristics in a stack. The sensor makes a true cross-stack measurement of the velocity along the entire path. In addition, since the instrument is measuring the vertical velocity component, it can handle variability, swirling, and cyclonic flow much better than a point source instrument. The instrument does not require straighteners or additional ductwork like Pitot tubes often do when used in challenging flow environments. While complex Pitot tube arrays may work in some applications, in virtually every case, one optical flow sensor could replace an entire Pitot tube array.

Among the requirements for Part 60 and 75, the OFS provides an automatic daily calibration (i.e. calibration error test) every 24 hours. The user may also initiate the calibration manually or adjust the duration and frequency of the automatic calibration cycle. The calibration takes place electronically and uses the reference calibration data to determine any error. Also, since the OFS does all of the processing in the digital domain, the technology exhibits virtually no drift, which tends to be common in analog-based sensor technologies.

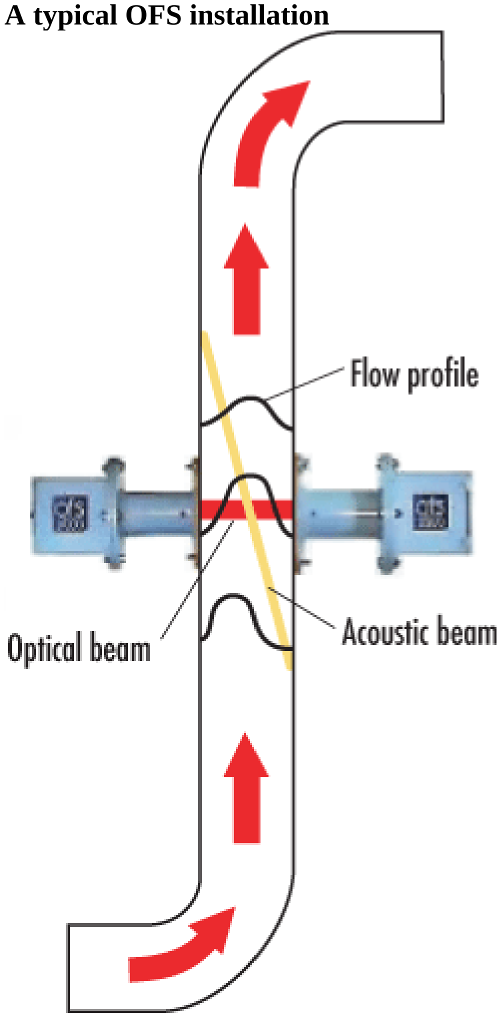
As for the interference check, the OFS exceeds the requirements. The instrument performs a continuous interference check by constantly monitoring the signal strength of both receptors (known as A and B). If, in the unlikely event, the signal strength of either A or B goes out of range, the user will learn of the problem immediately.

Sensitive to profile changes

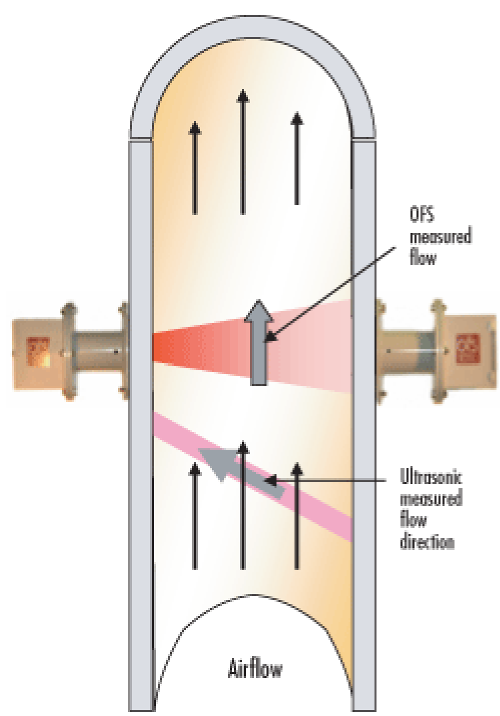
One of the major concerns for installing a path-averaged flow sensor is its siting requirement for some amount of leading and trailing linear length from bends or flow disturbances in the pipe or stack. Because the flow is constantly changing its profile along the flow path, the best location for any flow sensor is always at the place where the flow profile is well developed (consistent). However, for different type flow sensors, the siting requirements are different. Some types need very long and straight runs while others, like the OFS, can tolerate a much shorter linear length.

A typical installation for two different types of flow sensors might go like this. The OFS (using an optical beam) is installed perpendicular to the flow direction. It shoots a light across the same cross-section area of the flow. The total amount of flow is the average flow speed times in the cross-sectional area at that location.

A typical OFS installation



Ultrasonic compared to OFS installation



The OFS provides a line-averaged flow measurement that is most representative to the overall flow profile across that cross-section area. Whereas the ultrasonic flow sensor is required to install at an angle (45°) to the flow. It is clear the flow profiles change along the flow path. The ultrasonic sensor shoots a slant-path sound wave across different cross-section areas, which necessarily have different flow profiles. It is more sensitive to the profile changes along the path. Therefore, to obtain a representative flow measurement for an ultrasonic sensor, a uniform (or well-developed) flow profile location is required.

Usually the ultrasonic sensor cannot make a representative measurement unless there is a linear run length of more than 20 times the pipe diameter leading and 10 times the pipe diameter trailing from the elbow. However, this requirement can be greatly relaxed for the OFS. Because the OFS light beam shoots across the same flow profile cross-section, the OFS can make accurate representative line-averaged measurements, even for a less developed flow profile. Usually linear run lengths of two times the pipe diameter leading and one times the pipe diameter trailing are good enough for the OFS to make a representative flow measurement. For some extreme cases, OFS have installed right at the elbow of a pipe and provided satisfactory measurements.

Another consideration is the orientation of the installation of the flow sensor with respect to the direction of the flow. Because OFS measures the flow across the optical beam, the best orientation of an OFS sensor is the optical beam is perpendicular to the direction of flow. The measured flow rate is the line averaged flow rate across the whole pipe or stack cross-section. This configuration will give the most representative flow measurements across that cross-section. In addition, the measured flow rate is insensitive to the cyclic flow pattern usually existing in the pipe especially near the bends. Therefore, the OFS does not need a long linear length to get a well-developed flow profile to make a representative measurement.

Ultrasonic sensors measure the flow direction along the acoustic beam. Therefore, the best installation for an ultrasonic sensor is at the two ends of the pipe. However, we all know this installation requirement is hard if not impossible to implement in a practical situation. As a compromise, the ultrasonic sensor is usually installed at a slant configuration. Because of this compromised installation, the measured flow velocity is not the true flow velocity; it needs a correction factor dependent on the actual angle between the acoustic beam and the flow direction. This correction factor (always larger than one) also amplifies the uncertainty of the flow measurement. The larger the angle between the acoustic beam and the flow direction will produce a larger uncertainty of the flow measurement. An even more critical problem of this configuration is the measurement loses accuracy when the sensor faces any flow not in the direction of the mean flow, such as with a swirling flow. Therefore, it needs a well-developed flow profile to make a representative flow measurement. This is why the ultrasonic sensor is usually required to install far away from the bend of the pipe or stack. In some extreme situations, in order to shorten the linear length requirements, the ultrasonic sensor has to go in at a large angle to the flow direction almost direct across the pipe. Unfortunately, this will only deteriorate the measurement accuracy to the extent it is no longer a reasonable representative measurement of the true flow rate.

Question always dirty windows

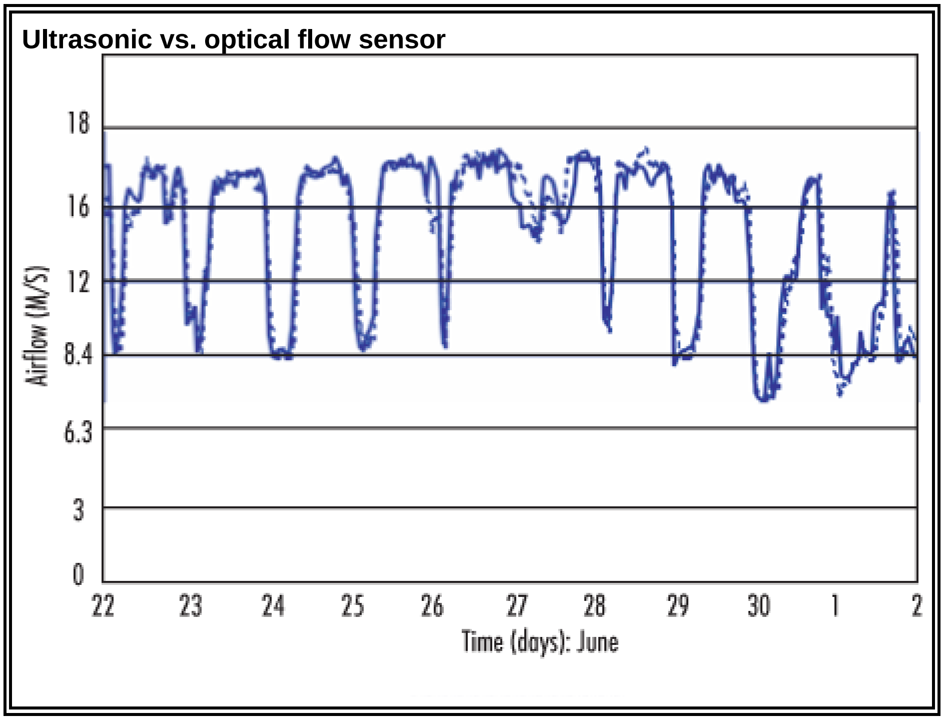
The relative accuracy of the optical flow sensor compared to Pitot tubes consistently meets the expectations for a flow sensor in Part 60 and 75. The optical flow sensor tested out at NIST. The NIST wind tunnel is one of the best facilities in the world for setting the standards for wind and flow instruments. The results showed the OFS is accurate and representative.

The accuracy of a Pitot tube method is in question for many reasons. Its first weakness is its point-source nature. To truly obtain representative flow data with a Pitot tube, the user must measure at many more data points than is normally feasible. This is evident in the case of the NIST wind tunnel with an average of more than 100 Pitot tubes. In addition, the Pitot tube does not account for swirling or cyclonic flow very well.

Temperature and pressure directly affect the Pitot tube result. On all these points, the optical flow sensor technology offers several advantages over the Pitot tube.

The optical flow sensor has tested in real stack environments. In direct comparison to two ultrasonic sensors configured in an X pattern across the test stack, the optical flow sensor showed good agreement. Over a 10-day average of each ultrasonic sensor, the optical flow sensor average over that same period was in between the two. This test took place in a coal-fired power station stack against two Relative Accuracy Test Audit (RATA) tested ultrasonic sensors.

Notice the daily cyclical changes in power usage, which show up in the airflow data.



Ultrasonic technology measures the flow along the direction of the path and therefore requires some degree of angle. Therefore, the sensor is not measuring the true cross-stack velocity in a direct way. Pressure and temperature gradient also affect ultrasonic readings.

The optical flow sensor is for process control measurements in power plants, refineries, and smelters. It is also at work in Part 75 and 60 facilities and has passed RATA tests in petroleum, power generation, and other industries. A RATA test took place for a major petroleum company at one of their U.S. refineries in April 2003. The unit passed successfully.

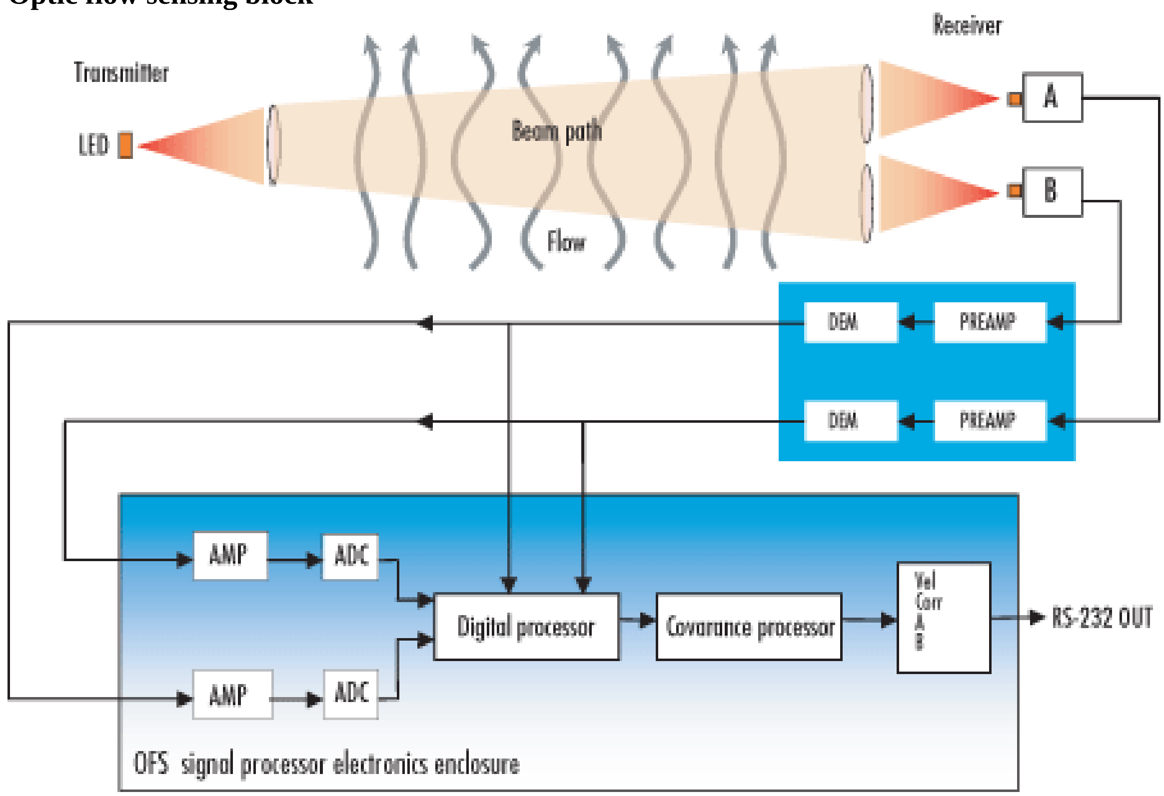
The science behind the optical flow sensor possesses evident advantages over the existing methods. The path average measurement makes it more representative vs. the point in-situ measurement of the Pitot tube. It makes a true cross-stack air velocity measurement, whereas the ultrasonic sensor must make a correction for its angled configuration in order to produce a relevant measurement. The instrument can measure cyclonic or swirling flow. The reading is independent of pressure, temperature, humidity, and opacity.

Due to its non-intrusive nature, the OFS does not create a pressure drop or affect the flow field like the intrusive Pitot tube. In addition, the Pitot tube is prone to fouling and plugging up. This exposure leads to more wear and tear than with the OFS. Even an ultrasonic sensor's transducers (which are very costly to replace) contact flue gas. The OFS's non-intrusive design ensures better long-term reliability and minimizes maintenance costs. The simple, same-level installation of the OFS allows the unit to easily fit in a vertical stack, horizontal duct, or pipe. The instrument can even operate in angled ducts. This flexibility along with the ability to handle high temperature applications makes the OFS useful for a wide variety of processes and industries.

With optical technology, the question is always about dirty windows or particulate build-up. First, the instrument will receive enough signals to obtain good data even with more than 90% of the light blocked in the stack. Nearly all the light must block out in the flow medium in order for the optical flow sensor to have any problem. The instrument typically requires window cleaning every six to 12 months. In negative pressure stacks, the natural circulation is usually sufficient to keep the windows clear enough for operation. In more extreme cases, factory (instrument-grade) air or a blower can supply purged air to protect the windows, if necessary. In addition, the instrument uses predictive software to inform the user ahead of time as to when the window requires cleaning. The instrument design considers vibration. The natural beam divergence allows for some vibration without affecting the instrument reading. A specially patented algorithm minimizes the effect of system vibration to the flow measurement. These features as well as sturdy flange mounts make the instrument ready for the physical industrial environment.

The components of the optical flow sensor are all solid-state. No mechanical parts are required for operation. This allows the instrument to have lower maintenance and higher durability boosting its mean-time-between-failure (MTBF). In addition, the instrument has intelligent processing for self-diagnostics and testing. The instrument will inform the user of a problem. Examples are low signal strength or an error in a component, and the like.

Optic flow sensing block



Low speed performance

A light source transmits a beam to the two receiving detectors through a turbulent flow. Along the path, flow turbulence modulates the optical beam. The two photo detectors detect the flow induced optical scintillations. Using a stochastic correlation technique, the flight time (t) of the signal detected by the two detectors is measurable. For a known separation (d) between the two detectors, the flow speed (v) can simply be obtained as $v = d/t$.

The DSP in the electronics box performs all the necessary calculations to obtain the flow speed.

A wide range of flow rates often exists in combustion, flare, and other applications. Flow rates may vary from near zero to 80m/s or more. Most flow-measurement techniques have serious limitations with more extreme flow rates, especially at the extreme low end. The ultrasonic technique has to compare the media flow rate to the speed of sound. When the flow speed is high in comparison to the speed of sound, nonlinear shock wave effects will severely degrade the accuracy of the measurement. At the other end, for extremely slow flow, at only a small fraction of the speed of sound, the measurement accuracy may err. For Pitot tubes, the slow flow only gives very small pressure differences that are usually difficult to measure accurately. Therefore for both ultrasonic and Pitot tube techniques, the accuracy of slow flow rate is at best questionable.

Unlike the ultrasonic technique, the optical scintillation technique does not need to compare the flow speed to any reference speed such as the speed of sound or the speed of light. The flow speed measured by OFS is independent of temperature, pressure, humidity, and opacity. As long as the flight time of the signals detected by the two detectors is measurable, accurate determination of flow speed is certain. Therefore, the flow rate measured by OFS has no lower limit. No matter how slow the flow is, it's possible to accurately gauge it. In the NIST wind tunnel test, at low speed, there were indications that the OFS measurement accuracy may even be better than the NIST standard that bases on Pitot tube measurements.

The OFS offers excellent performance over a wider flow range than other methods.

Behind the byline

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