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The Systematic and Random Errors of Portable Airflow Balancing Instrumentation with Various Ventilation System Fittings

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ABSTRACT

This paper presents and compares the results of a test program to determine the systematic and random errors of airflow instrumentation used in field balancing. The random errors determined apply to the instrument and its application on various fittings. Five instruments were tested on five different ventilation system fittings.

Test results show that each type of fitting requires a laboratory-developed correction factor for use with each instrument, with the exception of the collector, which can utilize a single factor for diffusers. The largest corrections, or "K-factors," were required for the velometer and deflecting vane anemometers when used on diffusers. Test results with diffusers mounted on two different types of elbows showed no difference in the K-factor. All instruments demonstrated precision or random error of ±1% to ±5 1/2% of reading for 1 1/2 standard deviations.

INTRODUCTION

Experience and judgment are the basis for determining the best instrumentation to use for airflow measurements in the field. Little is known about the random (or precision) error of individual instruments when applied to different field situations. An important consideration in testing and balancing is the overall accuracy of airflow measurements and the resulting quality of the system airflow balance. Therefore, a more thorough understanding of instrument errors, their order of magnitude, and causes, is required.

This paper discusses random and systematic (accuracy) error* test data for five selected field instruments on five common ventilation system fittings. The random error data are of greater significance since generalizations about the instruments tested may be applied to similar test fittings. The systematic error is limited to the specific fittings and instruments tested. This paper describes in some detail the types of instruments and fittings tested and the techniques used. Obviously, the systematic and random errors are dependent on these considerations.

The major errors encountered in field airflow measurements are instrument systematic error, instrument random error, and errors associated with how the instruments are applied to a particular case and how the results are interpreted. Systematic error refers to the consistent amount that an instrument's indicated value deviates from the true value.

*Random error: a statistical error that is wholly due to chance and does not recur. Systematic error: a persistent error that cannot be considered entirely due to chance (definitions per ASHRAE Handbook - 1981 Fundamentals, chapter 13).

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Systematic error can be eliminated with a correction curve or by calibration. Errors associated with the technique of using the instrument can be minimized with proper instruction, training, and application of accurate fitting correction factors. Random error, sometimes referred to as precision error, gives inconsistent results and causes readings to take random values on either side of a mean value. Random error data are reduced statistically and can be defined in statistical terms such as "mean value" and "standard deviation," whereas systematic error cannot. Random error is associated with the precision or repeatability of results of an instrument. In this paper, random error is a composite value containing other additional and inseparable factors. The random error due only to the instrument arises from such things as bearing roll, spring hysteresis, stickiness, friction, backlash, and slop. In addition, there is a repeatability factor or random error associated with contingencies in the particular application and fitting being tested. Such contingencies result, for example, from the skewed velocity profile associated with bends upstream of a fitting or "jetting" effects associated with aspirating diffusers. These additional variables, which alter the measurements, are not found when determining the instruments' random error in a laboratory wind tunnel. There is also the random error caused by the operator trying to mentally average the readings of an unsteady indicator, or the time factors associated with human reflexes when starting or stopping a timed measurement, and the overall measuring technique used.

The objective of these tests was to determine both the systematic error and random error of portable airflow instrumentation for shipboard field measurements. From the calculated systematic errors, average application or fitting "K-factors" were determined for various supply and return outlets and inlet fittings normally encountered during shipboard system balancing. These K-factors apply to particular shipboard ventilation system diffusers and fitting designs. Therefore, they may have very limited application elsewhere. The factors are presented primarily for comparison and discussion. For field airflow measurements and balancing, it is the responsibility of the balancing activity to obtain or determine the appropriate fitting factors.

In field applications, the largest errors introduced into airflow measurements are probably due to inconsistency in instrument use and measuring technique and the misapplication of correction factors. The investigation of these errors is beyond the scope of this paper but warrants consideration for future papers.

The random error test results are perhaps of greater importance in this report, since they are applicable to instruments and their general applications rather than to specific applications. The random error is much more difficult to determine then the systematic error, since it involves a statistical analysis. The random error is also that which is added to other field measurement errors and will most likely be one of the major errors, assuming every possible effort has been made to use the proper technique and accurately calibrate the instrument.

AIRFLOW MEASUREMENT ERROR INVESTIGATIONS

F. C. Hayes and W. F. Stoecker (1965, 1966a, b) selected a rotating vane anemometer, deflecting vane anemometer, thermal anemometer, and a variable airflow meter as representative of commercially available portable field instruments to determine airflow measurement accuracies at supply outlets and return intakes. Their findings indicated that for return intakes, all instruments required a calibration curve to account for systematic error and that the random error was within 2% of full scale at one standard deviation or ±3% at 1 1/2 standard deviations. The random error was established in a laboratory wind tunnel. Therefore, the error determined is attributed solely to the instrument's repeatability. They recognized that different instruments, when used on different return intake grilles or registers, yielded different correction factors. Tables of K-factors for return intakes were laboratory determined and further adjusted by grille manufacturers' tests. With this degree of refinement, they said, "flow measurements within 10% should be possible in most cases." Also, extensive measurements were made with a single 10-inch-round ceiling diffuser mounted on a square elbow, with and without an upstream damper, and compared to the diffuser mounted at the end of a straight duct. They found that considerable error (up to 51%) in flow measurements resulted when conditions at the diffuser were different from those for which the application factors were obtained.

Davies (1930) selected the rotating vane anemometer (RVA) as the most practical instrument for field airflow measurements through grilles and registers. He determined the systematic error for the RVA using various measuring techniques and methods of calculating flow rates through both supply and exhaust grilles. The grilles used in his tests were square punched grilles with various ratios of "free areas". His recommended method for determining flow rates for supply grilles mounted on both the end of the straight duct and an elbow was to hold the RVA against the grille and calculate the flow rate using an average of gross and net free area. For exhaust applications, the RVA was also held against the grille and the gross area was used for calculating the airflow rate. Current grille designs may differ. Therefore, more recent application factors should be used where available.

INSTRUMENTS SELECTED

Six instruments were selected for testing. The criteria were: portability, suitability for field use, durability, accuracy, and availability. The six instruments chosen were:

Rotating vane anemometer (RVA)

Deflecting vane anemometers (DVA)

Type 1: Swinging vane velometer

Type 2: Bridled vane anemometer with scoop

Type 3: Bridled vane anemometer without scoop

Collector with variable airflow meter

Hot wire anemometer

Rotating Vane Anemometer (RVA)

The standard rotating vane anemometer consists of a propeller or revolving vane connected through a gear train to a set of recording dials that read the linear feet of air passing in a measured length of time. It is made in various sizes. The most common are: 3 in (80 mm), 4 in (100 mm), and 6 in (150 mm). The 4-in size was tested.

This instrument requires frequent calibration and the use of a calibration curve to determine actual velocity. The instrument may be used for either supply or exhaust measurements when the necessary correction factors are applied to the readings. The standard instrument has a useful range of 200-3000 ft/min (1 m/s to 15 m/s); specially built models can measure lower velocities. In most instances, the RVA should be mounted on an extension handle and operated by one person dedicated to just controlling and positioning the anemometer. The mechanism should be allowed to come up to speed before actuating the counter. A multipoint traverse is made of the face of most fittings where airflow is being measured; traverse points should be no wider than 1 1/2 times the diameter of the anemometer. A continuous, timed traverse is entirely acceptable for field measurements, instead of a start-stop-record sequence for each traverse point, where the anemometer is held stationary for 30 seconds to one minute and then moved to the next point without stopping the counter or the timer. Total anemometer counts and total time are then used to calculate the average airflow. The orientation of the anemometer to the airflow and to the fitting face where airflow is measured is extremely important. The positioning must be done in a consistent and specified manner in order for correction factors to be applicable to subsequent measurements. For diffusers, the RVA is oriented perpendicular to the airflow at each traverse point to obtain the maximum instrument spin rate. For the screened outlet, the RVA is held flush against the screen as a continuous traverse is made and is stopped at each traverse point for 30 seconds. The technique used for the wire mesh filter requires that the RVA be turned to face the filter so that airflow entering the filter rotates the RVA in the positive direction. The RVA is held flush against the filter and a shroud ring is added to protect the dial face. The total time to make the traverse must be measured by a second person using a calibrated stopwatch. He also records the data. A calibration or instrument correction curve is used to convert the indicated velocity, obtained by dividing the anemometer reading in feet by the total time in minutes to obtain actual velocity. Note: Since this instrument is sensitive to the manner in which it is used, the calibration procedure has an effect on the calibration curve and resulting airflow calculation. Therefore, the correction factors determined by this test apply only when the instrument is calibrated by the method used by our calibration facility.

The anemometer has widest application for exhaust openings and cooling coil faces but can be used on perforated ceilings, supply openings, and diffusers. The RVA was used on all the test fittings.

Deflecting Vane Anemometer (DVA)

General: This class of instrument includes swinging vane, pivoting vane, and bridled vane anemometers. With these instruments an airstream impinging on a movable vane causes it to deflect. The amount of deflection varies with the air flowing through the meter section of the instrument, which is a function of the pressure available at the instrument inlet fitting and the size and configuration of this inlet fitting. The DVA is a direct reading instrument that gives instantaneous readings of airflow velocity directly in feet per minute. Three types were tested:

Type 1: This instrument is a swinging vane anemometer commonly referred to as a velometer. The velometer consists of a meter and a variety of probes and tips that connect to the meter via range selectors, probe holders, and flexible tubing. The meter has five scales to select from depending on the application, tip, and range selector: 0-300 ft/min (0-1.5 m/s), 0-1200 ft/min (0-6 m/s), 0-2500 ft/min (0-12.5 m/s), 0-5000 ft/min (0-25 m/s), and 0-10,000 ft/min (0-50 m/s). Only two scales were required for this test: 2500 ft/min and 0-5000 ft/min. The probe selections cover a variety of applications. However, the only one tested was the diffuser probe designed specifically for air velocity measurements at the face of supply or exhaust diffusers or screened openings. This instrument was used on all test fittings. Detailed instructions for use of the velometer are provided with the instrument. Correction factors, which are normally provided by the fitting manufacturer, must be used for flow measurements at most terminals.

Type 2: This instrument is a compact, bridled vane anemometer fitted with a multivane rotor in an instrument housing with an inlet scoop. The scoop is designed to seat and ride on the vane edges of supply diffusers. The spring-opposed rotor deflection is proportional to the airstream velocity pressure. A scale lock permits retaining the reading. A magnetic dampening feature reduces scale fluctuations. The unit tested had an operating range of 0-2500 ft/min (0-12.5 m/s). Similar to the diffuser tip of the velometer, the scoop is positioned into the areas of highest velocity (vena contracta) of the diffuser airflow. Velocities at multiple positions on the diffuser are recorded and averaged. The number and locations of recorded velocities as well as application factors for each type and size are normally provided by the diffuser manufacturer. The type 2 DVA was tested only on supply diffusers.

Type 3: This is a similar anemometer to the type 2 DVA but without the inlet scoop. It is fitted with an extension handle for positioning directly in the airstream. This instrument was tested on the screened outlet and the wire mesh exhaust filter. Typical units come in ranges of 0-1000 ft/min (0-5 m/s) or 0-3000 ft/min (0-15 m/s). The instrument tested had a range of 0-3000 ft/min. It is used in the same manner as the RVA, except that the reading is nearly instantaneous as the instrument is held squarely in the airstream for a maximum of five seconds and the scale locked to hold the reading.

Collector

A collector consists of a converging hood designed to fit over a supply or exhaust fitting to capture and direct the total airflow through a metering box. The metering box is square with fixed cross-sectional area that can be easily traversed with any portable field instrument. The collector also can be procured with a built-in multipoint pressure-sensing rake. The data from a rake sensing average static pressure and from a rake sensing average total pressure can be read out with any portable differential pressure device, such as a liquid or an electronic manometer or a magnehelic (aneroid) pressure gage. A rake sensing only total pressure can be read out also with instruments such as a variable airflow meter or a specially adapted velometer. Collectors can be used for either supply or exhaust applications and are essentially independent of individual fitting and diffuser correction factors. An instrument correction curve proportional to the air velocity being measured must be applied because of the airflow resistance of the collector. The metering section of the collector tested contained airflow straighteners and a single total pressure rake. The average velocity pressure was read out on a variable airflow meter. Since the velocity measurements are made in a fixed, known cross-sectional area, the meter reads out directly in standard cubic feet per minute. Correction factors are already integrated. A typical unit has an operating range of 50-150 cfm (.25-.75 m/s), 50-500 cfm (.25-2.5 m/s), 150-300 cfm (.75-1.5 m/s), 300-600 cfm (1.5-3 m/s), 400-1000 cfm (2-5 m/s), and 800-2000 cfm (4-10 m/s). The unit tested had a range of 150-300 cfm. On some collectors, the metering section size has to be changed for a change in range. Other designs maintain the same size and utilize a multiscaled meter. The errors presented in this paper are for the collector and variable airflow meter combination.

Hot Wire Anemometer

This instrument is a direct-reading velocity meter that depends on the cooling effect of the airstream on an electrically heated coil to evaluate the flow. The higher the flow, the greater the temperature reduction of the coil and the higher the reading on the dial. This heated element is very sensitive to air motion and low velocities. One available instrument has a low range of 10 to 300 ft/min (.05 to 1.5 m/s). Because the unit is direct reading, there is no need to use a stopwatch when taking data. However, when traversing a fitting, it is necessary to log the instantaneous readings and then to average them to obtain a final result. The probe is generally small in diameter 0.25 in (635 mm) to 0.375 in (950 mm) and can be used for direct traversing as with the pitot tube and the velometer. Most of the instruments are battery operated. The slow depletion of the batteries can gradually change the calibration of the indication meter. Some units having replacement tips require recalibration when a tip is changed. During this test the tip was replaced several times but the instrument was not recalibrated, thereby invalidating the data.

Instrument Calibration

All instruments were calibrated by the appropriate manufacturer before the tests except for the RVA, which was calibrated at our own facility using a calibration setup different from the manufacturer's. This had an effect on the systematic error, but not on the random instrument error, which is the primary effect being investigated.

FITTINGS TESTED

Representative shipboard supply and exhaust fittings were chosen for testing. One-way, two-way, and four-way blow ceiling supply diffusers and a combination supply and return diffuser were selected. These were commercial aspirating-type diffuser fittings in the following sizes:

BLOW	SIZE	RANGE OF AIRFLOWS	RANGE OF NECK VELOCITIES
One-Way	6 in x 9 in (.15 m x .23 m)	150-300 scfm (.75-1.5 m/s)	400 - 800 ft/min (2 - 4 m/s)
Two-Way	6 in x 9 in (.15 m x .23 m)	150-300 scfm (.75-1.5 m/s)	400 - 800 ft/min (2 - 4 m/s)
Four-Way	6 in x 9 in (.15 m x .23 m)	150-300 scfm (.75-1.5 m/s)	400 - 800 ft/min (2 - 4 m/s)
Four-Way	9 in x 9 in (.23 m x .23 m)	150-300 scfm (.75-1.5 m/s)	267 - 533 ft/min (1.36 - 2.71 m/s)

One size, the 9 in x 9 in, four-way blow was tested attached to a standard 1 1/2 x diameter bend rectangular elbow and a cushion head to determine the comparative effect. The same diffuser was tested with and without a deflector mounted in the neck of the diffuser to determine the comparative effect of a disturbed air inlet to the diffuser versus an undisturbed inlet. Fitting correction factors were available for the type 1 DVA for diffusers and for the RVA for screened outlets and inlets. They were not used in the presentation of results. A comparison of the available fitting correction factors and the ones developed by test are offered in the discussion section.

A 7 1/2-in (.19 m) diameter screened outlet fitting is a movable shipboard fitting. It is used in hot machinery spaces for personnel comfort and is referred to as a "blast terminal" since velocities are normally higher than supply diffusers. Velocities range from 1700 ft/min to 2600 ft/min (8.5 m/s to 13 m/s). The screen consists of a 2-x-2 mesh wire cloth of .063-in (16-mm) diameter wire. Seventy-five percent of the net flow area was used for flow rate calculations.

The standard air return or exhaust screen filter is a wire mesh, dry impingement filter used for removal of course, airborne particulates such as lint, dust, and grease. This type of filter is used at shipboard inlets to exhaust systems, at all cooling coil inlets, and as pre-filters on charcoal and high efficiency filters. The filter tested had an outside frame dimension of 19.5 in x 19.5 in (.495 m x .495 m). For calculating airflows, the gross flow area of 2.3 ft^2 (.214 m^2) was used. The velocity range tested was 650 ft/min to 950 ft/min (3.25 m/s to 4.5 m/s).

TEST SETUP AND PROCEDURE

The test setup consisted of a centrifugal fan, a supply side duct, and exhaust side duct. All fittings were tested on the supply side or downstream side of the fan with the exception of the wire mesh filter, which was tested on the exhaust side or upstream side of the fan. Flow was regulated with bleed fittings on both the exhaust and supply ducts. Actual flow rates were measured using a 10-point horizontal and vertical duct traverse with a Pitot tube and micromanometer. A straight duct section 4 in (.1 m) in diameter and 20 diameters in length was used for the Pitot traverse station. The diffusers were mounted on a board to simulate a ceiling mount and connected to the test duct with either the 90° turn with cushion head or the 90° elbow turn.

In all, there were eight different setups, each representing a different fitting or a change from cushion head to elbow upstream of the fitting.

Procedure

For each setup the flow was varied from 150 to 300 cfm (71 to 142 L/s) in 50 cfm (23.6 L/s) increments. The actual flow rate was recorded using a Pitot traverse at the test measurement station before and after each set of readings. For the individual readings in the flow set, changes were monitored using the centerline velocity pressure. A data set consisted of 20 readings for each instrument at each airflow. Air temperature and pressure were recorded periodically to convert data to standard conditions. Each diffuser tested was permanently marked with the locations for velocity measurements recommended by the diffuser manufacturer. For diffusers, the instruments used were the DVA, types 1 and 2, RVA, and the collector. Measuring locations were generally 3-4 in (.08-.1 m) apart. A 9-in-x-9-in (.23 m x .23 m), four-way supply diffuser, for example, had a total of 16 measurement points. Eight were on the outer periphery, four on the periphery of the middle vane, and four on the periphery of the center vane. One velocity measurement using a DVA for the 9 in x 9 in diffuser consisted of recording the 16 velocities, averaging them to obtain a single value, and then repeating this 20 times to obtain a set. For the RVA, a moving traverse technique was used. The instrument was moved over the entire face of the diffuser for a timed interval of one minute to obtain a single integrated velocity. The collector, of course, yielded a single averaged airflow reading without traversing. This was repeated 20 times to obtain a set. Each instrument was tested before changing the airflow. The wire mesh filter was sectioned into six-inch squares and the center of each of the 16 squares was used as the velocity-measuring location for the RVA and types 1 and 3 DVA. With the RVA, a continuous traverse with 30-second stops at each of the traverse points was made. The screened outlet was tested with the RVA, and types 1 and 3 DVA. A one-minute moving traverse was made with all these instruments.

Note that the moving versus fixed traverse technique with the RVA had been investigated previously by Davies (1930) and Wilson (1978). There is little difference between the two techniques provided there is not a wide variation in velocity, that at least 30 seconds per station are used on a spot traverse, and that at least two minutes are devoted to the moving traverse for a grille area of two square feet.

DATA ANALYSIS AND DATA REDUCTION

The sets of repeated measurements form the basis for a statistical analysis. A data sample of 20 readings is considered a small sample per ASHRAE Standard 41.5-75. However, the technique used is considered to provide a fair approximation of a multisample experiment.

From the 20-point data sample the mean value, $\bar{x}'$, was calculated by taking a straight arithmetic average. One and one-half standard deviations, $1.5\sigma'$, were then calculated using the recommended small sample approximation (see Note 1). The random error, corresponding to $\pm 1.5\sigma'$, is presented as a percentage of the mean value of the indicated velocity or flow rate. The selection of one and one-half standard deviations was arbitrary and is based on the probability that 86.64% of all the readings lie within the calculated mean value $\pm 1.5\sigma'$. The random error data is easily converted to $\pm 2\sigma'$ (95.5 percentile) or $\pm 3\sigma'$ (99.7 percentile) by multiplying $\pm 1.5\sigma'$ values by 1.33 and 2, respectively.

The statistical "confidence" that the mean values calculated are the best estimates of the true mean can be determined by the method for small samples described in ASHRAE Standard 41.5 using 19 degrees of freedom and the "student t-distribution" factor. This is briefly discussed in the conclusion.

To calculate airflow rates, $\bar{x}'$ is multiplied by the applicable flow area and then corrected to standard conditions.

NOTE 1. $$\sigma' = \frac{1}{n-1}\left[\sum_{i=1}^{n}(x_i-\bar{x}')^2\right]^{\frac{1}{2}}$$

σ' = estimated standard deviation for a sample of 20

n = sample size = 20

x_i = individual readings in the set

$\bar{x}'$ = estimated mean value of readings in the set

Airflow rates are calculated by using the neck area data provided by the manufacturer for the diffuser, the gross area inside the frame opening for the wire mesh filter, and the net open area for the screened outlet. Calculated flow rates are normally then multiplied by the fitting manufacturer's "application" or "correction" factor, where available. However, factors were available only for a limited number of applications. Therefore, none were used in order to leave all systematic error data on a common basis. It is noted that leaving the instruments' indicated velocities, or flow rates, uncorrected has no effect on the determination of random or precision error, which is the primary item being evaluated.

The only instrument that required correction of the indicated values by a calibration correction curve was the RVA. It is common practice, when using this type of instrument, to correct the indicated reading to an actual reading, no matter what the application. A correction curve is provided by the manufacturer or the calibrating facility for each instrument.

RESULTS

Indicated versus actual diffuser neck velocities for the three DVAs and RVA have been plotted. Figures 1, 2, and 3 show the one-way, two-way, and four-way blow diffusers, respectively. Figures 4, 5, and 6 reflect the test results for the collector, the screened outlets, and the wire mesh filter, respectively. Average K-factors varying from .40 to 1.27 are delineated in table 1 for each instrument and fitting combination.

The calculated average random errors for each instrument and fitting combination tested are shown in table 2. The average random errors ranged from ±0.8% to ±5.4%, as shown in table 2A, for 1.5 standard deviations when calculated using the indicated velocity or airflow as the base. The average random errors using the instruments' full scales as the base ranged from ±0.4% to ±3.4%, as shown in table 2B.

DISCUSSION

Figures 1, 2, and 3 for diffusers reflect the comparative magnitude of the corrections required to adjust the instruments' readings. Table 1 delineates the systematic error in terms of an average correction factor, "K-factor." Table 1 also shows the straight line equations for all plotted data and the corresponding data correlation coefficients. Individual values of velocity, K-factors, and random error for each flow rate tested are contained in appendix A. From figures 1, 2, and 3 it can be seen that the plotted curves are linear, as verified by the high correlation coefficients for the straight line equations in table 1, and that the indicated velocities are higher than the actual velocities. The two DVAs have similar correction curves and much larger indicated velocities than the RVA. This is understandable since the DVAs measure only the maximum velocities in the diffusers "vena contractor." To obtain the most accurate results, each type and style of diffuser requires its own fitting correction factor. However, from table 1, an average correction factor of .44 for the three diffusers with a type 1 DVA could be used with a maximum of ±5% error.

The curves shown in figures 1, 2, and 3 are for diffusers mounted on elbows without a deflector. The corresponding data points for each instrument tested for the diffuser mounted on the cushion head and for the diffuser with the deflector are shown in figure 3. Curves for these data are not plotted because there was essentially no difference (less than 1%) between the test results with elbows and cushion heads and the test results with and without the deflector. The variations in velocity at the diffuser face imposed by differences in upstream duct configurations did not have an effect. This evidently is due to the averaging effect of reading multiple points, similarity in flow patterns at the traverse points selected, and no significant static pressures being generated at the diffuser face. These results are consistent with Davies' findings in which RVA air measurements at supply grilles mounted at the end of straight ducts were compared to mounting arrangements using elbows and branch ducts with adjustable splitters. However, as Hayes and Stoecker demonstrated, there are certain upstream conditions, which, for diffusers, will create significant static pressures and velocity profile distortions at the plane of measurement and which can introduce as much as a 51% difference when compared with a diffuser mounted at the end of a straight duct.

The correction and actual curves for the collector, the only instrument tested that provides actual airflow rate instead of velocity, are shown in figure 4 for all the fittings on which it was tested.

As can be seen in figure 4 and table 1, a single correction factor of .94 could be applied to this instrument's readings on any of the diffusers tested with a maximum error of ±2%. A correction factor greater than 1, because of the restricting effect of the collector on the airflow, would have seemed more likely. However, there is a negligible flow reduction at low velocities (less than 200 ft/min) and the .94 factor may be attributed to the systematic correction for the variable airflow meter readout.

The test results on the screened outlet using DVA types 1 and 3 and the RVA are shown in figure 5 and table 1. The DVAs read 7-12% low whereas the RVA reads 22% low. Davies' tests (1930) using the same technique on a grille with 72% free area (versus 75% free area for the screened outlet) and at much lower velocities (factor of 8) gave results with the RVA that were low by 13%.

The test results on the wire mesh filter using the DVA types 1 and 3 and the RVA are shown in figure 6 and table 1. All instruments had indicated velocities much higher than the actual, calculated velocities. This was partly due to the gross filter area being used in the calculations. Each DVA read about 86% high and the RVA about 32% high. The correction factors varied very little (±4%) throughout the velocity range tested for each of three instruments. It is assumed that the factor determined is applicable only to that particular filter design. This is consistent with Davies' findings for the RVA on exhaust grilles. He found that the correction factor changed with the type of grille, the percentage of free area, and the velocity. Davies proposed using a curve of K-factor average values versus air velocity, which introduces a possible error of 3-10%.

It can be seen in table 2 and appendix A that the random error varies with velocity. Therefore, the maximum as well as the average random errors appear in tables 2A and 2B. Appendix A delineates the specific error values at each airflow. The maximum error did not consistently occur at either the high or low velocities. The average random error is the best overall indicator of an instrument's suitability for a particular application. Referring to table 2 it can be seen that the random error was generally independent of the geometry and type of diffuser and the duct entrance geometry (i.e., elbow or cushion head). The magnitude of the percent average random error for diffusers, calculated on the instruments' full scales, varied from 0.4% to 2.7%. However, for velocity ranges of 400 to 800 ft/min (2 to 4 m/s) for diffusers, it makes a considerable difference as to the instruments' scale ranges. For example, table 2B shows that the random error of the RVA for full scale averages only 0.9% but an actual average of 3.3% random error in terms of readings (as shown in table 2A) was experienced because of the particular scale range of 200-3000 ft/min (1-15 m/s) for the instrument used.

The random errors for all the instruments were smaller when applied to the screened outlet. This may be due to the higher velocities (25-50% higher) with the screened outlet as compared to the diffusers, and a more consistent velocity profile.

On the wire mesh filter, the RVAs precision improved for this inlet application. It also improved on the outlet applications as compared to its performance on diffusers. However, the type 1 DVA performed noticeably worse - 3.4% average (full scale) for the exhaust filter versus an average of 2.3% for the three diffusers. The type 3 DVA did equally well on both the screened outlet and the filter, averaging 1.1% (full scale).

The correction factors delineated in table 1, which correlate to systematic error, vary depending on the instrument and the application, with the following exceptions:

a. A single correction factor for the collector applies to the three diffusers tested and should apply to any diffuser when neck velocities are 400-800 ft/min (2-4 m/s).

b. A single correction factor of .44 for the type 1 DVA applies to the three diffusers within 5% and could apply to any diffuser when flow rates are 150-300 cfm (71-142 L/s). This value is within 2% of the diffuser manufacturer's recommended K-factor.

The proper correction factors should be used in balancing work and should be determined either from the literature or by test. Potential errors as large as -22% or +156%, as demonstrated by the data herein, are possible if no correction factor is used.

The composite random errors shown in table 2 are or the same order of magnitude as previously reported instrument random errors (Hayes and Stoecker 1965, 1966a) of ±3% for 1 1/2 standard deviation. These errors consist of the instrument's random error combined with random errors associated with inconsistencies and anomalies of the test technique, fitting, and duct setup. The average random error values varied with the instrument, velocity, and fitting, but all fell within a 3% band; the high was 3.4% and the low was 0.4%. These values are within acceptable limits for field-measurement work but must not be neglected when specifying test or balancing tolerances and results.

Using the confidence estimating technique for small samples per ASHRAE Standard 41.5-75, it was determined with 95% confidence that for the sample size of 20 data points the calculated mean velocity and airflow values are within ±2% of the true mean values.

RECOMMENDATIONS

The primary goal of the HVAC industry should be to improve the overall accuracy of field airflow measurements in order to raise the quality of system airflow balances. To help achieve this goal, application or fitting correction factors should be more carefully applied. The type and manufacturer of the fittings, the duct inlet geometry of the fitting, the instrument being used, and the technique for using the instrument should be taken into consideration. Where specific application factors do not exist, they should be determined by carefully conducted laboratory tests. Because of the current uncertainty in field airflow balances and measurements, further investigations are warranted.

Random error, as a contributor to instrument and airflow measurement error, should be statistically determined in laboratory tests using statistical sampling methods, multiple instruments of each type, and different instrument readers. Tests should be performed for all common instruments being used for field measurements. The amount of random error of each instrument for specific velocity ranges, applications, or use techniques should be determined.

Specific calibration procedures should be prepared and adopted for each type of instrument to provide a consistent baseline for the application of fitting correction factors.

REFERENCES

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TABLE 1

Systematic Error

FITTING	INSTRUMENT	AVG. CORRECTION FACTOR (K)*	EQUATION OF STRAIGHT LINE	CORRELATION COEFFICIENT	SEE FIG. NO.
One-Way Blow Diffuser	DVA, Type I	.44	Y = 2.53X - 140.1	.998	1
	DVA, Type II	.40	Y = 2.65X - 76.1	.999	1
	RVA	.69	Y = 1.63X - 95.4	.999	1
	Collector	.94	Y = 1.15X - 16.5	1.00	4
Two-Way Blow Diffuser	DVA, Type I	.42	Y = 2.34X + 36.0	.999	2
	DVA, Type II	.42	Y = 2.42X - 13.5	.999	2
	RVA	.93	Y = 1.09X - 7.2	1.00	2
	Collector	.94	Y = 1.18X - 23.2	.996	4
Four-Way Blow Diffuser	DVA, Type I	.46	Y = 2.22X - 24.3	.998	3
	DVA, Type II	.49	Y = 2.04X + 1.9	1.00	3
	RVA	.95	Y = 1.16X - 57.3	.997	3
	Collector	.92	Y = .953X + 22.8	1.00	4
Screened Outlet	DVA, Type I	1.13	Y = .747X + 301.3	.916	5
	DVA, Type III	1.07	Y = .998X - 132.3	1.00	5
	RVA	1.27	Y = .711X + 163.3	1.00	5
Wire Mesh Filter	DVA, Type I	.54	Y = 1.54X + 253.5	.971	6
	DVA, Type III	.53	Y = 1.85X + 22.6	.999	6
	RVA	.76	Y = 1.29X + 26.5	.999	6

*Actual Velocity = K x Indicated Velocity
Actual Airflow Rate = K x Indicated Airflow Rate

TABLE 2

Random Error

TABLE 2A

Random Error — Percent of Reading

INSTRUMENT	FITTING									
	SUPPLY DIFFUSER						SCREENED OUTLET		WIRE MESH EXHAUST FILTER	
	One-Way Blow		Two-Way Blow		Four-Way Blow*					
	AVG.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.	MAX.
DVA, Type 1	±3.8%	±4.4%	±3.7%	±5.0%	±2.5%	±2.9%	±0.8%	±1.1%	±5.4%	±10.7%
DVA, Type 2	±1.3%	±1.8%	±0.9%	±1.3%	±0.9%	±1.2%	-	-	-	-
DVA, Type 3	-	-	-	-	-	-	±1.5%	±1.9%	±1.6%	±2.1%
RVA	±2.9%	±4.2%	±2.9%	±4.4%	±4.0%	±7.6%	±1.4%	±1.7%	±1.5%	±1.8%
COLLECTOR	±2.1%	±2.9%	±2.7%	±3.5%	±4.1%	±10.3%	-	-	-	-

* Average of the two four-way blow diffusers tested

TABLE 2B

Maximum Random Error - Percent of Full Scale

INSTRUMENT	INSTRUMENT FULL SCALE	FITTING									
		SUPPLY DIFFUSER						SCREENED OUTLET		WIRE MESH EXHAUST FILTER	
		ONE-WAY BLOW		TWO-WAY BLOW		FOUR-WAY BLOW					
		AVG.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.	MAX.
DVA, Type 1	0-1200 ft/min (0-6 m/s) 0-2500 ft/min (0-12.5 m/s)	±2.6%	±3.3%	±2.5%	±3.1%	±1.9%	±1.7%	±0.5%	±0.4%	±3.4%	±7.4%
DVA, Type 2	0-2500 ft/min (0-12.5 m/s)	±0.8%	±1.2%	±0.5%	±0.8%	±0.4%	±0.6%	-	-	-	-
DVA, Type 3	0-3000 ft/min (0-15 m/s)	-	-	-	-	-	-	±1.2%	±1.5%	±1.0%	±1.3%
RVA	0-3000 ft/min (0-15 m/s)	±1.1%	±1.3%	±0.7%	±0.8%	±0.9%	±1.3%	±0.9%	±1.2%	±0.6%	±0.7%
COLLECTOR	150-300 cfm (71-142 L/s)	±1.7%	±2.1%	±2.0%	±2.2%	±2.7%	±5.6%	-	-	-	-

* Average of the two four-way blow diffusers tested

APPENDIX A

Test Data Tabulation

FITTING	INSTRUMENT	VELOCITY - ft/min (m/s) INDICATED	ACTUAL *3	K FACTOR *1	RANDOM ERROR ±1.5σ ±% IND. VEL.	±% FULL SCALE
DIFFUSER — 1-WAY BLOW	DVA, TYPE 1	941(4.78)	423(2.15)	.45	3.5	2.7
		1244(6.32)	547(2.78)	.44	3.2	1.6
		1528(7.76)	671(3.41)	.44	4.2	2.6
		1885(9.57)	791(4.02)	.42	4.4	3.3
	DVA, TYPE 2	1024(5.20)	419(2.13)	.41	1.5	.61
		1383(7.02)	539(2.74)	.39	1.2	.64
		1671(8.49)	667(3.39)	.40	1.8	1.2
		2029(10.31)	791(4.02)	.39	1.0	.77
	COLLECTOR *2	159cfm(75 L/s)	153cfm(72.2 L/s)	.96	1.7	.90
		213cfm(101 L/s)	199cfm(93.9 L/s)	.93	2.9	2.1
		263cfm(124 L/s)	246cfm(116.0 L/s)	.94	2.2	1.9
		322cfm(152 L/s)	294cfm(138.7 L/s)	.91	1.7	1.8
	RVA	595(3.02)	422(2.14)	.71	3.0	.70
		780(3.96)	538(2.73)	.69	4.2	1.3
		980(4.98)	666(3.38)	.68	3.2	1.3
		1200(6.09)	792(4.02)	.66	1.5	.75
DIFFUSER — 2-WAY BLOW	DVA, TYPE 1	1018(5.17)	417(2.12)	.41	3.3	2.8
		1295(6.58)	544(2.76)	.42	3.9	2.0
		1588(8.07)	651(3.31)	.41	5.0	3.1
		1865(9.47)	783(3.98)	.42	2.8	2.1
	DVA, TYPE 2	1029(5.23)	422(2.14)	.41	1.3	.65
		1305(6.63)	548(2.78)	.42	.65	.34
		1596(8.07)	670(3.40)	.42	1.2	.77
		1915(9.47)	785(3.99)	.41	.50	.39
	COLLECTOR *2	164cfm(77 L/s)	154cfm(72.6 L/s)	.94	3.5	1.9
		205cfm(97 L/s)	200cfm(94.3 L/s)	.98	2.8	1.9
		258cfm(122 L/s)	242cfm(114.2 L/s)	.94	2.4	2.1
		325cfm(153 L/s)	292cfm(137.7 L/s)	.90	2.1	2.2
	RVA	450(2.29)	419(2.13)	.93	4.4	.82
		590(3.00)	543(2.76)	.92	2.1	.50
		720(3.66)	670(3.40)	.93	2.9	.84
		865(4.39)	796(4.04)	.92	2.1	.74
DIFFUSER — 4-WAY BLOW WITH ELBOW	DVA, TYPE 1	899(4.57)	414(2.10)	.46	3.0	2.2
		1151(5.85)	541(2.75)	.47	2.6	2.4
		1464(7.44)	659(3.35)	.45	2.9	1.7
		1748(8.88)	804(4.08)	.46	1.7	1.2
	DVA, TYPE 2	843(4.28)	413(2.10)	.49	1.2	.40
		1104(5.61)	540(2.75)	.49	.85	.38
		1345(6.83)	659(3.35)	.49	.58	.30
		1612(8.19)	790(4.01)	.49	.97	.63

APPENDIX A

Test Data Tabulation (Con't)

FITTING	INSTRUMENT	VELOCITY - ft/min (m/s) INDICATED	ACTUAL *3	K FACTOR *1	RANDOM ERROR ±1.5σ ±% IND. VEL.	±% FULL SCALE
	COLLECTOR *2	164cfm(78 L/s)	154cfm(73 L/s)	.94	10.3	5.6
		212cfm(100 L/s)	197cfm(93 L/s)	.93	2.7	1.9
		270cfm(127 L/s)	245cfm(116 L/s)	.91	1.9	1.7
		294cfm(157 L/s)	294cfm(139 L/s)	.89	1.6	1.7
DIFFUSER — 4-WAY BLOW WITH ELBOW CON'T	RVA	410(2.08)	414(2.10)	1.01	7.6	1.3
		580(2.95)	539(2.74)	.93	3.8	.90
		710(3.61)	660(3.35)	.93	2.3	.66
		860(4.37)	800(4.06)	.93	2.1	.75
DIFFUSER — 4-WAY BLOW WITH CUSHION HEAD	DVA, TYPE 1	884(4.49)	407(2.07)	.46	2.5	1.8
		1137(5.77)	534(2.71)	.47	1.8	1.7
		1397(7.10)	657(3.34)	.47	1.8	1.0
		1717(8.72)	807(4.10)	.47	2.2	1.5
	DVA, TYPE 2	841(4.27)	412(2.09)	.49	.8	.3
		1095(4.56)	537(2.73)	.49	1.0	.4
		1326(6.73)	663(3.37)	.50	.7	.3
		1583(8.04)	807(4.10)	.51	1.1	.7
	COLLECTOR *2	165cfm(78 L/s)	153cfm(72 L/s)	.93	3.7	2.0
		209cfm(99 L/s)	199cfm(94 L/s)	.96	2.8	1.9
		265cfm(125 L/s)	244cfm(115 L/s)	.92	2.2	1.9
		325cfm(153 L/s)	298cfm(141 L/s)	.92	2.2	2.3
	RVA	430(2.18)	413(2.16)	.96	2.0	.4
		570(2.90)	536(2.72)	.94	2.5	.6
		705(3.58)	663(3.37)	.94	3.6	1.0
		860(4.37)	800(4.10)	.94	1.8	.6
SCREENED OUTLET	DVA, TYPE 1	1594(8.10)	1765(8.96)	1.10	.9	.5
		1987(10.10)	2174(11.04)	1.09	1.1	.9
		2030(10.31)	2522(12.81)	1.24	1.0	.4
		2313(11.75)	2522(12.81)	1.09	.5	.2
	DVA, TYPE 3	1610(8.18)	1739(8.83)	1.08	1.0	.7
		2032(10.32)	2179(11.06)	1.07	1.9	1.5
		2474(12.55)	2604(13.23)	1.05	1.6	1.5
	RVA	1410(7.17)	1756(8.92)	1.25	1.5	.9
		1720(8.74)	2179(11.06)	1.27	1.7	1.2
		2020(10.26)	2613(13.27)	1.29	0.9	.8
WIRE MESH FILTER	DVA, TYPE 1	1251(6.35)	652(3.31)	.52	2.0	1.0
		1430(7.26)	745(3.78)	.52	4.6	2.6
		1498(7.61)	855(4.34)	.57	4.2	2.5
		1734(8.81)	941(4.78)	.54	10.7	7.4
	DVA, TYPE 3	1182(6.00	625(3.17)	.53	1.7	.8
		1395(7.09)	745(3.78)	.53	1.3	.7
		1611(8.18)	850(4.32)	.53	2.1	1.3
		1760(8.94)	941(4.78)	.53	1.5	1.0

APPENDIX A

Test Data Tabulation (Con't)

FITTING	INSTRUMENT	VELOCITY - ft/min (m/s) INDICATED	ACTUAL *3	K FACTOR *1	RANDOM ERROR ±1.5δ ±% IND. VEL.	±% FULL SCALE
WIRE MESH FILTER CONT'D	RVA	875(4.44)	654(3.32)	.75	1.8	0.6
		980(4.98)	741(3.77)	.76	1.6	0.7
		1125(5.71)	857(4.35)	.76	1.2	0.5
		1245(6.32)	939(4.77)	.75	1.3	0.7

* 1 Indicated Velocity x K = Actual Velocity
Indicated Flow Rate x K = Actual Flow Rate

* 2 The collector readout is cfm (L/s).

* 3 Actual velocity values are neck velocities for diffusers, velocity through the net area for the screened outlet, and velocity through the gross area for the wire mesh filter.

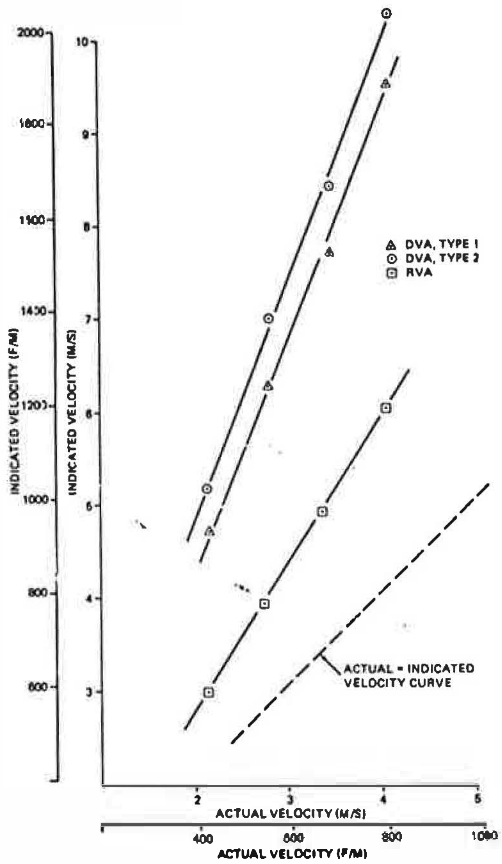

Figure 1. Instrument application correction curves for the one-way blow diffuser with elbow

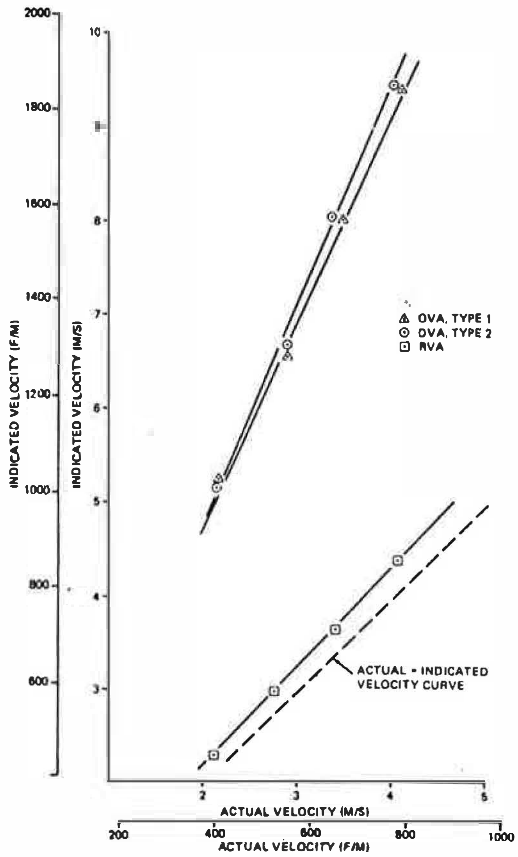

Figure 2. Instrument application correction curves for the two-way blow diffuser with elbow

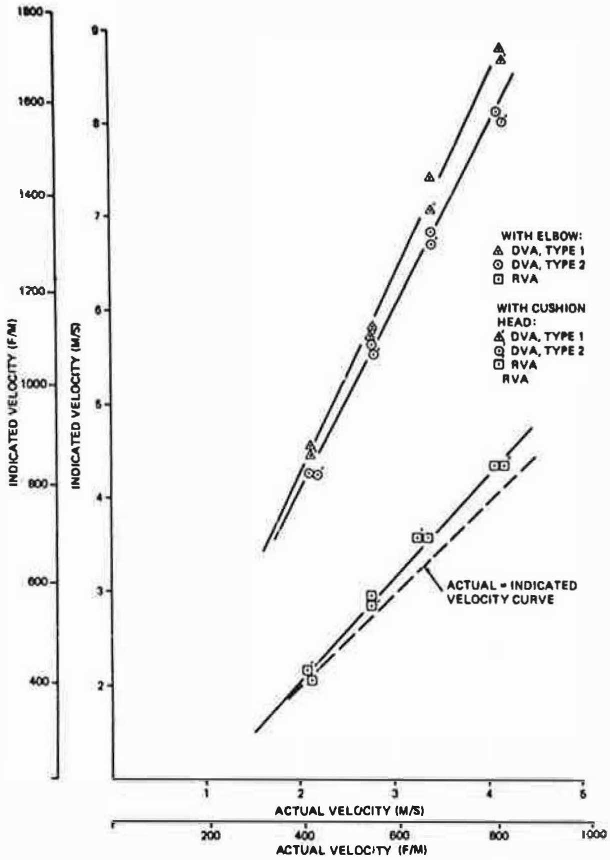

Figure 3. Instrument correction curves for the four-way blow diffuser

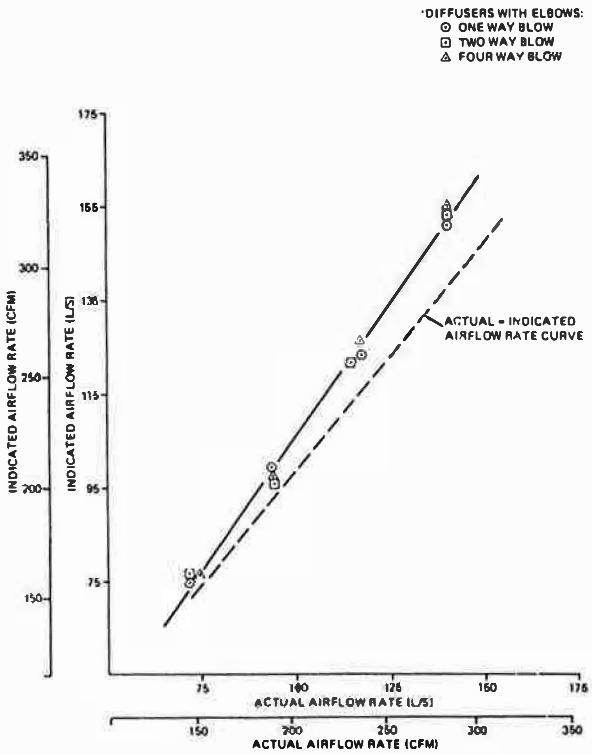

Figure 4. Instrumentation application correction curves for the collector

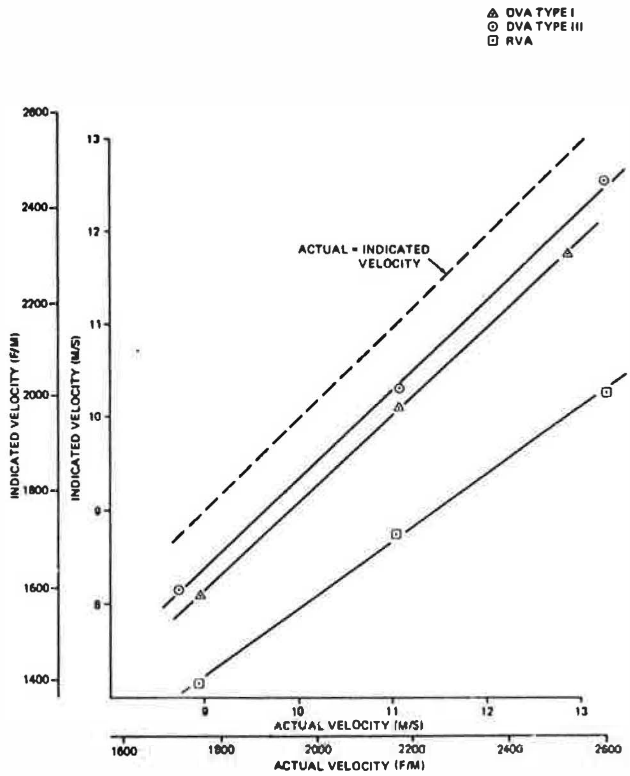

Figure 5. Instrument correction curves for the screened outlet

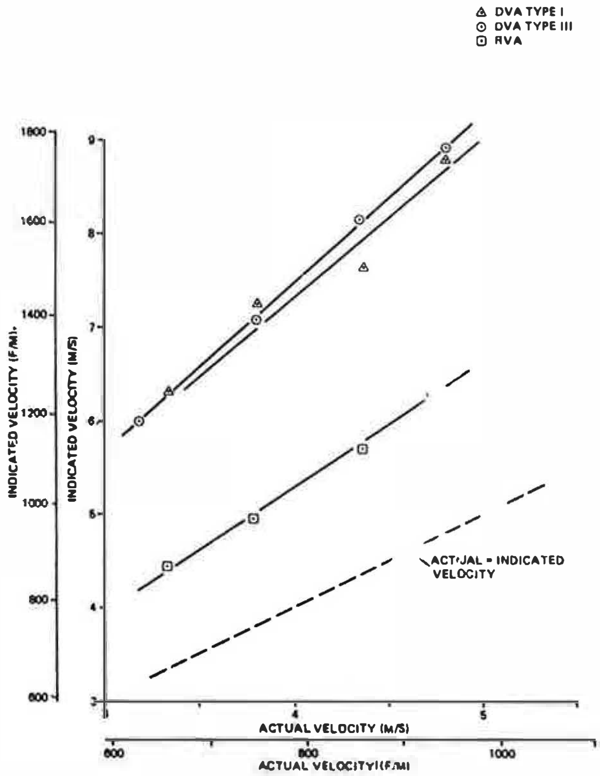

Figure 6. Instrument application correction curves for the wire mesh filter