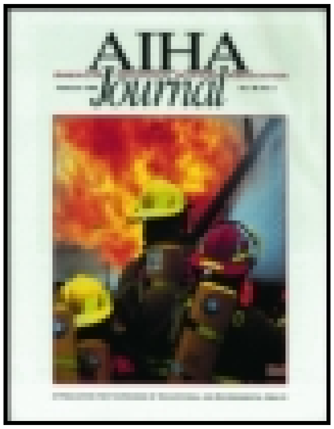

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An Evaluation of Industrial Ventilation Branch Screening Methods for Obstructions in Working Exhaust Systems

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This research evaluated the effectiveness of screening methods in identifying obstructed branches in industrial ventilation systems. These methods were divided into two categories: pressure comparisons and pressure ratio comparisons. The first category contained techniques that compare measured static pressures with the corresponding design static pressures or with previously measured pressures. Certain aspects of the method suggested in the *Industrial Ventilation Manual* were also tested. The second category compares the ratios of two measured pressures and includes the new reference ratio method. Data were collected from six industrial ventilation systems. Four of the systems were used to control wood dust, and two were used to control metal shavings from a saw-sharpening operation. Each system was tested for naturally occurring or deliberately inserted obstructions. Appropriate static and velocity pressures were measured to calculate each troubleshooting method's parameter. The change in the parameter was compared with a range of thresholds for the test cases. Receiver operator characteristic curves and bootstrapping techniques were used to identify the best method for determining the presence of obstructions or alterations. The pressure ratio methods were found to be substantially superior to the pressure comparison methods at detecting obstructions.

Keywords: monitoring, obstructions, pressure measurement, troubleshooting, ventilation

Ventilation systems are designed to reduce worker exposure to hazardous airborne materials. To ensure worker safety, the system must be operating effectively. A system may lose its effectiveness in controlling contaminants because of purposeful or inadvertent alterations to the systems or because of the development of obstructions within the ducts. These alterations and obstructions are often hidden, making visual inspection ineffective. Therefore, to detect these changes and prevent harmful situations, the system must be monitored and evaluated periodically using indirect indicators.

Several techniques have been developed that utilize the system's pressures to detect the presence of an alteration or an obstruction. These techniques fall into two categories: pressure comparison and pressure ratios. The pressure comparison category contains methods (which are defined in later sections) that compare a single static pressure measurement with a previously measured value or an expected value. This category contains the methods that for this article are designated as follows: the two-sided hood static pressure method (perhaps the most commonly used method), the one-sided hood static pressure method, and a modified version of the ''checkout procedure'' recommended in the *Industrial Ventilation Manual*.[1] Many textbooks refer to the need for periodic visual inspection and monitoring of hood static pressures. None give a lengthy discussion of what method to use or what threshold value to use when they do suggest a method.[2–7] Only the *Industrial Ventilation Manual* suggests a possible threshold for its method.

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Subscripts to Denote a Time

c = comparison value (i.e., from current round of data)

o = baseline or original value (i.e., from previous round of data)

Subscripts to Denote Location, Method, and Measurement

A = cross-sectional area normal to a duct

BrRatio = parameter computed for BrRatio method

D = duct diameter

end = End pressure measurement location

FPR = false positive rate

H = Hood pressure measurement location

i.d. = inner diameter

PJ = parameter computed for pressure jump method

RefRatio = parameter computed for RefRatio method

ROC = receiver operator characteristic (curve)

SP = mean static pressure at a cross section

$SP_{H_{one}}$ = parameter computed for $SP_{H_{one}}$ method

SP_{ref} = mean static pressure at the reference main or submain cross section

$SP_{H_{two}}$ = parameter computed for $SP_{H_{two}}$ method

TP = mean total pressure at a cross section

VP = mean velocity pressure

X_{br} = parameter computed for X_{br} method

The second category, pressure ratios, consists of three methods: the power loss coefficient (X_{br}) method, the branch static pressure ratio method (BrRatio), and a new method, the reference ratio method (RefRatio).

In a laboratory system, the X_{br} and BrRatio parameters were shown to vary little with changes of airflow in the system.[8] Both parameters were demonstrated to be independent of changes elsewhere in the laboratory system.[8,9] Values for both parameters varied if the branch they characterized had been altered or obstructed but remained nearly constant if an alteration was elsewhere in the system.

Two small field studies compared some of the various troubleshooting techniques.[10,11] Both studies demonstrated the ability of the X_{br} and BrRatio methods to detect obstructions. However, each study was based on a very limited data set with few obstructions. In addition, the Pinsky study[10] compared data collected over a short period of time. In practice, weeks, months, and years may go by before the system is monitored again. For this reason, the analysis of this study's data considered comparisons across a period of 3 months.

DESCRIPTION OF SCREENING TECHNIQUES

The troubleshooting method most commonly used in the field and the most frequently described in ventilation texts is the hood static pressure method. In this method, the hood static pressure (SP_H in Figure 1) is compared with a previously measured value. Preferably, the previous value would have been taken when the branch was known to be clean. These values are used in two versions of the hood static pressure method. In one version of the method (termed here the one-sided hood static pressure method or $\%SP_{H_{one}}$), if the magnitude of the hood static pressure has decreased, an obstruction is suspected in the branch or a downstream submain. An increase in the magnitude of a particular branch's SP_H is ignored as an indicator of changes elsewhere in the system.

$$\%SP_{H_{one}} = \frac{SP_{H_c} - SP_{H_o}}{SP_{H_o}} \times 100$$

$$\%SP_{H_{one}} = 0 \qquad \text{if } SP_{H_c} > SP_{H_o} \tag{1}$$

where SP_H = static pressure measured at the hood; o = original; c = comparison; and $SP_{H_{one}}$ = one-sided hood static pressure method.

The two-sided hood static pressure method[10] ($SP_{H_{two}}$) considers both increases and decreases in hood static pressure. Accepting more conditions as positive indications of an obstruction should increase the sensitivity of the method, but may result in a much lower specificity. The parameter for this comparison is computed as follows:

$$\%SP_{H_{two}} = \frac{SP_{H_c} - SP_{H_o}}{SP_{H_o}} \times 100 \tag{2}$$

where SP_H = static pressure measured at the hood; o = original; c = comparison; and $SP_{H_{two}}$ = two-sided hood static pressure method.

The *Industrial Ventilation Manual*[1] (IVM) has a ''checkout procedure,'' which assumes that each observed static pressure should equal the static pressure computed when the system was designed. This method is intended for use as an initial test of newly constructed systems but can be used to detect changes in existing systems. The method calls for the practitioner to first ensure that the fan setup (flow rate, fan static pressure, fan size, inlet and outlet conditions, fan speed and direction), air cleaning device, and duct/hood dimensions are set according to design values. Once those requirements are satisfied, all hood static pressures are measured. Like $SP_{H_{two}}$, any increase or decrease in hood static pressure beyond a certain percentage indicates an obstruction in the system. The *Industrial Ventilation Manual* suggests a ±10% threshold. If the change is greater than this threshold, then the first step is to search upstream of the hood measurement location for an obstruction. If one is found, then it is removed and the hood static pressures are measured again. If one is not found, then the pressure is measured for every junction in the system. An obstruction is assumed to be between the hood that shows a reduction in the magnitude of its hood static pressure and the most upstream junction that increases in pressure magnitude. Measurements are made upstream of the junction until the obstruction is detected. On the other hand, if the hood static pressure were to show an increase in magnitude and a search of the hood did not produce an obstruction then the duct is assumed to be free of obstruction, if the branch velocity is adequate.

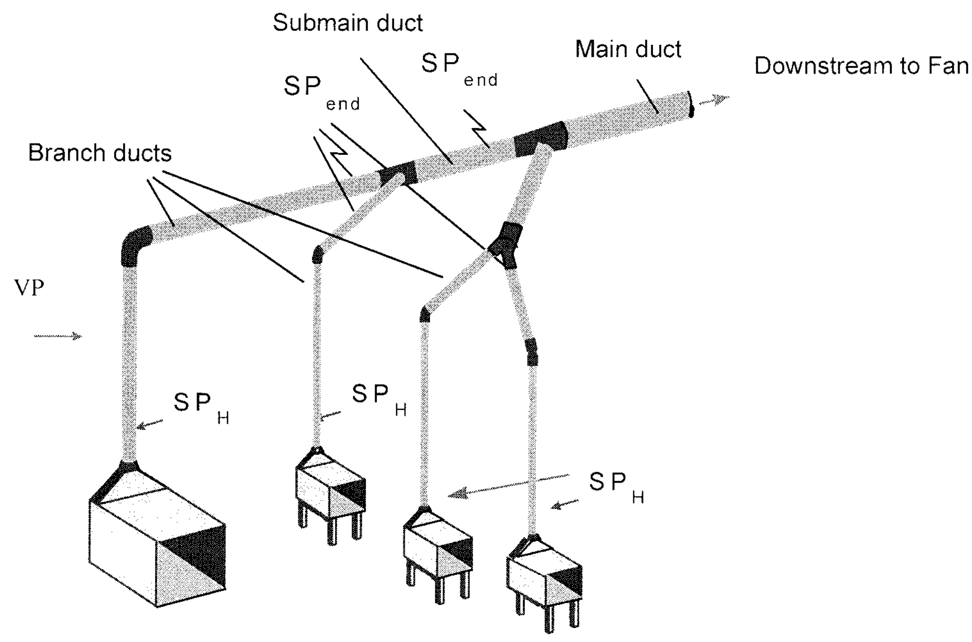

FIGURE 1. Sample system with measurement locations

In the authors' experience the method is extremely time-consuming and impractical as written. Most important, there is little reason for confidence that published loss coefficients will predict system pressure within ±10% accuracy. There has been no published study documenting the accuracy of loss coefficients in working systems, new or old. The conditions inside a real system's duct are quite different from the ducts tested in ventilation laboratories. In addition, in the authors' experience, the airflows through systems often deviate from design values by much more than 5%. Because even a 5% change in airflow will produce a 10% change in pressures, the ±10% recommendation clearly will frequently produce either false positives or false negatives, depending on whether the airflow is higher or lower than originally specified.

Finally, the method envisions testing whole systems. In many cases, the practitioner suspects a particular branch duct and wants to test just that. To allow for this and to avoid the problems of the IVM method, the authors employed its core assumptions: that obstructions located upstream of H would show a change in the SP_H beyond a certain threshold, and that an obstruction will be found to be between a location of decreasing pressure and a location of increasing pressure. Hence, one would suspect a branch duct was obstructed between H and end (see Figure 1) if the magnitude of SP_H fell and SP_{end} increased. The IVM method was modified to examine the two core assumptions. This modified method for the remainder of this study will be referred to as the pressure jump method (PJ).

Pressure Jump Method—Hood Obstructions

The first test was to determine how well the first phase of the method (assuming the fans were set correctly) detected obstructions when they were located only in the hood. $SP_{H_{two}}$ was used on a subset of data. Comparisons were made between branch measurements only when a branch was known to be clean and when a branch had an obstruction upstream of the hood measurement location.

Pressure Jump Method—Branch Core Pressure Reversal

The second test was to observe how well a decrease in the magnitude of the hood static pressure corresponding to an increase in static pressure measured downstream of the hood (the end of the branch) predicted an obstruction between the two points. If the branch were to have a SP_H higher than the design value, then no obstruction or alteration is indicated between the two points.

$$\%PJ = \frac{(SP_{H_c} - SP_{H_o})}{SP_{H_o}} \times 100$$

$$\%PJ = 0 \quad \text{if } |SP_{H_c}| > |SP_{H_o}| \quad \text{or} \quad \text{if } |SP_{end_c}| < |SP_{end_o}| \qquad (3)$$

where SP_H = static pressure measured at the hood; o = original; c = comparison; and SP_{end} = value measured at the end of the branch duct.

The Pressure Ratio Category

Power loss coefficients (X) are a measure of the resistance of the airflow within the duct.[12] The method's parameter is a ratio of the lost power (energy dissipated per time) to the kinetic power at the "exit" point. The X method can be used to calculate the resistance for any continuous portion of a ventilation system, but for the purposes of this study, it was used only on branches (X_{br}). The values X_{br} and the changes to it ($\%X_{br}$) computed for the hood entrance up to the "end" location in a branch (Figure 1) are as follows:

$$X_{br} = \frac{-(SP_{end} + VP)}{VP} \qquad (4a)$$

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

where X_{br} = power loss coefficient method parameter; VP_{end} =

velocity pressure at the end of the duct; o = original; and c = comparison.

The BrRatio method[12] is less time-consuming to use than the X_{br} method because it does not require a velocity pressure traverse. The BrRatio is the hood static pressure (SP_H) divided by the end static pressure (SP_{end}). The branch pressure ratio should perform equivalently to the X_{br} for branches because they are mathematically related.[12]

$$\text{BrRatio} = \frac{SP_H}{SP_{end}} \tag{5a}$$

$$\%\text{BrRatio} = \frac{\text{BrRatio}_c - \text{BrRatio}_o}{\text{BrRatio}_o} \times 100 \tag{5b}$$

Static pressures are extremely sensitive indicators of changes to a system. Shifts in static pressures are indicative of either an alteration somewhere in the system or of a change in the fan output. The latter is particularly troublesome because a shift in fan output does not necessarily mean an alteration in the system. This shift can negatively affect both the one and two-sided hood static pressure methods. RefRatio[13] normalizes the hood static pressure with a reference static pressure common to all of the branches in the system. This method has an advantage over the BrRatio method in that it requires fewer SP_{end} measurements. This would be particularly important in a system with a large number of branches. The ideal reference measurement would be taken upstream of both the fan and the air-cleaner and downstream of the last junction fitting.

$$\text{RefRatio} = \frac{SP_H}{SP_{ref}} \tag{6a}$$

$$\%\text{RefRatio} = \frac{\text{RefRatio}_c - \text{RefRatio}_o}{\text{RefRatio}_o} \times 100 \tag{6b}$$

SP_{ref} = static pressure measured in a main or submain close to the fan

APPARATUS

Ventilation Systems

Six systems were used in this study. Two systems were used to ventilate band saw and circular saw sharpening operations (“band saw” and “dry saw”). Branch duct sizes in both the band saw (Figure 2) and dry saw systems were 3.5 and 4 inches in diameter. The band saw branch velocities ranged from 500 to 3700 ft/min, whereas the dry saw system branch velocities ranged from 1000 to 4500 ft/min. The other systems in the study, “cabinet shop,” “mezzanine east,” “mezzanine west,” and the “model shop,” were used to control wood dust from typical woodworking operations. The cabinet shop branches had duct diameters ranging from 4 to 8 inches and with velocities ranging from 400 to 6500 ft/min. The mezzanine west and the mezzanine east systems contained branches with diameters of 4, 5, and 6 inches. The velocities for the mezzanine west branches ranged between 2000 and 6500 ft/min, and the mezzanine east system velocities ranged from 2000 to 5200 ft/min. The last system, the model shop, had branches whose velocities ranged from 500 and 3700 ft/min. These branch diameters were 5 and 6 inches. Ninety percent of the model shop’s data was collected for the Pinsky study[10] and classification of alterations for that system were based on notes made by Pinsky during her study. This indirect information may have led to differences in the categorization of alterations.

Measurement Equipment

All pressure measurements were made with an Alnor Compu-Flow ElectroManometer (Model 8530D-I, Alnor Instrument Co., Skokie, Ill.)[14] or with a TSI DP-Calc (Model 8702, TSI Inc., St. Paul, Minn.),[15] each with an accuracy of ±1% after zeroing. Both were calibrated periodically against a Dwyer “Hook gauge.” Pressure measurements were taken using Dwyer stainless steel pitot tubes (Model 167, Dwyer Instruments, Michigan City, Ind.),[16] which complied with AMCA/ASHRAE[17,18] specifications. Traverses were completed by using the log-linear method.[19] Pitot tubes were connected to the manometer using one-quarter inch i.d. with one-sixteenth inch wall thickness plastic tubing. Pressure readings were downloaded directly into a laptop computer employing the HV_Measure program, which was designed specifically for ventilation pressure acquisition and evaluation.[20]

Wet and dry bulb temperatures were measured using a battery-powered psychrometer (Model 3312–40, Cole-Parmer Instrument Co., Vernon Hills, Ill.) and were used to determine humidity and air density. The temperatures inside ducts in the system were assumed to equal the observed room temperature. Barometric pressures were not taken, as they typically have very little effect on the air density at this altitude. More important, each method involved comparisons that tended to cancel out the effects of barometric pressure.

A boroscope (Series 5, Olympus America, Melville, N.Y.) was used to inspect the inside of the ducts for obstructions. A boroscope is a portable periscope with a light source connected to the end. Throughout each system, inspection holes were drilled and a boroscope was used to view spots where accumulation was likely (hoods, elbows, junctions, and long, straight ducting).

Obstructions

Three types of obstructions were used in this study: naturally occurring obstructions, deliberately inserted weights, and dampers. A subjective weight classification scheme was developed based on the visually apparent percentage of the duct obstructed. Table I shows the various classification options with examples of what was seen in the field. Because the classification is rooted in the judgment of the investigator, misclassifications undoubtedly have occurred. Although the weight classifications of “light” and “very light” are not likely to change airflows significantly, they were included in the study because they provide very challenging tests for each method.

Naturally occurring obstructions were hard to compare because they were difficult to reach and measure in place. Removing the obstructions often shifted them or broke them into pieces so that the exact dimensions were unknown, which undoubtedly led to misclassification errors. In the absence of naturally occurring obstructions, weights of various shapes and sizes were placed in the duct whenever possible to pose significant challenges to each method.

When a naturally occurring obstruction was not present and the configuration of the duct did not allow for placement of a standard obstruction, a damper was then used to “obstruct” the system. The dampers were typically in the middle of a vertical run of duct where an obstruction is least likely to occur. One would expect that naturally occurring obstructions would be in or around elbows, at the bottom of vertical sections, or in the

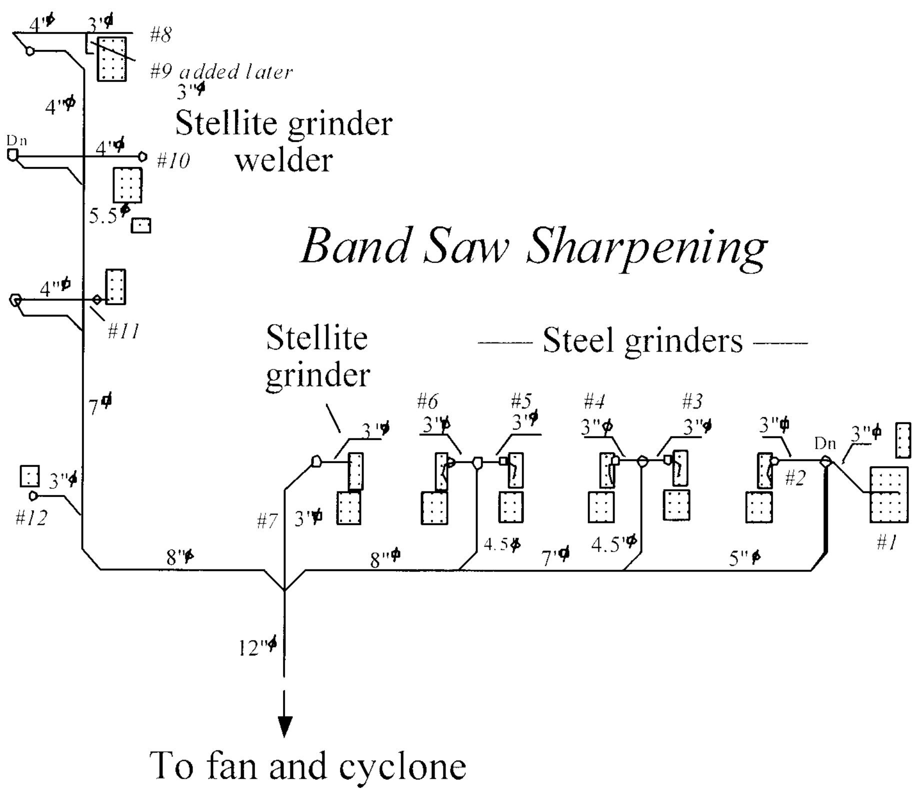

FIGURE 2. Layout of the band saw system

midst of long horizontal runs. However, it is not clear whether that would affect the validity of comparisons between different methods.

The ideal method would produce significant differences between the branch's clean parameter comparisons and the clean parameter-to-obstructed parameter comparisons. One would expect some blurring of this distinction (particularly the lower weights) due to misclassification of obstructions and borderline cases.

PROCEDURES

Description of Assessment Methods

Measurement locations were chosen in accordance with the *Industrial Ventilation Manual*[1] recommendations as much as possible. That is, measurements were usually taken at least seven duct diameters downstream and two duct diameters upstream of elbows, hoods, expansions, contractions, and other components.

TABLE I. Weight Classification Scheme, with Examples

Weight	Description	% Obstructed	Illustrative Examples
0	very light	0–1	Surface layer of dust or extremely clean
1	very light	1–5	Thin wood strip in duct Damper inserted 10% Dusting of sawdust or metal shavings
2	light	6–15	Wood strips inside duct blocking 15% Small clumps of metal shavings obstructing 10% Small change in position of flexible duct and hood opening adjustment Damper inserted 20%
3	moderate	16–40	3×5 inch brick placed in 6 inch diameter duct Lead weight blocking 20% of duct Damper inserted 30 to 40% Strips of tape covering 30% of hood
4	heavy	41–75	50% of hood opening covered with wood Damper inserted 60% of diameter
5	gross	76–90	(This weight class was not encountered in the systems.)
6	nearly plugged	91–100	Duct nearly completely filled with wood shavings

After the initial round of measurements, the system was inspected for alterations. A boroscope was used to examine the inside of ducts for naturally occurring obstructions in areas where they were likely to occur. Alterations and obstructions thus discovered were assigned a subjective classification code (discussed in following paragraphs). If obstructions or alterations were found, they were removed. If none were found, artificial obstructions were inserted or some dampers were partially closed. At that point, a second round of measurements was taken. On some days a different set of changes were made for third and fourth rounds. A number of months elapsed between the rounds of data that were compared.

Exclusion of Data

Cases were excluded from analysis when obvious errors in measurements were found (e.g., velocity profile consistent with plugging of one port of the Pitot tube) or because the conditions inside the duct were inadvertently not recorded. Cases were also excluded if there was a missing measurement that was necessary to compute any parameter (e.g., traverse for X_{br} method or a missing SP_H for all but X_{br} method). The X_{br} method data were also omitted from the analysis when the branch velocity was less than 900 ft/min in what was an otherwise high-velocity system. BrRatio cases were omitted when the SP_H and SP_{end} measurements were so close in value that the ratio was 0.97 or greater. These exclusions for BrRatio and X_{br} were cases with profound reductions in airflow that should be obvious by any method.

Analytical Procedure

For this study the data from all of the systems were pooled together for analyses. Analysis of variance and Scheffe post hoc tests were used to determine if the obstruction classifications were distinguishable from each other. Bootstrapping techniques and receiver operator characteristic curves were used to help determine which method was best for detecting obstructions.

The best method may also be judged by comparing the sensitivity and specificity for varying thresholds for each method. The ideal screening tool would have a sensitivity of 100% and a specificity of 100% at some threshold. A different combination of sensitivity and specificity may be obtained for each choice of thresholds. The optimum threshold is likely to be different for different methods. Because the optimum threshold value for each method was not known, it was necessary to examine performance over a wide range of thresholds.

Receiver operator characteristic (ROC) curves[21,22] provide a way to examine sensitivity and specificity over a wide range of thresholds all at once. To construct a ROC curve, the true positive rate (sensitivity) was plotted against the false positive rate (1–specificity) using an extremely broad range of useful thresholds. Using the plot, the better method was identified as the one that had the highest area under the curve (see Figure 3). A curve was generated and areas were computed for each method.

The bootstrap technique is a resampling method that provides an estimate of the uncertainty or accuracy of the parameter of interest without requiring any distribution assumptions regarding the data.[23] Bootstrapping calls for random samples of the data to be drawn and analyzed. These samples were used to determine the mean and standard deviation of the ROC curve areas and other statistics of interest. For the purposes of this study, 30 bootstrap iterations were done.

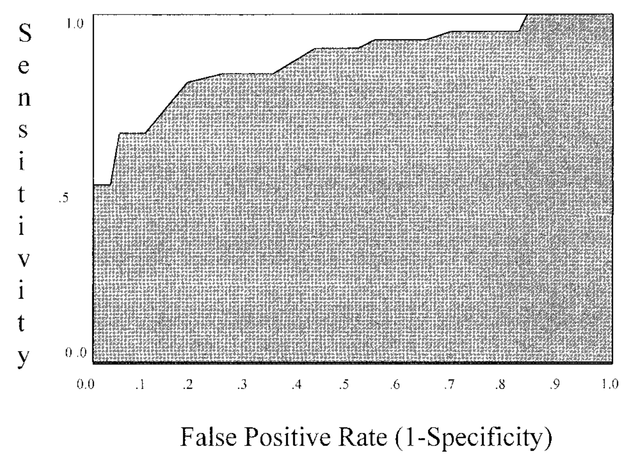

FIGURE 3. Example of a ROC curve

Test of Pressure Jump Method Key Elements

The procedures for this study are nearly identical to the main study with a few notable exceptions. First, only the data from the cabinet shop, mezzanine west, and mezzanine east systems were used in this analysis. Second, the data were separated by the section where the obstruction was located. The first study (hood obstructions) included cases in which the whole branch was clean or when the obstruction was located in the hood. The second study (branch core pressure reversal) included cases in which the branch was either clean or when the obstructions were between the hood and end measurement location (Figure 1). Third, the bootstrap techniques were not used in this study.

RESULTS AND DISCUSSION

Test of Pressure Jump Key Elements

Hood Obstructions—Element 1

As mentioned in previous sections, a good method should present a clear distinction between the range of magnitude changes of clean comparisons and the range of magnitude changes when the comparison branch is obstructed. For this portion of the analysis only obstructions in the hood were considered. This allows examination of the usefulness of the method when the obstructions are upstream of H. It is apparent from Figure 4 that the hood element portion of the PJ method will not do well because the range of parameter change for clean comparisons completely overlaps the range of obstructed comparisons. Although the comparisons containing heavy obstructions mostly lie above the 10% threshold line (solid line), no clear distinction may be made between it and comparisons of clean ducts. Figure 5 illustrates the range of clean hood static pressure comparison values over the length of the study. As can be seen from this figure, values of SP_H were highly variable for all branches. Examining these data, it is clear that a threshold of ±50% would be necessary if false positives were to be less than 10% of all true negatives. However, a 50% threshold would overlap almost all of the obstructed comparison values, thereby producing a very high false negative rate. The wide range of SP_H values for each branch probably reflects the effects of obstructions to other ducts in the system as well as variations in fan output due to varying pressures

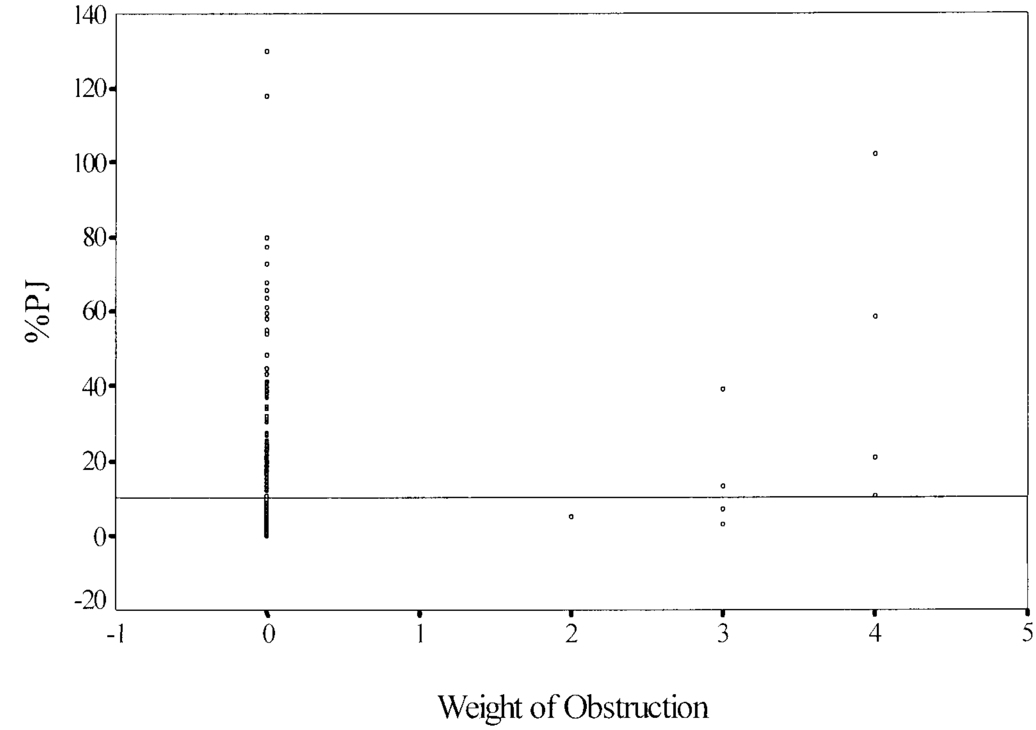

FIGURE 4. Scatter plot of %PJ by weights

across the air-cleaning device. Only a small fraction of the variations represented random error. Repeated measures taken during a period when there was no activity on the systems showed differences of less than 3%.

The ROC Area column in Table II gives further evidence that this method will not do well in detecting obstructions that are upstream of the hood measurement location. None of the weight categories has a very good ROC area, nor do they have very good sensitivity at the 10% threshold. The exception is for Weight 4 obstructions. Though the sensitivity at the 10% threshold is excellent, the false positive rate is much too high at that threshold for this to be a useful method. Conversely, if one were to arbitrarily choose a respectable false positive rate (20%), then the corresponding sensitivity for this method (Table II) is too low to be useful.

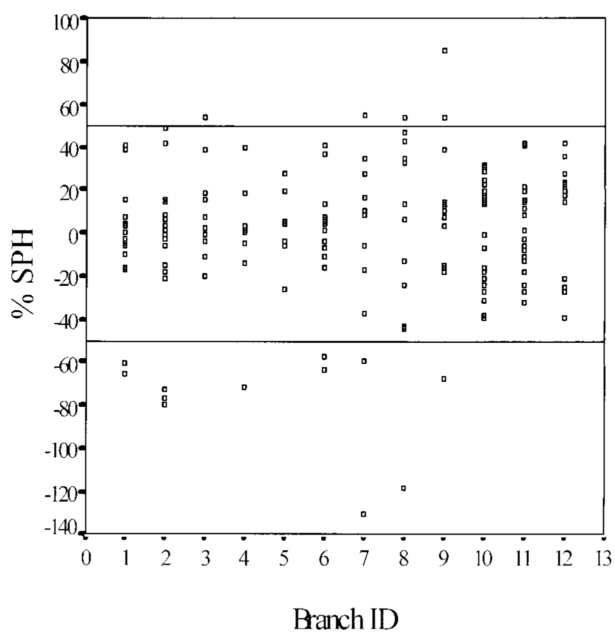

FIGURE 5. Scatter plot of clean $\%SP_H$ values by branch

Branch Core Pressure Reversal—Element 2

The pressure reversal method fared a little better for the core of the branch (between H and end). The ROC area values (Table III) were only marginally better. The sensitivity at the 10% threshold was very good for each weight classification of obstructions. However, the false positive rate at this threshold is still much too high to be of any use. The more respectable 20% false positive rate had poor sensitivities associated with each classification. There is little here to indicate that the method will work well. Therefore, this modified method was left out of the larger study.

TABLE II. Element 1—Hood Obstructions

Weights Included	ROC Area	Sensitivity (@ 10% Threshold)	False Positive Rate (@ 10% Threshold)	Sensitivity (@ 20% False Positive Rate)
All	0.58	75%	68%	38%
Class 3	0.38	50%	69%	25%
Class 4	0.77	100%	68%	50%

TABLE III. Element 2—Pressure Reversal in Branch Core

Weights Included	ROC Area	Sensitivity (@ 10% Threshold)	False Positive Rate (@ 10% Threshold)	Sensitivity (@ 20% False Positive Rate)
All	0.62	80%	66%	46%
Class 2	0.51	71%	65%	33%
Class 3	0.69	83%	66%	60%
Class 4	0.84	100%	66%	50%

TABLE IV. Weight Comparison (Scheffe Post Hoc)

Weight Comparison	$SP_{H_{one}}$ P-Value	$SP_{H_{two}}$ P-Value	X_{br} P-Value	BrRatio P-Value	RefRatio P-Value
0–1	0.999	0.999	0.999	0.999	0.966
0–2	0.999	0.961	0.954	0.602	0.044
0–3	0.064	0.007	0.0000	0.0000	0.0000
0–4	0.0000	0.0000	0.0000	0.0000	0.0000
0–6	0.027	0.0001	0.0009	0.0003	0.0000

Primary Study

Pooled Data

The data were first pooled together for analysis to determine the methods' applicability across several systems, as well as to optimize corresponding thresholds. The data also were analyzed by system to determine if there were problems for individual systems or branches that would not have been apparent when the data were pooled.

As seen in Table IV, the lighter obstructed weight comparisons (Weights 1 and 2) in each method were often indistinguishable from the clean condition comparisons. However, only the Weight 3 category (Table IV) for the $SP_{H_{one}}$ method failed to reach a statistically significant difference.

The ROC areas of the pressure ratio methods exceeded 0.90 only if Weights 1, 2, and 3 were excluded (Table V). The inability to detect Weights 1 and 2 is not necessarily a problem because they have relatively little effect on airflow distribution. Guffey[12] demonstrated that it takes at least a 20% shift in X_{br} to produce a 5% shift in airflow. The percentage difference between clean conditions and Weights 1 and 2 for the X_{br} method in this study was typically below 19%. This result suggests that these weight classifications had very little effect on airflows and were therefore unimportant. The comparisons given a Weight 3 classification were excluded to determine how well the methods work for obstructions that should be detected easily.

As shown in Figure 6 (the ROC curves for each method are without Weights 1 and 2), the BrRatio, the RefRatio, and the X_{br} methods performed the best for these data. Scheffe post hoc tests by method indicated no significant differences ($p>0.2$) between the RefRatio, BrRatio, and X_{br}. Otherwise, all differences among the methods were highly significant ($p<0.005$). General Linear Model analysis (Datadesk, Princeton, N.J.) of the results show that the area under the curve was significantly related ($p<0.05$) to the ventilation systems and to the troubleshooting method employed.

Individual Systems

The results for each system were also analyzed separately (Table V). The results were similar to the results found when the data were pooled. The $SP_{H_{one}}$ method performed poorly in every system. $SP_{H_{two}}$ ROC areas varied from system to system, but were still generally much lower than those of the RefRatio, X_{br}, and BrRatio methods. The one exception was with the model shop

TABLE V. System ROC Areas by Weight Difference

System Name	Wt. Diffs Excluded	Total Cases	Pressure Comparison Methods		Pressure Ratio Methods		
			$SP_{H_{one}}$	$SP_{H_{two}}$	X_{br}	BrRatio	RefRatio
All systems	none	704	0.40	0.64	0.76	0.79	0.75
All systems	1	677	0.40	0.66	0.79	0.81	0.76
All systems	1, 2	612	0.43	0.70	0.88	0.90	0.79
All systems	1, 2, 3	525	0.40	0.78	0.92	0.91	0.85
All systems[A]	none	607	0.39	0.66	0.79	0.79	0.8
All systems[A]	1, 2	601	0.44	0.73	0.88	0.9	0.87
All systems[A]	1, 2, 3	578	0.42	0.83	0.91	0.91	0.90
Band saw	none	75	0.20	0.66	0.78	0.76	0.84
Band saw	1	68	0.18	0.70	0.83	0.82	0.85
Band saw	1, 2	56	0.19	0.77	0.98	0.93	0.91
Band saw	1, 2, 3	44	0.31	0.97	1.00	1.00	1.00
Dry saw	none	107	0.35	0.70	0.93	0.88	1.00
Dry saw	1, 2	103	0.27	0.70	0.97	0.92	1.00
Cabinet shop	none[A]	139	0.40	0.57	0.75	0.77	0.61
Cabinet shop	1, 2	133	0.43	0.58	0.75	0.81	0.58
Cabinet shop	1, 2, 3	105	0.02	0.27	0.85	0.56	0.44
Cabinet shop[A]	1	120	0.41	0.59	0.76	0.78	0.80
Cabinet shop[A]	1, 2	112	0.45	0.60	0.74	0.81	0.82
Mez. east	none	110	0.49	0.68	0.77	0.75	0.75
Mez. east	1, 2	99	0.56	0.77	0.86	0.87	0.83
Model shop	none	78	0.42	0.58	0.60	0.72	0.79
Model shop	1, 2	41	0.69	0.81	0.80	0.88	0.91
Mez. west	none	193	0.56	0.70	0.80	0.86	0.82
Mez. west	1, 2	180	0.53	0.70	0.88	0.95	0.91
Mez. west	1, 2, 3	167	0.53	0.80	0.90	0.97	0.98

[A]Without Branch 1 of cabinet shop.

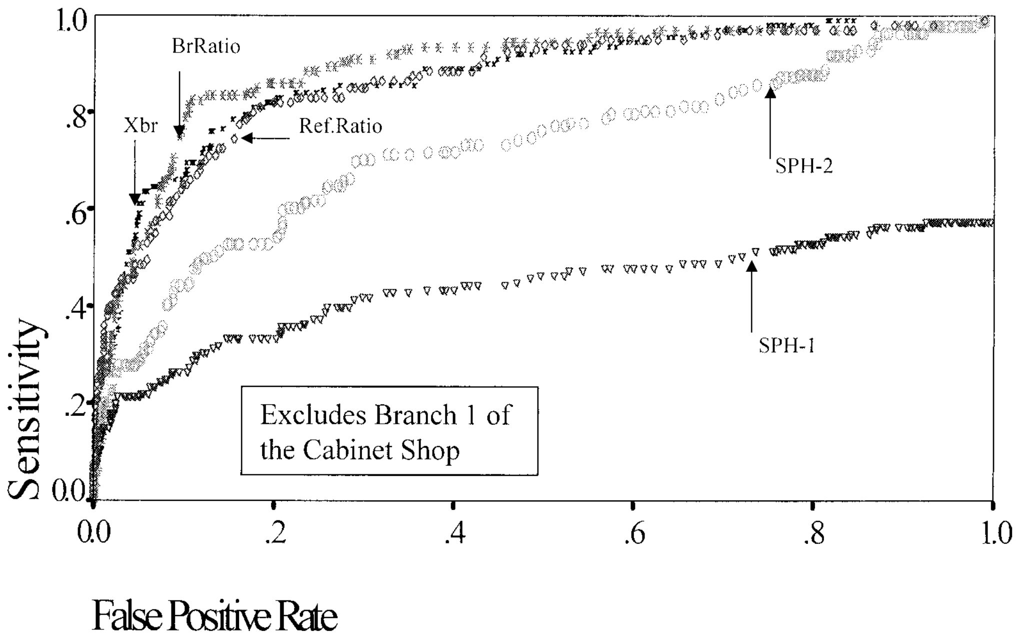

FIGURE 6. ROC curves

data, where $SP_{H_{two}}$ performed nearly as well as each of the pressure ratio methods for moderate obstructions. The RefRatio method was sometimes higher than X_{br} and BrRatio, but most often the three methods were nearly equivalent. Across the systems, the pressure ratio methods were superior to the pressure comparison methods.

Method Thresholds

It is important to pick the threshold for each method that provides the optimal tradeoff between sensitivity and false positive rates. To make an informed decision as to which threshold to use, it would be useful to know the sensitivity for each weight of obstructions and the accompanying false positive rate for a particular method's threshold. The optimal threshold for each method depends on the importance placed on false negatives and false positives. False negatives represent missed obstructions, which may produce higher exposures to workers due to decreased airflow to the hood. False positives will lead to wasted time and effort. A large number of false positives by a given method may discourage further troubleshooting efforts. The wisest course of action is to choose a threshold that minimizes false negatives while minimizing the number of false positives.

Table VI shows the thresholds for each method that produce false positive rates (FPR) of 10% and 20%. The lower the weight category, the less sensitivity that was achieved, as illustrated by Table VI.

As expected, the $SP_{H_{one}}$ method had poor sensitivities at these FPR values. $SP_{H_{one}}$ never reached higher than 65%, even at FPR=20% for the highest weighted obstructions. The X_{br} method achieved the highest sensitivity for Weight 4 comparisons,

TABLE VI. Thresholds for 10% and 20% False Positive Rates and the Resultant Sensitivities

					% Sensitivity for Each Weight Difference					
Method	% Threshold	No. Cases	Prevalence	% False Pos.	All	Very light	Light	Moderate	Heavy	Gross Near Plug
$SP_{H_{one}}$	35	543	32	20	29	12	22	33	31	63
	46	543	32	10	19	5.9	7.3	25	23	63
$SP_{H_{two}}$	35	543	32	20	48	12	35	45	80	100
	46	543	32	10	35	6	16	32	69	100
X_{br}	17	560	30	20	61	16	29	78	97	100
	25.5	560	30	10	51	11	14	63	94	100
BrRatio	8	543	32	20	65	18	38	85	89	100
	11.5	543	32	10	58	6	27	78	86	100
RefRatio	11	459	31	20	65	33	38	75	90	100
	21	459	31	10	44	6.7	12	48	84	100
RefRatio[A]	10.4	379	33	20	70	45.5	42	80	90	100
	20	379	35	10	49	18	21	55	83	100

[A]Minus Branch 1 of cabinet shop.

whereas the BrRatio and RefRatio methods were somewhat lower. The BrRatio method was superior to the other methods for Weight 3 classifications. The $SP_{H_{two}}$ method, while perfect in detecting the large obstructions, was otherwise inferior to the pressure ratio methods.

Each of the methods continued to produce poor results for the lower weights. It is also useful to consider the results when Branch 1 of the cabinet shop is removed from the analysis. This may be justifiable because it had very low velocity through it due to a highly restrictive orifice near the duct entry to the hood. The branch had a velocity consistently below 900 ft/min, a very high static pressure, and was frequently obstructed. This branch was automatically removed from the analysis for the X_{br} and BrRatio methods because it met the exclusion criteria. Removing the branch from the analysis for the other methods (Table V and Table VI), only affected the results for RefRatio. Exclusion of the branch increased the RefRatio's sensitivity for lower weights from 33 to 45.5%.

CONCLUSIONS

For these systems, each of the pressure ratio methods was superior to the pressure comparison methods. $SP_{H_{one}}$ was dramatically inferior to the other methods and should be abandoned as an obstruction screening tool. The core elements of the method suggested in the *Industrial Ventilation Manual*[1] were tested on a subset of data. There was little to suggest that this method would perform well. Therefore, the method was left out of further analysis.

Because there was no significant difference among the pressure ratio methods, practitioners should employ the pressure ratio method most appropriate for their system. The optimum choice for a given system would depend on the level of effort the practitioner is willing to put forth. For a system in which the branch conditions do not automatically eliminate certain methods, the optimum method is a matter of convenience and time. For a system with many branches, RefRatio is the least time-consuming. For systems with few branches or with difficult access to a reference location, the BrRatio may require lower effort. If one intends to determine airflows anyway, then the X_{br} method should be considered. Finally, because the three methods employ different combinations of measured parameters, use of them in combination should provide clues to measurement errors and further reduce the incidence of false positives and negatives.

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