Airflow control is important to assure proper air change requirements, space pressurization, and personal safety. However, airflow measurement devices are often misapplied because they are not widely understood. This article seeks to provide the technical understanding needed to select and apply them properly in a pharmaceutical setting.

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Airflow Measurement and Control in Pharmaceutical HVAC Applications

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Introduction

The performance of HVAC systems in GMP manufacturing, drug discovery, and animal facilities can be improved by applying permanently installed measurement devices to monitor airflow volumes. Problems related to maintaining and balancing air flow rates for purposes of satisfying air change requirements and space pressurization are solved with volumetric airflow control. Integration of measurement devices with Direct Digital Controls (DDC) allows for the continuous control of air volumes, alarming of failures, and the automatic trending of flow data and alarm histories.

While they offer many benefits, engineers often shy away from active airflow control because the measuring devices are considered temperamental. The perception that measuring and controlling airflow is difficult is tied to the fact that it is one of the least understood areas of HVAC control, and therefore equipment and control strategies are very often misapplied. Once application issues are understood, the design, installation, commissioning, validating, and maintenance of the airflow control devices are no longer problematic and the pharmaceutical user can realize the significant benefits they offer.

Types of Devices Available

For some significant reasons, measuring air flow volume in ductwork is different than measuring flow in pipes. Ducts tend to be larger, most often rectangular, and their paths are far more contorted than their piping system counterparts. While it is usually easy to get the requisite "straight runs" of pipe for flow measurement, getting the same with ductwork is difficult. This difference is accentuated by the fact that air in an HVAC system is transported at duct pressures very close to atmospheric pressure and is highly compressible. These conditions produce a great degree of profile distortion and turbulence which must be accounted for in both the design and application of the measurement device.

Most airflow measuring devices offered commercially today are descendents of the pitot traverse methods used manually for balancing HVAC system air volume. The manual determination of air volume requires acquiring multiple point velocity readings across the face of a duct, perpendicular to the airflow direction. These readings are then summed to determine the average face velocity and then multiplied by the area of the duct to find the total volume of flowing air. Single point velocity measurement commonly used in pipes is not appropriate be-

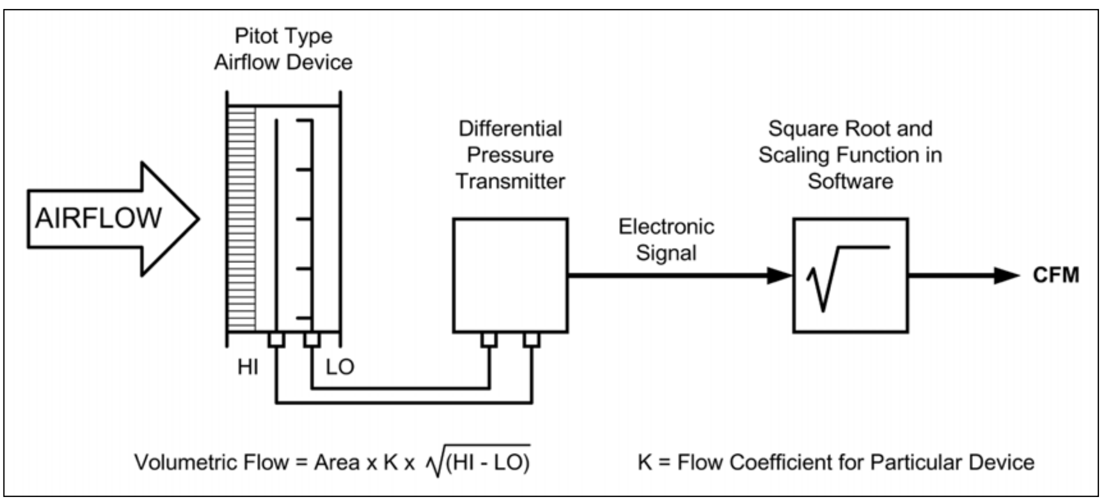

Figure 1. Elements of a Pitot airflow measuring device.

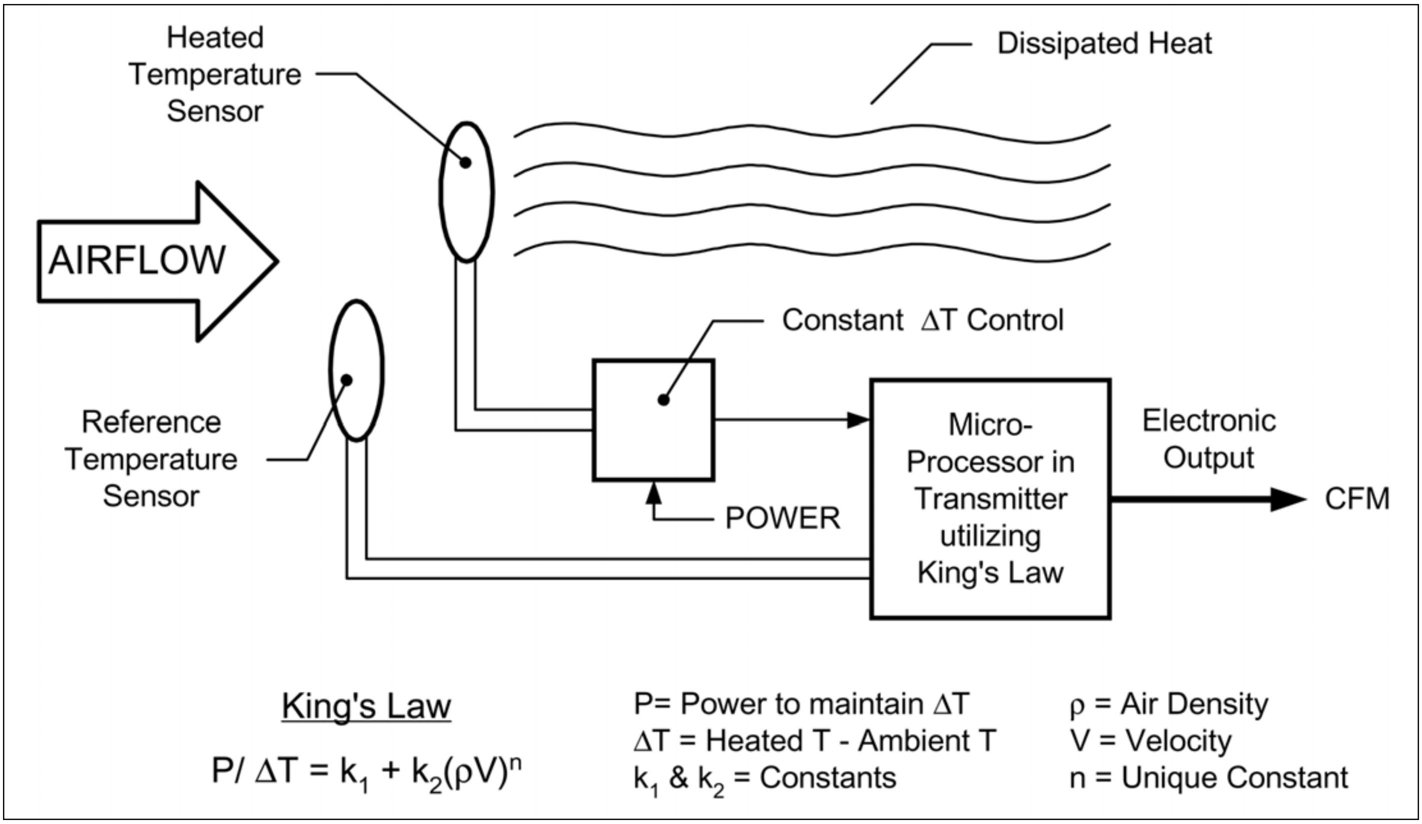

Figure 2. Principle of operation, thermal velocity sensor.

cause the sufficient straight runs required to create a uniform flow profile over a wide range of flow conditions are rarely available in HVAC ductwork. Unlike gas flow measurements in pipes, HVAC air flow need not be pressure or temperature compensated because conditions are so close to the standard conditions of 14.67 psia (1 bar) and 68ºF (20ºC).

Three predominant technologies are used for continuous flow measurement in ducts; differential pressure producers, vortex shedding devices, and thermal anemometers. For reasons associated with technical difficulty and high cost, ultrasonic technologies based on time of flight and Doppler shift have not proven commercially viable for airflow measurement in HVAC ducts. As offered for service in all, but the smallest HVAC ductwork, commercially available units for each technology come in multipoint velocity averaging configurations with electronic output signals that are compatible with most DDC systems.

Differential producing units utilize an array of high and low pressure tubes with holes drilled strategically along the length of the tubes to traverse the duct face - *Figure 1*. The high pressure tube array has holes drilled on the side facing into the airflow and they sense total pressure which is the static pressure in the duct plus the velocity pressure created by the pressure of air impacting the holes. The method of generating the low pressure varies depending on the specific manufacturer, but the most common method has holes drilled at 90° to the airflow direction so as to only sense the static pressure component. The difference between the high and low pressures sensed is indicative of the flow volume or velocity. The analog value of the pressure developed is measured by a transducer and fed electronically to a control system where duct area and a flow constant are multiplied by the square root of the differential pressure to calculate the flow volume.

Vortex shedding devices use an array of individual sensors arranged across the face of the ductwork to sense point velocities. Each sensor includes a trapezoidal “shedder” element which creates eddy currents or vortices as the air moves over it - *Figure 2*. As eddies alternately form and shed from the sides of the shedder, they create pressure “pulses” which are directly proportional to the velocity of the air. Transducers sense the pressure fluctuation frequency from individual shedders. Companion electronics convert the multiple sensor frequencies to velocities which are averaged and scaled before being sent to the DDC system as an electronic output signal.

Like the vortex shedding devices, thermal anemometer systems utilize an array of sensors to measure point velocities. Each sensor incorporates two temperature sensors, each with a known relationship between electrical resistance and surface temperature - *Figure 3*. One sensor measures duct air temperature while the other has a current applied sufficient to hold it at a fixed temperature differential above duct temperature; usually 50°F (27°C). The amount of current required to hold the differential temperature is measured and used in a formula utilizing King’s law to determine the point velocity. The electronics then average the point velocities to determine the average velocity through the unit and hence the volume.

The duct mounted elements in the differential pressure and vortex shedding devices fit the definition of a “primary element” because they convert air velocity to a more easily measured physical property; differential pressure in the case of the former and pressure pulse frequency for the later. The accompanying secondary elements which are transducers measure these quantities and convert them into an electronic signal. Thermal devices utilize active elements which measure the velocity directly. The performance characteristic of individual thermal sensors must be quantified at the factory and programmed into the electronics.

The benefit of a primary-secondary type of device is that the performance of the duct mounted primary is a function of the geometry of the sensor which is fixed and will not change over time unless mechanically altered; in essence, the primary calibration can not "drift." Technically, from the standpoint of calibration, the user need only be concerned with maintaining the calibration of the companion transducer. The maintenance requirements of each type of device are largely a function of the condition of the air flowing in the duct. Because they stagnate the velocity at the point of impact, total pressure holes on differential pressure devices tend to collect dirt if the air stream is fouled or water if the air is saturated. Likewise, any build up of dirt on the surface of thermal sensors or water mist in the air will change the heat transfer characteristic of the sensors adversely affecting the accuracy. Vortex shedding sensors will be more robust in this regard, but may eventually foul if subjected to sticky particulates that are common in coating pan exhaust flows. In these applications, provisions should be made to facilitate removal for periodic cleaning which should not damage either of the three sensor types.

Table A presents the performance characteristics of each technology although products from individual manufacturers may vary.

Selection and Sizing of Devices

Several important application issues must be understood and evaluated before selecting and sizing a device. These are the expected maximum and minimum controlled flow rates, airborne contaminants, and installation limitations. Duct pressure and air temperature need only be considered if they exceed what is normally encountered in HVAC systems. The designer must be very realistic about defining the application requirements first and then selecting the device to match. Yet to be invented is the perfect measurement device, capable of meeting every application, so proper selection is the key to success.

The maximum controlled flow rate defines the upper range of the volumetric flow that is required by the application and correspondingly the lower is defined by the minimum. Note that zero flow does not constitute a minimum, even though the system may achieve it when either the fan is off or the damper is closed. Both the minimum and maximum flow volumes should be converted by calculation into flow velocity at the point of measurement because the limits of operation for duct airflow devices are set by velocity, not volume. The turndown ratio is the maximum flow expected divided by the minimum, and is important because some flow measurement technologies provide wider turndown than others.

Many pharmaceutical exhaust applications have corrosive fumes, condensing moisture, hair, dander, or agglomerating particulates so the expected level of contamination must be considered. Contamination may eliminate some technologies as well as determine the appropriate materials of construction. Combustibles present in either the measured air stream or the air surrounding the accompanying electronic instrument will drive the need for either intrinsic safety or explosion proof construction.

Devices should be sized based on the application requirements first, and the designer's specified duct size last. The fact is that most application problems result when either the measurement device or accompanying control damper is blindly selected to match the duct; an error routinely made when using airflow measurement and control devices in ductwork with coils and filters which require low face velocities. Over-sizing forces the flow measurement device and control dampers to operate at the bottom fringe of their performance range. Once this error is committed, the only solution is to replace the device and a section of duct in the field with a smaller one. By comparison, the first cost of duct transitions is small, smaller area flow devices are less costly, and the resulting increase in system pressure loss is mostly recoverable.

Locating Devices

All commercially available airflow measurement devices are affected by duct conditions up and downstream of the device. While commercially available devices are designed to handle the twists and turns in the ductwork, extremes create turbulence which degrades the performance of the device. Each manufacturer offers suggestions for mounting limitations in the form of a "Minimum Installation Requirement Guide;" however, these should be taken for worst case guidance only. The designer must realize that the recommendations typically show only one duct disturbance producing mechanism located either up or downstream of the device, and in only one plane. The reality is that in the typical ducting system there are multiple turbulence producing mechanisms, which exist both before and after the device, and in three planes. Therefore, the designer should try to achieve the best possible locations based on the space constraints at hand and not just focus on achieving the minimums. The locations should be reviewed again when sheet metal shop drawings are received because it is common for the contractor to change locations to minimize fabrication costs.

Keeping in mind that turbulence is the principal cause of device inaccuracy, using the following rules will keep the designer out of trouble. First, strive to keep the minimum flow velocities above 500 fpm (2.5 mps). Turbulence and flow profile distortions are more prevalent at low velocities. Second, avoid locations close to the discharge of obstructions in the ductwork such as humidifier grids, smoke detector tubes, etc. Use common sense when assessing these.

Third, avoid locations where air is decompressing such as at the discharge of a fan or damper, after elbows, and after expanding transitions upstream of filters and coils. In these locations, air velocity is dropping and physics dictates that the kinetic energy associated with the higher velocity must be transferred so much of it goes to turbulence. One of the most common yet easily avoidable mistakes is to locate the airflow sensor after the control damper rather than before. Control engineers do this intuitively because in most control applications, the sensor must come after the adjusting device; as is the case with a temperature sensor and a heating coil. As the airflow volume entering a flow sensor and damper is the same

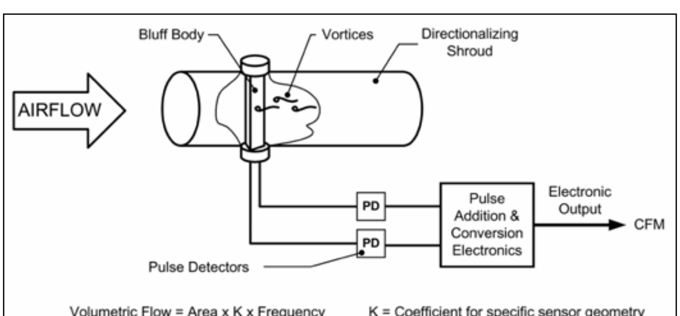

Figure 3. Principle of operation, vortex shedding sensor.

Capability	Pitot with Transducer	Vortex Shedding	Thermal
Inherent Sensor Curve	Square Root	Linear	Power
Velocity Range Ultra Low; <350 fpm (1.75 mps) Low; 350 to 750 fpm (1.75 to 4.0 mps) Mid Range; 750 to 5000 fpm (4 to 25 mps) High; >5000 fpm (25 mps)	 Poor Fair Excellent Good	 Poor Good Excellent Good	 Excellent Excellent Good Fair
Secondary Device affecting system accuracy?	Pressure Transducer	None	None
Usable Turndown	4 to 1	15 to 1	10 to 1
Performance in various flow streams Clean air High moisture, non-condensing High moisture, condensing Corrosive vapors (w/compatible materials) Particulates, Powder, Dander, Animal Hair	 Excellent Good Poor Good Fair to Poor	 Excellent Good Good Good Good	 Excellent Good Poor Fair Fair to Poor
Complexity	Simple	Moderate	Moderate
Bench Calibration Method	Pressure Source	Frequency Generator	Air Velocity Source
Field Calibration Method	Duct Traverse	Duct Traverse	Duct Traverse
Relative Cost based on small duct and galvanized construction. Pitot will be highest if stainless steel.	Lowest	25% more than Pitot	25% more than Pitot

Table A. Airflow measurement device performance.

as what exits, this is neither necessary nor advisable. Dampers create tremendous turbulence, and therefore flow devices should be mounted upstream of them.

The majority of pharmaceutical applications are for zone control and this translates to relatively small flow volumes and ductwork. The smaller size means comparatively short lengths of up and downstream ductwork are needed to create workable duct locations which are better than the minimums required by the manufacturers.

Presented in Figure 4 is an installation detail for an optimal flow station installation in an application which must be validated. The layout includes a reduction in duct area which serves to both increase the velocity and compress the flow. Just as decompression is to be avoided, compressing the airflow actually improves the performance of the station and reduces the need for straight runs of ductwork. The detail also includes a straight run section ahead of the flow device to allow manual traverse readings for validation purposes.

The installation of a section of three inch (7.5 cm) deep by half inch (one cm) diameter cell flow straightener is inexpensive and advisable in most supply and clean exhaust applications. While it does not modify the velocity profile across the duct face, straightener does reduce turbulence and directionalizes flow so it is parallel to the walls of the duct. Flow straightener is available in a frame from flow device manufacturers and while not absolutely required, it significantly quiets both the device and traverse measurements. For maintenance reasons, straightener should not be used in applications with particles or corrosive fumes.

Device Accuracy

Customer expectations for accuracy are often tighter than reasonably achievable in the field which creates a variety of unintended problems. The first reason is the tendency to specify the datasheet or reference accuracy of the flow measurement device; most commonly plus or minus two percent of reading. The second is the misconception that manual field measurement verification techniques can produce check accuracies of the same order of magnitude as the flow device.

The wide size and volume variations of duct airflow devices adds to the difficulty of obtaining traceable bulk airflow measurements. NIST calibration services for bulk air (gas) volume measurements limit meter size to a maximum of eight inch diameter and so achieving traceability is most often accomplished by referencing to traceable air speed instrumentation. An alternate method utilizes flow nozzles with known pressure drop characteristics and traceable differential pressure measurement instrument.

Up until recently, there have been no uniform standards for airflow measuring device manufacturers to rate their products. Most manufacturers determined the reference accuracy by testing one size sample in what can only be described as perfect conditions. These reference conditions produce optimal inlet conditions and repeatable results, but being devoid of the twists and turns found in the typical ducting system, rarely reflect the installed performance the user can expect to achieve in the field.

The majority of testing standards often referenced for the determination of airflow volumes are for either lab use or manual field duct traverses. These include the ACGIH method,[1] ASHRAE standards 41.2-1987,[2] and 111-1988[3] as well as ISO standard 3966.[4] In the mid 90s, in an attempt to harmonize the test methods and achieve some accuracy rating stability, a test standard was developed by the Air Movement and Control Association International (AMCA) specifically for permanently mounted airflow measurement devices. The AMCA standard was subsequently adopted by ANSI in 1997 as an American National Standard and became ANSI/AMCA 610-95.[5]

AMCA/ANSI 610-95 suggests testing results for one size are not scalable, and therefore should be conducted on a wide variety of small to large sizes. The AMCA test method utilizes three different configurations or "Figures" as shown in Figure 5. AMCA Figure 1 is essentially a reference condition with no up or downstream obstructions. Figure 2 tests a flow station after an elbow and Figure 3 tests the flow station located before a modulating damper. It should be said that when specifying datasheet accuracy, most manufacturers list only the Figure 1 accuracy determination which yields the best accuracy and is consistent with the pre-AMCA datasheet accuracy. Accuracy derived from Figures 2 and 3 will typically not be as good, but should be requested as the data is more indicative of field conditions.

When evaluating device accuracy for a specific application, the designer should calculate the total measurement system accuracy in terms of a percent of reading at the minimum and maximum flow readings. With differential pressure producing measurement systems this is complicated because the accuracy of the primary device is usually expressed in percent of reading while the transducer is expressed in percent of full scale. To determine the transducer accuracy, it must be converted from the plus and minus pressure reading at a specific flow to the corresponding plus or minus flow volume - *Figure 6.* This is then used to determine the transducer accuracy as a percent of flow reading. The total measurement accuracy is then determined by calculating the square root of the sum of the squares of the individual device accuracies.

Rules of thumb, while having some basis in science, typically evolve based on experience and such rules can be stated for airflow measurement devices in typical applications. When devices are properly sized and located, minimum velocities are kept above 500 fpm (2.5 mps), and turn down requirements are within those specified for each of the devices, achieving an installed accuracy of ±5% of reading is within reason. The extent to which accuracies will deviate when turn down or low velocity limits are pushed will vary based on the particular type of device technology.

Field Verification

The installed performance of airflow measuring devices should always be verified in the field by manual traverse techniques, even if the application will not be validated. The obvious reasons for doing so are to confirm that the device is calibrated correctly and the corresponding input to the control system is properly scaled. However, the most significant reason for doing so is to account for what might be termed the "system effect." While a commonly used term for describing why an installed fan does not achieve specified performance, the "system effect" phenomenon is also applicable to airflow devices.

Simply put, because of the individual nature of twists and turns in the ductwork in each application, in very few cases will the output from the flow device line up exactly with the verification by airflow traverse. In fact, discrepancies of up to ten percent may be observed. However, if the airflow measurement device has been properly sized and located, repeatability will be excellent and the deviation can be corrected with confidence.

The question then becomes, what should be corrected: the calibration of the flow device or the scaling in the controller receiving the flow signal? Surely either method is acceptable, but it is the writer's opinion that the adjustment of the flow calibration factor in the controller is the best place to make this adjustment. By doing so, calibration of the flow device remains traceable to the factory and calibration of the controller remains linked to the device location in the field. If the flow measurement device must ever be repaired or replaced the manufacturer is likely to ship a unit calibrated to the original standard. When installed and connected to the controller with the location specific calibration factor, the device will work accurately. Of course, any such adjustments should be noted in the calibration records for the device so a record exists of what the correction was and why it was made.

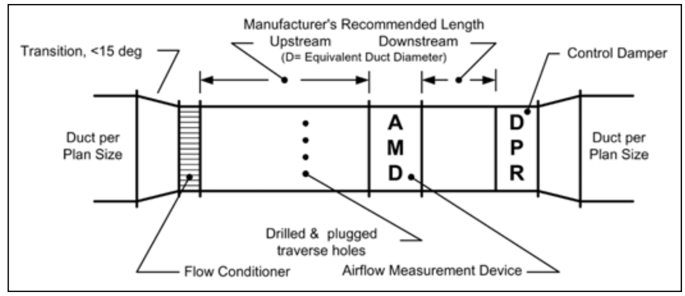

Figure 4. Flow station installation detail.

The accuracy of the field testing and calibration is subject to the methods and equipment used as well as the technique of the individual taking the manual readings. With regard to rectangular ducts, there had been significant controversy[6] as to which method of point placement is more accurate, the equal area method or more complicated logarithmic Tchebycheff method. Published comparison testing of the two methods[7] would indicate the selection of the traverse location has more to do with the accuracy achieved than the method used.

Individual pharmaceutical companies should standardize on one of the previously referenced field testing standards. The procedure dictated by that standard should be clearly defined in an SOP and used without shortcuts. Finding good locations at which to perform the traverse is critical to achieving accurate readings. The suggested installation detail in Figure 4 includes a location for traverse readings to eliminate this variable.

Point velocity measurements are typically made with either a pitot tube and electronic manometer, or a portable thermal anemometer. Modern instruments include a wide variety of convenience features including automatic conversion of pitot pressures to flow velocity and multi-point averaging. Some also will allow the entry of the duct size so the test instrument will automatically display volume. The author would suggest not using this feature, having witnessed on more than one occasion the wrong duct area being inadvertently entered. Record the average velocity and duct area separately, then perform the math to obtain duct volume. While requiring an extra step, this provides the ability to retrace how a device was calibrated should a question ever arise. Recording individual traverse points is also of value because the data helps to understand the velocity profile which is needed to evaluate questionable measurements.

Even with the proper standardized procedures in place, it is likely that two individuals using the same test equipment in the same traverse location will get different results. This is attributable to the differences in the handling of the equipment. Still, when an accepted procedure is used, traverse locations are good, quality test and measurement equipment is used, and the technician is careful; accuracies of ±5% should be achievable by field traverse. Of course, these accuracies will degrade quickly if either of the key ingredients is left out.

Many test and balance contractors will utilize an alternative device called a capture hood to determine flow. A capture hood determines the volume supplied or exhausted to the room through individual registers, grilles, or diffusers. Readings from all devices served by the duct with the airflow measurement device must be summed to determine the flow through the duct. Capture hood readings are easier to make than multi-point duct traverse because they can be made from within the room and fewer individual readings are generally required.

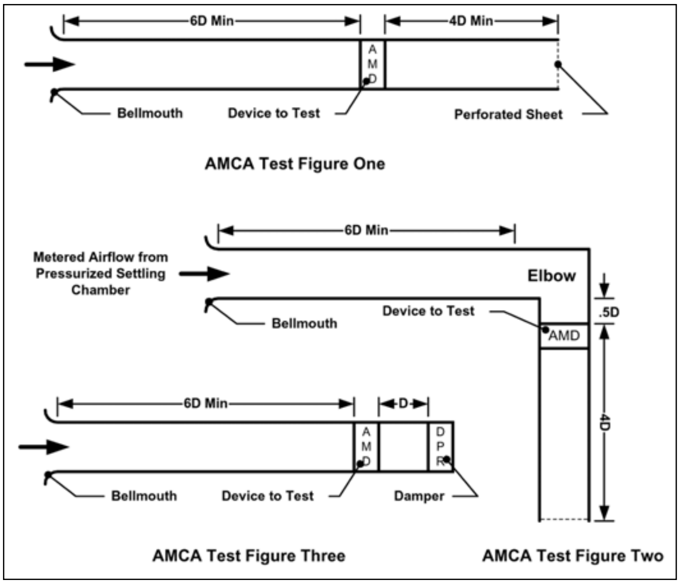

Figure 5. AMCA test configurations.

The author would warn against using capture hoods unless good traverse readings are impossible to obtain. The capture method is particularly problematic because hoods are inherently less accurate, do not seal tightly to the diffusers, and will not account for leakage in the duct between the flow measurement device and the room. Furthermore, at the end of a long day of taking capture hood measurements, it is not uncommon for the test and balance technician to omit one or more diffusers, or add in diffusers which are served by another duct. While using capture hoods to measure exhaust flows is a common practice, published reports[8] of errors in excess of 25% at low flows give reason to believe results obtained with this technique should be scrutinized carefully.

When comparing the results of a duct traverse with the output of a flow device, one must not become carried away with attempting to get the devices to match perfectly. Given the previously explained expectation of achievable accuracies of ±5% of reading for both the installed device and the test traverse, RSS analysis indicates it is possible for the difference between readings to be 7% apart, yet the actual flow to be equal. This is because the reading from each device is within its tolerance envelope. The author would suggest that if the readings are within the combined tolerance envelope for both the installed and test devices, no corrections should be made. Successive calibrations will only serve to frustrate those involved in the process without an improvement in the end result.

If the readings are outside of this tolerance, the traverse and associated math should be questioned first, then the controller scaling, and finally the flow measurement device. Many a device has been needlessly adjusted because of traverse errors, equipment problems (like cracks in the pressure tubing), or an error in measuring the duct dimensions which caused the area to be incorrect.

Using Airflow Measurements for Closed Loop Control

Oftentimes complaints about the stability of airflow control loops and the resultant "hunting" are incorrectly attributed to the measurement device. Unlike the control of temperature, which is a relatively slow process given that heating and cooling coils have thermal inertia, airflow changes almost instantaneously when a damper is moved. The speed makes tuning quite simple and dictates low proportional gains with fast integration rates. Derivative control is not used for airflow in HVAC systems. Instability is most often caused by using temperature control tuning constants for flow control.

Other factors which can contribute to control loop instability are dead-band (a.k.a. slop) in damper linkages or slow damper actuator speeds. Electric damper actuators tend to be slower than their pneumatic counterparts, but this should not be a problem (unless the process dictates a high speed as with fume hood control) if the integration rate is properly matched to the actuator speed. The same is true of pneumatic damper actuators because of the time required to pump up or bleed down the air volume contained in the control lines or the actuator itself. Using a high capacity electronic to pneumatic converter (I/P) may not solve the problem if the connecting line is long and highly restricted. Placing the I/P at the damper will help with this problem. Pneumatic piston actuators should have wide spring ranges and pilot positioners are strongly recommended. Following these rules and understanding the nature of the problems can prevent many hours of tuning frustration and headaches.

Flow control loops should never be used in series within the same ductwork system and this mistake is made often. A common example is to measure and control the individual flows to zones served by an air-handler, as well as the total air-handler flow by modulating fan speed with a variable speed drive. It is inevitable that the supply fan flow loop will conflict with the zones, resulting in instability. It is better to let the fan capacity be controlled by static pressure so that controls can match the fan speed to the inlet duct pressure requirements of the zone flow controls. Properly setup and tuned, a change in flow at one or more zones should never destabilize control at any other zone, or at the fan static pressure controller.

Other Flow Devices

A special type of flow measurement device is available which is designed for mounting in the inlet of a fan. Fan inlet probes have become a common problem solver when it is impossible to find good flow measurement locations in the ducting system. Probes are installed in the inlet of a fan and take advantage of the compression that occurs in the inlet bell which improves flow profile.

While they work well, the author feels fan inlet sensors should be used as a fall back and not the device of first choice. This is because fan inlet probes induce turbulence into the inlet of the fan, and therefore can negatively affect fan performance. While this impact may be negligible on a fan with a large inlet or low inlet velocities, it becomes significant if the fan is small or inlet velocities start exceeding 5000 fpm (25 mps).

The correlation between the factory calibration and field readings with fan inlet probes is less predictable than duct probes and dependent on the inlet conditions at the fan. Factors such as inlet duct configurations, belt guard placement, and distance to the air-handler walls can have a significant effect on the "out of the box" accuracy. While the readings are repeatable, calibration corrections as great as 25% are not uncommon.

Finally, there is a class of flow control devices which do not measure flow, but because of their wide use merit discussion. Not to be confused with venturi type differential producing flow meters, venturi valves are self-contained volumetric flow regulators. Much like the ubiquitous pressure regulators found throughout most facilities, venturi valves rely on a spring controlled force balance mechanism to control the flow volume at a specific setting. The specific flow setting is determined by the positioning of an external lever which is done either manually by a balancing technician or automatically by an electro pneumatic positioner.

Venturi valves do not inherently measure flow, although they can be purchased with what is called a "flow feedback signal." However, this signal is an electronic prediction of what the flow should be given the specific lever position; not what it actually is. In applications where the flow must be known to the operator or recorded for batch records, the author would suggest that the flow be measured by an independent flow sensor of the types discussed previously.

Conclusion

When properly selected, sized, installed, and applied, permanently installed air flow measurement and control equipment can be incorporated into a control system with a minimum amount of problems. The knowledge offered in this article will set the user and designer on the path to using airflow devices in pharmaceutical applications with success. More importantly, the benefits of controlling air change rates and flow balances for safety, product quality, and space pressurization can be realized.

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About the Author

Ken Kolkebeck is President of Facility Diagnostics and has spent nearly 30 years in the control field, most of it in the specialized area of controls for critical ventilation systems. For 15 years, Kolkebeck served as president of Tek-Air Systems, a company he founded that manufactures air flow and fume hood control equipment. Kolkebeck holds a BS in electrical engineering from Worcester Polytechnic Institute, Worcester, MA and has several patents awarded and pending for air flow measuring devices. He is the developer of two generations of systems for laboratory and fume hood air flow control. A past chairman of the Air Movement and Control Association's Air Flow Measurement Station Division, Kolkebeck also was a co-author and Review Committee Chairman for the ANSI/AMCA Air flow Measurement Device Test Standard 610-95. He is also a member of ISPE and ASHRAE.

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Actual Volume	Velocity Pressure	Pressure Transmitter Low Vel. Pressure	Pressure Transmitter High Vel. Pressure	CFM Reading Lowest	CFM Reading Highest	Error in CFM Lowest	Error in CFM Highest
CFM	inches wc.	inches wc.	inches wc.	CFM	CFM	%	%
2,000	0.2500	0.2475	0.2525	1,991	2,011	-0.43%	0.57%
1,000	0.0625	0.0600	0.0650	981	1,021	-1.95%	2.06%
500	0.0156	0.0131	0.0181	459	539	-8.28%	7.78%

Transmitter Range: 0-.25" wc (0-62.28 Pa) Accuracy: +/- 1% Full Scale or +/-0.0025" wc.

Basis: One square foot duct with velocity pressure producing differential flow sensor.
Only pressure transducer component is considered.

Figure 6. Converting pressure transducer accuracy to flow accuracy.

Concludes on page 58.