An Evaluation of Industrial Ventilation Troubleshooting Methods in Experimental Systems

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This study determined the efficacy of specific methods of identifying and locating obstructions and alterations to industrial exhaust ventilation systems under challenging conditions when measurement errors were minimized. Two traditional screening methods were evaluated: (1) two variations of the hood static pressure method and (2) a severely modified version of the "Check-out" method. Three proposed pressure ratio methods also were evaluated and compared with the traditional methods. Two full-sized experimental ventilation systems in two ventilation laboratories were tested. One system had five branch ducts, the other had eight, with branch duct diameters ranging from 4 to 7 inches. To create challenge, each system received multiple alterations and, in some cases, the airflow level was changed throughout the system. For each round of measurements (1) different combinations of alterations were made to some ducts; (2) on a given system, relevant pressures and flows were determined for each duct using calibrated pressure sensors and standard pitot tubes held in a traversing device; and (3) the numbers of true and false positives and negatives for each screening method were computed for a broad range of threshold values. Sensitivities were plotted against the false positive rates for all thresholds for each method. The area (A_{ROC}) under the resulting "receiver operating characteristic curves" was computed for each method. Variability was simulated using bootstrap methods to determine significance of differences. In addition, the thresholds that would achieve 10 and 20% false positive rates were determined for each method and the accompanying sensitivities compared. The pressure ratio methods detected nearly all nontrivial obstructions with nearly zero false positives ($A_{ROC}=1$). The direct pressure comparison methods showed substantially inferior performance for the substantial challenges presented in these tests. The latter may be useful under less challenging conditions but were of dubious utility in locating obstructions under the ranges of conditions tested.

Keywords: direct pressure comparison method, pressure ratio method, ventilation

Ventilation systems protect workers from potentially hazardous exposures. Like any other complex system, ventilation systems need to be monitored, evaluated, and maintained to ensure proper functioning.

Screening methods that evaluate changes to measured pressures and flows are important troubleshooting tools. A good screening method should reliably reject cases in which no substantial change has occurred as well as reliably detecting obstructions, leaks, and other deleterious alterations. Many texts discuss troubleshooting ventilation systems, but they rely on visual inspection or give little guidance in interpreting changes in performance.[1–5] In particular, even when texts suggest using measured pressures to indicate problems, little guidance is given as to what percentage change in pressure or flow measurement values should trigger what may be a time-consuming intervention. In addition, there has been no documented proof that current methods can reliably detect significant obstructions without producing a discouragingly high rate of fruitless searches.

This study compares the effectiveness for five different screening methods using data taken from ventilation systems in two ventilation laboratories. The data were collected for other purposes but lend themselves well to the issues of interest in this study. Results from the data collected in ventilation laboratories can suggest the efficacy of various screening methods if the errors contributed by poor measurement conditions are minimized. A separate work, to be published separately, describes the results of a field study, which included a range of measurement conditions from good to very poor.

For this study the efficacies of screening methods are compared using receiver operating characteristic curves developed for the analysis of medical screening tests.[6,7] Variability was simulated using bootstrap methods[8] to allow determination of significance of differences. In addition, the thresholds that would achieve 10 and 20% false positive rates were determined for each method, and the accompanying sensitivities are compared.

DESCRIPTION OF SCREENING METHODS

This section briefly describes the "screening methods" (i.e., pressure evaluation methods) that are tested in this study. In each case the change from a previous observation to the current value would be compared with a threshold. If the change exceeded the threshold, one would consider taking action to discover the obstruction or alteration that produced it.

Two-Sided Hood Static Pressure Method

The most commonly used screening methodology in the field and the most frequently described in the ventilation texts is the hood static pressure method.[1,9,10] As stated in *Industrial Ventilation* (hereafter referred to as IVM), the "continued effectiveness [of hoods] is assured so long as the original value is not changed."[pp. 9–13] An increase or decrease in value may indicate problems because "restrictions of the cross-sectional area will reduce the airflow although the hood suction may increase or decrease."

For the current study, this method is called the $\%SP_{H_{two}}$ method to distinguish it from a variation of it discussed in the following section. The parameter to be compared with a threshold of change is computed as

$$\%SP_{H_{two}} = \frac{SP_{H_C} - SP_{H_o}}{SP_{H_o}} \times 100 \qquad \textbf{(1)}$$

where

$$SP_H = \text{hood static pressure}$$
$$C = \text{current}$$
$$o = \text{previous}$$

Note that SP_H is a negative pressure.

One-Sided Hood Static Pressure Method

In the experience of the authors, many practitioners seem to ignore increases in the magnitude of SP_H and act only when SP_H values fall. This study evaluated the adequacy of that approach, hereafter labeled the $SP_{H_{one}}$ method. The parameter compared with a threshold of change is computed as

$$\text{For } \%SP_{H_{two}} < 0: \qquad \%SP_{H_{one}} = \%SP_{H_{two}} \qquad \textbf{(2a)}$$
$$\text{For } \%SP_{H_{two}} \geq 0: \qquad \%SP_{H_{one}} = 0 \qquad \textbf{(2b)}$$

It could be argued that the method is intended only to detect increases in resistance, so the order of each pair of comparisons

was contrived so that condition C always had the greater weight of obstruction. Because there may be circumstances when detection of a reduced resistance is important, the analyses was repeated without contriving the order and the results displayed separately.

One can easily conceive of conditions when SP_H could increase in magnitude despite the occurrence of an obstruction. For example, if the fan speed were substantially increased from a previously inadequate level, the increase in SP_H due to that could exceed the reduction attributable to an obstruction downstream of H. For another example, an obstruction upstream of H would nearly always produce an increase in SP_H. The greater the blockage, the more SP_H would increase in magnitude. In many cases an obstruction upstream of H would be easily discerned by visual inspection. However, in the authors' experience it is sometimes tediously difficult to gain visual access up to H. However, no obstructions were placed upstream of H in any of the test conditions.

Pressure Jump Method

Another potential screening method is the Check-out method described in IVM.[9] As stated in the text, "It is intended as an initial verification of the design computations and contractor's construction in new systems [commissioning], but it may be used also for existing systems when design calculations are available or can be recomputed."[pp. 9–23]

The method detects obstructions by comparing observed static pressures with "design" values based on loss coefficients and target airflows. After ensuring that the fan itself is not the source of incorrect fan airflows, the method eventually evaluates pressures in the branch ducts and submains to locate possible obstructions. Substituting the design values for SP_{H_o}, the $SP_{H_{two}}$ method first is employed to determine whether there is an obstruction upstream of H. If one is found, it is removed and the junction pressure is measured for every junction in the system. Measurements are then made upstream of the junction fittings until the obstruction is detected. The obstruction is assumed to be between the most upstream junction that shows an increase in pressure magnitude and downstream of the hood that shows a reduction in pressure magnitude. Hence, if the junction pressure magnitude increases and the magnitude of SP_H decreases for a branch, the obstruction is somewhere between H and the junction. Otherwise, the duct is assumed to be free of problems and one would continue looking in other branches and submains.

The authors encountered serious difficulties in applying the method as written to long-installed systems. Among other problems were the difficulties of predicting static pressures in long-installed systems and the likelihood that certain steps in the method often would prove very difficult to execute in real systems. A full discussion of those limitations, the steps that could be taken to reduce their severity, and the analyses of the results would further lengthen and complicate this presentation. For that reason, those analyses and results will be presented in a separate publication.

This article instead explores a simple-minded application of one concept employed within the IVM procedure: if the magnitude of pressure has decreased at one location and increased at a downstream location, an obstruction will be found between those two locations. One would expect this method to work very well if the two measurement locations happened to be immediately up- and downstream of the obstruction. It is not so clear what would happen if the measurement locations were at H and the end of a given branch. This study applied the concept to determining whether a given branch was obstructed based solely on the pressures at SP_H and SP_{END} for that branch.

This pressure jump method uses the parameter, %PJ, computed from:

For $abs(SP_{END_C}) \geq abs(SP_{END_o})$: $\%PJ = \%SP_{H_{one}}$ **(3a)**

For $abs(SP_{END_C}) < abs(SP_{END_o})$: $\%PJ = 0$ **(3b)**

SP_{END} = SP value measured at the end of the branch duct (note that it is always negative in sign)

$abs( )$ = absolute value of the value within the brackets (used here to reduce confusion from the signs of the pressures)

The added requirement of an increase in SP_{END} suggests that the method would have fewer positive indications (whether true or false) than the one-side SP_H method. Like the one-sided SP_H method, the %PJ method ignores increases in the observed SP_H. That is a particularly dubious practice if it is possible for the duct to be obstructed upstream of H without being easily observed. However, for this study no hoods were obstructed. As with the $\%SP_{H_{one}}$ method, the order of each pair of comparisons was contrived so that obstruction for the condition labeled C always had the greater weight. Hence, the method would be unable to detect undesirable reductions in resistance (e.g., leaks, disconnected components, etc.).

Power Loss Coefficient Method

An X-value is the ratio of the lost power (energy dissipated as heat) to the kinetic power at the "exit" point for any continuous portion of the ventilation system.[11] Values of X can be computed from values measured in the field for individual fittings, whole branches, submains, groups of branches and submains, or the entire system of ducts. As has been demonstrated elsewhere,[12,13] an X-value is largely independent of airflow level or changes to other parts of the system. That property would seem to make it ideal for evaluating changes to airflow.[14] Indeed, for the simple case of a branch duct, the sum of velocity pressure coefficients for the components in the branch is an estimate of X for the branch.

For this study, values of X were computed for each branch (X_{br}) and the percentage changes from time o to time C in each were computed from

$$X_{br} = -\left(\frac{SP_{END} + VP}{VP}\right)$$ **(4a)**

where X_{br} = equivalent resistance of the branch upstream of "END" VP = VP at the end of a given duct

$$\%X_{br} = \frac{\%X_{br_C} - \%X_{br_o}}{\%X_{br_o}} \times 100$$ **(4b)**

The computations for values of X for fragments of a system that include converging or diverging flows (e.g., submains) are far more complicated than the simple relationships of Equation 4a. However, only branches are considered in this work. The efficacy of X values when applied to submains will be considered in another publication.

Branch Pressure Ratio Method

Calculation of X-values requires time-consuming pitot traverses to determine velocity pressures. Static pressures are generally easier and quicker to measure. As has been shown elsewhere,[14] the ratio of any two static pressures in a system is mathematically related to the X-values of the ductwork upstream of the locations where the pressures

were measured. Thus, if the X-values for both sections are constant, the pressure ratio must be constant. Conversely, if the ratio of pressure changed, one or both X-values must have changed.

The ratio of SP_H to SP_{END} within a branch is a convenient choice, allowing the possibility of investigating individual branches independently of other changes to the system. The parameters computed are BrRatio and %BrRatio:

$$BrRatio = \frac{SP_H}{SP_{END}}$$ **(5a)**

$$\%BrRatio = \frac{BrRatio_C - BrRatio_o}{BrRatio_o} \times 100$$ **(5b)**

Note that if BrRatio is near unity, it is because the resistance downstream of H is small compared with the resistance upstream of H. Thus, addition of even a very large obstruction upstream of H would have very little effect on the ratio. Likewise, if the ratio is near zero, even a very large new obstruction downstream of H could have very little effect on the ratio. Hence, the method is not helpful if BrRatio is near zero or near unity for the "before" and "after" cases.

Reference Ratio Method

Calculation of BrRatio requires two pressure measurements for each duct (SP_H and SP_{END}). Because the SP_{END} measurement generally requires use of a ladder, it would be convenient if a single pressure (SP_{ref}) taken at one location could serve as the normalizing pressure for every SP_H rather than measuring SP_{END} for every duct. The pressure at the end of the most downstream submain or at the end of the first main duct[15] are convenient choices. The parameters employed are

$$RefRatio = \frac{SP_H}{SP_{ref}}$$ **(6a)**

$$\%RefRatio = \frac{RefRatio_C - RefRatio_o}{RefRatio_o} \times 100$$ **(6b)**

where SP_{ref} = common reference static pressure.

Comparing Airflows

The main goal of maintenance is to assure that airflows through each hood continue at desired levels, so one could simply measure airflows in the system and compare them with "design" (i.e., target) values. This study did not evaluate that method, but the results from the hood static pressure methods should be comparable because the hood static pressures were highly correlated ($R^2 > 0.98$) to airflows for this data. The airflow was highly correlated to SP_H because there were no changes to the resistance upstream of H in this study. Interpreting the significance of changes in airflow levels for a given duct would have the same problems as interpreting changes in SP_H values.

Furthermore, in the experience of the authors, the time and effort required to determine airflows is much greater than the time and effort required to measure static pressures (especially SP_H). Thus, if one intends to measure airflows, it is relatively little additional effort to take the static pressure measurements necessary to apply the other methods discussed in preceding sections.

APPARATUS

Ventilation Systems

Ventilation systems located in two ventilation laboratories were employed in four studies done originally to test other hypotheses.

FIGURE 1. Union Bay ventilation system
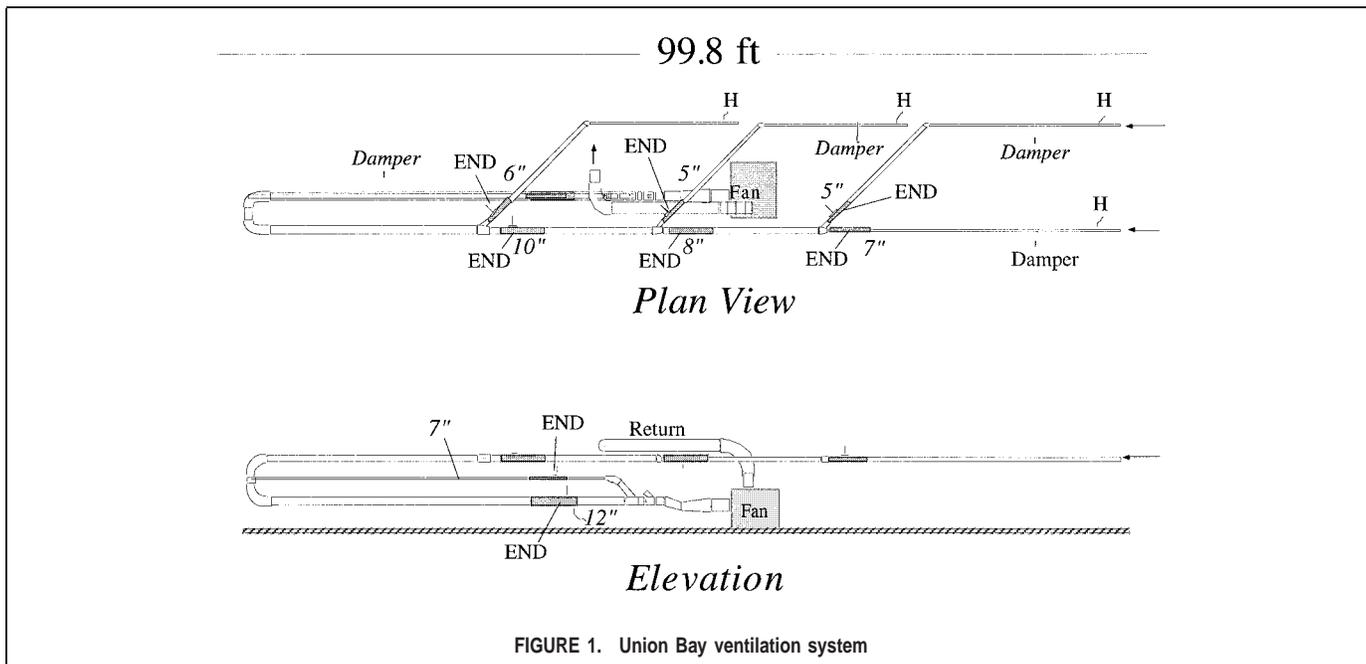
The Carrel,[16] Spann,[17] and Colvin[12] studies were done on the same five-branch duct system in the University of Washington Union Bay ventilation lab[18] shown in Figure 1. Branch duct diameters ranged from 4 to 7 inches. Branch ducts were 10 to 20 feet in length and had zero or one elbow for each branch. Submain ducts included zero or two elbows. Duct velocities ranged from 2900 to 5500 ft/min for each study.

The Geiger study [19] was done at the University of Washington Northlake ventilation laboratory, the successor to the Union Bay facility. The duct system (see Figure 2) included eight branches having duct diameters ranging from 4 to 6 inches. Branch ducts were 20 to 35 feet in length and included one to three elbows for each branch duct. Submain ducts were 10 to 20 feet and included zero or one elbow. Duct velocities ranged from approximately 2900 to 5500 ft/min.

All branch ducts drew air through plain duct openings. The ducts were 22 or 24 gauge and spiral-wound in 10-ft lengths,

which were cut in length to fit. Elbows in ducts below 6 inches in diameter were stamped with 1.5 diameter (D) radii of curvature. Elbows in larger ducts were five-piece construction with 2.0 D radii of curvature. Laterals joined junction fittings at the midpoint of tapered bodies at 30 or 45° entry angles. Duct segments and elbows were joined by 4- to 6-inch long pieces that were of slightly smaller diameters than the ducts they joined.

Fan output varied only because of changed resistance in the branches for all studies except that of Spann, who varied fan speed to change airflows by 50% for some rounds of data collection.

Measurement Equipment

All pressure measurements were taken with standard hemispherical head Dwyer® stainless steel pitot tubes (model 167, ⅛-inch diameter, 6- or 12-inch insertion depths, 1.5-inch lead tube, Michigan City, Ind.). Pitot tubes were held in permanently mounted
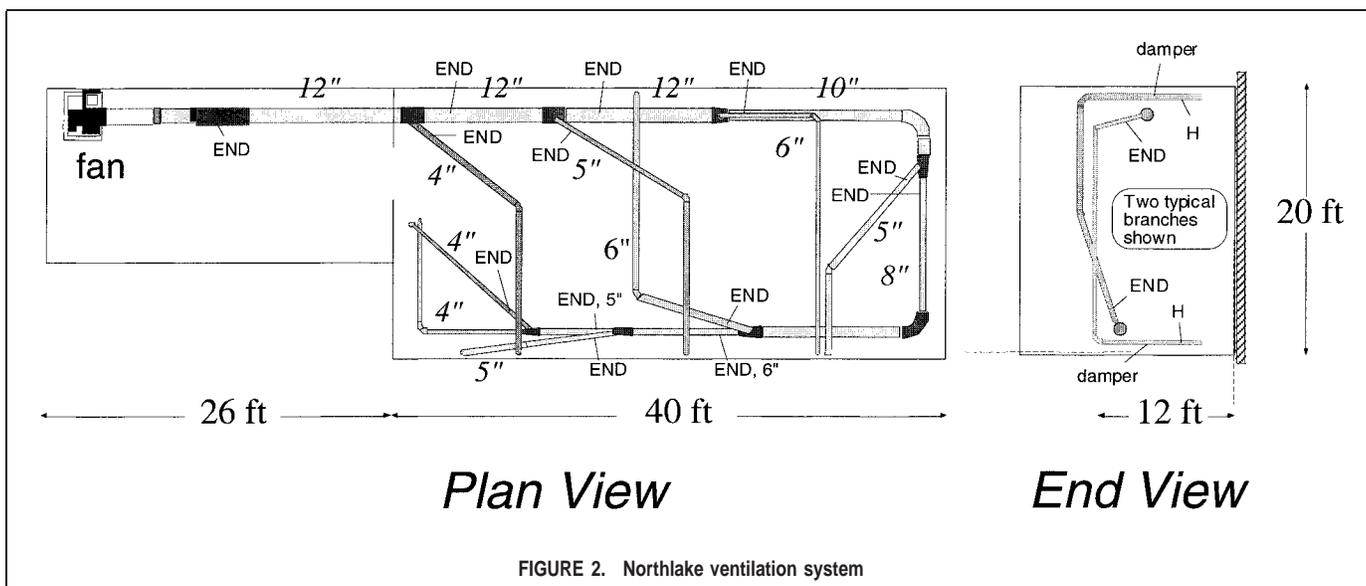
FIGURE 2. Northlake ventilation system

TABLE I. Weight Classifications for Dampers

1	very light	<10%
2	light	10 to 20%
3	moderate	30 to 40%
4	substantial	40 to 60%
5	gross	80%

TABLE II. Numbers of Obstructions

Weight	Description	All Studies	Colvin	Geiger	Spann	Carrel
0	no obstruction	88	20	17	28	23
1	very light	2	0	1	0	0
2	light	16	4	12	0	0
3	moderate	22	7	12	3	0
4	substantial	46	2	43	1	0
5	gross	10	0	10	0	0
6	blanked off[A]	10	0	0	0	10

[A]Not included in the analyses because obvious by any method

holding devices,[20] which provided optimal control over probe orientation and insertion depth. Insertion depths were based on the log-linear method.[21] The pitot tubes were connected to the manometer using quarter-inch internal diameter, one-sixteenth-inch wall-thickness plastic tubing.

Pressures were sensed using either Omega PX154 Series pressure transducer sensors (Omega Engineering Inc., Stamford, Conn.), or TSI model 8702, DP-Calc digital manometers (TSI Inc., St. Paul, Minn.) connected to the serial port of a computer. The pressure devices were calibrated against a Dwyer Hook Gage (series 1425, Michigan City, Ind.) with 0.001 in.w.g. resolution.

Dry bulb temperatures were measured using standard laboratory thermometers. A battery-powered Psychro-Dyne psychrometer (Cole-Parmer Instrument Co., Vernon Hills, Ill.) was employed to determine humidity and air density. Temperatures were assumed to be the same for all hood openings.

Data Acquisition and Analysis

Hood static pressures were measured at 3 to 5 D downstream from the duct opening and SPEND values were measured 4 D to 6 D upstream of junction fittings. Velocity pressure traverses were taken at the SPEND measurement locations.

To facilitate data collection, digital manometer readings were sent directly into computers using one of two specially written computer programs designed for pressure data acquisition.[22,23] Using measured pressures, humidity, and temperature, the computer programs calculated airflows, static pressure ratios, and X-values for all branches and submains for which the data was input. Sensitivities, false positive ratios, and areas under the operator characteristic curves (A_{ROC}) were computed, and bootstrap sampling was done using a computer program specially written by the first author. Those data were then imported for analysis and presentation of results using Data Desk, version 5.0 (Data Description, Ithaca, N.Y.) and SPSS (SPSS, Chicago, Ill.).

Obstructions

For all but the Colvin and Carrel studies, obstructions were simulated using adjustable slide-gate dampers constructed to be airtight. The dampers were located in branch ducts at least 5 D downstream of H locations and at least 10 D upstream of end locations. Changes

from initial insertion depth were measured using a steel ruler. The "weights" of these "obstructions" were divided into the five categories shown in Table I. Less than 10% insertion into the duct was considered a very light obstruction. Higher weights were assigned to progressively greater insertion depths.

For the Carrel study no obstructions were inserted, but some branch ducts were completely blanked off to reduce airflow through them to zero. For the Colvin study, four specially constructed obstructions (see Figure 3) were tested before the study to determine their loss coefficients, and each obstruction was assigned a weight. Their resistance ranged from the equivalent of 2 to 20 typical elbows, with each unit having roughly twice the resistance of the one ranked next lower. For consistency with weightings employed for the other tests, Moderate+ was grouped with Moderate. Each flat, thin, metal obstruction had a different open area, but all were roughly symmetrical across the duct cross-section to avoid substantially changing the uniformity of the downstream airflow. The obstructions were placed in the ducts at least 5 D downstream of the SPH measurement location and at least 20 D upstream of the SPEND measurement location. Each flat, thin, metal obstruction was placed between the joints of two sections so that they were perpendicular to the flow.

As shown in Table II, the Geiger study had a high proportion of substantial obstructions, whereas Spann and Colvin had relatively few. When all studies were pooled together the distribution of weights was dominated by moderate and substantial obstructions.

PROCEDURES FOR EACH STUDY

Carrel Study

The Carrel study[16] of the Union Bay five-branch system had no obstructions. Instead, at least one branch was sealed tight for each experimental round. Eight rounds of data were collected.
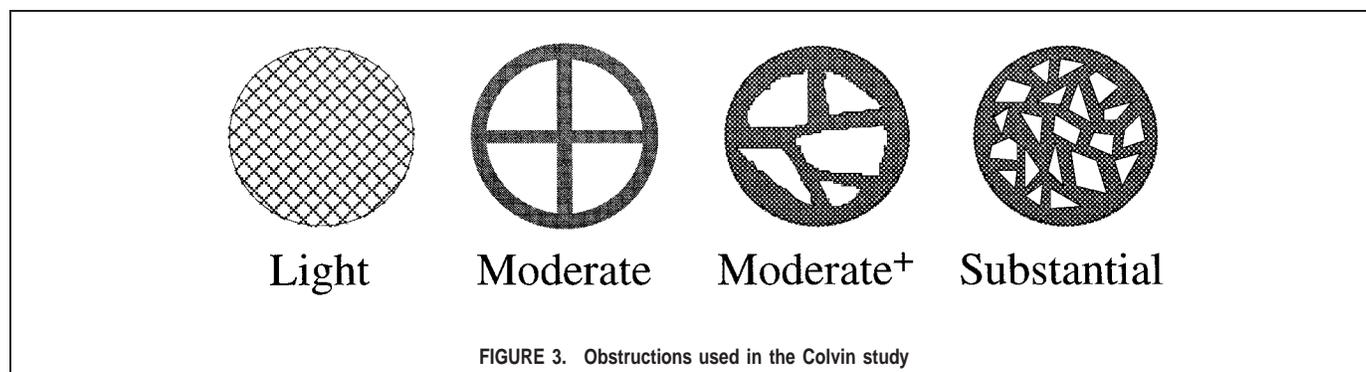

Light   Moderate   Moderate+   Substantial

FIGURE 3. Obstructions used in the Colvin study

Even casual inspection would reveal when a branch has no air-flow, so the "obstructed" branches were not included in the analysis and the study contributed no positive cases to the pooled data. Without positive cases, the sensitivity is always zero, making A_{ROC} zero as well. However, the cases presented opportunity for false positives on the remaining ducts.

Colvin Study

The Colvin study[12] of the Union Bay five-branch duct system employed various specially made obstructions the actual resistances of which were independently determined. Different combinations of two- to three-branch ducts were partially obstructed with one of the four obstructions for 10 rounds of data collection.

Spann Study

The Spann study [17] of the Union Bay five-branch duct system employed slide-gate dampers as obstructions. The measured insertion depth for the damper for each branch for each round was used to assign weights for the degree of obstruction. For 10 rounds of tests, three or four branch ducts were partially obstructed. For three other rounds, no ducts were obstructed.

Geiger Study

The Geiger study [19] was conducted on the eight-branch North-lake laboratory duct system. The obstructions were slide-gate dampers inserted to measured insertion depths. The measured insertion depth for the damper for each branch for each round was used to weight the degree of obstruction. For half of the 16 rounds all dampers were open. For the other half, five to seven of the branches had degrees of damper insertion depths.

Common Procedures

Before each study each system was prepared by finding and sealing all leaks until measured velocities upstream of the fan were less than 100 ft/min. The order of tested conditions, including replications, was selected randomly. For each measurement day, the following steps were taken.
(1) The fan was turned on at least 30 min before measurements began.
(2) The prescribed set of obstructions was inserted or the dampers adjusted to the prescribed insertion depths for that test condition. Ducts with an obstruction or a nonzero insertion depth for the damper were considered "actually positive" (i.e., obstructed). The other ducts were "actually negative" (i.e., unobstructed).
(3) For each branch in random order, values of SPH and SPEND were measured and the pitot traverses performed.
(4) SPEND was measured for each submain.
For analyses the following procedure was followed.
(1) For all cases the method value was computed (e.g., %BrRatio) from measured values and compared with the threshold. If the magnitude of the method value exceeded the current threshold, the method "indicated positive." Otherwise, it "indicated negative."
(2) For 500 thresholds ranging from 0 to 2000%, it was determined whether each method had correctly identified whether each duct was obstructed for each threshold: (a) true positive: method indicated positive and the duct was actually obstructed; (b) false positive: method indicated positive and the duct was actually not obstructed; (c) true negative: method indicated negative and the duct was actually not obstructed; (d) false negative: method indicated negative and the duct was actually obstructed.

(3) The data was put into several subsets, including subsets for each original study and a set of all cases.
(4) Bootstrapping: A new data set was developed by randomly sampling[8] from all the cases in Step 2 for a given subset of data (e.g., all cases, Spann alone, Geiger alone, etc.). This was repeated 30 times to create 30 bootstrap data sets for each subset of interest in addition to the original data set.
(5) The sensitivity and false positive ratio were computed for each combination of threshold and method for each data set.
(6) The sensitivities at the false positive rates of 10 and 20% were determined for each method for each data set.
(7) The sensitivity was plotted against the false positive rate for all of the thresholds for a given method for each data set. A_{ROC} was computed for each plot.
(8) Differences in mean values of A_{ROC} for a given data set were analyzed for significant differences for different methods using the variability produced by bootstrap methods.

RESULTS AND DISCUSSION

Relationships between Weights and Screening Parameter Values

In each study the obstructions were both known and relatively easy to rank by degree of obstruction (see Table II for prevalence rates). Ideally, each screening parameter would show progressively higher values with increasing degrees of obstruction. Most important, if a method is to distinguish obstructed from unobstructed ducts, the range of values for clean conditions should always be less than the values that occurred when an obstruction was present.

As shown in Figure 4, the range of values of $\%SPH_{two}$ for clean conditions overlapped the values obtained when the ducts were partially obstructed. The dotted horizontal line represents the threshold that would produce no false positives for that method (i.e., the greatest percentage change of the parameter observed when the ducts were clean). Based on these data, one would expect $\%SPH_{two}$ to have poor ability to discriminate between clean and obstructed ducts. As a result, one would expect that high sensitivities could be obtained only at the cost of many false positives. Similar problems can be shown for $\%SPH_{one}$ and $\%PJ$.

The three pressure ratio parameters (%BrRatio and %Xbr) discriminated much better between clean and obstructed conditions for Weights 3, 4, and 5. No method did well in distinguishing between clean conditions and Weights 1 and 2, but %BrRatio and %Xbr did the best.

Although there was overlap between pressure ratio values for Weights 3, 4, and 5, some of the overlap between the differently weighted obstructions may reflect inconsistencies in assigning a priori weights to obstructions. The crucial issue is the distinction between "clean" and conditions sufficiently obstructed to shift airflows enough to affect hood performance and settling of airborne particulates in the ducts. The authors are aware of no research that has demonstrated the sensitivity of hood performance or settling in ducts to modest changes in airflow levels, but for this discussion it is assumed that diversions of less than 5% are probably quite tolerable.

As has been demonstrated elsewhere,[14] a value of %Xbr greater than 20% is required to change airflow distribution by more than 5%. For this data, weights above 2 had values of %Xbr that could have produced shifts in airflow exceeded 5% for all but one case (see Table III), providing some justification for focusing on cases
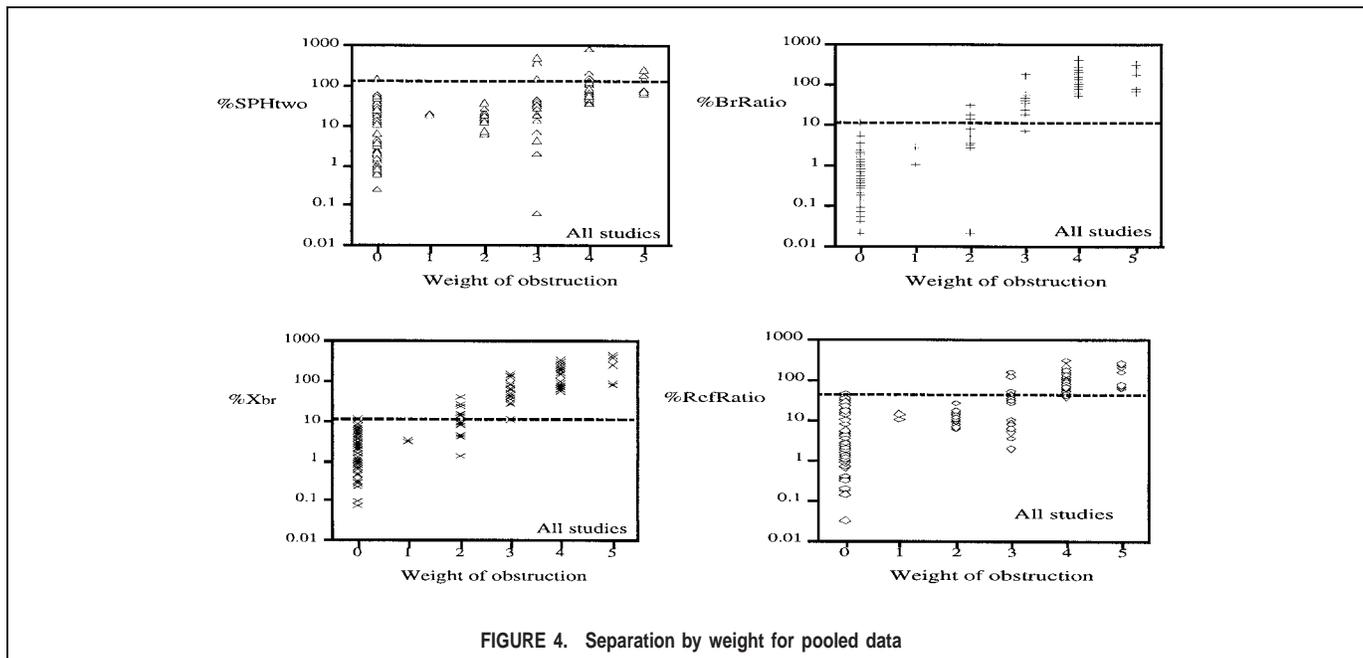
FIGURE 4. Separation by weight for pooled data

in which assigned weights exceeded a value of 2. Only one of the clean conditions produced a %Xbr value associated with a shift of 5% in airflows, demonstrating the repeatability of X_{br} determinations. Note that because errors in Xbr are directly affected by errors in estimating airflow levels, it would be pointless to plot observed changes in airflow to observed changes in Xbr.

Areas under the Operating Characteristics Curves

Operating characteristics curves were plotted for each method (see Figures 5 and 6) and the areas under the curves were computed (see Table IV), allowing a broad comparison of the efficacies of different methods.[6] When each of the laboratory studies was considered individually, the values of A_{ROC} were more variable than when the data were pooled.

Results from Individual Studies

The Carrel study added only negative cases, so its areas under the curve were all zero. All methods did extremely well for the Colvin study (possibly because obstructions with low weights in that study should have been classified much higher), but the Geiger and Spann studies presented more of a challenge to all of the methods. The %Xbr method did extremely well on all studies, and values for %BrRatio were extremely high for all but the relatively low value of 0.89 for the Spann study. The %PJ, %SP$_{Hone}$, and %SP$_{Htwo}$ values were much lower than the values for %BrRatio and %Xbr for all but the Colvin study.

TABLE III. Predicted Frequency of Greater than 5% Shifts of Airflow

Weight	No. Cases	Percentage Exceeding
0	87	1
1	2	0
2	16	19
3	22	91
4	46	100
5	10	100

For the Spann study the value of A_{ROC} for %PJ was zero because that method failed to detect any obstructions, probably because of the low prevalence of substantial changes (7%), and because the fan output was changed substantially for different rounds of experiments within the study. The "commissioning method" in IVM requires that the fan be adjusted to "design" rotation rate before attempting to detect locations. Failing to do that in these tests would have violated the requirement if we were evaluating that method as it is written. However, the authors are dubious
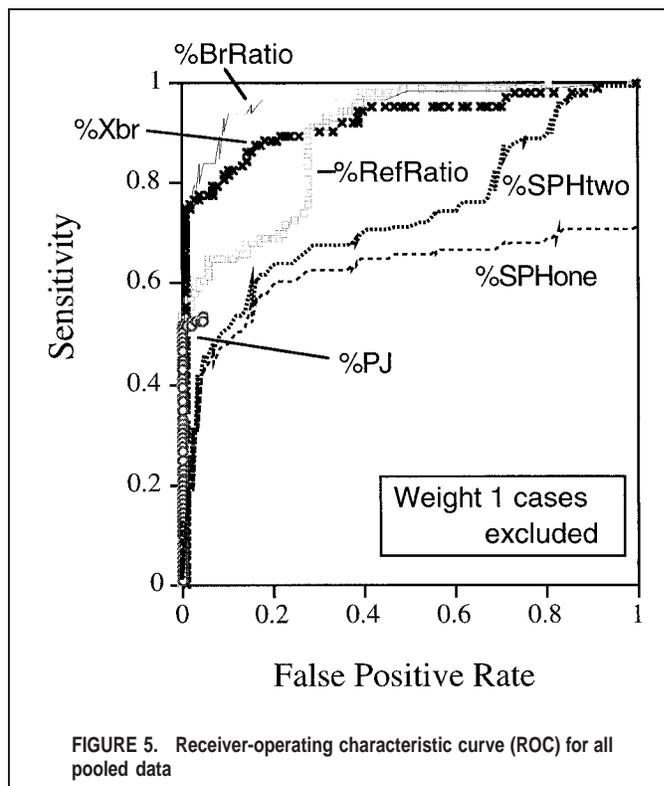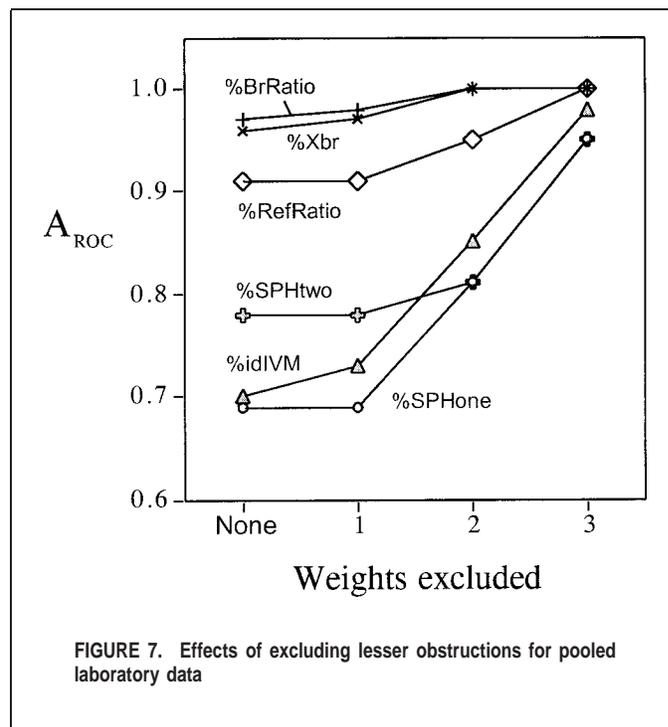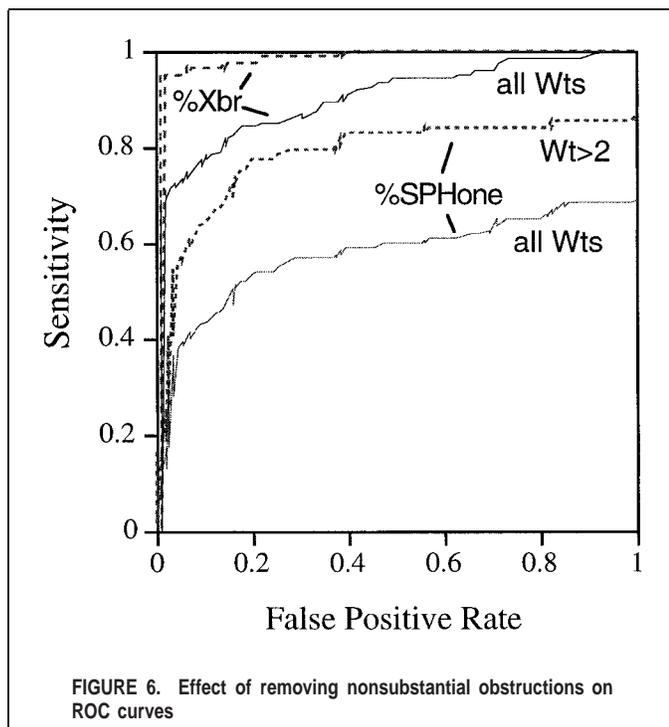

FIGURE 5. Receiver-operating characteristic curve (ROC) for all pooled data

FIGURE 6. Effect of removing nonsubstantial obstructions on ROC curves

FIGURE 7. Effects of excluding lesser obstructions for pooled laboratory data

that many practitioners could or would make such fine adjustments in systems that have been in operation for a year or more before beginning to look for obstructions.

Pooled Data from All Studies

As shown in Table IV and Figure 7, when all data were pooled, the %BrRatio and %Xbr performed the best and SPH_{two}, SPH_{one}, and %PJ performed relatively poorly. Removing the lower-weighted obstructions generally improved the values of A_{ROC} for each method, but the three direct pressure comparison methods had values of A_{ROC} exceeding 0.90 only when all but very substantial obstructions were considered.

When paired pooled t-tests for each combination of methods were performed, the differences in mean areas for methods were significantly different ($p<0.001$), except for %BrRatio versus %Xbr. Omitting the lesser changes in resistance (Weights 1 and 2) made little difference in the significance of the comparisons or in

the rank order of values of A_{ROC} for the different methods. Similar results were found from general linear model analysis of data (Datadesk of Princeton, N.J.) and the conservative Scheffe post hoc tests.

Sensitivity Achieved at Low False Positive Rates

Values of A_{ROC} are a broad measure of the potential efficacy of a screening method, but they do not directly indicate the best threshold for that method. Indeed, the optimal threshold for a given method depends on the relative importance one would give to false negatives and false positives. False negatives represent missed obstructions, which may ultimately produce higher exposures to workers. False positives lead to wasted time and effort, which may discourage further troubleshooting efforts. Given the choice between detecting more minor obstructions and minimizing false positive rates, it may be prudent to select the thresholds that minimizes negative searches.

TABLE IV. Areas under the Curve for Laboratory Studies

Study	Weights Excluded	Percentage of Cases with Weight					Direct Pressure Comp. Methods			Ratio Methods		
		None (0)	Very light (1)	Light (2)	Moderate (3)	Substant (>4)	SPH one	SPH two	% PJ	% Xbr	% Br Ratio	% Ref Ratio
All lab	none	45	6	14	9	26	0.69	0.78	0.70	0.96	0.97	0.91
	1	48	0	15	9	28	0.69	0.78	0.73	0.97	0.98	0.91
	1, 2	56	0	0	11	33	0.81	0.81	0.85	1.00	1.00	0.95
	1, 2, 3	63	0	0	0	37	0.95	0.95	0.98	1.00	1.00	1.00
Carrel	none	83	0	0	0	17	N/A	N/A	N/A	N/A	N/A	N/A
Colvin	none	60	11	9	16	4	0.93	0.93	0.92	0.99	1.00	0.92
	1	67	0	10	18	5	0.95	0.95	0.94	1.00	1.00	0.95
	1, 2	75	0	0	19	6	0.97	0.97	1.00	1.00	1.00	0.97
Geiger	none	17	2	13	13	55	0.61	0.62	0.72	0.95	0.97	0.69
	1	18	0	13	13	56	0.63	0.64	0.74	0.96	0.98	0.70
Spann	none	86	5	2	5	2	0.77	0.78	0.00	0.96	0.89	0.88
	1, 2	91	0	2	5	2	0.99	0.99	0.00	1.00	1.00	0.99

TABLE V. Suggested Thresholds and Their Efficacies for Branch Ducts

Method	Includes Removal of Obstructions	% Threshold	% False Pos.	% Sensitivity for Each Weight					
				All Wts. (1–5)	Very Light (1)	Light (2)	Moderate (3)	Substantial (4)	Near Plug (5)
SPH_{one}	yes	34	11	25	0	0	5	37	60
SPH_{one}	yes	36	5	23	0	0	0	35	60
SPH_{one}	no	34	11	55	0	0	9	89	100
SPH_{one}	no	36	5	50	0	0	0	84	100
SPH_{two}	irrelevant	40	11	57	0	0	18	89	100
SPH_{two}	irrelevant	50	8	50	0	0	14	76	100
%PJ	yes	0	3	34	0	6	32	41	60
%PJ	yes	5	1	33	0	6	27	41	60
%PJ	no	0	3	72	0	19	50	98	100
%PJ	no	5	1	71	0	19	45	98	100
%Xbr	irrelevant	10	2	85	0	38	91	100	100
%Xbr	irrelevant	12	0	85	0	38	91	100	100
%BrRatio	irrelevant	10	1	86	0	44	91	100	100
%BrRatio	irrelevant	15	0	81	0	13	91	100	100
%RefRatio	irrelevant	20	19	72	0	6	55	100	100
%RefRatio	irrelevant	40	6	60	0	0	18	96	100

The thresholds recommended in Table V were selected to achieve 90% sensitivity in detecting Weight 4 and 5 obstructions without producing more than 5 or 10% false positive ratios, if possible. If a method could achieve 100% sensitivity in detecting substantial obstructions with a false positive rate lower than 5%, its threshold was selected to produce the lowest possible false positive rate while achieving a sensitivity of at least 50% for Weight 3 obstructions.

In computing sensitivities, two variations were considered. In addition to the usual case of attempting to detect new obstructions, the methods were also employed to do the reverse: detect the removal of an obstruction. The latter was added to the analyses because there may be cases in which a marked reduction of resistance indicates a problem (e.g., leak in the duct, a damper opened when it should have been partially closed, etc.). For that analysis, the number of removals was roughly equal to the number of additions.

As shown in Table V, the least impressive results were for %SPH$_{one}$ and %SPH$_{two}$, which could detect less than a fifth of the Weight 3 obstructions. The %PJ method was much better, mainly because it almost never produced false positives even with a threshold of zero. It detected 64% of Weight 3 obstructions while maintaining a false positive rate of only 3% (note that it cannot have a greater sensitivity because the threshold was zero). The %Xbr and %BrRatio methods had even better sensitivities than %PJ while allowing similarly trivial false positive rates. Unlike the results with A$_{ROC}$, the %RefRatio method was not as good as %PJ, but was much better than %SPH$_{one}$ and %SPH$_{two}$.

One would expect the %SPH$_{one}$ or %PJ to be unable to detect reductions in resistance, and, as shown in Table V for cases labeled "Includes removal of obstructions," that expectation was met. Likewise, because the other methods are based on both positive and negative values of change, one would expect it to be irrelevant whether the resistance increased or decreased.

CONCLUSIONS

For the ideal conditions in these laboratory studies, the pressure ratio methods were superior to the direct pressure comparison methods. The results suggest that the %Xbr and the %BrRatio methods have the potential to reliably detect and locate obstructions and alterations. The %RefRatio method was not quite as effective. The remaining methods performed relatively poorly compared with %Xbr and %BrRatio, but they continue to have the compensating attraction of requiring somewhat less information.

Based on the results of this study, the %SPH$_{one}$ method should be abandoned. If only SPH will be measured, the %SPH$_{two}$ method is the better choice because it also requires only measurements of SPH and is superior to %SPH$_{one}$ in values of A$_{ROC}$ and in sensitivities at reasonable false positive rates (e.g., 10 to 20%). Although the method produced inferior results when compared with the pressure ratio methods, it may be a good choice for systems that are well-maintained and frequently monitored.

Even when the errors associated with predicting "design" pressures were removed, the method of locating obstructions in ducts in the Check-out method of IVM[9] (i.e., the %PJ method) did not work as well as the pressure ratio methods. This finding does not negate the value of the other parts of the Check-out procedure. Indeed, the BrRatio method could be employed within the Check-out procedure.

Although not tested directly in this study, it is likely that the pressure ratios would be far more successful in detecting leaks in ducts than would the traditional methods.

The thresholds obtained from this study should be used only when evaluating systems under similarly ideal conditions. One would expect that thresholds for typical systems should be much higher because of the variability introduced by poor measurement conditions.

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APPENDIX

The Industrial Ventilation Check-Out Procedure

The relevant portions of the procedure are listed below, followed by an extended discussion of its limitations.[9]

1. Determine the volumetric flow in duct with a pitot traverse. If volumetric flow matches design, go to Step 4; otherwise, continue with 1a.
   a. Check fan size against plan;
   b. Check fan speed and direction of rotation against design;
2. If a discrepancy is found and corrected, return to Step 1. If not, measure fan inlet and outlet static pressures and compute the fan static pressure. Using fan table, check flow, fan static pressure and fan speed (RPM). If agreement is acceptable although at some other operating point than specified, fan is satisfactory, and trouble is elsewhere in the system. Go to Step 3.
3. If the fan inlet static pressure is (more negative) than calculated in the design, proceed to Step 4. If the fan outlet pressure is more positive than design, proceed to Step 8
4. Measure hood static pressure on each hood and check against design. If correct, go to Step 10; otherwise, continue with Step 4a.
   c. Check size and design of hoods and slots against plan;
   d. Examine each hood for obstructions.
5. After all hood construction errors and obstructions have been corrected, if hood static pressures are correct, return to Step 1; if too low, proceed to Step 6.
6. Measure static pressure at various junctions in ducts and compare with design calculations. If too high at a junction, proceed upstream until static pressures are too low and isolate the trouble. In an area where the loss exceeds design . . . . [check for alterations from design and obstructions]. If the static pressure is too low, proceed downstream and locate the trouble.
7. After correcting all construction details that deviate from specifications, return to Step 1.
8. Measure pressure differential across air-cleaning device and check against manufacturer's data. If loss is excessive, make necessary corrections and return to Step 1. If loss is less than anticipated, proceed to Step 8a.
   a. Check ducts, elbows, and entries as in Step 6a and 6b.
   b. Check system discharge type and dimensions against plans.
10. Measure control velocities at all hoods where possible. If control is inadequate, redesign or modify hood.
11. The above process should be repeated.

This procedure can be difficult, confusing, and time-consuming to follow as written, perhaps accounting for the absence of any case studies or other published verification that it actually works. Indeed, despite contacts with several hundred ventilation practitioners, the authors have yet to encounter evidence that anyone has followed this procedure to locate obstructions in ducts, successfully or not.

If followed as written, the method can require a great deal of measurement and remeasurement. This is true because:

(1) It envisions finding and repairing one problem at a time, then remeasuring and starting again. Hence, each obstruction and alteration is likely to require another full set of measurements.

(2) It requires determining all hood airflows and all junction pressures if the magnitude of even one SPH value is less than 90% of its expected value after ruling out the hood as the source of the pressure change. In the authors' experience, it would be remarkable if at least one hood did not show a 10% drop in pressure from "expected" values.

The procedure makes unstated assumptions that may be untrue or impracticable:

(1) Step 1b requires that the fan be adjusted to the design rotation rate. Unless the fan is driven by a variable frequency drive, it can be quite tedious to adjust a fan speed to within 5% of a particular rotation rate. Given that pressures in the system vary with rotation rate squared, a seemingly modest 5% deviation in fan speed can produce 10% changes in pressure throughout the system. Considering the contributions of random measurement errors, even a 15% deviation from "design" values may indicate nothing. Because the "action level" recommended by IVM is only 10%, it is clear that the fan speed must be set with unusual precision to employ the method reliably.

(2) It assumes that that the pressure calculation method described elsewhere in IVM computes values that should match observed values if the system is installed according to "design." Instead, there are many inaccuracies in the method if applied for this purpose.

(a) So-called junction pressures cannot be assessed in a meaningful way because of the conditions inside of a junction fitting.

(b) The "corrections" to airflows due to differing pressure requirements can produce effects far upstream of the two ducts being "balanced," a fact not considered in the computations.

(c) The loss coefficients used for computations may be inaccurate. They are based on clean ducts under ideal laboratory conditions, not the harsher conditions often found in industry. Different sources[9,24] employ different values for the same component, reducing confidence further. In addition, it is possible that differences in manufacturing techniques produce sharp differences in resistances that are not reflected in values recommended by any source. Finally, it is quite possible that the resistance to flow through ducts in many systems changes greatly over the service life of the system in ways not completely compensated for by the practice of increasing the value of the expected roughness when doing the design computations.[9]

(d) The fan inlet pressure may be highly uncertain for the reasons listed above, but also because predicting normal operating pressures for many air-cleaning devices (e.g., baghouses) cannot be predicted precisely nor operated at a particular set point. Hence, repairing the air-cleaner if "excessive" pressures are noted does not assure that the fan inlet pressure is within 10% of design values.

(e) Many systems are modified frequently. In the authors' experience, it is rare for practitioners to recompute "design" values based on the new conditions.

Considering the imperfections in setting fan speeds and the uncertainty of the resistance to flow afforded by the air-cleaner and ducts, one would not be surprised to find deviations in fan airflows of 5% or more from design values even if the system and fan were installed perfectly and the duct system had experienced no obstructions or leaks. Because a 5% deviation in airflow creates a 10% deviation in pressure, there is a great potential for false positives and negatives when using the check-out method with the recommended threshold of 10%, especially when one considers the variability due to random measurement errors.

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