Evaluating Airflow-Measuring

Sources of differences between expected and actual performance

INTRODUCTION

The proper selection of airflow measurement devices is critical to the performance of today's state-of-the-art HVAC control systems. As in most things that are promoted as nearly identical, true operational or lab comparisons of products may not provide similar results. Many of the requirements and limitations of one measurement technology are often mistakenly thought to apply to every other, especially when the comparison involves two similar technologies.

Accuracy and repeatability vary dramatically between measurement instruments and are most significantly influenced by: the inherent advantages / disadvantages of the basic technology, the manufacturer's understanding of the technology employed, the quality of basic components used, consistency in the manufacturing process and the conditions found at the measurement / installation location. There is really nothing unexpected revealed in this article, if you only take a few seconds and use common sense when thinking about it.

This article offers an overview of the functional and performance differences in currently available instrumentation technology used to improve the control of ventilation systems in buildings throughout the world. Beyond the analysis, it offers practical information to be used when comparing or specifying these products, providing the means to insure that the level of performance you need is provided.

Our focus is on the two most popular technologies used for permanently duct-mounted commercial measurement systems:

Devices

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Velocity Pressure devices (Pitot arrays, Pitot probes, Piezo rings, and other ΔP methods) and Thermal Dispersion devices (microprocessor-based instruments using some form of thermistor sensors). It intentionally excludes discussion of vortex shedding and RTD-type industrial instruments, which are generally applied in industrially contaminated environments and/or high temperatures and are more expensive. They are not commonly used in commercial settings.

HISTORY

Historically, the merits of each brand of airflow instrumentation have their claimed performance rooted in the inventiveness of the manufacturer's sales and marketing activities. Because of variations in measurement techniques and the measurement equipment used, it is nearly impossible to validate the performance of velocity pressure-based, permanently mounted instruments under field conditions using field references as the comparison standard. There are many reasons for this, the most important is the inability to minimize the uncertainty in measurement to the point where it is statistically less significant. A superiority in accuracy of 10:1 (reference to instrument under test) is required by most scientific and academic sources to provide reliable measurement comparisons.

Furthermore, even under laboratory conditions, the performance differences among applied velocity pressure-based devices cannot be easily obtained without this superiority. Comparison of the published performance charts of 'AMCA-certified' products confirms this issue.

The promise of improved comfort control and the energy savings potential of Variable Air Volume (VAV) air distribution designs was broken early during its development by the lack of instrumentation reliability at both the AHU and at the terminal units. Systems were simply too difficult to control and maintain. "Pressure independence" is essential to their function. Consistently reliable instrumentation is essential to maximize their performance and realize the initial promise.

A better technology was necessary to allow designers and building operators to avoid the inherent limitations of pressure-based devices, including many sources of measurement error:

- instrument placement (resulting in variations due to turbulence)
- measurement sampling (averaging) error
- field calibration reference using manual instruments,
- uncertainties due to manual measurement techniques
- measurement corrections required for zero drift, non-repeatability, non-linearity and temperature effects
- allowances required for air density changes,
- effect of improper installation
- effect of improper maintenance, and
- the cost-dominated component selection criteria (transducer range and FS accuracy).

Secondary instrument considerations included:

- installation time and setup costs
- setup requirements often overlooked by subcontracts
- lack of commissioning standards
- lack of cooperation among TAB and Controls subcontractors
- initial and recurring instrument calibration requirements
- continuous maintenance requirements, and
- low velocity (turndown) limitations.

THERMAL DISPERSION

Advanced thermal dispersion (TD) airflow measurement technology was introduced in 1985. Within the scope of this article and in consideration of the previously mentioned limitations, it is defined to include only microprocessor-based designs. Analog electronic instruments using thermistor sensors exhibit unacceptable response times and are usually unreliable, with major deficiencies in performance when operating over the expected equipment operating temperature range. Also interesting to note is that not all microprocessor-based designs are capable of overcoming these deficiencies, but can be differentiated from all other types of thermal-based velocity measurement technologies. Although, this article will use the term and features generically, the designer or user must insure that the performance expected can be supplied by the selected vendor by understanding the differences between them.

TD technology is currently used by control systems in a wide range of office buildings, laboratories, healthcare and educational facilities to ensure healthy indoor air quality and economy of operation. Some TD manufacturers produce instruments that feature a combination of electronic components and some provide totally independent sensing elements. One TD manufacturer produces instruments that are factory calibrated to NIST-traceable velocity reference standards. When properly designed and applied with a sufficient density of sensing elements, some TD instruments can overcome (or minimize) the placement limitations and measurement uncertainties inherent in the use of velocity-pressure instruments. This does not mean all of them can.

There are three U.S. manufacturers of TD air flow measurement instruments and at least one meets all of those qualifications. Their products are markedly different in component specifications, functions and design features. Although the three may appear to be similar in form and construction, a closer comparison of their design implementation, qualitative value, historical reliability, application limitations and verifiable performance yields surprising differences between them.

Early thermal dispersion arrays (prior to 1993) were significantly influenced by duct turbulence and placement conditions similar to velocity pressure arrays. Airflow measuring stations often exhibited a "false high" reading in these situations. Since the technology determines airflow by relating the heat transfer rate from a warm body to the airstream, duct locations having excessive eddies and turbulence tend to remove more heat from the sensor compared to its reaction during factory wind-tunnel calibration, and hence, higher readings.

Enhancements to one TD sensor design in the early 1990's placed the heated sensor in the turbulent wake created by the sharp leading edge of the sensor probe assembly. This "preconditioning" effect essentially made the airflow across the sensor more "turbulent" than the worst-case duct disturbance effect, therefore allowing for the condition to be created consistently. This design feature was further exploited during the calibration process. As a result, when combined with a sufficient density of sensor nodes, these particular thermal dispersion sensors are influenced far less by duct disturbances. The design's advantages was proven in full scale laboratory testing. (Fig.4, pg.7) With advanced TD instruments, often only 0.75 to 1.5 simple equivalent duct diameters [(width + height)/2] is sufficient for accurate measurement when higher sensor density devices of this type are applied. Contrast this to the 3 duct diameter industry minimum required of other devices.

In the spring of 2000, over 350 units of this design of TD devices were installed at the Advanced Measurement Lab complex at NIST in Gaithersburg, MD (http://aml.nist.gov/). These devices have performed without the necessity of field calibration or other maintenance requirements and are reported to be functioning well, without a single reported sensor failure since installation over seven years ago.

TD technology should not be confused or compared on any level with thermal anemometers, hot-wire devices or any other form of analog electronic velocity measurement. The term "Hot-wire anemometer" is typically used (incorrectly) as a generic term or all inclusive of a specific type of airflow measurement device. The negative impact in using a generic term implies to the reader that all products in the group possess similar properties and limitations. This association is advantageous for some manufacturers of lesser performing instruments who benefit from the superior characteristics of other instruments. At the same time, this is clearly a disadvantage for the manufacturers of superior instruments who then suffer from the assumption of inferior characteristics due to user experiences with lesser performing products.

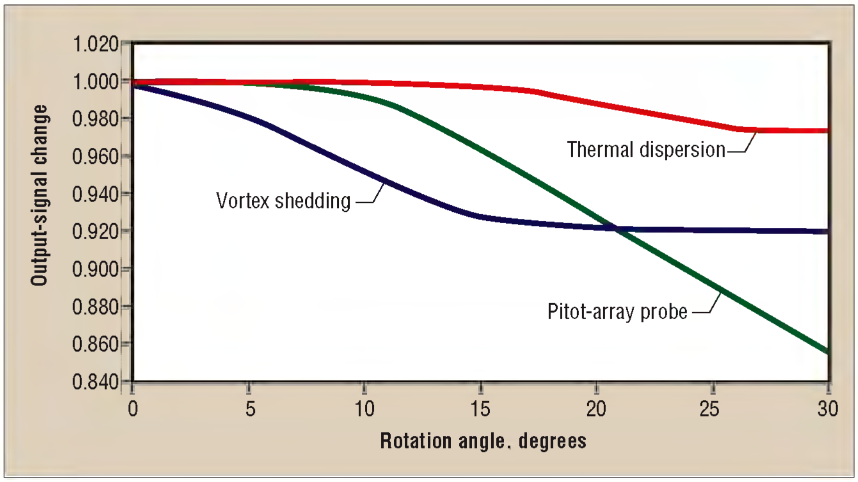


FIGURE 1. Effect of instrument rotation on output signal.

** Refer to Technical White Paper Airflow Measurement for HVAC Systems – Technology Comparison - Thermal Dispersion versus Pitot Tube Arrays at http://www.airflowmeasurement.com/Web_Pdfs/AirflowMeasurement_Comparison.pdf* *to the measured air stream, but the precise determination of air-stream temperature at the point of measurement.*

Hand-held thermal (single-point) instruments generally use unshielded thermistors, making them very sensitive to the direction and multiple vectors of airflow. They are typically analog devices, and as such, have a tendency to drift from zero. They usually require regular recalibration and 'zeroing.' They also tend to perform satisfactorily only when applied within a narrow temperature band, when used at favorable locations and at specific airflow angles.

On the other hand, at least one permanently-mounted TD product has a published operating temperature range of -20 to +160 deg F and a design that limits the impact of rotational misalignment from improper installation. Tests performed by the manufacturer confirm the device's immunity to improper installation (rotation relative to airflow angle). The test monitored the output signal while rotating the sensing device up to 30 deg from optimum (perpendicular to airflow). The results clearly demonstrate the TD device's superior performance as compared to the two other significant competing technologies used in commercial HVAC. The results are depicted in the plot below. (Fig.1)

TD instruments are not totally immune to the operating conditions found in today's buildings, although they are comparatively superior to Pitot arrays in almost every regard. TD performance is dependent upon the thermal transfer of energy (heat) from the sensing element to the measured airstream, as well as the precise determination of airstream temperature at the point of measurement. Conditions that could affect thermal transfer (insulating materials or liquid water) could also impact the ability of the instrument to function as designed. The TD manufacturer's selection of the type and design of the sensing elements employed will ultimately impact all of the following elements:

- instrument cost,
- instrument MTBF ('mean time between failures' - reliability),
- instrument sensitivity to environmental changes,
- instrument stability over time and changing temperatures,
- the instrument's ability to perform reliably without mechanical failure due to continuous temperature cycling between heating and cooling,
- the validity of the manufacturers' factory calibration process,
- the need for or lack of interchangeability of instrument components or subsystems, and
- the environmental application limitations on product placement (e.g. 'Do not mount at intake openings' or 'Must be mounted parallel to the duct').

Prior to instrument selection, each of these elements and their implications for the success or failure of the system design must be considered.

Although continuously soaked by condensation from coils or carryover from exterior louvers, water alone will not damage some TD devices that are designed to withstand it. When consideration is given during the instrument's design, the impact of liquid water immersion on TD performance is temporary, with normal performance resuming as the sensor surface returns to ambient RH levels.

Insulating materials that could potentially bind to the tiny thermistor sensing elements are rarely an issue to thermistors designs. However, there are some uncommon conditions where specific materials combine with a binding agent (atomized grease or high humidity), and may require occasional light cleaning of the debris from the sensors. Typically, common dust and airborne particulate found in outside air and conditioned air ventilating systems is not capable of accumulating and producing an insulating value sufficient to materially impact the thermal transfer characteristics of the sensor. The impact on performance from common airborne dust and dirt is negligible to bead-type glass encapsulated sensors. No information is available on this issue for epoxy-coated or diode case thermistor designs.

PITOT-STATIC TUBES vs. VELOCITY PRESSURE ARRAY

The term "Pitot-Tube" array is also used incorrectly as a generic term for "permanently installed instruments." This tends to mislead uninformed readers that these devices posses the same properties, capabilities and limitations as the instrument referenced within the expression. As mentioned earlier, an association that elevates a technology's characteristics is one reason that many manufacturers continue to use and take advantage of these terms.

The laboratory Pitot-static tube is a 'primary' instrument. This is an instrument having physical properties that have been scientifically proven to provide a predictable level of measurement performance, albeit with known application limitations. The Pitot array is not a primary instrument. The Pitot-static tube and the

"A Pitot-static tube in the hands of a skilled testing and balancing technician is still a highly trusted method of obtaining field test information."

Pitot array share only the use of the velocity pressure (P_v) relationship in the determination of velocity and thereafter the calculation of air volume. It is this relationship that allows Pitot arrays to compare favorably to Pitot tubes when used for calibration or validation in the field where both are subject to uncertainties in measurement from the same conditions.

However, a Pitot-static tube in the hands of a skilled testing and balancing technician that calculates average velocities through a Pitot-static tube traverse after selecting a suitable test location in the field is still a highly trusted method of obtaining field test information. They are important to the initial testing and balancing of many systems. This method is also the basis of many laboratory test standards (e.g. ANSI/AMCA 210 and ANSI/ASHRAE 41.2), but is susceptible to error creeping into the process due to the normal inconsistencies of human application. This is one reason for deviations experienced between seemingly identical traverse measurements taken successively with fans and dampers locked in one position.

There are approximately six noteworthy manufacturers in North America of various types of velocity pressure-based, duct-averaging products. There are at least twelve more manufacturers of VAV box pickups, fan inlet Piezo rings, flow balancing hoods, calibration and research devices, all based on these principles. All use the P_v relationship to calculate velocity and as a result share many of the same application and operational limitations.

As applied to commercial ventilating systems, this measurement technology has been around since the 1960's, coincidental to the growing acceptance of VAV air distribution designs. Most Pitot array manufacturers also offer various ranges of P/E transducers and other electronic control devices that allow them to function with DDC control systems. The Pitot array ducted station is only one component of the measurement system that individually contributes to the total uncertainty of the measurement at the host controls input terminals. A pneumatic output is no longer a preferred interface method for building controls. The differential pressure must first be converted to an electronic signal, and then transmitted to the host controls or an intermediate device, either of which must then be programmed to make the analog output linear-to-flow.

Velocity Pressure arrays, Pitot arrays and Self-averaging arrays are all names for the same product species. It is a bifurcated device that separately equalizes total and static pressure within a length of partitioned tubing for differential measurements through small sampling holes positioned at a cross-sectional plane in the duct. A single differential pressure is measured between two compartments or equalizing manifolds. The raw output is assumed to be the "average" from numerous ports providing a non-linear differential pressure. This analog result must then be output electronically to a controller or display. It is made linear by an integrated transmitter, by a separate intermediate device ('square-root extractor') or by other methods of calculation following transmission of the non-linear signal and its analog-to-digital (A/D) conversion within the host controller.

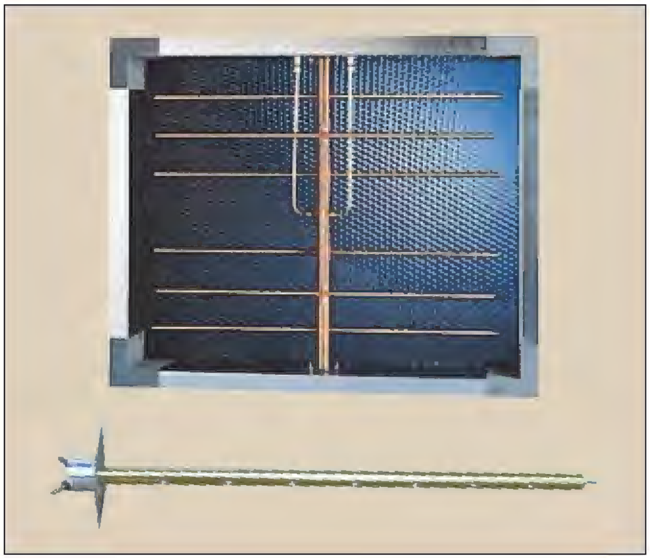


FIGURE 2. Types of Ducted "Self-Averaging" Pitot Arrays.

Professional TAB contractors measure the cross sectional average velocity in a duct by recording individual readings at specific locations on a plane perpendicular to airflow direction. Each Pitot reading is determined by evaluating the equation $V=4005*(\Delta P)^{0.5}$, where ΔP is expressed as inches of H_2O. This generalized relationship uses a constant (4005) that assumes standard conditions of altitude and temperature. The formula does not account for changes in air density due to variation in air temperature and barometric pressure (altitude). The readings are simply added together, divided by the number of measurements and a final average airflow rate is determined.

Taking a high number of readings throughout the duct can help compensate for changes in the velocity profile. It tends to reduce the uncertainty by increasing the number of samples in the average; however, it also increases the total time required to complete the determination of all the data needed for averaging (ISO3966).

A single differential pressure is measured between two compartments or equalizing manifolds.

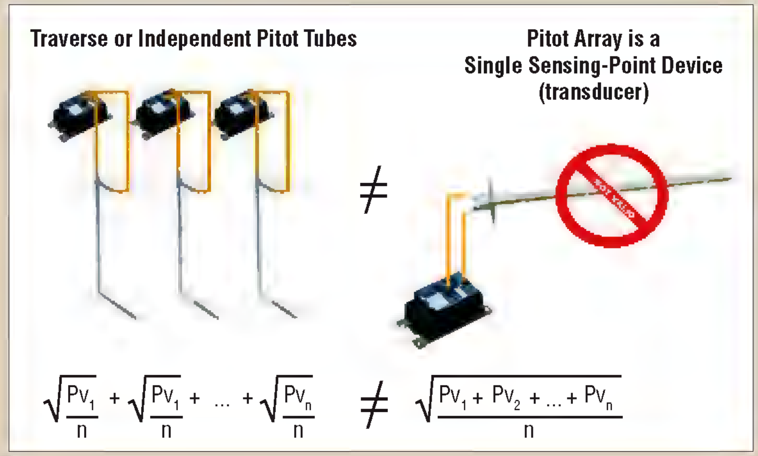
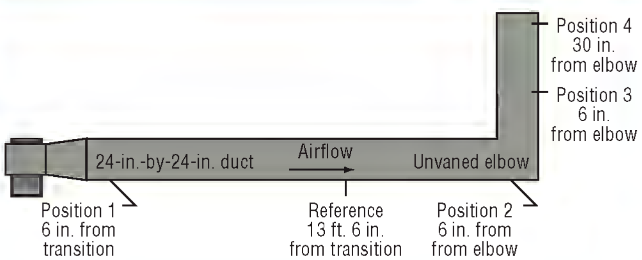


FIGURE 3. Pitot Array Averaging Error.

Deviation from reference position		
Position	Pitot array*	Thermal dispersion
1	25.90%	-2.3%
2	0.20%	-4.6%
3	45.30%	-5.6%
4	35.40%	-0.1%



*Differential-pressure measurements with pressure sensor. 0.05 percent of reading accuracy to eliminate transducer contributions to total measurement uncertainty and focus solely on placement-induced errors.

FIGURE 4. Effects of Placement on Performance – Advantages of Independent Sensors

Manufacturers of Pitot arrays promote high sampling 'sensor' densities (tiny holes in collector tubing) as a product feature and suggest that the sensor density of other devices using independent sensing elements is inadequate. The manufacturers associate the quantity of these perforations in collector tubing with the required quantity of velocity measurements necessary to satisfy ISO 3966, ASHRAE Std. 111, AMCA 203, or any of the TAB Guideline requirements.. They are not equivalent and any direct comparison is physically and mathematically invalid. (Fig.2)

Pitot arrays theoretically average the velocity profile; however, in practice, pressure equalization actually occurs along the length of a common collector tube, before the airflow rate is determined by a single sensing element (the pressure transducer).

Thus, they have far less sensor density than any device with true multiple independent sensors. The output of a Pitot array can only represent the average reading across a duct that exhibits equal pressure distribution at all areas; certainly difficult under controlled laboratory conditions, and extraordinarily unlikely in actual field applications. Since Pitot arrays are so sensitive to placement conditions, significant lengths of ductwork are required between disturbances to completely develop the necessary pressure profile across the array to allow optimum measurement performance.

The differences between single-sensor and truly independent sensor technologies is easily demonstrated in theory, and confirmed in laboratory testing.

The use of a normal single point velocity pressure-to-velocity calculation assumes that there is no difference if P_v is averaged before v is determined at multiple points. Mathematically, a significant error is introduced to the result (8 – 18% of reading), when compared to any method of averaging independent velocity determinations. This error is exclusive of any contribution to error from the pressure transducer or linearization.

A published industry technical White Paper based on a technical discussion of these technologies, and supported by test results (Fig. 3) compares the influences on performance by upstream and downstream disturbances, as well as:

- The effect on individual sensor accuracy (effect of "turbulence")
- The effect on overall sampling error of the array (effect of the velocity profile)
- The effect of placement of the sensor probe with respect to the velocity vector plane (rotation effect)
- The calibrated accuracy of the sensor(s)
- The calibrated accuracy of the transmitter/transducer
- Long-term stability

For details and explanation, refer to the technical White Paper* available at http://www.airflowmeasurement.com/Web_Pdfs/AirflowMeasurement_Comparison.pdf)

All Pitot arrays claim to provide an "accuracy of 2 percent." Two percent 'of what' however, is not indicated. The terminology is at best misleading and implies that this level of measurement performance is actually achievable in the field, and without regard for differences in the application or in the uncertainty contributed by all of the other components needed in the P_v system to produce a linear duct average velocity signal to the controller. The implication is that the stated "accuracy of 2 percent" makes the device equal to all other products with a maximum uncertainty in measurement of "+/-2% of reading."

"More reliable and consistent measurement devices can improve results for TAB professionals, but only for those that understand the differences between the devices that they find in the normal course of their work."

This claim overstates the capability of Pitot array technology and oversells performance expectations. In ideal laboratory conditions, with professionally selected research equipment and test set up (as in AMCA Standard 610-06), Pitot arrays can produce a measurement uncertainty of +/-2% from a reference. In this case the reference is the AMCA lab, which contributes its own level of measurement precision and increases the total uncertainty in the determination. Pitot arrays cannot consistently provide the claimed 2% level of combined total uncertainty under field conditions, against field references using unknown quality P/E conversion equipment and unknown linearization methods. Typically, Pitot array comparison is made only a with other P_v devices, which lessens the contrast to the P_v reference standard used and makes the comparison more favorable to the particular device under test.

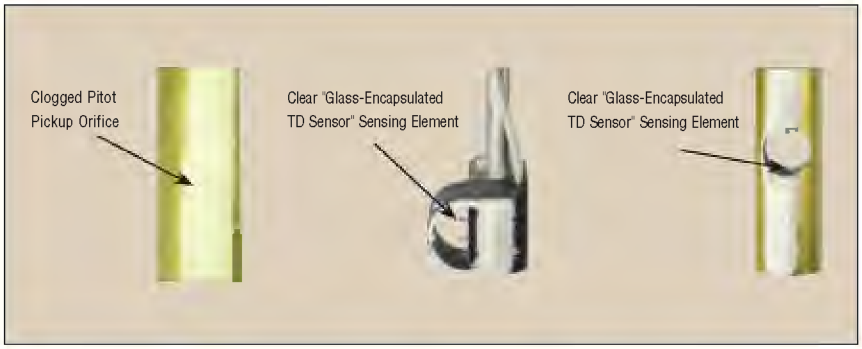


FIGURE 5. Dust Loading Test Results – Pitot array compared to two TD sensor configurations

The accuracy of velocity pressure devices rely on the physical sampling of air through an array of many tiny sampling ports engineered to specific dimensions. Regular maintenance of these ports must be performed in order to prevent clogging of the orifices and to ensure proper performance of the measurement device. Most Pitot array suppliers offer the option of a pressurized purge system, intended to reduce the manual labor associated with regular cleaning of the sampling port orifices. The effectiveness of these purge systems has never been evaluated, however the cost of a separate instrument air system can be many times the cost of the measurement devices.

The accuracy of pressure based instruments with pressure cavities that have no apparent method of drainage is also concerning. Although output readings may appear to remain acceptable when water accumulates, the entire premise supporting the theory on averaging pressures is invalidated.

Combined moisture and airborne debris in the airstream of return fans will impact the performance potential and increase the maintenance needs of ANY instrument placed in such unsuitable locations. Pitot arrays physically sample the particulate laden air and are inherently susceptible to

through an array of many tiny sampling ports engineered to specific dimensions.

these conditions. Vigilant attention to, and regular cleaning of sensors is necessary to prevent failure in their ability to detect variations in velocity profiles. Particulate buildup continues to be the Achilles' heel of Pitot array sensors.

In contrast, TD sensors feature a very large relative area of through-flow and an extremely small surface area for the individual sensing element. With their thermal conductivity intact, this allows TD sensors to continue to operate as designed in defiance of normal dust buildup, making them inherently immune to fouling from most common types of dirt. The binding effects of moisture combined with the insulating properties of some contaminants can degrade the thermal conductivity of individual thermal sensors and require only a light cleaning to restore their original performance.

In many cases, such as with fan tracking applications, repeatability, linearity and turndown are more important than absolute accuracy. Repeatability is the only measurement attribute important in the application of volumetric fan tracking control. Fan inlet conditions are unpredictable and therefore not conducive to situation based comparison studies. Conditions are extreme to the point of undesirability. It is the last possible airflow measurement placement some recommend. While it eliminates some design issues for the engineer, other troublesome installation issues arise (e.g. access to the reverse side of dual inlet fans in the field) as well as fan sound and fan performance issues that most P_v inlet installations generate.

At least one TD manufacturer has developed a fan inlet mounting arrangement that overcomes all of these issues and greatly reduces the potential impact to more sensitive plenum fan performance to less than 1% of rated flow. Furthermore, the design of this particular TD instrument provides consistently repeatable measurement in the most challenging airflow measurement applications.

The difficulty in determining the true baseline volumetric calculation and the resulting impact on control accuracy is compounded by the difficulty in determining the actual area of the plane in the inlet cone where the measurement device is to be installed. This is true for any airflow measurement technology applied at fan inlets. However, when the instrument produces measurements that are repeatable, it can be set up in the field with the assistance of TAB professionals to produce reliable and repeatable results. This is important as accessibility for maintenance or replacement is diminished, especially with many dual inlet fan designs and air handler configurations.

For additional reference materials on the topics of Indoor Air Quality, ventilation and pressurization control, etc. visit http://www.automatedbuildings.com/editors/ldamiano.htm.

CONCLUSIONS

Many types of velocity measurement products from numerous sources have been applied successfully and not-so-successfully over the past 40 years. The information provided here can be used to make better decisions on equipment selection, application and instrument placement. With this additional knowledge, you increase the probability of your next project operating more efficiently and reliably. With more reliable and consistent measurement devices becoming more pervasive, opportunities increase for their use by TAB professionals to improve the results of their tasks and reduce the labor required to perform their functions, but only to those that understand the differences between the devices that they find in the normal course of their work.

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Len is author of numerous technical articles and the co-author of "CO2-Based Demand Control Ventilation - Do Risks Outweigh Rewards?" and "Measurement for the Control of Fresh Air Intake - an IAQ Prerequisite," both published in the ASHRAE Journal, October 2004 and January 1990 respectively.

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