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Optical Flow Sensing: A New Approach to an Old Problem

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ABSTRACT

Airflow sensing in an industrial environment such as a stack or exhaust duct is a difficult challenge. Existing technologies like ultrasonic and Pitot tubes require significant maintenance and installation effort and can suffer from nonrepresentativeness leading to a misreporting of mass flow. For example, Pitot tube devices only measure at one point and may under or over report the true flow. Ultrasonic devices must be installed at 2 levels on the stack. In addition, both ultrasonic and Pitot devices are intrusive to the media and may become clogged or corroded leading to inaccurate measurements and high maintenance costs.

The optical anemometer using a non-intrusive atmospheric scintillation technology was designed to solve these problems. Optical flow sensing was approved in 1998 as an equivalent Method 14 technology for compliance with the USEPA MACT rules. A number of optical anemometers are installed at primary aluminum producers around the world. The optical flow sensor was designed for measuring in the relatively short diameters (1-10 m) of stacks and ducts.

The optical flow sensor uses many powerful features to enhance its performance. First, the instrument uses the concept of scintillation to measure airflow velocity. Infrared or visible light from the device is modulated by the optical scintillation in the air stream. The sensor measures the movement of the scintillated light to determine the airflow velocity. Unlike the Pitot tube and ultrasonic techniques, this velocity measurement is completely independent of temperature and pressure. Second, the product uses DSP (Digital Signal Processing) a faster, more efficient way to process data. Third, the optical flow sensor uses built-in self-test and diagnostics to monitor its own performance. Fourth, the sensor complies with all USEPA sanctioned tests for a flow sensor. Fifth, the instrument can link with a PC, PLC (mainframe), CEM (Continuous Emissions Monitor) or other data collection device, which accepts digital output.

The optical anemometer is installed at one level and measures through glass windows across the stack or duct. This means that installation costs are low and product life is long since the measurement is non-contact. True representativeness of the data is assured due to the path-averaged nature of the measurements and verified by thorough testing at the US National Institute of Science and Technology (NIST) Wind Tunnel and a 837 Mw generating station versus two RATA-tested ultrasonic sensors.

INTRODUCTION

The optical flow sensor and its predecessor, the optical anemometer (aka LOA sensor), 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. Starlight twinkling is a common example of scintillation.

Scintillation effects are caused by optical refraction occurring in small parcels of air whose temperature and density differ from their surroundings. (*See Figure 1 – Scintillation Diagram)* Parcels as small as several centimeters may be detected by the LOA. The strength of the atmospheric turbulence is commonly represented as a refractive index structure constant, expressed by the term: C_n^2. The LOA transmitter emits a modulated beam of infrared light. The 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 (C_n^2). The amplitude of the scintillation is related to the strength of the turbulence. The twin modules in the receiver furnish the capability of measuring cross wind 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 is related to the wind speed.

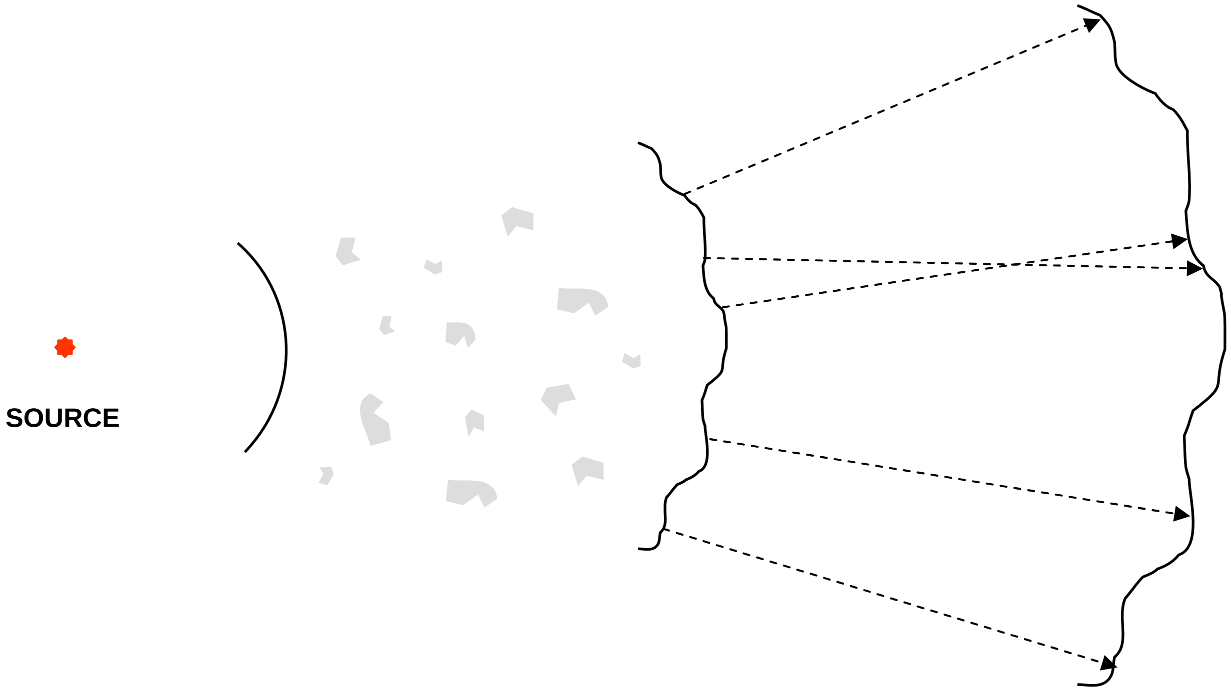

Figure 1- Scintillation Diagram – Light passes through pockets of air with different temperature and density. The refraction or scattering of the light through those parcels of air is called scintillation or optical turbulence. By calculating the movement of scintillation, OFS can measure air velocity in a stack.

Figure 2 – Effect of Scintillation or Optical Turbulence on a laser after traveling through the atmosphere

The optical scintillation has a proven track record and history. It has been used for nearly 30 years to measure crosswind outdoors. This same technology was modified for industrial airflow monitoring in the aluminum industry. This instrument measures the air velocity along a pot room roof vent typically 500-700 m 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 directions outside.

The EPA approves the optical anemometer for Method 14 (as an equivalent method in air monitoring compliance rule for the aluminum 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 US rely on this technology to provide air velocity measurements. The EPA has also purchased optical anemometers and used them for airflow measurements in chlor-alkali 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.

At the present time, most utility generation plants satisfy their Part 75 airflow measurements via two predominant methods: Pitot tube and ultrasonic sensors. Both methods have their own strengths and weaknesses. The optical flow sensor provides a better technological solution versus these more traditional methods. This paper will discuss these advantages as well as the nature of the technology and provide evidence that the optical flow sensor is a viable alternative to the existing methods. In addition, the aspects revealed about the optical flow technology will demonstrate not only that the sensor meets the high standards of Part 75 flow requirements but also can be used for a wide range of other applications, industries, and site conditions. The instrument can cover everything from environmental airflow compliance in the utility industry to process control in ducts in aluminum smelters.

The Pitot tube is the reference method but it is a point measurement. Installation of the Pitot tube is simple. However, non-uniform flow such as cyclonic or swirling is a problem for this technology. The ultrasonic sensor provides a path-averaged measurement. But the instrument requires a very costly angled installation and an angle correction, which could be effected by the nonuniformity of flow. Both instruments need purge or blower. Both methods are problematic due to their intrusive nature especially in extreme conditions.

After approving the instrument, EPA officials suggested that the optical anemometer should be applied to smokestacks for Part 75 flow sensing. As a result, the optical flow sensor was developed. The optical flow sensor uses the same technology as the optical anemometer. The major difference is that the OFS uses smaller optics to measure the shorter path lengths (stack diameters).

DESCRIPTION OF OPTICAL FLOW SENSOR

The optical flow sensor consists of a transmitter, receiver, and control box. The transmitter and receiver are simply installed to flanges on opposite sides of the stack perpendicular to flow direction. The transmitter contains a visibly red LED, which emits a beam to the receiver. The receiver houses two receptors, which sends the signal to the control box. The box contains the DSP (digital signal processor) and other electronics for processing and communications. The output is then sent to user’s data collection unit via RS-232 and 4-20 ma output, or as an option using 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 tombstone that holds the emitter. The red beam can be seen on the receiver on the other side. In addition, reflectors on the receiver face help highlight the beam. Often, adjustment is not required after installing on flanges.

The optical flow sensor provides several advantages over existing technologies:

1) true non-intrusive set-up,
2) path-averaged results,
3) simple non-diagonal installation,
4) result independent of temperature and pressure,
5) direct cross-stack velocity measurement, and
6) no moving parts, solid state construction.

The optical technology allows the sensor to sit behind windows “looking” through the stack chamber. No part of the instrument is exposed to the direct flow of 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 tranducers are exposed to the direct flow as well 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. The optical flow sensor can be utilized in very extreme conditions such as explosive and high heat application. The sensor can be behind protective windows or flange extensions if needed.

The path-averaged result of the flow sensor 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. Also, 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 in more challenging flow environments. Another great advantage to the user is that fewer sensors are required to measure complex flow fields. One optical flow sensor could replace an entire Pitot tube array.

Installation of the optical flow sensor is not angled like ultrasonic sensors. The configuration is perpendicular to the flow across the stack on the same horizontal plane. *(Refer to Figure 3 – Configuration of Optical Flow Sensor*) The user simply places the transmitter and receiver on flanges on opposite sides of the stack chamber. The optical alignment of the instrument is accomplished easily by adjusting the two dials for controlling horizontal and vertical adjustment on the transmitter. This typically takes 15-20 minutes. Once the voltage signals are balanced and peaked within the proper range, the unit is properly aligned and ready to measure optical flow sensor. The electronics enclosure is typically placed near the receiver or at a control room.

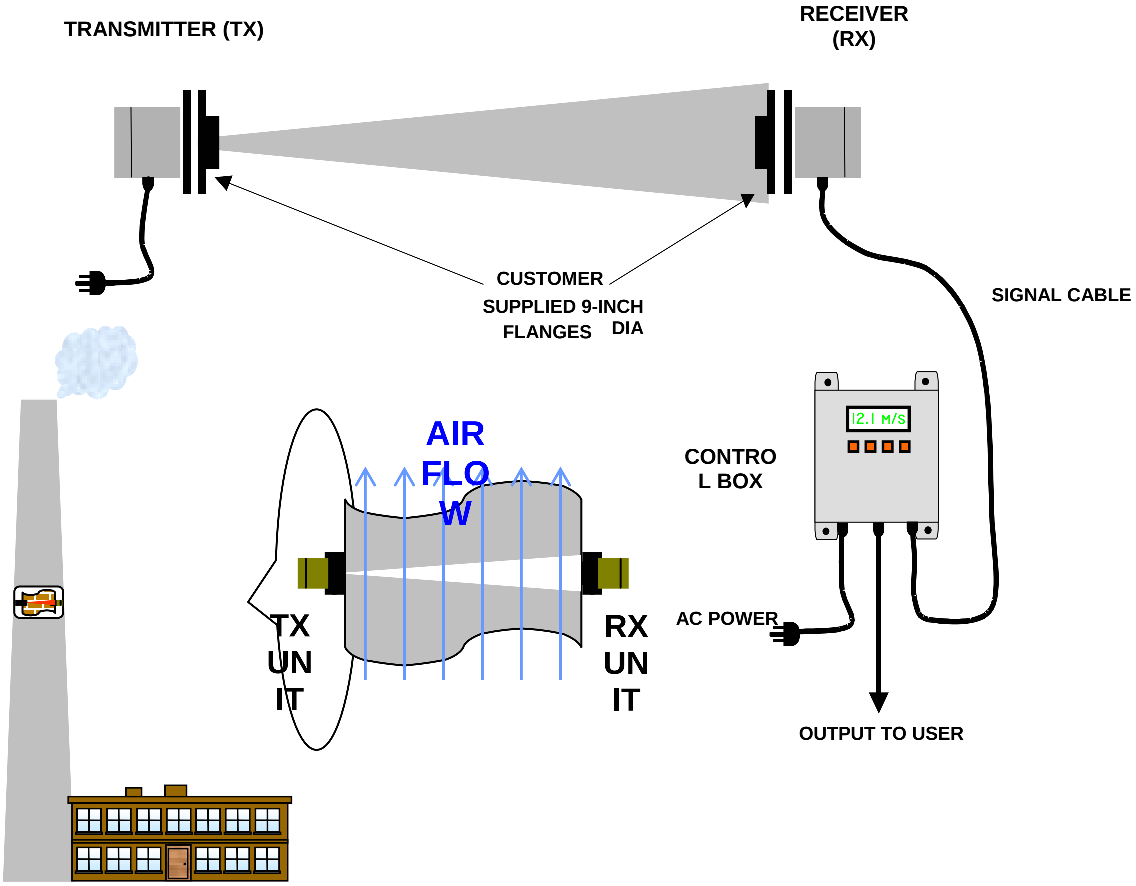

Figure 3 – Configuration of Optical Flow Sensor

Among the requirements for Part 75, the optical flow sensor provides an automatic daily calibration (i.e. calibration error test) every 24 hours. The user may set time or the instrument will perform the daily calibration automatically. The calibration is done electronically and uses the reference calibration data to determine the error. A distinct advantage with this optical technology in regards to the calibration test is that sensor has virtually no drift.

As for the interference check, the optical flow sensor exceeds the requirements on this front. The instrument performs a continuous interference by constantly monitoring the signal strength of both receptors (known as A & B). If in the unlikely event the signal strength of either A or B goes out of range, the user will be informed immediately that there is a problem. As long as the range for A and B is between .1 to 9.99 V (a factor of 100), the unit will measure the true flow rate.

The relative accuracy of the optical flow sensor compared to Pitot tubes consistently meets the expectations for a flow sensor in Part 75. The optical flow sensor was tested at NIST (formerly the US Bureau of Standards, now the National Institute of Scientific & Technology). The NIST wind tunnel is one of the best facilities in the world for setting the standards for wind and flow instruments. Measurements at NIST are made by an average of many Pitot tube arrays. This test was done without any curve fitting done to the optical flow sensor. (*Refer to figure 4 - NIST Wind Tunnel Test).* In addition, the test provides the optical flow sensor technology with another important supporting element to the technology, which the EPA considers favorable, NIST traceability. Soon, the optical flow sensor will go beyond traceability to official NIST certification. There are plans to complete this certification soon. Results not only demonstrate the optical technology's accuracy but also its representativeness.

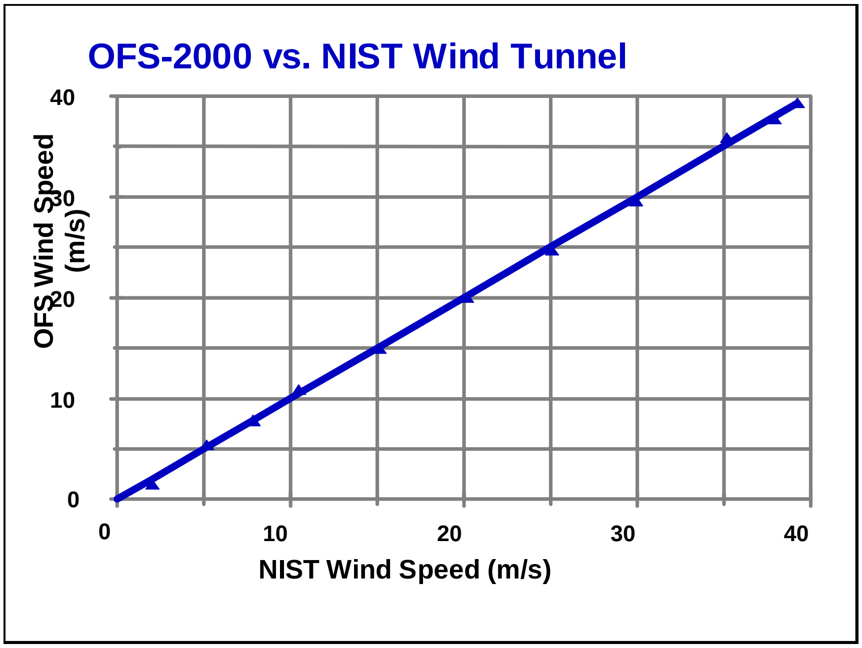

Figure 4 - NIST Wind Tunnel Test:
Pitot vs. Optical Flow Sensor

The accuracy of a Pitot tube method has been challenged 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 what is normally feasible as is evident with the case of the NIST wind tunnel with an average of about one hundred. Also, 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 is the better choice over the Pitot tube.

The optical flow sensor has also been tested in real stack environment. In direct comparison to two ultrasonic sensors configured in an X pattern across the test stack, the optical flow sensor showed good agreement. Over 10-day average of each ultrasonic, the optical flow sensor average over that same period was in between the two. (*See figure 5 – Comparison of Ultrasonic vs. Optical Flow Sensor*). This test was conducted in a coal-fired power station stack against two RATA tested ultrasonic sensors. It is clear that the daily cyclical changes in power usage are reflected in the airflow data.

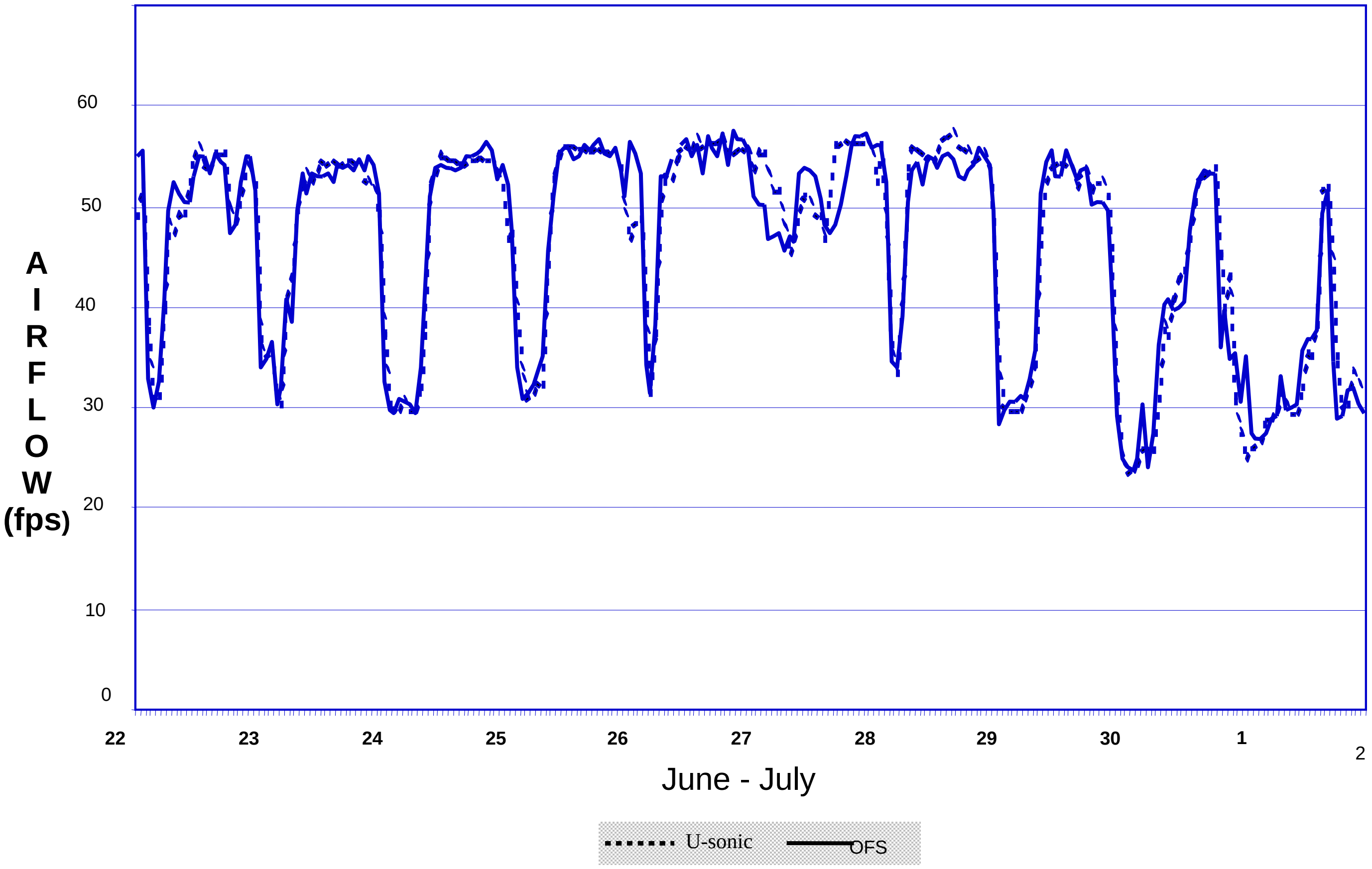

Figure 5 – Comparison of Ultrasonic vs. Optical Flow Sensor

Ultrasonic technology is measuring flow along the direction of path and therefore requires some degree of an 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 science behind the optical flow sensor possesses evident strengths over the existing methods. The path average measurement makes it more representative vs. the point source Pitot tube. It takes a true cross-stack air velocity measurement. The instrument can measure cyclonical or swirling flow. The reading is independent of pressure and temperature. The instrument can perform well under longer path lengths (wider stack diameters-up to 10 m).

With optical technology, the question is often raised about dirty windows or particulate build-up. First, the instrument will receive enough signal to obtain good data even with more than 90% of the light blocked in the stack. Nearly all the light must be blocked in the medium in order for the optical flow sensor to have any problem. The instrument typically requires window cleaning every 6-12 months. In a negative pressure stacks, the natural circulation is usually sufficient keep the windows clear enough for operation. In more extreme cases, factory air or a blower option can be supplied 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 is designed with consideration for vibration. The instrument has shock absorbers mounted in both heads to guard against it. In addition, the natural beam divergence allows for some vibration without affecting the instrument reading. 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 MTBF. In addition, the instrument has intelligent processing for self-diagnostics and testing. The instrument will inform the user of a problem. For example, low signal strength, error in a component, etc.

CONCLUSION

The optical flow sensor is a viable tool for Part 75 airflow measurement in stacks versus the traditional Pitot tubes and ultrasonic sensors. The optical flow sensor affords the user a distinct combination of advantages which the other methods do not offer: 1) Non-intrusive, not directly exposed to the stack flow, 2) Path averaged measurement for more representative results, 3) Simple, non-angled installation which lowers cost vs. ultrasonic, 4) Result independent of temperature and pressure, 5) Direct cross-stack velocity measurement, and 6) No moving parts, solid state construction. In addition, the optical technology is proven and tested. It is patented, approved by the EPA for airflow monitoring (Method 14 equivalent), NIST traceable, relied on for almost 30 years to make atmospheric and environmental measurements, and has virtually no drift. No other flow sensor currently available in the environmental monitoring industry meets these conditions.