

Airflow Measurement for HVAC Systems – Comparing Technologies

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INTRODUCTION

The proper selection of airflow measurement devices can be critical to the performance of today's state-of-the-art HVAC system. Many of the requirements and limitations of one technology are often mistakenly thought to apply to every other. Not all technologies result in equal performance, even when used under similar conditions. Accuracy and repeatability vary between technologies and are most dramatically influenced by installation location, airflow rates, and required system turndown.

The two most common airflow measurement technologies commonly used in HVAC systems are: (1) totally electronic thermal dispersion and (2) differential pressure based Pitot arrays. Designers should understand the advantages and limitations of each technology prior to selecting a device for a specific application

A BRIEF HISTORY OF AIRFLOW MEASUREMENT FOR HVAC

During the period when pneumatic controls dominated the industry, differential pressure based airflow measurement was the logical choice for HVAC applications. The Pitot-static tube could transmit the square root velocity equivalent of a single point, the velocity pressure, directly to the host control system.

When VAV systems began to dominate designs, there became a significant need to measure airflow rates for volumetric fan tracking. Enterprising individuals recognized the limitations of single point measurement and developed the averaging Pitot tube array. Although the device introduced a sampling error from averaging a nonlinear pressure signal, the technology was sufficient to meet the requirements of early VAV systems.

Direct digital control (DDC) systems began to replace traditional pneumatic systems in the early 1980's. Airflow measurement required an additional "transducer" to convert the pneumatic signal to an electronic equivalent for the DDC system. Because the differential velocity pressure was very small, the error of the conversion was significant and is still today a significant source of uncertainty when using Pitot tube technology.

Airflow measuring devices used in traditional HVAC systems were designed for basic balancing and thermal comfort. Maximum airflow rates of 2,500 FPM typified most systems. A working turndown of 3 to 1, or a minimum velocity of approximately 800 FPM, was accepted as the minimum airflow rate that airflow measurement devices needed to operate at. In addition, a minimum "straight run" of 10 duct diameters was required for "acceptable" measurement accuracy. In many cases, a flow-straightening honeycomb was required to minimize the averaging error of the manifold.

As HVAC system technology increased, so did the requirement for more accurate and stable airflow measuring devices. During the 1980's new technologies entered the airflow measurement arena. One technology utilized the principle of thermal dispersion. The new technology provided the host control system with a single, linear signal for airflow using an array of independent sensors without any additional transducers. In addition, thermal dispersion devices could accurately measure airflow rates down to still air (although the practical application of such measurement is rarely encountered). The thermal dispersion device also could provide the host control system with a signal for average temperature.

UNDERSTANDING THE DIFFERENCES BETWEEN THE TECHNOLOGIES

Comparing technologies that are vastly different is not a simple task. Besides the principle of measurement (thermal or differential pressure), there are a number of subtle factors that have a dramatic effect on overall performance. The primary factors are listed below and will be evaluated in subsequent sections of this article.

Influence of up and down stream disturbances:

- Effect on individual sensor accuracy (effect of "turbulence")
- Effect on overall sampling error of the array (effect of the velocity profile)

- Calibrated accuracy of the sensor(s)
- Calibrated accuracy of the transmitter/transducer
- Effect of placement of the sensor probe with respect to the velocity vector plane (rotation effect)
- Long-term stability

INFLUENCE OF UP AND DOWN STREAM DISTURBANCES

Duct fittings and accessories, including elbows, transitions, fans, dampers, and plenums will create excessive duct eddies (“turbulence”) and velocity profiles that will add to the uncertainty of measurement for airflow measuring devices. Thermal dispersion devices are influenced by these disturbances differently than differential pressure based devices. A leading manufacturer of thermal dispersion airflow measuring devices conducted extensive testing over a period of more than one year to evaluate the effect of up and downstream disturbances on both thermal dispersion devices and differential pressure based Pitot tubes and arrays.

Effect on Individual Sensor Accuracy (effects of “turbulence”)

Thermal Dispersion Devices

The scope of this article will be limited to the thermal dispersion measurement technology developed by Ebtron. A subsequent project could compare various thermal technologies.

Early (prior to 1993) thermal dispersion arrays were significantly influenced by duct turbulence. Airflow measuring stations placed in locations close to duct disturbances often exhibited a “false high” reading. Since the technology determines airflow by relating the heat transfer rate from a warm body to the velocity, duct locations having excessive eddies or turbulence removed more heat from the sensor than it was exposed to under factory wind-tunnel calibration, hence, the high reading.

Enhancements to the 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 (figure 1). This “preconditioning” effect essentially made all of the airflow across the sensor more “turbulent” than the worst-case disturbance effect, therefore allowing for the condition to be created and used during the calibration process. As a result, thermal dispersion sensors are influenced less by duct disturbances than any other technology, based on laboratory testing. Often, less than 1 equivalent diameter is adequate for accurate measurement when high sensor density devices are applied. These statements will be supported in research data presented later in this paper.

Pitot Tubes and Arrays

Both laboratory Pitots and averaging Pitot arrays are influenced by turbulence in a similar manner. The velocity, V , is expressed as

(equation 1)

$$V=(2\Delta P/\rho)^{0.5}$$

where ΔP is the differential pressure, and ρ is the density of the air.

The differential pressure is small compared to the total pressure of the air stream in most HVAC environments. The resulting signal-to-noise ratio is significant when sampling small fluctuations in total pressure of the air stream (figure 2). For example, a duct having a total pressure of 2.0 in.H₂O and a pressure fluctuation of $\pm 1\%$ will experience fluctuating “noise” of ± 0.02 in.H₂O. The velocity pressure associated with 1,000 FPM is equal to 0.062 in.H₂O. In this case the “noise” is nearly 1/3 of the total signal. The effect is amplified when Pitot instruments are placed closer to disturbances and at lower air flow rates. As a result, it is not uncommon for air balance professionals using differential pressure based devices to indicate negative or “unreliable” airflow rates near elbows, on the inside portion of the duct where the airflow is lowest. Newer hand-held devices actually force unreliable readings to 0 FPM, which can add to field measurement uncertainty when traversing in less than optimal duct locations.

Testing has indicated that in many cases, there was still a net positive airflow present when differential pressure based devices indicated negative or unreliable flow rates (see Placement Test Summary). As a result, and in order to achieve maximum potential performance, differential pressure devices should only be applied when the circumstances allow placement in greater than approximately 10 equivalent duct diameters of straight duct (7.5 duct diameters downstream and 3 upstream).^{4,5,6}

Effect on the Overall Sampling Error of the Array (effect of the velocity profile)

Both thermal dispersion and Pitot arrays determine the average velocity for conversion to a volumetric rate by sampling the velocity profile. Thermal dispersion measures velocity directly, while Pitot arrays sample the distribution of total and static pressures that represent velocity.

How many sampling points are required for accurate measurement and what should the sensor distribution be? Will x number of sensing points in a thermal dispersion device yield the same performance as x number of sampling points on a Pitot array?

International Standard ISO 3966, Measurement of fluid flow in closed conduits - Velocity area method using Pitot static tubes (1977)³, defines the currently accepted method for traversing ducts. The standard assumes the existence of a specific velocity profile function and recommends a specific number of measurements and the location of such measurements within the duct using the "Log-Tchebycheff" method. According to the Standard: "By hypothesis the mathematical form of the velocity distribution law as a function of the distance from the wall is logarithmic in the outermost elements of the section and polynomial in the other elements." The Standard recommends a minimum of 25 points be measured in rectangular ducts. The Standard has also been adopted as the basis of ASHRAE Standard 111¹.

A number of authors have commented on ISO 3966 and the use of the "Log-Tchebycheff" method. One manufacturer of thermal dispersion sensors offers its airflow devices with sensor distribution based on either the "Equal Area" method or "Log-Tchebycheff" method. However, testing has been inconclusive as to the best choice for most HVAC environments since the distribution makes assumptions that do not necessarily characterize the flow profiles of many HVAC duct systems, which have numerous fittings and disturbances. It is critical to recognize that the Standard is based solely on the use of Pitot static tubes. Uncertainty analysis presented in the Standard clearly indicates that a number of systematic and random errors are associated with the technique. "Errors in the estimation of local velocity" include those contributed by the velocity fluctuations during the traverse and turbulence and error due to inclination of the Pitot tube. "Errors in the estimation of flow rate" add uncertainty contributed by the positioning of the Pitot tube. All of these factors are unique to hand-held Pitot tube traverses. As a result, sampling theory dictates that a larger number of sampling points will result in a better estimation of the true average and minimize experimental error. The number of sampling points recommended by this method cannot be transposed to permanently mounted duct devices which do not have all of the inherent systematic and random errors associated with field measurement.

ASTM Standard D 3464-75, "Standard Test Method for Average Velocity in a duct using a Thermal Anemometer"², specifies 4 to 20 sampling points, depending on the size of the duct.

Tests conducted at the U.S. Army Construction Engineering Research Laboratory (UACERL) evaluating sensor density of traverses and various airflow measuring devices, concluded that low sensor density probes (3 sensors in a 22" x 40" duct) resulted in the same accuracy as a 35 point traverse measurement⁴.

Thermal Dispersion Devices

The manufacturer determined the optimum number of independent thermal sensors required for accurate measurement in a series of laboratory tests. Early airflow measuring devices of this type provided up to 4 sensors per square foot, in accordance with previous ASHRAE guidelines. That sensor density would yield an installed accuracy of $\pm 2\%$ when installed in accordance to factory guidelines. Practical considerations suggested that a decrease of installed accuracy by 50% to $\pm 3\%$ would result in adequate performance for installations requiring precise measurement of airflow rates. The following guidelines were developed from laboratory testing and field experience for precision airflow applications. The guidelines are based on duct size and are the sensor density provided with specific airflow measurement system models:

Ducts and plenums:	
Area (sq.ft.)	# Sensors
<=1	2
>1 to <4	4
4 to <8	6
8 to <12	8
12 to <16	12
>=16	16

Performance under a variety of duct locations can be found in the Placement Test Summary section of this document.

In many cases, such as with fan tracking applications, repeatability, linearity and turndown are more important than installed accuracy. Reduced sensor density devices are available at a lower price. For applications requiring an installed accuracy $\pm 6\%$ or better, a model with a lower sensor density will result in satisfactory performance. A more economical model with a fixed total of 4-sensors per unit, will result in an installed accuracy of $\pm 10\%$ or better. In many cases, these lesser sensor density devices can be adjusted in the field and result in excellent performance with the same long term stability as the precision model with the highest sensor density. Similarly, fan inlet devices using this technology provide repeatability, linearity and turndown with lesser-installed accuracy. Variability in the fan inlet, including the existence of disturbances (belt-guards, bearing housings, etc.) and inlet entry conditions (proximity of walls and partitions) generally results in an installed accuracy of $\pm 10\%$ and require field adjustment. For fan tracking applications, adjustments are simple and require that intake and exhaust dampers are closed with the recirculation damper in the full open position. Either one station or readings from an air balance contractor are used as a reference and a correction factor for the unit(s) to be adjusted is calculated.

Pitot Tubes and Arrays

Professional TAB contractors traverse a duct and record individual readings. Each reading is determined by evaluating the equation $V = 4005 \cdot (\Delta P)^{0.5}$, where ΔP is measured as in.H₂O. This generalized relationship does not account for changes in air density due to changes in air temperature and pressure. The readings are added together and a final average airflow rate is determined. Taking multiple readings throughout the duct can compensate for changes in the velocity profile.

Pitot arrays, by definition, average the velocity profile before the airflow rate is determined. The arithmetic difference between individual methods can result in a significant error in airflow measurement. Manufacturers of Pitot arrays boast high sensor densities and suggest that the sensor density of devices using independent sensors, is inadequate. On the contrary, Pitot arrays are only single sensor devices (the pressure transducer) using multiple pickup points and have far less sensor density than devices that have true, independent sensors. The differences can be easily demonstrated both theoretically (figure 3) and in laboratory testing (see: Placement Test Summary).

Placement Test Summary

Various duct configurations were setup in the research laboratory. An Ebtron model GTx116-PC probe was used as the thermal dispersion device. The GTx116-PC was configured based on catalog recommendations of 2 probes, 3 sensors each, for a total of 6 sensing points. A leading manufacturer's averaging Pitot was used with an MKS Baratron, 0.05% of reading, industrial pressure sensor and transmitter. The Pitot array was configured as 2 probes, 7 pickup points each, for a total of 14 pickup points as recommended by the manufacturer for the duct size being evaluated. The following summary is indicative of tests conducted in the lab.

Elbow Tests

A duct system was constructed using 24" x 24" galvanized duct. 18 feet of straight duct was connected to a transition from a backward inclined centrifugal fan. At the end of the straight portion of duct, a 90-degree elbow was installed. An additional 8 feet of straight duct was connected to the elbow. A reference point was selected at a position 11 feet downstream of the transition from the fan.

The fan speed was maintained at nominal velocities of 250, 500, 1000, 1500, and 1750 FPM using a variable speed drive. Each airflow measuring device was placed at the reference position and measurements were recorded using a Fluke Helios datalogger. Without changing the speed of the fan, each airflow measuring device was positioned at a number of points up and downstream of the elbow. Each device was evaluated against its own reference point measurement. Composite data is used in all summary figures.

Both devices performed well when turning vanes were installed (Figure A). However, there was a significant difference in performance in the absence of turning vanes (Figure B). The maximum uncertainty of the thermal dispersion device was 10% while the Pitot array exceeded 50%.

A similar test was setup for return duct analysis. Since turning vanes are not routinely installed in return ducts, the test was conducted in the absence of turning vanes. Once again a similar difference in performance was measured (Figure C).

The elbow test clearly demonstrates that the thermal dispersion probe with 6 independent sensors outperformed the averaging Pitot array with 14 pickup points close to the elbow. Most of the error of the Pitot array can be explained by the inequality shown in figure 3.

Another test was run downstream of the transition from the fan. Data is summarized in Figure D and once again demonstrates superior performance of the independent sensing thermal dispersion probe.

Although locations could have been selected where the Pitot array performed well, it is critical to recognize that this test was based on a single disturbance only. Actual HVAC environments have considerably more variable conditions. As a result, designers should select an airflow measuring device that can perform under difficult conditions. Minimum placement requirements cannot always be achieved in “real-world” systems and installing contractors do not always place devices where designers intended.

An additional test was conducted to determine the performance characteristics of both devices near an intake damper. Each device was installed upstream of an opposed blade damper. The damper was connected to a plenum, which was connected to a wind tunnel. The damper was positioned at 100%, 75%, 50%, and 25% of stroke to determine “damper interaction”. Results are shown in Figure E and demonstrate that the thermal dispersion device was not influenced by the velocity profile upstream of the damper. On the other hand, the Pitot array was unable to produce reliable measurements.

CALIBRATED ACCURACY OF THE SENSOR(S)

Thermal Dispersion Devices

Each thermal dispersion sensor is comprised of two, hermetically sealed “bead-in-glass” thermistor probes. One thermistor probe measures the ambient air temperature and the other is “self-heated” and measures the power dissipated to the air stream. Resistance/temperature data is carefully collected in precision constant temperature baths and serialized tracking. The two thermistor probes are mounted in a housing to make an individual “sensor”. Each individual “sensor” is calibrated in a wind tunnel at 15 velocities, starting from still air, between 0 and 5,000 FPM (0 and 10,000 FPM on fan inlet sensors). The calibration reference standard used by the production wind tunnel is sent annually to the National Institute of Standards and Technology (NIST) where it undergoes tests in the facility’s low speed and high-speed wind tunnels. The uncertainty of the production calibration is better than $\pm 2\%$ of reading.

Pitot Tube Arrays

Pitot arrays rely on the physical relationship between differential pressure and velocity. Their calibration factor, K, is generally assumed to be unity (1). However, in practice, the calibration factor is rarely equal to 1. The factor is variable, and a function of the Reynolds number, Re, which is expressed as

$$Re = Vd/\nu$$

where V is the velocity, d is the diameter of the Pitot tube, and ν is the kinematic viscosity.

Therefore, using a single calibration factor (common for commercial HVAC devices) will result in error in measurement as the airflow rate varies. They are normally “calibrated” in the field and referenced to a duct traverse with hand-held instruments or some other secondary source.

Nonetheless, Pitot tube arrays can demonstrate accuracies of $\pm 2\%$ (not including the pressure transducer), when compared to laboratory test tunnels having very “flat” velocity profiles with sufficiently high Reynolds numbers (i.e. $V > 600$ FPM).

CALIBRATED ACCURACY OF THE TRANSMITTER OR TRANSDUCER

The published sensor accuracy of the thermal dispersion device to the host controls includes the error of the transmitter. Because the accuracy of the differential pressure output of the Pitot arrays is stated separately from the pressure transducer, the combined accuracy of the two devices is often misinterpreted. In most cases, the pressure transducer is the greatest source of error when using Pitot tubes and arrays. Understanding transmitter and transducer error is critical when selecting an airflow-measuring device for an application.

Thermal Dispersion Devices

All transmitters required with this technology use state-of-the-art microprocessor based designs. Voltages from individual sensors are multiplexed and converted to binary with precision analog-to-digital (A/D) converters. The binary signals are then processed through a proprietary algorithm to calculate the airflow rate and temperature of each sensor using precision floating-point math routines. Individual airflow rates (and temperatures) are averaged for a final output to the host controls. A typical sensor will exhibit a 1.5 volt change between 0 and 400 FPM. The electronics can resolve that voltage to approximately 0.002 volts. As a result, transmitter error is negligible. The bottom line is that devices are “percent of reading” throughout the entire calibrated range. Neither the maximum or minimum airflow rates affect the selection and performance of the device.

Pitot Arrays

The accuracy (and cost) of pressure transducers varies widely. All pressure transducers used for commercial HVAC applications have their accuracy stated as a “percent of natural span”. Therefore, a pressure transducer with a span of 0 to 1 in.H₂O with an accuracy of 1%, will have an uncertainty of 0.01 in.H₂O throughout the entire range of the sensor. Because the relationship of airflow to differential pressure is a square root function, the uncertainty of the pressure transducer results in significantly greater and greater “per cent of reading” errors as the airflow rate is turned down (figure 4).

The maximum uncertainty for pressure transducers having published accuracies of 1%, 0.5%, 0.25%, and 0.1% are indicated in Tables 1, 2, 3, and 4 respectively. When reviewing the tables, recognize that the “natural span” of a pressure transducer cannot be changed and the “usable” full scale of the device should be selected at no greater than 90% of the natural span. For example, an application having a maximum velocity of 2,000 FPM should select a pressure transducer with a natural span of 0 to 0.5 in.H₂O. If the minimum velocity to be measured was 500 FPM, the potential error from the transducer and a 2% of reading Pitot tube would be 18% with a 1% transducer, 10% with a 0.5% transducer, 6% with a 0.25% transducer and 3.6% with a 0.1% transducer. Remember, these uncertainties do not include the errors of an averaging Pitot array that may result from velocity profiles. Many return ducts (and fan inlets) have significant airflow turndown since the outside airflow rate is generally a constant. In addition, outside air intakes with an airside economizer can also experience significant turndown if a separate, minimum outside air damper is not installed. Therefore, great care should be given to the selection and application of Pitot arrays and transducers.

High performance, “percent of reading” industrial pressure transducers are available but their cost (usually in excess of \$5,000) makes their application in HVAC environment not practical.

EFFECT OF PLACEMENT OF THE SENSOR PROBE WITH RESPECT TO THE VELOCITY VECTOR PLANE (ROTATION EFFECT)

Whether or not an airflow measuring device is influenced by rotation with respect to the velocity vector plane depends on the installing contractors' ability to properly install the airflow measuring device. Wind tunnel tests evaluated thermal dispersion probes and averaging Pitot probes. Each probe used its properly aligned position for an initial reference measurement. Measurements were taken at 5° increments between 0° (reference position) and 30°. Results are shown in figure 5.

CONCLUSIONS

Designers must understand the true “apples to apples” comparison when selecting airflow measuring devices that utilize different technologies.

Thermal dispersion devices have been designed to measure accurately under turbulent conditions created by up and downstream duct disturbances. Differential pressure based Pitot tubes and arrays require longer straight duct runs than the thermal dispersion devices tested as a result of a smaller signal-to-noise ratio.

Disturbances have a dramatic effect on the duct velocity profile. The velocity profile requires that multiple points be measured to produce an accurate airflow rate. Permanently mounted devices have fewer systematic and random errors than field measurement and can produce more reliable measurement with fewer sampling points. Thermal dispersion devices independently determine the airflow rate at each measurement point prior to averaging. Pitot arrays average nonlinear velocity pressure signals from multiple pickup points. Averaging errors exceed those of devices using independent sensors, even when the number of pickup points far exceeds that of the independent sensing device.

Each thermal dispersion sensor is wind tunnel calibrated at 15 points against reference standards that are regularly verified by NIST. Pitot arrays use a single flow coefficient and assume that the calibration factor is unity throughout the entire airflow range.

Thermal dispersion transmitters use microprocessor-based designs with high accuracy A/D converters to measure sensor voltages. All algorithms are processed using floating-point math routines. As a result, the transmitter adds negligible error to the measurement. Pitot tube array performance is significantly influenced by the accuracy of the pressure transducer, which is typically a “percent of full scale”. The square root relationship between velocity and velocity pressure requires extreme caution by the designer when selecting pressure transducer accuracy and span. Useable turndown is limited by the transducer accuracy.

Based on additional laboratory tests it was determined that thermal dispersion probes can withstand greater rotation in the duct than probe-type Pitot arrays, although both devices should be installed as close to parallel to the airflow vector plane as possible.

Over the past several decades, the requirement for HVAC airflow measurement has changed. Pitot arrays have dominated the industry since their inception and have influenced the perception of the engineering community about the limitations and reliability of airflow measurement instruments. Thermal dispersion devices provide design engineers with a versatile option that can be competitive with Pitot array systems.

References

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- ⁶ ANSI/ASHRAE. Standard 111-1988 -- Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning, and Refrigeration Systems. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA

figure 1

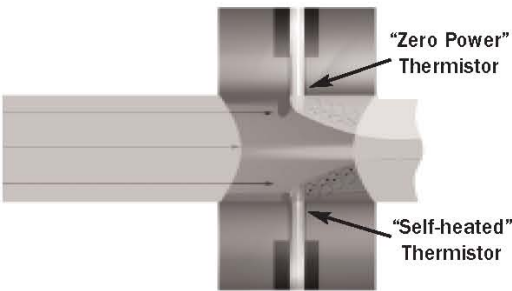


figure 2

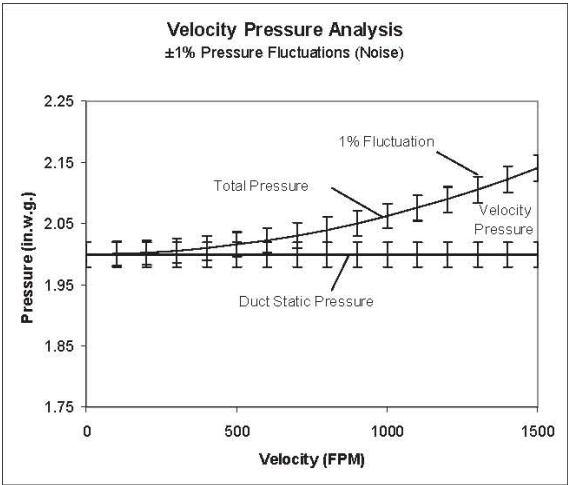


figure 3

$$\frac{\sqrt{P_{V_1}}}{n} + \frac{\sqrt{P_{V_1}}}{n} + \dots + \frac{\sqrt{P_{V_n}}}{n} \neq \sqrt{\frac{P_{V_1} + P_{V_2} + \dots + P_{V_n}}{n}}$$

figure 4

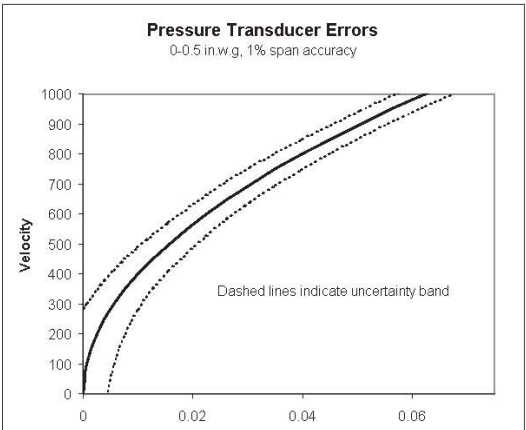
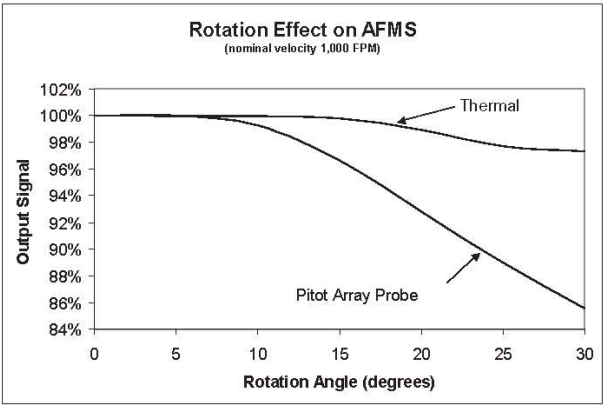


figure 5



Placement Test in 24" x24" Test Tunnel

THERMAL DISPERSION
2 Probes x 4 Sensors per probe

PITOT TUBE ARRAY
2 Probes x 7 Pickup Points per probe

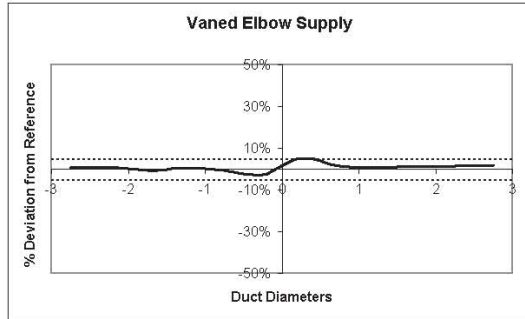


Fig. A

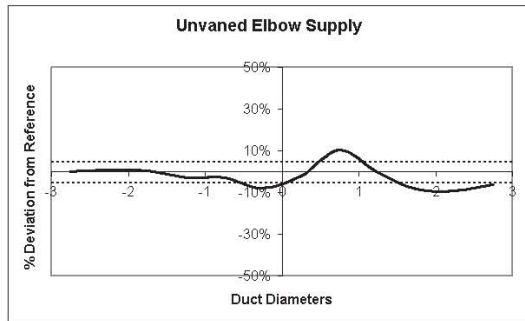
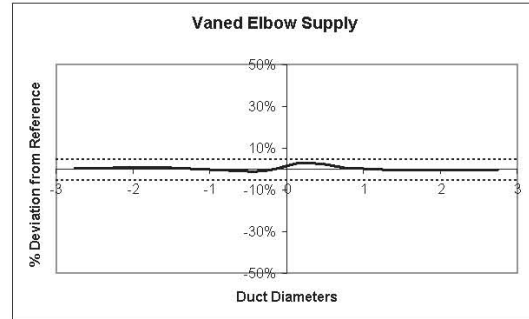


Fig. B

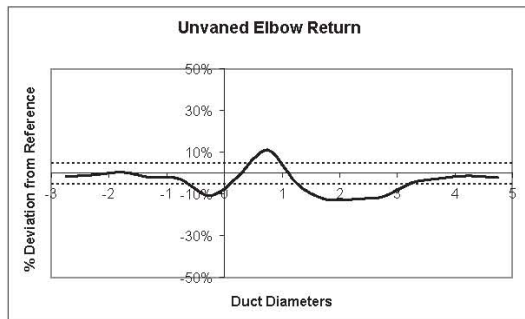
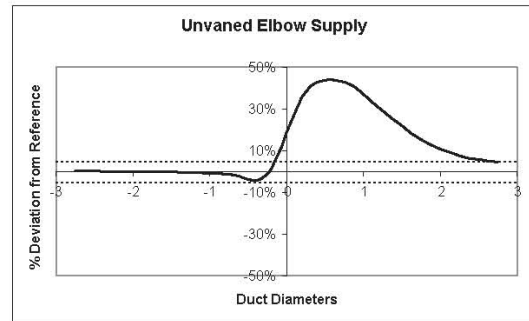


Fig. C

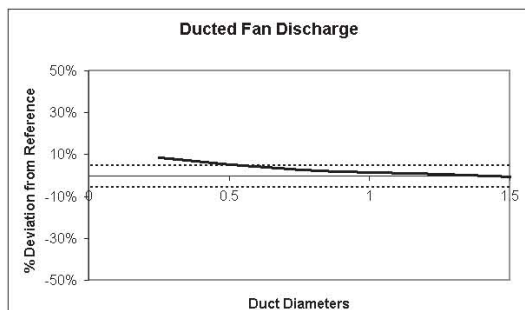
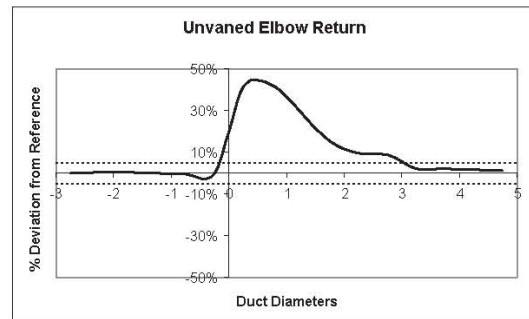
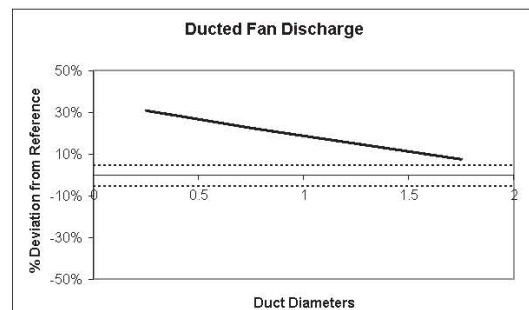


Fig. D



Placement Test in 24" x24" Test Tunnel

THERMAL DISPERSION

2 Probes x 4 Sensors per probe

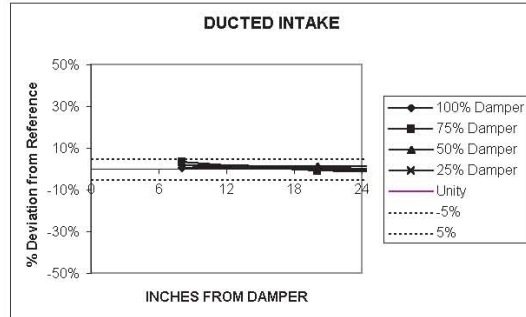
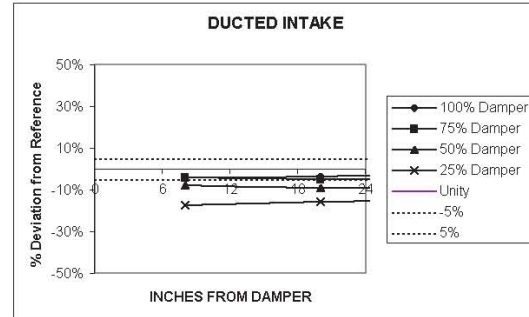


Fig. E

PITOT TUBE ARRAY

2 Probes x 7 Pickup Points per probe



Combined Uncertainty of a Laboratory Pitot Array and Transducer

Error DOES NOT INCLUDE averaging errors of Pitot arrays

Assumed accuracy of Pitot array is 2% of reading

Table 1 - 0.1% Span Accuracy

Natural Span	F.S. FPM	Airflow Rate Across Array						
		10,000	5,000	2,500	1,000	500	250	100
10	12,665	2.1%	2.3%	3.3%	10%	36%	159%	402%
5	8,955		2.2%	2.6%	6.0%	18%	104%	285%
2	5,663		2.1%	2.3%	3.6%	8.4%	29%	179%
1	4,005			2.1%	2.8%	5.2%	15%	122%
0.5	2,831			2.1%	2.4%	3.6%	8.4%	47%
0.25	2,003				2.2%	2.8%	5.2%	22%
0.10	1,266				2.1%	2.3%	3.3%	10%
0.05	895					2.2%	2.6%	6.0%

Table 2 - 0.25% Span Accuracy

Natural Span	F.S. FPM	Airflow Rate Across Array						
		10,000	5,000	2,500	1,000	500	250	100
10	12,665	2.2%	2.8%	5.2%	22%	122%	255%	635%
5	8,955		2.4%	3.6%	12%	47%	179%	450%
2	5,663		2.2%	2.6%	6.0%	18%	104%	285%
1	4,005			2.3%	4.0%	10%	96%	201%
0.5	2,831			2.2%	3.0%	6.0%	18%	139%
0.25	2,003				2.5%	4.0%	10%	75%
0.10	1,266				2.2%	2.8%	5.2%	22%
0.05	895					2.4%	3.6%	12%

Combined Uncertainty of a Laboratory Pitot Array and Transducer

Error DOES NOT INCLUDE averaging errors of Pitot arrays

Assumed accuracy of Pitot array is 2% of reading

Table 3 - 0.5% Span Accuracy

Natural Span	F.S. FPM	Airflow Rate Across Array						
		10,000	5,000	2,500	1,000	500	250	100
10	12,665	2.4%	3.6%	8.4%	47%	179%	360%	898%
5	8,955		2.8%	5.2%	22%	122%	255%	635%
2	5,663		2.3%	3.3%	10%	36%	159%	402%
1	4,005			2.6%	6.0%	18%	104%	285%
0.5	2,831			2.3%	4.0%	10%	36%	201%
0.25	2,003				3.0%	6.0%	18%	139%
0.10	1,266				2.4%	3.6%	8.4%	47%
0.05	895					2.8%	5.2%	22%

Table 4 - 1.0% Span Accuracy

Natural Span	F.S. FPM	Airflow Rate Across Array						
		10,000	5,000	2,500	1,000	500	250	100
10	12,665	2.8%	5.2%	15%	122%	255%	509%	1268%
5	8,955		3.6%	8.4%	47%	179%	360%	898%
2	5,663		2.6%	4.6%	18%	104.2%	227%	568%
1	4,005			3.3%	10%	36%	159%	402%
0.5	2,831			2.6%	6.0%	18%	104%	285%
0.25	2,003				4.0%	10%	36%	201%
0.10	1,266				2.8%	5.2%	15%	122%
0.05	895					3.6%	8.4%	47%