3359 (RP-451)

#4799

AIRFLOW MEASUREMENTS AT COIL FACES WITH VANE ANEMOMETERS: STATISTICAL CORRELATION AND RECOMMENDED FIELD MEASUREMENT PROCEDURE

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ABSTRACT

A procedure for measuring the volume flow rate of air through a heating or cooling coil is presented. When a pitot tube traverse is impossible or impractical, the rotating vane anemometer procedure described and verified here will provide volume flow rates with similar uncertainty in the results. The rotating vane anemometer procedure was shown to produce estimates of volume flow rate at coil faces to within ±7%. The procedure is valid in a velocity range of 100 to 1100 fpm, and upstream disturbances such as elbows, partially blocked coils, dampers, and fan blasts had virtually no effect on the accuracy of using the K-factor procedure as long as the measured velocities were positive and relatively uniform.

BACKGROUND

The field-measured airflow rate is used for the certification of the performance on new systems, improvement or redesign of existing systems for efficient energy performance, and documentation of a system's performance for the purpose of analyzing maintenance and quality problems. The measurement of air flow is usually a testing and balancing responsibility, and the accuracy of the measurement is important to designers, owners, manufacturers, and installers of the systems.

The primary objective of this project was to establish measurement correction factors and a precise measurement technique for accurately determining the airflow rate using a rotating vane anemometer at the face of heating and cooling coils. The velocity of the airstream was determined at several positions by using a rotating vane anemometer in contact at the downstream coil face. From such readings, an average coil velocity can then be determined. The correction factor is to be determined by accurately measuring the identical volume airflow rate elsewhere in the coil airflow system using flow nozzles, dividing it by the coil face area, and then dividing this true face velocity by the average air velocity measured with the rotating vane anemometer.

Very little research has been conducted on the use of the rotating vane anemometer in nonuniform airstreams such as at coil faces. Over the years, it has been assumed that the rate of the air flow determined with these instruments is of questionable accuracy; however, it has been shown that usable results can be obtained with properly determined correction factors for certain applications. Therefore, the scope of this project was to determine correction factors that can be applied to the standard airflow rate formula that will improve the measurement accuracy using rotating vane anemometers. The formula is:

$$Q = A \times MV \times K \tag{1}$$

where

Q = volume flow rate of air
A = coil face area
MV = measured average velocity at the downstream coil face using a rotating vane anemometer
$= \sum_{i=1}^{n} V_i/n$
V_i = measured velocity at a specific i position on the downstream coil face
n = the number of positions where V is measured
K = correction factor

The correction factor, K, is a function of the measured air velocity, number of rows of tubes, number of coil fins, tube spacing, tube diameter, and possibly the nonuniformity of the approach velocity profile to the upstream coil face.

Foltz (1984), Int-Hout (1985), Parkin (1929), Tuve and Wright (1939), Wilson (1978), Caplan (1954), and Suppo (1984) all discuss the various types of instrumentation that can be used for making velocity measurements in HVAC applications. It can be concluded from these studies that different locations in the system (supply grille, exhaust grille, coil face, etc.) determine the type of instrumentation that should be used for field applications. The general conclusion is that the rotating vane anemometer is probably the instrument best suited for field measurements with nonuniform velocities.

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A specific procedure was developed for taking the velocity measurements at the coil face, and the limitations of the technique will be established. The correction factor, K, is determined for a face velocity range of 150 to 1000 fpm for a representative selection of commonly manufactured and installed coils with a variable number of rows in the coil, fins per inch, coil tube spacings, and coil tube diameters. The effect of various upstream conditions on the use of the procedure has also been determined for such configurations as upstream elbows, fan blasts, dampers, and partially blocked coils, as reported in a previous paper by Howell and Sauer (1989).

STATISTICAL DATA ANALYSIS

Data for the coils with no upstream disturbance to the velocity profiles were used to develop statistically based equations for the K-factor as a function of the measured average velocity, MV, and parameters of the coil construction.

Statistical Model Selection

A statistical analysis (SAS) program was used to analyze various models for regression equations for the data collected in this project. This program is commonly used for testing models that represent the functional relationship of data.

The set of data used was for the 4-in. anemometer head data collected both in a previous project (Howell et al. 1984) and in the current project. The data contained 484 sets of data for all coils, which were identified as C, D, E, F, G, H, I, J, K, L, M, N, O, and Z. Coil set Z contained data for six coils from previous measurements. Therefore, 19 different coils are represented in this data set, which covers a wide range of values for rows, fins per inch, tube outside diameter, tube spacing, fin thickness, staggered and in-line tubes, and flat or configured fins. In addition, the average measured face velocity ranged between 100 and 1100 fpm. The 4-in. anemometer head data set was selected since it was the head size specified for the project. However, the model determined from this analysis should apply equally as well for the 2 3/4-in. and 1-in. anemometer heads. For each head size, different coefficients for each variable must be obtained.

For each of the 484 sets of data, the following variables were determined and included in the statistical analysis:

- K = correction factor for air at the density at which the anemometer was calibrated
- MV = average measured air velocity at the downstream coil face obtained by taking the average of 38 (19 pairs) velocity readings using the 4-in. anemometer (ft/min)
- ROW = rows of tubes
- FPI = fins per inch
- SP = tube spacing (in.)
- OD = tube outside diameter (in.)
- T = fin thickness (in.)

The statistical model analysis involves scanning the full data set (484 points) for high leverage and high influence points and ensuring that such data are not unreasonable or extraneous to the data set. In all of the models, K was found as a function of the above variables (MV, ROW, FPI, SP, OD, and T) and also MV^2 and MV^3. In addition, a percent free area term

$$C = (24 - (FPI \times T + 24/SP)D)/24 \quad (2)$$

was calculated and used as a variable. Most of the models considered were combinations of six variables.

A data point is called a "high leverage" point if a slight change in y_i (MV, MV^2, MV^3, ROW, FPI, SP, OD, T, or C) will produce an appreciable change in K. There are two criteria for selecting high leverage points:

a) If $p > 0$ and $n-p-1 > 50$, then there is high leverage if

$$h_i > [2(p + 1)]/n \quad (3)$$

where

- h_i = i[th] diagonal element of the H matrix in $[y = H\,y]$ where this relates the measured to the predicted value of parameters
- p = number of independent variables
- n = number of data sets

For this set of data and most of the models, $n = 484$ and $p = 6$; therefore,

$$h_i > [2(6 + 1)]/484 \quad (4)$$

or

$$h_i > 0.029 \text{ for high leverage}$$

b) If n is very large with respect to p, then high leverage will exist if

$$[(n-p-1)(h_i - 1/n)]/(1-h_i)p > F_\alpha (p, n-6-1) \quad (5)$$

or

$$h_i > [pF_\alpha / (n-p-1) + 1/n] / [1 + pF_\alpha / (\eta - \pi - 1)] \quad (6)$$

where

$$F_\alpha (p, n-p-1) = F_{0.10} (6, 484-6-1)$$

From an appropriate table in the program's User's Manual with $\alpha = 0.1$, $p = 6$, and $484-6-1 = 477$, $F_\alpha = 1.77$. Therefore, for $h_i > 0.024$, high leverage will exist.

From the statistical analysis of the data set containing 484 points, only 23 sets were found to exhibit a slight tendency toward high leverage. This means that less than 5% of the data sets fell out of the range of being reasonable values.

A point is said to have "high influence" if deletion of that point from the data set will produce an appreciable change in one or more of the components making up the total value of K. These are usually outliers or points far away from the regression line. High influence can be detected by using Cook's distance criterion, which is a measure of the impact of the i[th] observation on the estimated regression coefficients. The i[th] observation has a substantial influence on the regression if the percentile value of the corresponding F distribution is 50% or more. For this situation,

$$F = F_{0.5} (p+1, n-p+1) = F_{0.5} (6+1, 484-6-1) = F_{0.5} (7, 477) = 0.907$$

Therefore, if Cook's distance, $D_i > 0.907$, the i[th] observation has high influence. The highest D_i found in the 484 sets of data was 0.03 so that no observation has a substantially high influence.

Nine models were tested for a regression model using the statistical analysis. The nine models included different

TABLE 1
Regression Analysis Models

MODEL	NUMBER OF VARIABLES	VARIABLES	R_a^2	R^2
1	6	*MV, ROWS, FPI, SP, OD, T*	0.537	0.543
2	6	MV^2, *ROWS, FPI, SP, OD, T*	0.463	0.470
3	6	MV^3, *ROWS, FPI, SP, OD, T*	0.413	0.420
4	7	*MV*, MV^2, *ROWS, FPI, SP, OD, T*	0.624	0.630
5	8	*MV*, MV^2, MV^3, *ROWS, FPI, SP, OD, T*	0.626	0.632
6	3	*MV, ROWS, C*	0.206	0.211
7	3	*MV, ROWS, 1−C*	0.206	0.211
8	7	*MV*, MV^2, MV^3, *ROWS, FPI, SP, OD*	0.625	0.631
9	6	*MV*, MV^2, *ROWS, FPI, SP, OD*	0.624	0.629

numbers of variables as well as different combinations of the variables. They are listed in Table 1 along with the R_a^2 and R^2 values. R^2 is the coefficient of correlation for a single-parameter regression relation. A perfect correlation (throughout the full range of measured values) would have a value equal to one. R_a^2 is the coefficient of correlation adjusted to the fact that there is more than one parameter or variable determining the regression value of *K*. Since we are looking at three to eight variables in each model, the R_a^2 is the appropriate one to evaluate.

Another parameter determined by the statistical analysis is C_p—the Mallow Statistic. It is an index of correlation for multi-independent variable regression models. For a good correlation model, C_p should be approximately equal to the number of independent variables plus 1. For the four best models in Table 1, the value of C_p was excellent.

From Table 1, it is seen that models 4, 5, 8, and 9 have the largest R^2 or R_a^2 values, which indicate the best regressions. Further detailed evaluation of each of these using the T-test and collinearity tests showed Models 5 and 9 as being the best models of the nine considered. Results for these two are provided below:

Model 5

Number of Variables = 8
Variables: *MV*, MV^2, MV^3, *FPI, SP, OD, T, ROWS*
$R^2 = 0.632$ $R_a^2 = 0.626$
Model C_p = 9.0 (very good)

i) T-tests indicate that the coefficients of *T* and MV^3 may be zero.
ii) Forward selection procedure entered MV^3 and *T* last.
iii) Backward selection procedure removed only *T*.
iv) Stepwise selection procedure added and then removed *T*.
v) There was strong multi-collinearity between MV^2 and MV^3.

From these results, *T* should be removed due to negligible influence on the value of *K*, and MV^3 should be removed to eliminate the multi-collinearity.

Model 9

Number of variables = 6
Variables: *MV*, MV^2, *ROWS, FPI, SP, OD*
Model Cp = 7.0 (very good)
$R^2 = 0.629$ $R_a^2 = 0.624$

i) T-tests indicated no problems with any of the variables.
ii) There was no indication of any multi-collinearity problems with the variables.
iii) The forward selection procedure indicated that the order of entry of the variables was: *FPI, MV*, MV^2, *SP, OD, ROWS*.
iv) The backward selection procedure indicated that all variables should stay in the model.
v) The stepwise selection procedure showed that the variables were entered into the model in the same order as in the forward selection procedure and all remained in the model.

Model 5 has a slightly higher R_a^2 value than does Model 9, and both models have equally good values for C_p. Model 9 does not have the multi-collinearity problems that exist in Model 5. In addition, from a practical point of view, Model 9, with a smaller number of variables, would be a better choice for field use. For these reasons, Model 9 was chosen as the best regression model to predict *K* from the known or measured data.

It should also be mentioned that in order to prevent problems with values of the different independent variables having orders of magnitude differences, scaling of variables was tried. The regression coefficients remained unchanged, indicating the program automatically compensated for order of magnitude differences in the variables. Therefore, no scaling was done for any of the variables.

Model Development at Downstream Coil Faces

Model 9 was used to develop equations for all three anemometers. This equation is:

$$K = a_0 + a_1 \times MV + a_2 \times ROWS + a_3 \times FPI + a_4 \times SP + a_5 \times OD + a_6 \times MV^2 \quad (7)$$

The 19 sets of standard and offset values of *K* were averaged, and the average face velocity, *MV*, was corrected to the air density at which the anemometer was calibrated (standard density). In addition, the K-factor was also corrected to the value for standard density air. The correction for *K* was:

$$KSTD = [(CFM \times 13.33/SpVOL)/FAC]/[VAVG \times (13.33/SpVOL)^{1/2}] \quad (8)$$

and the correction for *MV* was:

$$MVSTD = VAVG \times (13.33/SpVOL)^{1/2} \quad (9)$$

where

KSTD = coil K-factor for standard density air
CFM = actual volume flow through the coil (ft^3/min)
SpVOL = specific volume of air passing through the coil (ft^3/lb)
FAC = coil face area (ft^2)
VAVG = average face velocity obtained from averaging all of the anemometer readings taken (38) at the coil face (ft/min)
MVSTD = average face velocity read at the coil face, corrected for anemometer calibration (ft/min)

This correction is necessary since the anemometer is calibrated at standard density conditions, and it is necessary to correct this velocity reading to standard density

TABLE 2

K-Factor Coefficients for Vane Anemometers at Coil Faces

Coefficient or Factor	4" Head Anemometer	2 3/4" Head Anemometer	1" Head Anemometer
a_0	0.65204515	0.43683959	0.65630868
a_1	0.000176163	0.000244074	0.000206599
a_2	0.000971875	0.003190674	−0.01618829
a_3	−0.00674507	−0.01287297	−0.01075565
a_4	0.04736985	−0.19805658	−0.10284339
a_5	−0.09111685	0.88839435	0.3255312
a_6	−8.68316 E-08	−1.14222 E-07	−7.88255 E-08
R_a^2	0.66	0.87	0.86
Points	218	55	54

air. The equation for the coil K-factor then becomes

$$KSTD = a_0 + a_1 \times MVSTD + a_2 \times ROWS + a_3 \times FPI + a_4 \times SP + a_5 \times OD + a_6 \times MVSTD^2 \quad (10)$$

where

FPI = fins per inch
SP = tube spacing (in.)
D = outside tube diameter (in.)

In the following development and discussion, the standard density K-factor (*KSTD*) is used the same as *K* and the face velocity (*MVSTD*) is used the same as *MV*. That is, it is implied in the calculations that the average face velocity is always corrected to the density of air at which the anemometer was calibrated and the K-factor is always corrected to standard density air. These corrections are done according to the above equations.

The appropriate data for each anemometer were selected from the data base and corrected to standard conditions. These data were then input to the statistical program and the coefficients for each size of anemometer were determined to give the best fit to the data available. The results from this statistical evaluation are given in Table 2.

The major thrust for this project was to investigate the K-factor for the 4-in.-diameter rotating vane anemometer, so the majority of the data were for that size. Six coils were tested using the 2 3/4-in. and 1-in. anemometers. For some coils, it was not possible to obtain 10 velocity readings due to larger pressure drops through the coil, so only 9 readings may be present. It can be observed in Table 2 that the correlation factor R_a^2 is better for the 2 3/4-in. and 1-in. anemometers than it is for the 4-in. This is most likely due to a larger variation in the coil parameters in the 4-in. size than in the other two sizes. This is a result of more coils (19) being tested for 4-in. than for the 2 3/4-in. and 1-in. sizes (6 coils). However, the correlation still appears to be quite good for all three sizes, as will be pointed out later.

RESULTS

4-Inch Anemometer Analysis

Figure 1 shows the K-factor comparison between measured and predicted values using the 4-in. anemometer. The predicted value was from Equation 10 using the coefficients in Table 2. The lines in Figure 1 show a ±10% difference between the two values. All of the data lie within these and most of the data lie within ±7%.

Figure 2 shows the variation between predicted and measured values of *K* as a function of the *VMAX/VMIN* variable. *VMAX* is the largest anemometer velocity reading out of the 38 total readings and *VMIN* is the smallest. This variable represents the diversity of the velocity readings at the coil face, and the largest value observed in this data set was 1.8. It is apparent from Figure 2 that there is no relationship between *VMAX/VMIN* and the percent variation. Again, this figure shows that the majority of the data are predicted within ±7%.

In Figure 3, the percent difference between predicted and measured K-factors for all coils is plotted vs. the

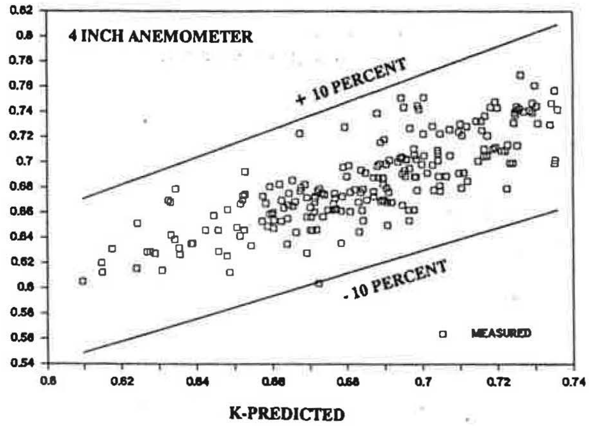


Figure 1

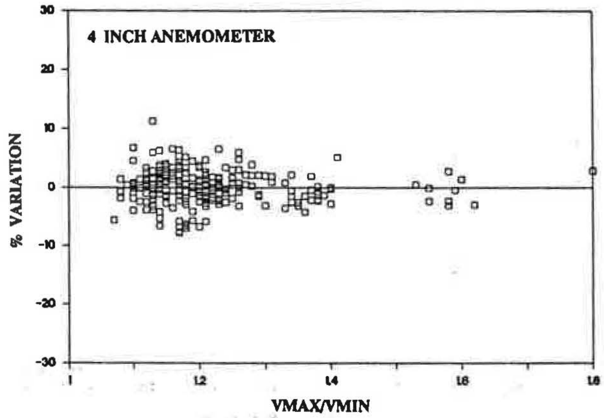


Figure 2

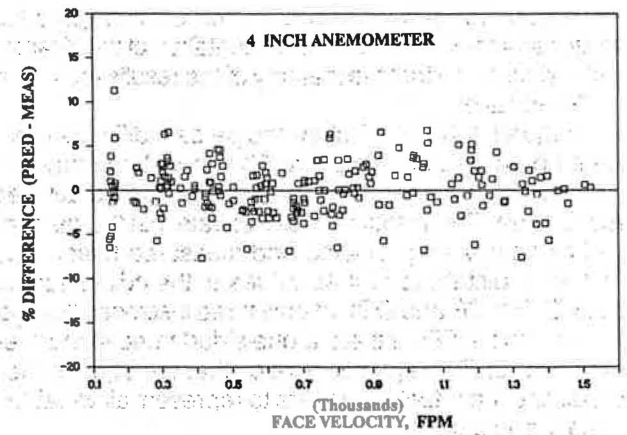


Figure 3

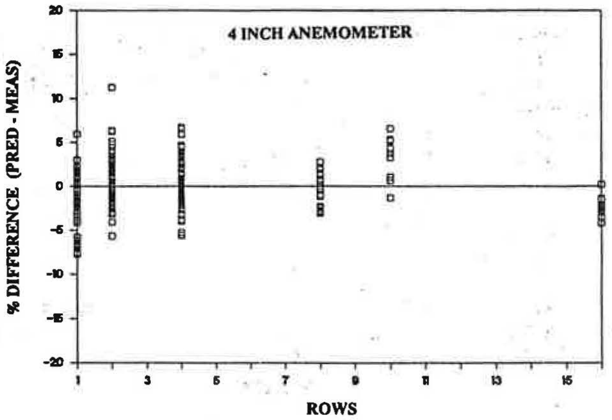


Figure 4

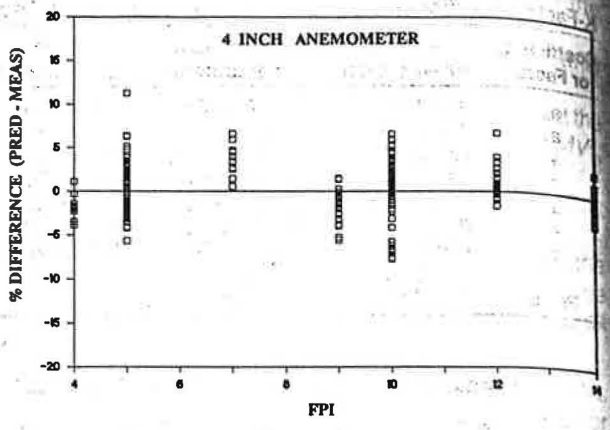
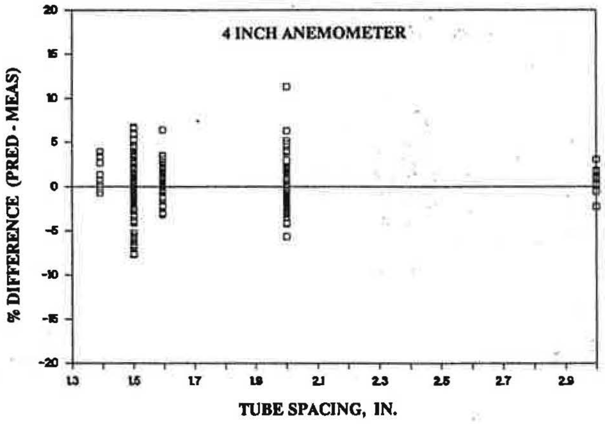


Figure 5



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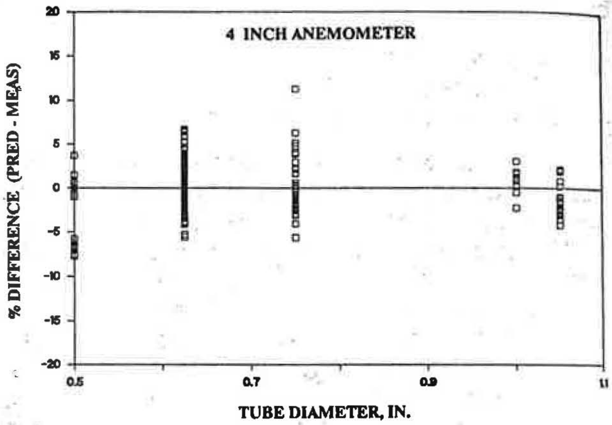

Figure 7

measured average face velocity at the coil. This figure illustrates that there is uniform representation of the K-factor with velocity and that the majority of the results are within ± 7% variation.

Figures 4 through 7 show the percent difference between predicted and measured K-factors for number of rows, fins per inch, tube spacing, and tube diameter, respectively. These four figures illustrate that the percent variation between predicted and measured K-factors is uniformly distributed for all values of the coil variables (*ROWS, FPI, SP,* and *OD*). In only three instances (10 and 16 rows and 7 *FPI*) is there a one-sided trend in the prediction error. This again illustrates that the equation for predicting the K-factor appears to represent all variables equally and uniformly.

2 3/4-Inch Anemometer Analysis

The measured K-factor for a 2 3/4-in.-diameter anemometer head is shown compared with the predicted K-factor in Figure 8. The predicted value was calculated using Equation 10 and the coefficients from Table 2 for this size of anemometer (*K* is for standard density air). There appears to be more dispersion at the lower values of *K* than for the higher values. The percent variation between the predicted and measured K-factor is shown in Figure 9 as a function of *VMAX/VMIN*. Again, there is no relationship between the percent variation and *VMAX/VMIN*. The results for this anemometer applied to the six coils show a ±5% agreement between measured and predicted K-factors, which is slightly better than for the 4-in. anemometer. The better agreement may be due to the facts that not as many coils were tested and not all of the extremes of *ROWS, FPI,* and *SP* or *OD* were included for the 2 3/4-in. anemometer.

1-Inch Anemometer Analysis

The measured K-factor for the 1-in.-diameter rotating vane anemometer is shown compared to the predicted K-factor in Figure 10. The predicted K-factor was obtained using Equation 10 and the coefficients from Table 2 for this size of anemometer (*K* is for standard density air). The distribution appears to be reasonable for this particular case. In Figure 11, the percent variation between the predicted and measured K-factor is shown plotted vs. *VMAX/VMIN*. There is no trend with respect to *VMAX/VMIN*, but there is only about ±10% accuracy with this smaller size of anemometer.

Parametric Analysis

In this section, the various parameters affecting the prediction of the K-factor are analyzed individually for all three sizes of rotating vane anemometers. These parameters are *MV, ROWS, FPI, SP,* and *OD*. For each study, the coefficients that are not being analyzed are set equal to zero and the one that is being analyzed is varied through a typical range for that variable.

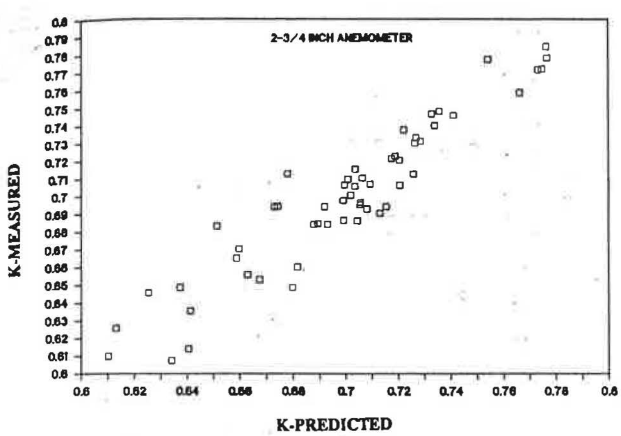

Figure 8

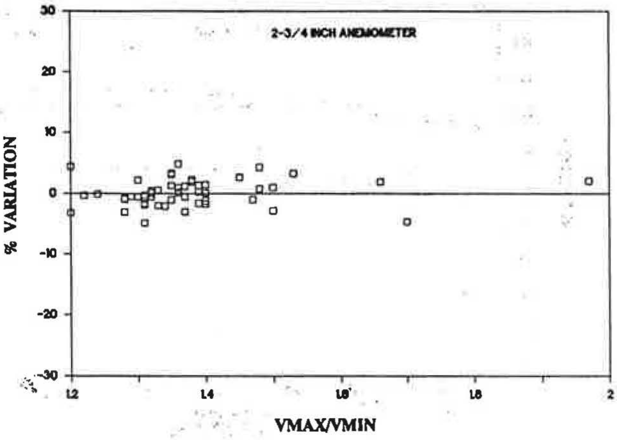

Figure 9

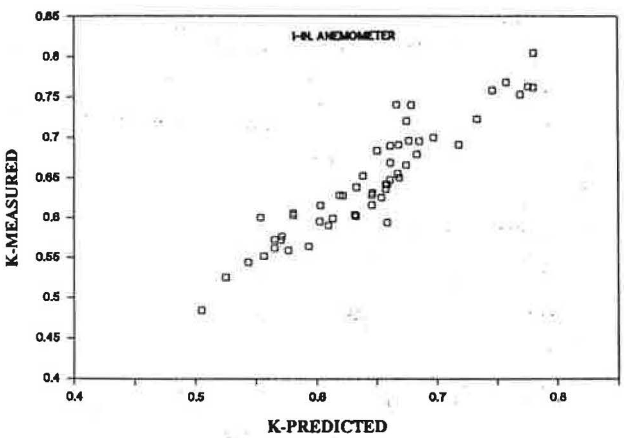

Figure 10

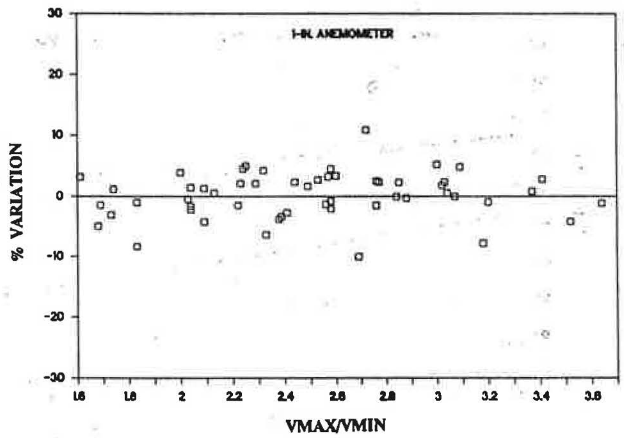

Figure 11

For the effect of velocity on the K-factor, the following equation is used:

$$KSTD = a_0 + a_1 \times MVSTD + a_6 \times MVSTD^2 \quad (11)$$

The coefficients for a_0, a_1, and a_6 were taken from Table 2 for the appropriate size of anemometer. In Figure 12, the results for the 4-in., 2 3/4-in., and 1-in. anemometers are shown. All three sizes show the same trend where K increases with velocity up to 1000 to 1200 fpm and then decreases slightly. The difference in the value for the 2 3/4-in. anemometer is due to the effect some of the other parameters (*ROWS, FPI, SP*, and *OD*) have on the constant a_0.

For the effect of rows of tubes on the K-factor, the following equation was used:

$$KSTD = a_0 + a_2 \times ROWS \quad (12)$$

The coefficients from Table 2 were used for a_0 and a_2 for each size of anemometer. In Figure 13, the results for the 4-in., 2 3/4-in., and 1-in. anemometers are plotted vs. the number of rows up to 16. The 4-in. and 2 3/4-in. anemometers have the same trend—larger K for more rows. The 1-in. anemometer has the opposite trend. The only apparent reason for this is the statistical analysis of the data where this size of anemometer head exhibited this type of response for the number of rows.

The same thing was done for fin spacing and the equation used was as follows:

$$KSTD = a_0 + a_3 \times FPI \quad (13)$$

Again, the values for a_0 and a_3 were taken from Table 2 for each size of anemometer. The results are illustrated in Figure 14 for up to 16 fins per inch. All three sizes of anemometer head exhibit the same trend—a decrease in K-factor for higher fins per inch. This might be expected, since more fins per inch make less area available for air flow, resulting in a higher velocity through the free area. This tends to give a lower K-factor because of the anemometer response characteristics.

Similar calculations were carried out for tube spacing, *SP*, and tube outside diameter, *OD*. These results are given in Figures 15 and 16, respectively. Again, due to the sign of the coefficients and the magnitude of the coefficients, there are different trends with the different sizes of rotating vane anemometers. These differences are due apparently to the statistical evaluation of the data and how the particular parameter affected the measured K-factor for the size of anemometer used.

SUMMARY

Experimental measurements of volume flow rate of air through coils have been made and compared with predicted airflow rates obtained by measuring the velocity at several locations and the air density. Comparison of these two values yields what is called a K-factor or correction factor. If the K-factor is known a priori, then the volume flow rate of air can be obtained by measuring an average face velocity at the coil, the face area, and the air density.

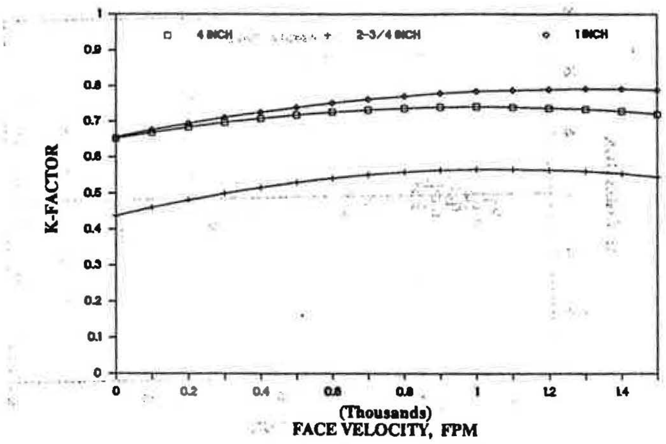

Figure 12

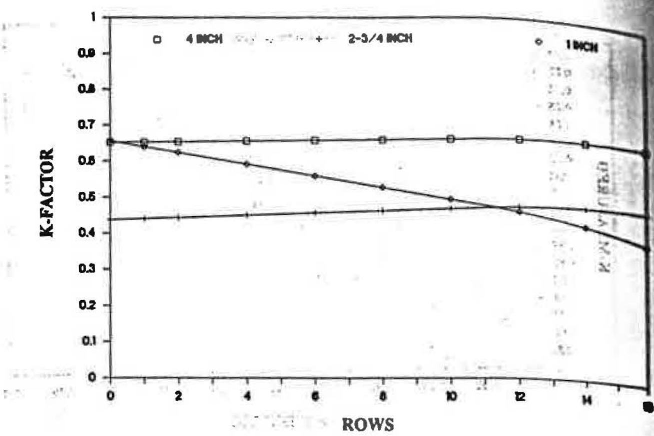

Figure 13

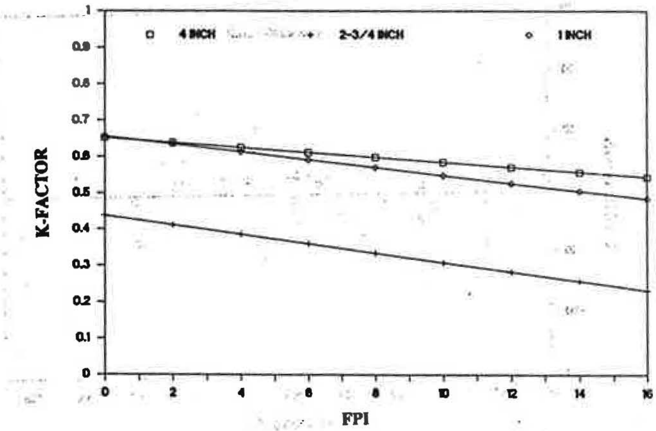

Figure 14

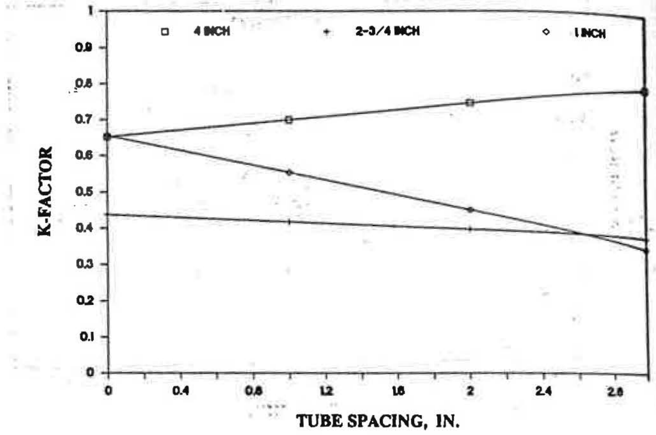

Figure 15

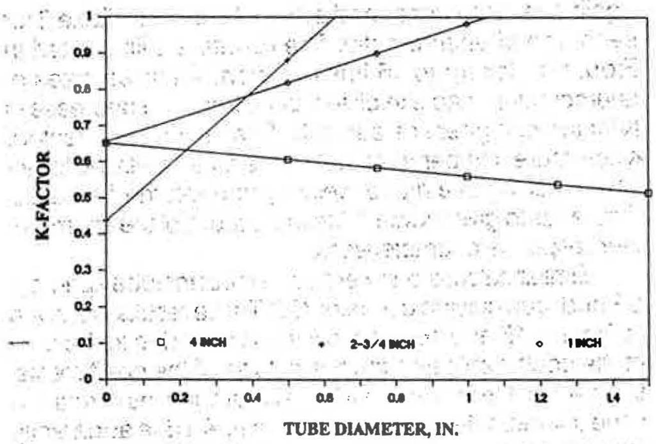

Figure 16

Equations for the K-factor were obtained for rotating vane anemometer heads having diameters of 4 in., 2 3/4 in., and 1 in. These K-factor equations are a function of measured average velocity, rows of tubes deep, fins per inch, vertical tube spacing, and tube outside diameter. The equations were selected from the best statistical models, which gave the highest correlation factors for the range of coil variables and velocities obtained during the experimental phase. The average face velocity ranged from 100 fpm to 1100 fpm, the rows of tubes ranged from 1 to 16, the fins per inch ranged from 5 to 14, the vertical tube spacing ranged from 1.39 in. to 3 in., and the tube outside diameter ranged from 0.5 in. to 1.05 in.

Whenever a pitot traverse is impossible or impractical, the 4-in. rotating vane anemometer is recommended as the alternative procedure for making the velocity measurements necessary to determine the volume flow rate. The anemometer should be calibrated to standard air density and, therefore, the velocity readings must be corrected to standard air density. The 38 recommended readings are to be taken in the standard and offset patterns in order to incorporate coil and anemometer geometry into the velocity reading location. These 38 readings then need to be averaged.

A detailed procedure is given in Appendix A for applying the K-factor concept to coil volume flow measurements. Use of this procedure should result in measuring the volume flow rate at the coil face to within $\pm 7\%$. This $\pm 7\%$ uncertainty includes the $\pm 1\%$ to 2% instrument error (exclusive of usage error). The uncertainty of $\pm 7\%$ in the 4-in. rotating vane anemometer method compares with the typical uncertainty in the pitot traverse method of 5% to 10%. However, it should be kept in mind that the pitot tube traverse procedure is not practical below about 600 fpm velocity, whereas the rotating vane anemometer method described in Appendix A is valid from 200 to 1500 fpm.

Appendix B shows the application of the procedure given in Appendix A to 27 sets of flow measurements. For all of these calculations, the average percent difference between the predicted and measured volume flow rate was 5.65%.

As a practical matter, the procedure of using the rotating vane anemometer on a wet coil should not be carried out. With water on the coil and possible droplets of water impinging the anemometer, the velocity measurements become uncertain. Caution should be used in applying this technique to coils when there is water on the surface.

Upstream disturbances such as elbows, partially blocked coils, dampers, and fan blasts had virtually no effect on the accuracy of using the K-factor procedure, as long as the measured velocities were positive and relatively uniform.

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APPENDIX A

Measurement and Calculational Procedure

The procedure for applying the K-factor concept to determine the volume flow rate at coil faces is:

Step 1 Mark the coil so that standard and offset location readings can be taken. This should be done according to the pattern indicated in Figure A-1. The values for the dimensions in Figure A-1 are given in Table A-1.

Step 2 Measure the coil height and width, and calculate the coil face area from

$$A = H \times L$$

(NOTE: Face area does not include area of the frame.)

Step 3 With the air flowing through the coil, measure the air dry-bulb temperature, wet-bulb temperature, and air pressure. Calculate the specific volume of the air flowing through the coil from

$$v = (R_a T/P)(1 + 1.6078\, W)$$

where

- v = specific volume, ft^3/lb
- R_a = gas constant for air, 53.35 $ft\text{-}lb_f/lb_m$ R
- T = absolute temperature, R
- P = total absolute pressure, lb_f/ft^2
- W = humidity ratio, lb_v/lb_a

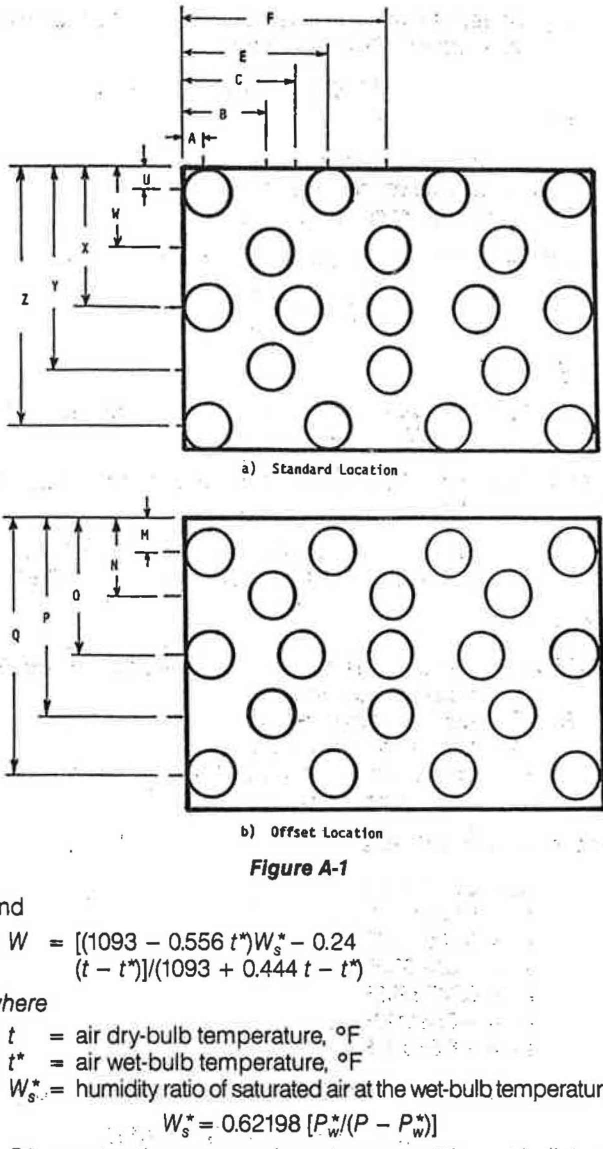

Figure A-1

and

$$W = [(1093 - 0.556\, t^*)W_s^* - 0.24\,(t - t^*)]/(1093 + 0.444\, t - t^*)$$

where

- t = air dry-bulb temperature, °F
- t^* = air wet-bulb temperature, °F
- W_s^* = humidity ratio of saturated air at the wet-bulb temperature

$$W_s^* = 0.62198\, [P_w^*/(P - P_w^*)]$$

- P_w^* = saturation pressure for water vapor at the wet-bulb temperature

Step 4 Using a calibrated rotating vane anemometer (calibrated to standard density air), take 19 velocity readings at the standard location and 19 readings at the offset location (Figure A-1). These are to be fixed location readings allowing a reasonable time for the anemometer to respond to the velocity at that location (5 to 15 seconds).

TABLE A-1
Dimensions for Taking Readings for the Standard and Offset Reading Patterns

$A = D/2$	$U = D/2$
$B = (L + 2D)/6$	$W = (H + D)/4$
$C = (L + D)/4$	$X = H/2$
$E = (2L + D)/6$	$Y = (3H - D)/4$
$F = L/2$	$Z = H - D/2$
$M = (D + SP)/2$	
$N = (H + D - 4SP)/4$	
$O = (H - SP)/2$	
$P = (3H - D - 2SP)/4$	
$Q = (2H - D - SP)/2$	
H = Height of Coil	
L = Length of Coil	
D = Diameter of Rotating Vane Anemometer Head	
SP = Tube Spacing of Coil	
All in consistent units.	
Coil Face Area = $H \times L$	

Step 5 Correct the measured velocity readings from Step 4 to standard density air according to:

$$MVSTD = V \times (13.33/v)^{1/2}$$

where

V = measured velocity
v = specific volume of air, ft^3/lb
$MVSTD$ = velocity of standard density air

Step 6 Determine the average velocity reading at the coil face using:

$$MVSTDAV = \sum_{i=1}^{38} MVSTD_i/38$$

where

$MVSTDAV$ = the average air velocity for the 38 measured coil velocities

Step 7 Determine the K-factor for this coil from the following equation:

$$KSTD = a_0 + a_1 \times MVSTDAV + a_2 \times ROWS + a_3 \times FPI + a_4 \times SP + a_5 \times OD + a_6 \times MVSTDAV^2$$

where

$MVSTDAV$ = the average standard air velocity for the 38 measured coil velocities (ft/min)
$ROWS$ = number of rows deep of tubes in coil
FPI = fins per inch for the coil
SP = tube spacing at coil face (in.)
OD = tube outside diameter (in.)

and for 4-in. anemometers

a_0 = 0.65204515
a_1 = 0.000176163
a_2 = 0.000971875
a_3 = −0.006745072
a_4 = 0.04736985
a_5 = −0.09111685
a_6 = −8.68316 E-08

Step 8 Calculate the volume flow rate through the coil from

$$QSTD = A \times MVSTDAV \times KSTD$$

where

$QSTD$ = volume flow rate of standard density air

Step 9 If the actual volume flow rate is desired, calculate this from

$$QACT = QSTD \times v/13.33$$

where

$QACT$ = volume flow rate of actual density air through the coil

---

SPECIAL NOTE: Steps 3 and 5 (the density correction) may be neglected if the corresponding degree of accuracy is not necessary, consistent with the requirements of the job and the time and effort available. The following table gives the relative effect of neglecting the density correction:

DENSITY CHANGE, %	VARIATION IN VELOCITY, %
0	0
1	0.50
2	1.00
3	1.49
4	1.98
5	2.47

APPENDIX B

Example Calculations

The procedure given in Appendix A was applied to three different coils for three different velocities (low, medium, and high), using the three different sizes of anemometer. The three coils selected were the H coil (1 row, 4 FPI, 1.5-in. spacing, and 0.625-in. OD), the N coil (4 rows, 9 FPI, 1.5-in. spacing, and 0.625-in. OD), and the I coil (10 rows, 10 FPI, 1.5-in. spacing, and 0.625-in. OD). The actual volume flow rate was measured in the flow facility, and the estimated flow rate was calculated using the procedure given in Appendix A. The results are presented in Table B-1.

From Table B-1, it can be seen that the largest difference between predicted and measured cfm was +14% and the smallest was -0.49%. This appears to be quite reasonable. In Table B-2, the averages for all of the readings, for the individual coils, for the individual velocities, and for each size of anemometer are presented.

For all 27 cases, the average percent difference was 5.65%, which is consistent with the comparison of the actual to the measured K-factor discussed previously, where a 7% difference was observed. Each of the coils considered separately had a similar percent difference (4.79% to 6.54%), as did each of the three velocities (4.73% to 6.84%). The 2 3/4-in. anemometer had a low percent difference (2.16%), and the 1-in. anemometer had a higher (7.91%) percent difference.

TABLE B-1
Results of Applying the K-Factor Procedure and Comparing It to the Actual Measured Volume Flow Rate

	ANEMOMETER SIZE IN.	*CFM* MEASURED	*SP* VOLUME ft³/lb	*MV* MEASURED FPM	*MV* STANDARD FPM	*K*	*CFM* STANDARD ESTIMATED	*CFM* ACTUAL ESTIMATED	DIFFERENCE ACTUAL CFM %
	4	6344	14.1	1435	1395	0.717	6001	6348	−0.063
	4	3112	14.1	719	699	0.721	3024	3199	2.79
H-COIL	4	1218	14.1	304	296	0.685	1217	1287	5.66
1 ROW	2 3/4	6344	14.1	1327	1290	0.771	5968	6313	−0.49
4 FPI	2 3/4	3112	14.1	672	653	0.757	2966	3137	0.80
1.5″ Spacing	2 3/4	1218	14.1	286	278	0.706	1178	1246	2.30
D = 0.625″	1	6344	14.1	1477	1436	0.780	6720	7108	12.04
	1	3112	14.1	733	713	0.754	3226	3412	9.64
	1	1218	14.1	307	298	0.701	1253	1325	8.78
	4	1206	14.2	338	327	0.658	1291	1375	14.00
	4	3055	14.2	778	751	0.693	3123	3327	8.90
N-COIL	4	6311	14.2	1615	1565	0.672	6310	6722	6.51
4 ROWS	2 3/4	1206	14.3	290	281	0.650	1097	1177	−2.40
9 FPI	2 3/4	3055	14.3	722	697	0.700	2956	3171	3.8
1.5″ Spacing	2 3/4	6311	14.3	1397	1354	0.720	5792	6213	−1.5
D = 0.625″	1	1206	14.2	331	321	0.600	1159	1234	2.4
	1	3055	14.2	826	797	0.660	3151	3356	9.85
	1	6311	14.2	1523	1476	0.680	5995	6386	1.20
	4	5312	14.4	1330	1280	0.692	5315	5742	8.09
	4	3225	14.4	808	777	0.693	3231	3490	8.22
I-COIL	4	1241	14.4	326	313	0.655	1230	1329	7.09
10 ROWS	2 3/4	5312	14.4	1203	1157	0.728	5054	5460	2.79
10 FPI	2 3/4	3225	14.4	752	724	0.715	3106	3355	4.03
1.5″ Spacing	2 3/4	1241	14.4	303	291	0.660	1152	1224	−1.37
D = 0.625″	1	5312	14.5	1635	1573	0.566	5342	5811	9.34
	1	3225	14.5	1034	995	0.564	3367	3662	13.55
	1	1241	14.5	410	393	0.505	1191	1296	4.43

TABLE B-2
Analysis of the Results Given in Table B-1

	% DIFFERENCE	AVERAGE FOR ALL
COIL		
H	4.74	
N	5.62	5.65
I	6.54	
VELOCITY		
LOW	5.38	
MEDIUM	6.84	5.65
HIGH	4.73	
ANEMOMETER SIZE		
4″	6.88	
2 3/4″	2.16	5.65
1″	7.91	