Optical Flow Sensing
A New Approach to Combustion Air Monitoring

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ABSTRACT

Airflow sensing in an industrial environment such as a stack or exhaust duct is a difficult challenge. Combustion airflow provides some of the greatest challenges as a result of high temperature, particulate loading, confined installation space and concerns over representativeness of the measurement location, yet the accuracy of combustion air monitoring can have a large influence on the ability to control combustion efficiency. Existing technologies such as 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. Recent EPRI studies indicate Pitot tube flow monitors over report flow from 2 to 5%. 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 small diameters (0.2-10 m) of stacks and ducts.

The optical flow sensor uses many powerful features to enhance its performance. These include: (1) the concept of scintillation such that the velocity measurement is completely independent of temperature, pressure, humidity, opacity and is a path-length average across the duct; (2) the product uses DSP (Digital Signal Processing); (3) sensor uses built-in self-test and diagnostics to monitor its own performance; (4) sensor complies with all USEPA sanctioned tests for a flow; (5) the instrument can link with a PC, PLC (mainframe), CEM (Continuous Emissions Monitor) or other data collection device, which accepts digital and/or analog output. For combustion air measurements 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 case studies including a 837 Mw generating station versus two sensors calibrated in comparison to a reference method.

INTRODUCTION

The optical flow sensor (OFS) and its predecessor, the optical anemometer (a flow sensor which uses the same technology as the OFS but measures along much longer path lengths: 100m to 1 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. Starlight twinkling is a common example of scintillation. Light passes through pockets of air with different temperature and density. 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.

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)*

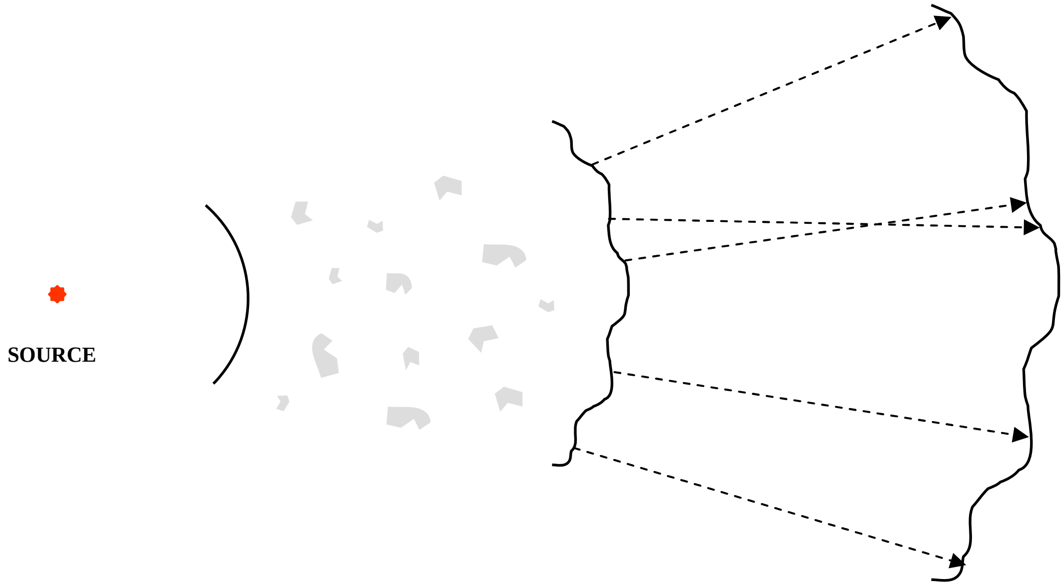

FIGURE 1- SCINTILLATION DIAGRAM

Figure 2 shows the effect of scintillation of optical turbulence on a laser beam after travelling through the atmosphere. Parcels as small as several centimeters may be detected by the LOA (Long Baseline Optical Anemometer). The strength of the atmospheric turbulence[1] is commonly represented as a refractive index structure constant 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 2 – EFFECTS OF SCINTILLATION OF OPTICAL TURBULENCE ON A LASER BEAM AFTER TRAVELLING THROUGH THE ATMOSPHERE

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 200-1000 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 approved 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 acquired 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 petroleum facilities satisfy their Part 60 & 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 technological solution better than 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 60 & 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 petroleum 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 a purge or blower. Both methods are problematic due to their intrusive nature, especially in extreme conditions.

After approving the optical scintillation instrument for Method 14 equivalency, EPA officials suggested that the optical anemometer should also be applied to smokestacks for Part 60 & 75 and similar 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).

In addition to Part 60 & 75 applications, the Optical Flow Sensor can also be used in the process control applications. Due to the technology’s versatility and non-intrusiveness, the OFS can work in a wide variety of industries. 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.

DESCRIPTION OF OPTICAL FLOW SENSOR

The optical flow sensor consists of a transmitter, receiver, and control box. The transmitter and receiver are simply installed on flanges on opposite sides of the stack perpendicular to flow direction. The transmitter contains a 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, re-adjustment is not required after installation.

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, pressure, humidity, and opacity**
5) **direct cross-stack velocity measurement, and**
6) **no moving parts, solid state construction.**

The optical technology allows the sensor to be located external to the stack and 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 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 installed behind protective windows or flange extensions may be utilized 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. 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 the stack flow. The electronics enclosure is typically placed near the receiver or at a control room.

Among the requirements for Part 60 & 75, the optical flow sensor provides an automatic daily calibration (i.e. calibration error test) every 24 hours. The user may set the time or the instrument will perform the daily calibration automatically. The calibration is done electronically and uses the reference calibration data to determine any error. A distinct advantage with this optical technology in regards to the calibration test is that the OFS has virtually no drift.

As for the interference check, the optical flow sensor exceeds the requirements. The instrument performs a continuous interference check 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.

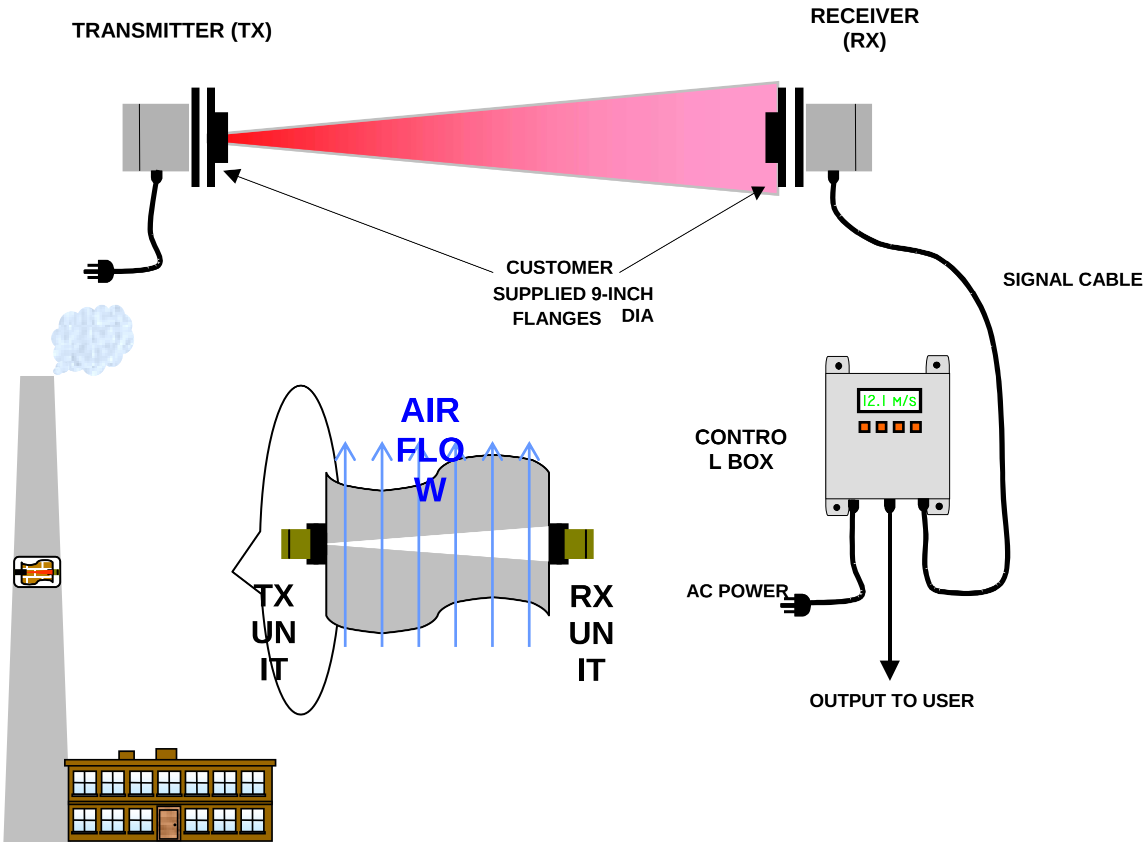

FIGURE 3 – CONFIGURATION OF OPTICAL FLOW SENSOR

The relative accuracy of the optical flow sensor compared to Pitot tubes consistently meets the expectations for a flow sensor in Part 60 & 75. The optical flow sensor was tested at NIST (formerly the US Bureau of Standards, now the National Institute of Standards & Technology). The NIST wind tunnel is one of the best facilities in the world for setting the standards for wind and flow instruments. This test was done without any curve fitting done to the optical flow sensor. (*See Figure 4 - NIST Wind Tunnel Test*).[2] The results demonstrate that the OFS is accurate as well as representative. For more details on this NIST test of the optical flow sensor, please refer to the official NIST report.[3]

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 is normally feasible. This is evident in the case of the NIST wind tunnel with an average of more than one hundred Pitot tubes. 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.

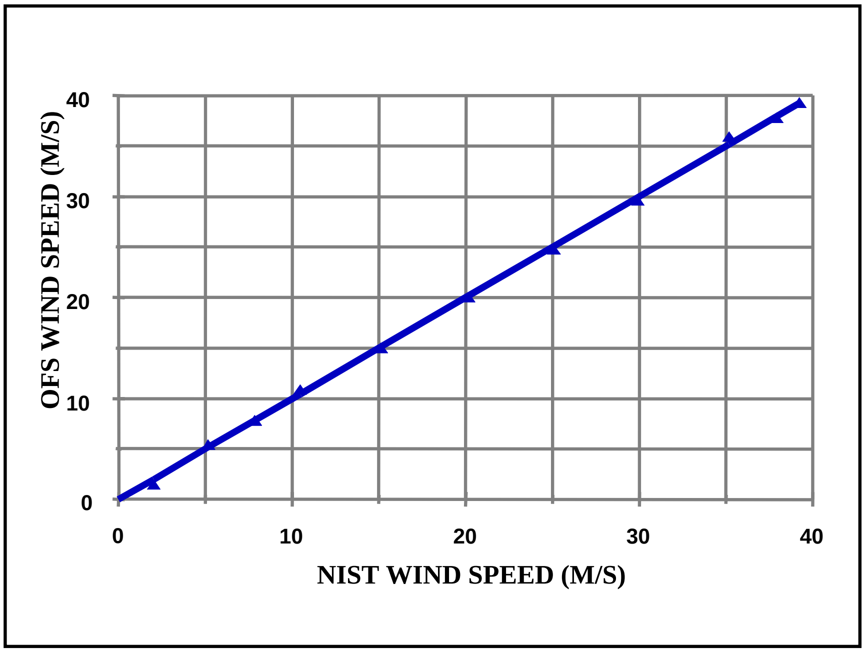

FIGURE 4 -WIND TUNNEL TEST: NIST STANDARD VS. OPTICAL FLOW SENSOR

The optical flow sensor has also been 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 10-day average of each ultrasonic sensor, the optical flow sensor average over that same period was in between the two. (*See Figure 5 – Comparison of Ultrasonic vs. Optical Flow Sensor*)[4] 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.

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 used for process control measurements in power plants, refineries, and smelters. It is also installed in Part 75 & 60 facilities and has passed RATA tests in petroleum as well as other industries. The latest RATA test was conducted for a major petroleum company at one of their US refineries in April 2003. The unit passed successfully. One example of OFS RATA test results is shown above (*See Figure 6 - RATA Test Data*).[5] The data provides the relative accuracies for a 3-load RATA test performed at a coal-fired 182 Mw stack at a US power plant. The average relative accuracy for all three-loads is about 1.3%.

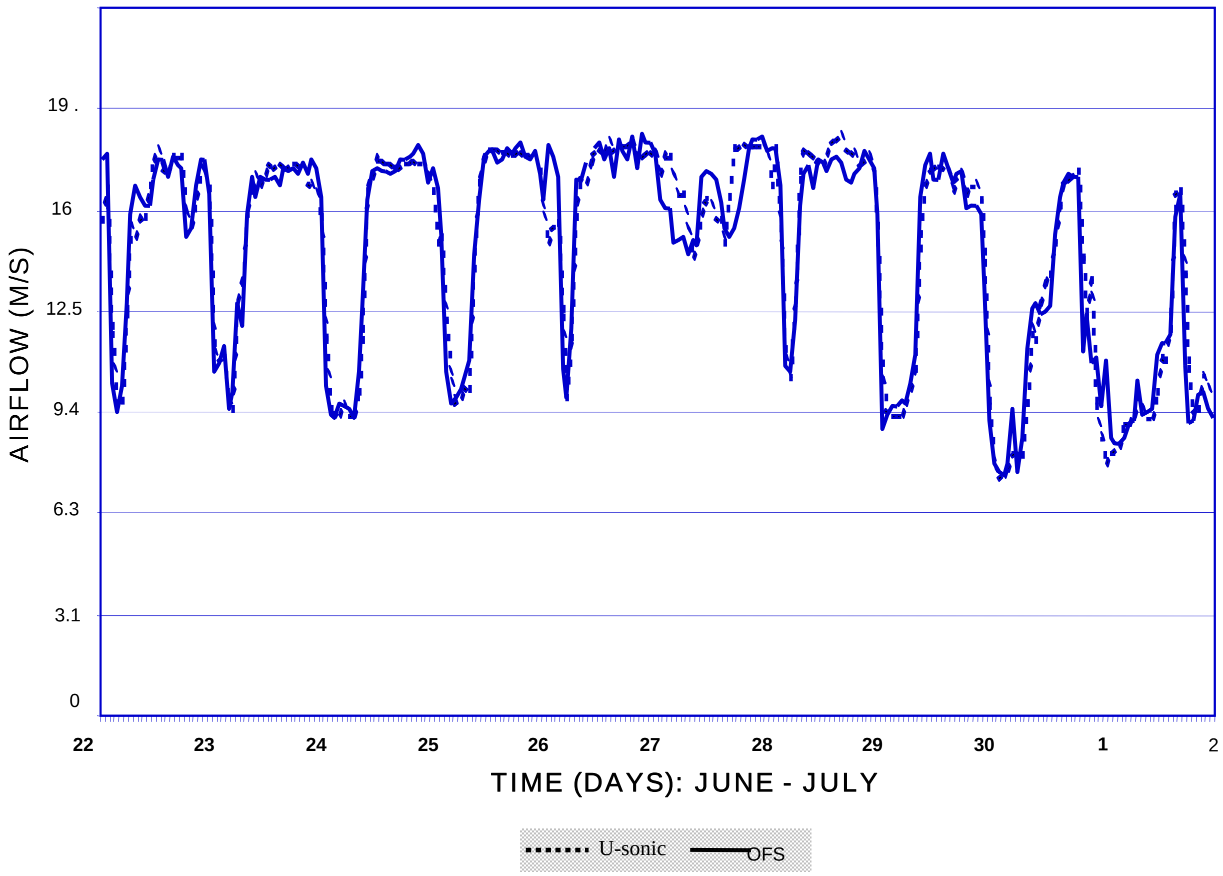

FIGURE 5 – COMPARISON OF ULTRASONIC VS. OPTICAL FLOW SENSOR

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) are exposed to the flue gas. The OFS's non-intrusive design ensures better long-term reliability and minimizes maintenance costs..

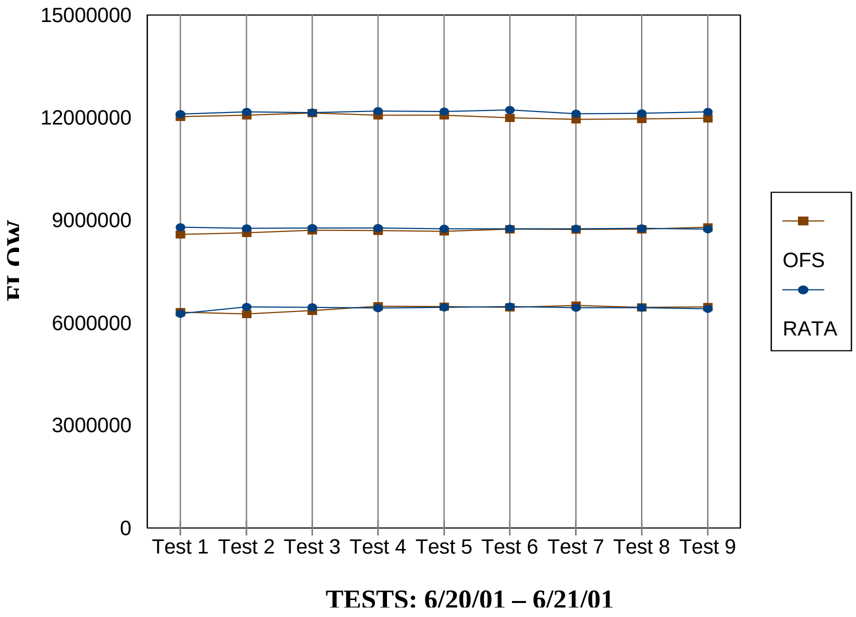

FIGURE 6 – RATA TEST DATA: OFS MEASUREMENT VS. RATA REFERENCE (PITOT TUBE) SCFH = standard cubic feet per hour

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 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 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 flow medium in order for the optical flow sensor to have any problem. The instrument typically requires window cleaning every 6-12 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 is designed with consideration for 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 MTBF (Mean Time Between Failure). 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, etc.

CONCLUSION

As the economic conditions pressure facilities to further increase process or combustion efficiency and lower costs, the performance of the flow measurement becomes even more significant. Increasing the reliability and representativeness of flow measurements translate into real cash savings for end-users. The optical flow sensor is a viable solution for process control airflow measurements versus the traditional Pitot tubes and ultrasonic sensors. The optical flow sensor affords the user a distinct combination of advantages that the other methods do not offer: 1) Non-intrusive, not directly exposed to the stack flow (does not create pressure drop or affect the flow field) 2) Path averaged measurement for more representative results, 3) Simple, non-angled installation which lowers cost vs. ultrasonic, 4) Result independent of temperature, pressure, humidity, and opacity. 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 tested, has been Part 60 & 75 certified, relied on for almost 30 years to make atmospheric and environmental measurements, and has virtually no drift. The OFS has demonstrated its performance through direct comparisons with ultrasonic sensors and Pitot tubes especially in RATA tests. The instrument is currently being used for applications in many fields including the petroleum, aluminum, cement, pulp & paper, and utility industries. No other flow sensor currently available meets these aforementioned conditions and characteristics.

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[4] Dr. Ting-I Wang & Eric Buhr, “OFS-2000 Optical Flow Sensor Certification Test Data”, Optical Scientific Inc., 9/00, Appendix C, Figure 3.

[5] Dr. Ting-I Wang, “Report of RATA Test of Optical Flow Sensor”, Optical Scientific, Inc., 6/01, p. 5, Figure 1.