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SENSORS

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Air flow in pipes and ducts is known to be turbulent. This may lead some to conclude that air is hard to measure.

Advanced Thermal Sensors for Air Duct Flow Measurement

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Air flow can be measured using pitot tubes, venturies, target meters, turbines, vortex shedding, and thermal type instruments, either as single point or averaging array local velocity sensors. Customer choice for one of these device types for use in a particular application is based on price, accuracy, stability, temperature, temperature range, pressure, pressure range, reliability, maintenance requirements, chemical compatibility, ruggedness, and understanding of technology. In many industrial applications where there is a lack of sufficient straight line run or where the temperature of the gas is different than the ambient, installed measurement instrumentation requires a field adjustment to obtain an acceptable calibra-

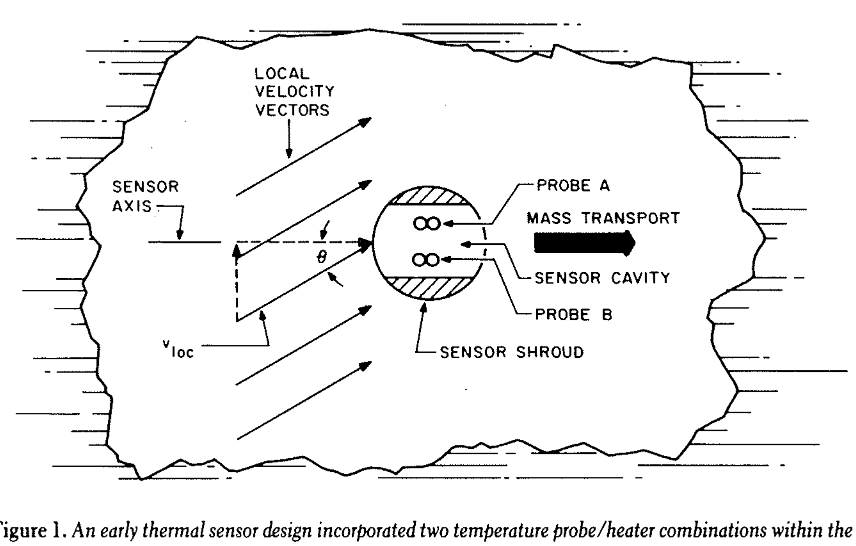

Figure 1. *An early thermal sensor design incorporated two temperature probe/heater combinations within the sensor housing. (The heater with probe B is a "dummy"—present only for mass balance.) The gas' local velocity vector is shown as v_{loc} and the incident angle as θ. A measured temperature differential is related to the logarithm of flow rate; direct reading mass flow rate is available after signal linearization.*

tion. This practice is generally independent of the measurement principle being employed and applies to single point and multipoint averaging array measurements. This adjustment is sometimes necessary in spite of the fact that each sensor has been calibrated in a flow system by the manufacturer.

An investigation of this problem was begun to determine the cause for the apparent discrepancy. Its solution has resulted in a patent pending sensor modification that virtually eliminates the source of the discrepancy and its associated error.

THE PROBLEM

Flow measurement in ducts having a cross-sectional size measured in square feet and straight line runs less than 20 times the minimum cross-sectional dimensions are generally approached using an averaging technique in which several sensors are located on a support structure. The sensor outputs, each representative of a local velocity, are averaged to obtain a mean duct velocity, and this value is used to determine the duct flow rate.

Choosing this multipoint method implies that a single point measurement would not suffice since the stream profile is not adequately developed. (Should the profile be fully developed, a strategically located single velocity sensor could be used to represent an average duct velocity, which in combination with a theoretical profile description would provide a reasonably accurate duct flow rate.) As an example, if the duct is of circular geometry, symmetric points from the center of the duct, along a diameter, may have different local velocities and, therefore, each should be measured and averaged. Since symmetry does not exist, the regions of high speed (and higher local pressure gradient) will have a velocity vector component directed toward the region of low speed (lower local pressure gradient). The result is that each sensor in an array may be influenced by a local velocity that is not aligned with the sensor's geometric axis, which, by design, is aligned parallel to the duct axis. In all cases, regardless of sensor technology or type, calibrations by the manufacturer are performed with the velocity vector aligned with the sensor's geometric axis.

Gross error can result from sensors, used either in single point (small cross-section lines) or multipoint arrays, that respond completely to the local speed of the flowing gas rather than to the velocity component aligned with the duct axis. The response problem is applicable to a greater or lesser degree to all sensor types just mentioned. We will focus here, however, on thermal type sensors.

In Figure 1, a thermal sensor of an earlier type is shown located in a duct conveying a gas having an incident local velocity vector depicted as v_{loc}. Probe A contains an electrical heater and a temperature sensor in intimate contact. Probe B contains a reference temperature sensor and a "dummy" heater for mass balance, again in intimate contact. Under the condition of constant electrical power to the heater, the measured temperature differential becomes dependent on the logarithm of flow rate for an incident angle of θ degrees. The signal can be linearized to display mass flow rate in any desired units. Similar sensors with the heater and temperature sensor separated by a small gap have also been used in industry for single point and averaging flow measurement.

The problems associated with the previously mentioned thermal sensors for off-axis velocity vectors are shown in Figure 2. Curve I represents a typical output signal resulting from a constant flow speed having an incident angle θ, with respect to the sensor axis. Compare this response with an ideal response, Curve II, which depicts the cosine component of the incident velocity vector, (representative of the duct axis mass transport rate); the error is significant. As an example of the error amount, consider a velocity vector with an angle of -30 degrees. Ideally, the mass transport component of the incident velocity vector should provide an output signal indicating $100 \times \cos 30 = 87$, or 87 percent of the incident velocity; i.e., should a swirl exist in the duct where the velocity incident on the sensor is 240 ft/min at an angle of -30 degrees, the sensor would indicate only $240 \times 0.87 = 208$ ft/min, since this is the velocity at which the gas is being transported along the duct axis.

However, thermal sensors of the type described above are currently used in duct averaging and will provide an output signal, shown as Curve I in Figure 2. The

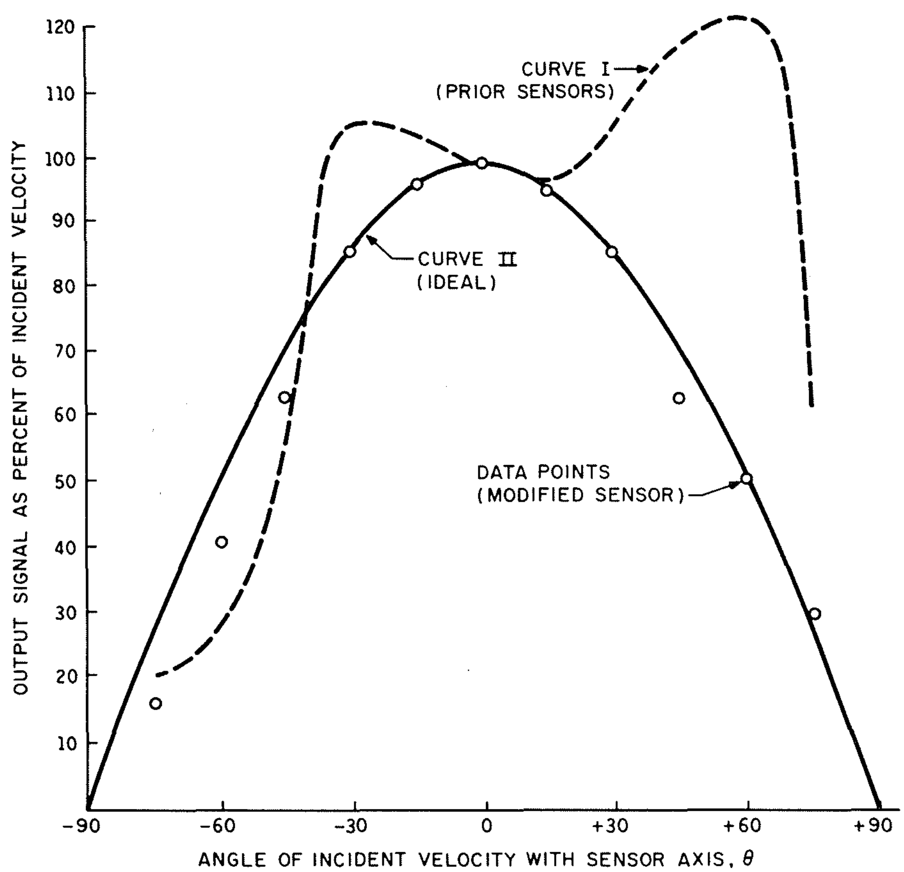

Figure 2. *The performance of previous types of thermal sensors (Curve I) is compared to that of a modified thermal sensor (open data points) and to an ideal response (Curve II).*

curve shows an indicated local velocity of 105 percent of the incident velocity at an angle of −30 degrees. Using the previous example, for 240 ft/min the instrument would indicate 240 × 1.05 = 252 ft/min. The error in measuring the local mass transport along the duct would be (252 −208)/208 = 0.21, or 21 percent. Thermal sensors having a different probe geometry will deviate from Curve I but still fall short of approaching the ideal curve.

The data for Curve I were obtained on one sensor type of the current geometries

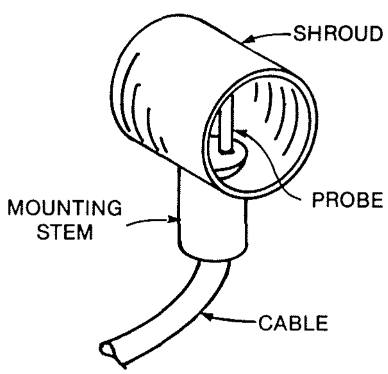

Figure 3. *The modified thermal air flow sensor includes an extended shroud.*

used in industry. It can only be inferred that the shape of the response is typical and that only the smallest of incident angle variations can be tolerated. Using such devices places strict requirements on conditioning the gas stream either through long straight line sections and/or employment of adequately designed flow straighteners.

These problems are not associated only with currently used thermal sensors. None of the other types of previously mentioned sensors have a response curve following that of Curve II in Figure 2. It is the latter response (Curve II) that provides a true measurement of the amount of material transported in the duct.

The common pitot tube output signal falls off abruptly as the angle of incidence deviates from 0 degrees. Some sensor types employ a design that causes them to be essentially immune to the incident angle except at large angles. Again, this is not correct since it does not respond to the desired cosine component of the velocity vector.

THE RESOLUTION

Analysis of the response curve for current thermal sensors has led to an innovative modification of the sensor head components to include a shroud section for probe support and protection. Figure 3 shows one form of the housing structure, a slightly elongated shroud, of the modified sensor. The complete sensor head can be attached to a support arm for multipoint array measurements, or it can be configured for single point installations.

To demonstrate the improvement, measurements were taken using the same sensor and electronics previously used in obtaining the data of Curve I in Figure 2, with the exception that the head section included the shroud modification. The open circles in Figure 2 represent measured data points which conform, within experimental error, to the theoretically desired response.

CONCLUSIONS

The performance of this new sensor approach eliminates error associated with nonidealized duct flow profiles and permits true duct transport flow measurements by means of single point or flow averaging techniques. This method eliminates the discrepancy between calibrated sensor heads and installed duct system measurements. The actual design modification can also be applied to other flowmeter types to better approximate the desired cosine distribution.

Another advantage of the new sensor head is the ability to measure the magnitude and direction (velocity vector) of fluid flow. To perform the measurement, the sensor head is located on a manipulating arm and oriented to obtain maximum output. The fluid speed is determined from the measured output, and its direction is determined by probe head axis orientation. Measurements of this type are important to drying tower performance and large duct flow profile determination.

The modified sensor is not only good for a system exhibiting a reasonable flow profile requiring flow averaging, but also for reliable measurements in air ducts having short straight runs where the flow profile is so severe that flow straighteners are inadequate.

A single probe of the new type can be used to obtain a true transport velocity flow profile by scanning a plane of the duct with its axis aligned with the duct axis. Analysis of the profile data would then permit selection of a fixed probe location for accurate measurement of mass transport. This approach has, as always, the limitation that the mass transport range be narrow and that local geometries be fixed, e.g., no local damper variations.

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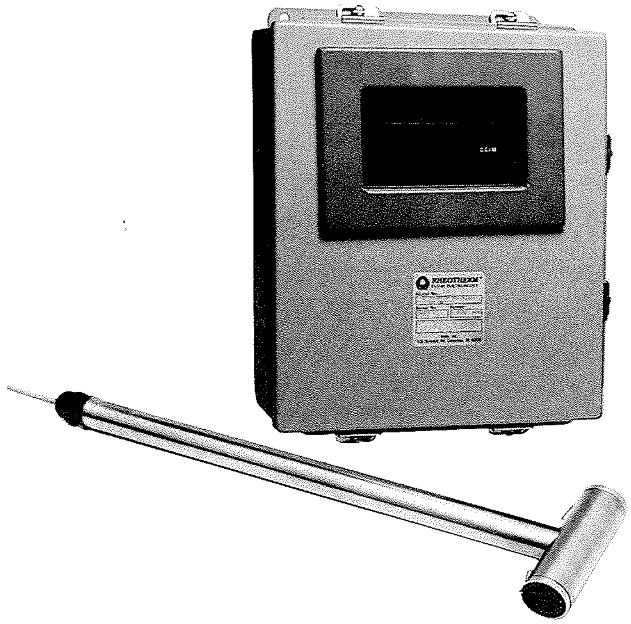

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