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A Goal Method and a Target Method for Balancing Exhaust Ventilation Duct Systems with Dampers

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This work presents and discusses two approaches to adjusting dampers, here called the Goal and Target Methods. A form of the Goal Method is commonly employed but has not been clearly described or discussed elsewhere. The Target Method is a novel variation of so-called “proportional” methods. Detailed step-by-step procedures for each are presented. It is likely that the most common method of balancing the airflows in ventilation systems is simply to adjust the damper in each branch in turn until the observed airflow for each branch duct (Q_{br}) equals the goal airflow ($Q_{br-goal}$). This is a simple Goal Method. It is difficult and time-consuming due to interactions among branches and with the fan. As one adjusts a damper to reduce airflow in that duct, all other airflows increase. As each damper is inserted, the overall resistance of the system increases, reducing fan output. The Target Method uses target values of centerline velocity pressure (VP_{cl}) or hood static pressure (SP_h) computed from the measured values of VP_{cl} and SP_h multiplied by factors intended to account for (a) initial Q_{br} and $Q_{br-goal}$, (b) the interactive effects of dampers on branch airflows, and (c) a model that predicts the reduction in fan airflow due to the dampers. Simulations on a computer spreadsheet predict that the Target Method will produce better accuracy for fewer adjustments than the goal method, but it is more computationally difficult.

Keywords balancing, dampers, ventilation

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BACKGROUND

The distribution of airflows in exhaust ventilation systems often diverges from needed values due to adding and removing branches, replacing hoods, and responding to changes in airflow requirements due to changes in work practices, process temperatures, etc. Rather than changing duct sizes or otherwise altering the duct system to achieve the distribution that is needed, in most cases practitioners instead install dampers on branch ducts and adjust them to “balance” the airflows to meet current requirements. This work presents and discusses two approaches to adjusting dampers,

here called the Goal and Target Methods. A form of the Goal Method is commonly employed but has not been clearly described or discussed elsewhere. The Target Method is a novel variation of so-called proportional methods. Detailed step-by-step procedures for each are presented.

The most common method of balancing the airflows in ventilation systems is simply to adjust the damper in each branch in turn until the observed airflow for each branch duct (Q_{br}) equals the goal airflow ($Q_{br-goal}$). This is a simple Goal Method. It is difficult and time-consuming due to interactions among branches and with the fan. As one adjusts a damper to reduce airflow in that duct, all other airflows increase. As each damper is inserted, the overall resistance of the system increases, reducing fan output.

The Target Method uses target values of centerline velocity pressure (VP_{cl}) or hood static pressure (SP_h) computed from the measured values of VP_{cl} and SP_h multiplied by factors intended to account for (a) initial Q_{br} and $Q_{br-goal}$, (b) the interactive effects of dampers on branch airflows, and (c) a model that predicts the reduction in fan airflow due to the dampers. Simulations on a computer spreadsheet predict that the Target Method will produce better accuracy for fewer adjustments than the Goal Method, but it is more computationally difficult.

Dampers are ventilation devices used to adjust the airflows through the branches in a duct system. A damper reduces the airflow to a given branch by adding its own resistance (X_{damper}) to the branch’s initial resistance to flow. X_{damper} can be computed from the total pressure due to the damper divided by the velocity pressure just upstream from the damper. For a given damper, X_{damper} increases with the fraction of the duct cross-section blocked by the damper. As X_{damper} increases, the total resistance of the branch increases correspondingly and more airflow is diverted to alternate pathways. By judicious adjustment of all dampers in a system, one can force the relative airflows through the branches to achieve a desired distribution. This is called balancing with dampers.

The set of X_{damper} values required to achieve a given airflow distribution can be predicted mathematically but requires a daunting amount of information about the entire duct system.⁽¹⁾ For that reason, it is likely that nearly all dampers are adjusted

using trial and error methods. That is, one adjusts and readjusts the damper while comparing the observed pressure or flow to the level desired for that damper.

It can be frustrating and tedious to adjust dampers to achieve desired airflow distributions, especially if one employs the strategy of adjusting each damper until its observed airflow equals the airflow goal for that branch duct. Although that strategy (Goal Method) appears to be commonly used, there is no detailed procedure for it published in the literature. In addition, a new balancing method (the Target Method) is proposed. Other sections discuss issues related to use of dampers and the bases for the proposed methods. Finally, both the Goal Method and the Target Method are tested by mathematically simulating damper adjustments on a 6-branch ventilation system.

Strategies for Adjusting Dampers

One strategy to achieve a new distribution is to adjust each damper to a target value of X_{damper} . This can be done using orifices whose resistances to flow can be predicted or by using estimates of X_{damper} determined experimentally for common damper types, such as the estimates published by Crowder and Loudermilk⁽²⁾ and Idel'chik.⁽³⁾ In addition, the Static Pressure Ratio Method⁽¹⁾ uses resistances to predict the ratio of the hood static pressure to the static pressure just upstream of the junction fitting for each branch duct and then bases adjustment of dampers on achieving the predicted ratios. The difficulty in each case is in predicting the values of X_{damper} that are required to achieve the desired distribution of airflows. The computations require a sophisticated pressure model of the installed system,⁽²⁾ making such predictions difficult without specifically written software.

The most commonly used balancing procedure is what will be called here the Goal Method. Different individuals may have somewhat different strategies, but the basic procedure is to adjust the first damper so that for it the observed branch airflow (Q_{br}) equals the airflow goal for that branch ($Q_{\text{br-goal}}$), then adjust the second damper so that $Q_{\text{br}} = Q_{\text{br-goal}}$ for it, and so on until all dampers have been adjusted to achieve the desired airflows. If done correctly, the observed fan airflow (Q_{fan}) will equal the goal fan airflow ($Q_{\text{fan-goal}}$).

Unlike the Goal Method, for a "proportional" method of damper adjustment, one adjusts all of the dampers until the fraction of total airflows for each branch duct equals the desired fraction instead of adjusting to achieve $Q_{\text{br}} = Q_{\text{br-goal}}$:

$$Q_{\text{br}}/Q_{\text{fan}} = Q_{\text{br-goal}}/Q_{\text{fan-goal}} \quad (1)$$

where

- Q_{br} = observed airflow in a branch duct
- Q_{fan} = observed airflow at the fan inlet
- $Q_{\text{br-goal}}$ = desired ("goal") airflow in the branch duct
- $Q_{\text{fan-goal}}$ = desired airflow at the fan inlet

Equation 1 can be rearranged to:

$$Q_{\text{br}} = Q_{\text{br-goal}}(Q_{\text{fan}}/Q_{\text{fan-goal}}) \quad (2)$$

Note that $Q_{\text{br}} = Q_{\text{br-goal}}$ only if $Q_{\text{fan}} = Q_{\text{fan-goal}}$. Hence, in the proportional methods, one first adjusts all the dampers to some common value of $Q_{\text{br}}/Q_{\text{br-goal}}$ then adjusts the fan output so that $Q_{\text{fan}} = Q_{\text{fan-goal}}$. SMACNA⁽⁴⁾ describes a proportional method for balancing supply air ducts. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)⁽⁵⁾ suggests balancing proportionally but does not provide details how that should be accomplished.

OBJECTIVES IN BALANCING AIRFLOWS

Dampers and fans should be adjusted together to provide sufficient airflow to each hood ($Q_{\text{br-goal}}$) while minimizing energy costs. Minimizing energy costs requires minimizing the total fan airflow (Q_{fan}) and the fan pressure. However, minimizing energy costs should be given lower priority than keeping all hood airflows at or above their goal levels.

It may be acceptable to have somewhat excessive airflows through some hoods as long as Q_{fan} is kept as low as possible. Q_{fan} can be measured just upstream of the fan or computed from mass balance from the sum of branch airflows:

$$Q_{\text{fan}} = \left(\frac{1}{df_{\text{fan}}} \right) \sum_{i=1}^n df_i Q_{\text{br}_i} \quad (3)$$

where

- i = ith branch duct
- df = density factor (ratio of actual to standard density)
- n = total number of branch ducts in the system

For the system as a whole, the least energy is consumed if the fan airflow (Q_{fan}) is the minimum possible value ($Q_{\text{fan-goal}}$), the level at which all branches have airflows exactly equal to their respective $Q_{\text{br-goal}}$ values. $Q_{\text{fan-goal}}$ can be computed from mass balance as:

$$Q_{\text{fan-goal}} = \left(\frac{1}{df_{\text{fan}}} \right) \sum_{i=1}^n df_i Q_{\text{br-goal}_i} \quad (4)$$

Densities vary throughout the systems, but in many systems the values of df upstream of the air-cleaning device are within 3% of each other. For those systems, the df terms can be omitted from Eqs. 3 and 4 with little effect on damper adjustment computations.

The level of airflow in each branch is determined both by the fan and by the damper adjustments. In the Goal Method, the desired level of airflow is achieved without adjusting the fan speed by using dampers alone. In proportional methods, the purpose of the dampers is limited to achieving the desired *distribution* of airflows (i.e., each hood receives the desired fraction of the total airflow). Because the distribution stays the same over very broad ranges as the fan speed is changed,⁽⁶⁾ the desired *level* of airflow for each branch can then be achieved by adjusting the fan output after all dampers have been adjusted.

Thus, for the proportional methods, the goal when adjusting dampers should be to force each branch duct to carry the same

proportion ($\%Q_{br-goal}$) of its goal airflow as all other branch ducts:

$$\%Q_{br-goal} = \left(\frac{Q_{br}}{Q_{br-goal}} \right) \times 100\% \quad (5)$$

Hence, a system is perfectly distributed when all values of $\%Q_{br-goal}$ equal the same value. Another goal in balancing should be to minimize the fan total pressure (TP_{fan}).

The level of damper resistance (and thus the fan pressure) is affected by the strategy of adjusting dampers. For the Goal Method adjusting dampers also "chokes" the fan down to $Q_{fan-goal}$. For proportional methods the fan speed is adjusted so that $Q_{fan} = Q_{fan-goal}$. Because the dampers are not used to reduce Q_{fan} any more than necessary to achieve desired proportions, the resistance added to the total system resistance by dampers is minimized. Hence, fan pressure required for proportional methods is always less than or equal to the amount required in the same system for the Goal Method.

Measure of Effectiveness of Damper Adjustments

The two main goals for airflows are that all hoods have sufficient airflow and that the total be otherwise minimized. Thus, if the value of any $\%Q_{br-goal}$ falls below unity then the fan airflow must be increased so that the minimum value of $\%Q_{br-goal}$ becomes unity. If that is done, all branch airflows would change proportionally to the inverse of the minimum value of $\%Q_{br-goal}$ prior to adjusting the fan. Thus, the excess airflow relative to $Q_{fan-goal}$ can be computed before adjusting the fan output from:

$$\% \text{ Excess } Q_{fan} = 100\% \left[\frac{100\%}{\% \min Q_{br-goal}} \times \frac{Q_{fan}}{Q_{fan-goal}} - 1 \right] \quad (6)$$

where

$\% \min Q_{br-goal}$ = minimum ratio of actual to desired airflow among all branches

For example, if $Q_{fan}/Q_{fan-goal} = 1.40$ and $\% \min Q_{br-goal}$ is 82%, then the total $\% \text{ Excess } Q_{fan-goal}$ computed using Eq. 6 is 71%. A $\% \text{ Excess } Q_{fan-goal}$ of less than 5% probably would be considered excellent by most ventilation practitioners and 10% probably would be considered acceptable.

FAN ADJUSTMENTS

Because fan airflow is inversely related to system resistance, fan airflows will decrease as dampers are inserted. Modeling the interactive effects of damper adjustments and fan output is beyond the scope of anything published to date. However, it may be possible to estimate the ideal fan airflow ($Q_{fan-ideal}$) by considering the effect on the fan airflow of adjusting dampers to a perfect relative distribution.

One extreme would be no change in fan output with damper insertions. That is, the fan airflow is independent of damper resistance and the effect of inserting a damper is solely to shift airflows to other branches. Hence, Q_{fan} would equal $Q_{fan-open}$ no matter how dampers were adjusted. The other extreme

would occur if the fan airflow were so profoundly affected by increases in resistance with damper adjustments that the reduction in fan airflow equals the reduction in branch airflow. In that case, all $\%Q_{br-goal}$ values would equal the lowest initial branch airflow ratio ($\% \min Q_{br-goal}$) and the value of Q_{fan} would equal $Q_{fan-goal}$ multiplied by $\% \min Q_{br-goal}$.

The actual airflow after damper adjustments would fall somewhere between those two extremes. Where it fell would depend on the values of X_{damper} for all dampers as well as on the fan curve. Predicting that operating point would require a model of the effects of the dampers on resistance and a model of the effects of resistance on the fan output. Without such models, one must make an educated guess. For example, one simply could use the middle of the range as a guess:

$$Q_{fan-after-balancing} = \frac{Q_{fan-open} + (\% \min Q_{br-goal}/100\%)Q_{fan-goal}}{2} \quad (7)$$

where

$Q_{fan-after-balancing}$ = fan airflow after dampers are adjusted but before the fan output is adjusted
 $\% \min Q_{br-goal}$ = minimum value of $\%Q_{br-goal}$ after all dampers have been adjusted but with no adjustment to the fan

Because $Q_{fan-after-balancing}/Q_{fan-open}$ represents the relative airflow due to damper adjustment, then if one wished the airflow to equal $Q_{fan-goal}$ after adjusting dampers, the fan airflow should be adjusted to:

$$Q_{fan-ideal} = Q_{fan-goal} \left(\frac{Q_{fan-open}}{Q_{fan-after-balancing}} \right) \quad (8)$$

Combining Eqs. 5 and 8 produces:

$$Q_{fan-ideal} = Q_{fan-goal} \times \left(\frac{Q_{fan-open}}{Q_{fan-open} + (\% \min Q_{br-goal}/100\%) Q_{fan-goal}} \right) \quad (9)$$

Equation 9 also can be stated as:

$$Q_{fan-ideal} = \left(\frac{Q_{fan-open}}{Q_{fan-open}/Q_{fan-goal} + (\% \min Q_{br-goal}/100\%)} \right) \quad (10)$$

It is useful to define the FanFactor as the ratio of $Q_{fan-open}$ to $Q_{fan-ideal}$. From Eq. 10 this would be:

$$\text{FanFactor} = \frac{Q_{fan-open}/Q_{fan-goal} + (\% \min Q_{br-goal}/100)}{2} \quad (11)$$

After all dampers have been adjusted, all branch airflows should be measured and compared to $Q_{br-goal}$ values. The fan speed should be adjusted from its current rotation rate (ω_1) so that the branch with the minimum $\%Q_{br-goal}$ value has sufficient airflow. That will be accomplished at a new rotation rate (ω_2)

that can be computed, perhaps a modest safety factor (e.g., 5%), from:

$$\omega_2 = \frac{\omega_1(1 + \text{Safety Factor})}{\% \min Q_{br-goal}/100\%} \quad (12)$$

For example, suppose that after all dampers have been adjusted, the minimum value of $\%Q_{br-goal}$ is 0.82, assuming that no safety factor is included. Applying Eq. 12, the necessary fan rotation rate could be estimated as:

$$\omega_2 = \omega_1/\% \min Q_{br-goal} = \omega_1/0.82 = 1.22\omega_1$$

Note that an increased fan rotation speed and static pressure may require upgrading the fan motor to one with a higher power rating.

Adjustment Goals for Each Damper for the Goal Method

Although the goal in balancing is to provide the desired airflow for each branch, determining airflow from Pitot traverses can be time-consuming, especially if they are done for each minor adjustment in insertion depth. It may be more convenient to use goal values that are easier to measure but are proportional to airflow squared, such as the centerline velocity pressure (VP_{cl}) or the hood static pressure (SP_h).

Because velocity pressure (VP) and hood static pressure (SP_h) both are proportional to Q^2 , it is possible to use either as the indicator that the airflow has been adjusted to $Q_{br-goal}$:

$$VP_{cl-goal} = VP_{cl-open} \left(\frac{df_{goal} Q_{br-goal}}{df_{open} Q_{br-open}} \right)^2 \quad (13)$$

where

$VP_{cl-goal}$ = centerline velocity pressure that should exist when the observed airflow equals $Q_{br-goal}$

$VP_{cl-open}$ = centerline velocity pressure measured with all dampers open

Note that use of Eq. 13 does not require that the pipe factor (i.e., V_{avg}/V_{cl}) equal 0.9 or any other fixed value. Likewise,

$$SP_{h-goal} = SP_{h-open} \left(\frac{df_{goal} Q_{br-goal}}{df_{open} Q_{br-open}} \right)^2 \quad (14)$$

If density does not vary significantly from the time prior to adjustments to the time the dampers are adjusted, the density factor terms cancel out in Eqs. 13 and 14.

There is no available published evidence that demonstrates whether SP_h values are more reliable surrogates for Q_{br} than are VP_{cl} values.

Adjustment Targets for Each Damper in the Target Method

There are three problems with adjusting dampers to achieve a goal value: (1) if the fan airflow is insufficient, the process will fail, forcing the practitioner to adjust the fan output and start over; (2) if the fan airflow is excessive, the fan pressure will be higher than could be achieved using proportional methods;

and (3) the branch airflow and static pressures will rise as each subsequent damper is adjusted. The first two problems are sufficient reason to prefer proportional methods for most systems.

The third problem is perhaps responsible for a great deal of the frustration associated with using any variant of the Goal Method even when the fan airflow is sufficient; adjusting any damper changes *all* airflows. Only the last branch adjusted will have $Q_{br} = Q_{br-goal}$. For all others Q_{br} will exceed $Q_{br-goal}$, with the first branches to be adjusted showing the greatest excesses. Because $VP_{cl-goal}$ and SP_{h-goal} are proportional to $Q_{br-goal}$ squared, the same is true of them. Clearly, the target value during adjustments should be lower than the goal values for all except the last branch adjusted, and the branches adjusted first should have the greatest reduction. That is, one should adjust to a Q_{target} , $SP_{h-target}$, or $VP_{cl-target}$, each of which are different from $Q_{br-goal}$, SP_{h-goal} , and $VP_{cl-goal}$, respectively.

There is no experimental or theoretical basis for predicting this order effect. For lack of a better alternative, extensive trial and error simulation experiments using ventilation design software were used to produce the following adjustments based on order:

$$\%k = (n/N)^{0.0445} \times 100\% \quad (15)$$

where

$\%k$ = factor based on the order of damper adjustment
 n = sequence number for adjustment of the damper
 N = total number of branch ducts

The values predicted by Eq. 15 are presented as rough guesses only. Clearly, the optimum values of $\%k$ plausibly would vary with both the system and the degree of change of its distribution of airflows.

Another correction in estimating the target can be made for insufficient or excessive fan airflows. Rather than adjust the fan output prior to adjusting dampers, one simply could increase target airflow proportionately to the excess with the intention of adjusting the fan airflow after damper adjustments have been completed. Hence, considering the effects both of the $\%k$ -factor and the FanFactor, the target values of Q , SP_h , and VP_{cl} can be stated respectively as:

$$Q_{target} = \%k \times \text{FanFactor} \times Q_{br-goal} \quad (16)$$

$$VP_{cl-target} = \left(\frac{\%k \times \text{FanFactor} \times Q_{br-goal}/Q_{br-open}}{VP_{cl-open}} \right)^2 \quad (17)$$

$$SP_{h-target} = \left(\frac{\%k \times \text{FanFactor} \times Q_{br-goal}/Q_{br-open}}{SP_{h-open}} \right)^2 \quad (18)$$

If the expression for FanFactor and $\%Q_{br-goal}$ are substituted into Eqs. 16, 17, and 18, then:

$$Q_{target} = \left(\frac{\%k}{2(\%Q_{br-goal})} \right) \times \left(\frac{Q_{fan-open}}{Q_{fan-goal}} + \frac{\% \min Q_{br-goal}}{100\%} \right) Q_{br-open} \quad (19)$$

$$VP_{cl-target} = \left[\left(\frac{\%k}{2(\%Q_{br-goal})} \right) \times \left(\frac{Q_{fan-open}}{Q_{fan-goal}} + \frac{\% \min Q_{br-goal}}{100\%} \right) \right]^2 VP_{cl-open} \quad (20)$$

$$SP_{h-target} = \left[\left(\frac{\%k}{2(\%Q_{br-goal})} \right) \times \left(\frac{Q_{fan-open}}{Q_{fan-goal}} + \frac{\% \min Q_{br-goal}}{100\%} \right) \right]^2 SP_{h-open} \quad (21)$$

The median value of $VP_{cl}/VP_{cl-goal}$ and SP_h/SP_{h-goal} provide two other targets that are useful if the dampers are relatively close to their ideal settings and under- and over-adjustment are grossly in balance. Those conditions are likely to occur if dampers are adjusted to the targets computed with Eqs. 19, 20, and 21. If over adjustments and under adjustments are equally present, then the fan airflow will change negligibly if the damper adjustments are now set to perfect settings. Hence, the airflow in a given branch is little affected by adjusting all of the other branch's dampers. Hence, each damper can be adjusted independently. Because the goal is to have a common pressure ratio and the median ratio should change very little with further damper adjustments, one can adjust dampers to achieve the median values of $VP_{cl}/VP_{cl-goal}$ and SP_h/SP_{h-goal} :

$$VP_{cl-target} = VP_{cl-goal_i} \times \text{median}\{VP_{cl}/VP_{cl-goal_i}\} \quad (22)$$

$$SP_{h-target} = SP_{h-goal_i} \times \text{median}\{SP_h/SP_{h-goal_i}\} \quad (23)$$

Equations 22 and 23 would predict the values of VP_{cl} and SP_h if all branches' pressure ratios were identical (but then no adjustments would be necessary) but they should apply well if the range of ratios of $VP_{cl}/VP_{cl-goal}$ and SP_h/SP_{h-goal} is relatively small (e.g., all within $\pm 20\%$). It is possible that the order of adjustment is irrelevant, but a cautious course would be to adjust the dampers that are the most over adjusted and under adjusted alternately.

TWO PROCEDURES FOR ADJUSTING DAMPERS

Although the Goal Method probably has been used extensively for decades, there is no published, detailed procedure for it. It would be useful for comparison to have step-by-step procedures for both the Goal and the Target Methods.

Goal Method Procedure With or Without Prior Fan Adjustment

If the steps listed below (and depicted in Figure 1) are followed, each hood should receive an airflow greater than or equal to its value of $Q_{br-goal}$:

1. Determine the desired airflow ($Q_{br-goal}$) for each hood. Compute $Q_{fan-goal}$ from Eq. 4.
2. Open all dampers, taking care to protect the fan motor; since the power it uses may increase substantially.

Optional: partially close dampers for ducts whose airflows are known to be highly excessive.

3. Do Pitot traverses and measure VP_{cl} and SP_h for each branch duct, then compute the open damper value of airflow (Q_{open}) for each branch duct.
4. Compute the initial Q_{fan} from the sum of the observed airflows using Eq. 3 and compute $Q_{fan-ideal}$ using Eq. 10. Compute $FanFactor = Q_{fan-open}/Q_{fan-ideal}$ or use Eq. 11.
5. Adjust the fan speed or fan damper prior to adjusting dampers if $FanFactor$ is less than unity (i.e., insufficient fan airflow). Consider it if $FanFactor$ is greater than 1.4; otherwise the fan pressure will be much higher than necessary. If it is to be done, adjust the fan output until $FanFactor$ is close to unity.
6. Compute $VP_{cl-goal}$ or SP_{h-goal} for each branch duct using Eq. 13 or Eq. 14, respectively.
7. Determine the order to adjust dampers based on decreasing values of $\%Q_{br-goal}$, except where that order is highly inconvenient.
8. Adjust each damper in turn until it is observed for that branch that the observed value equals the goal value.
9. Repeat Step 8 (i.e., second round).
10. If necessary, repeat Step 8 (i.e., third round).
11. Do a full Pitot traverse for each branch duct to determine the final observed airflows (Q_{br}) and all $\%Q_{br-goal}$ values Eq. 5.
12. If the lowest value of $\%Q_{br-goal}$ (i.e., $\% \min Q_{br-goal}$) is less than 1.0, increase the fan speed based on Eq. 12.

Note that an upgrade of the fan motor might be required for the new conditions. In some cases the fan itself may have to be replaced.

Target Method Procedure

For this method, dampers are adjusted to achieve target VP_{cl} or SP_h values using Eqs. 20 or 21 in the first round and Eqs. 22 or 23 for a second round. The fan output is not adjusted until all damper adjustments are done. Steps 1–4 are the same as for Goal Method procedure.

1. Determine the desired airflow ($Q_{br-goal}$) for each hood. Compute $Q_{fan-goal}$ from Eq. 4.
2. Open all dampers, taking care to protect the fan motor, since the power it uses may increase substantially. Optional: partially close dampers for ducts whose airflows are known to be highly excessive.
3. Do Pitot traverses and measure VP_{cl} and SP_h for each branch duct, then compute the "open" damper value of airflow ($Q_{br-open}$) for each branch.
4. Compute the initial Q_{fan} from the sum of the observed airflows using Eq. 3 and compute $Q_{fan-ideal}$ using Eq. 10.
5. Consider adjusting the fan speed or fan damper prior to adjusting dampers if the airflows are so deficient that static and velocity pressures are too low to measure accurately. If it will be changed, adjust the fan output until $Q_{fan}/Q_{fan-ideal}$ is close to unity.

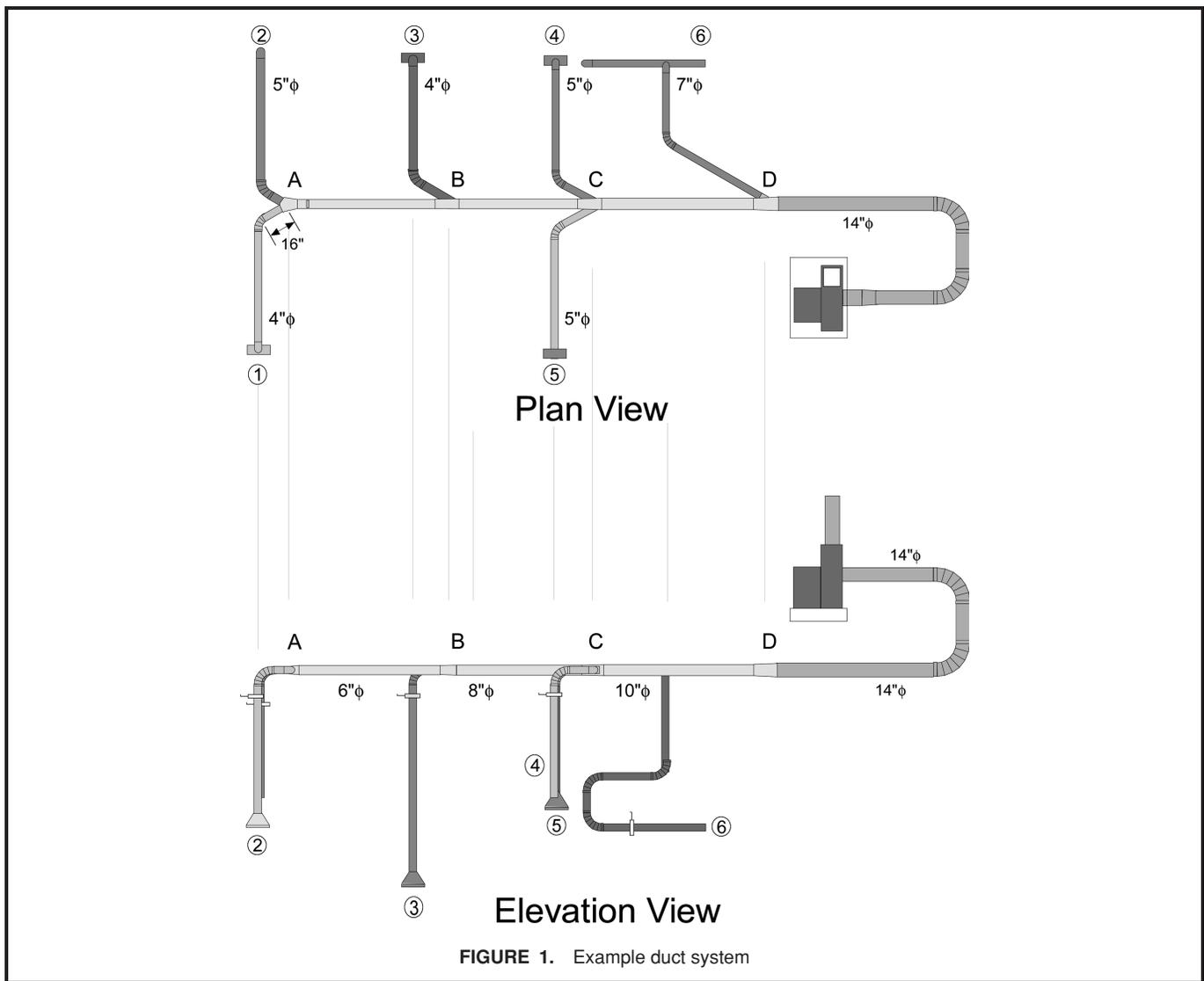


FIGURE 1. Example duct system

6. Determine the order to adjust dampers based on decreasing sufficiency of airflow (i.e., decreasing values of $%Q_{br-goal}$). Determine the value of k for each duct using Eq. 15.
7. Compute $VP_{cl-goal}$ (Eq. 13) and $VP_{cl-target}$ (Eq. 22) or SP_{h-goal} (Eq. 14) and $SP_{h-target}$ (Eq. 3) for each branch duct.
8. Beginning with the branch with the greatest value of $%Q_{br-goal}$ and continuing through to the damper with the least value of $%Q_{br-goal}$, adjust each damper in turn until:

$$VP_{cl} = VP_{cl-target}$$
 Or,

$$SP_h = SP_{h-target}$$
 Leave the damper open for the branch for which $%Q_{br-ratio}$ initially was the least.
9. After the first round is complete, measure SP_h or VP_{cl} for each branch again.
10. Compute for each branch the resulting ratio of SP_h to SP_{h-goal} or the ratio of VP_{cl} to $VP_{cl-goal}$ and determine the median value for each set of ratios. Compute the new target values of SP_h or VP_{cl} using Eqs. 22 or 23.
11. Adjust each branch damper so that its measured value equals the target value SP_h or VP_{cl} determined in the previous step. Note that the order of adjustments should probably be different from the first round. Begin with the duct whose ratio of SP_h/SP_{h-goal} or $VP_{cl}/VP_{cl-goal}$ is the greatest, followed by the least, and alternate between the next highest and the next lowest until roughly one-half of dampers have been adjusted a second time. If necessary, adjust all dampers.
12. Do a full Pitot traverse for each branch duct to determine the final observed airflows (Q_{br}) and all $%Q_{br-goal}$ values Eq. 5.

- Adjust the fan speed based either on Eq. 12 or so that the lowest value of $\%Q_{br-goal}$ (i.e., $\%minQ_{br-goal}$) equals 1.0.

Note that an upgrade of the fan motor might be required for the new conditions. In some cases the fan itself may have to be replaced.

EXAMPLE SYSTEM AND COMPUTATION

To demonstrate the effects of following the steps in each method, the system in Figure 1 was simulated using the methods discussed in this section. Thus, the “original” values of airflow ($Q_{br-open}$) and hood static pressures (SP_{h-open}) in Table I represent realistic values that could exist at some fan speed. The values of $Q_{br-goal}$ were selected to make balancing the system challenging. The values of $\%Q_{br-goal}$ were computed for the prebalancing conditions in Table I using Eq. 5. With a range of $\%Q_{br-goal}$ values of 0.82 to 2.57 when the dampers were open, the system airflow was poorly matched to desired levels. The sum of the current branch airflows was 40% greater than the sum of the airflow goals for the branches, indicating that the fan speed was probably moderately excessive.

The estimates of the effects of adjusting dampers were made with a custom Excel spreadsheet developed to compute pressures and flows using the velocity pressure American Conference of Governmental Industrial Hygienists’ (ACGIH[®]) method⁽⁷⁾ with the following modifications:

- Loss coefficients up and downstream of the junction fitting were computed using a method described elsewhere.⁽⁸⁾ On this example system, that method would produce less than 5% deviations in airflows from *Industrial Ventilation*.⁽⁷⁾ On other systems, the deviations could be substantially larger.
- The effects of correcting the airflow when the magnitude of a submain junction pressure was less than the required branch junction pressure were applied to all ducts upstream of that submain, not just to the submain itself. The effects on upstream airflows are proportional to $Q_{corr}/Q_{br-goal}$ where Q_{corr} is computed using the ACGIH

method. The pressures upstream of the submain are proportional to the square of $Q_{corr}/Q_{br-goal}$.

- The effect of a damper on the pressure in a branch was simulated by adding a term for X_{damper} to the sum of velocity pressure loss coefficients for each branch duct.
- The effect on the fan airflow of increased system resistance as dampers were adjusted was simulated by modeling the relationship between the resistance of the system (X_{system}) and the airflow level produced by the fan (Q_{fan}) at a fixed rotation rate. The resistance of an entire system can be approximated by:^(1,2)

$$X_{system} = \frac{TP_{fan}}{VP_{fan\ inlet}} \quad (24)$$

where

TP_{fan} = fan total pressure
 X_{system} = unitless measure of the resistance of the duct system

The values of X_{system} produced in the two examples ranged from roughly 12 to 22. The airflow level produced by the fan used for the simulations for the range of given level of X_{system} were modeled by:

$$Q_{fan} = \omega (C_0 - C_1 X_{system}) \quad (25)$$

C_0 and C_1 must have units consistent with the units of Q_{fan} and ω . For airflow in m^3/s and rotation rate in Hz, the units of both are m^3 . For airflow in ft^3/min and rotation rate in revolutions per minute, the units of both coefficients are ft^3 .

The fan used in the example problems is an Aerovent (Minneapolis, Minn.) centrifugal fan (No. 315BI-SWCB-3435-3) with a wheel diameter of 14 in. The coefficients in Eq. 25 were determined from linear regression ($R^2 = 99\%$) of X_{system} with Q_{fan} values where both were determined from the Aerovent fan tables. The resulting value of C_0 was ($1.03\ ft^3$) and C_1 was ($0.014\ ft^3$).

- Pressures were computed first using the loss coefficients, duct lengths, etc., taken from the duct system in Figure 1 and the target airflows, Qt_1 , in Table I. The corrected

TABLE I. Initial Measurements With Dampers Open and Goals for the Example Problems

Branch	Diameter mm (in.)	$Q_{br-open}$ m^3/s (ft^3/min)	$VP_{icl-open}$ kPa (in. w.g.)	SP_{h-open} in. w.g.	$Q_{br-goal}$ m^3/s (ft^3/min)	$\%Q_{br-goal}$	$VP_{cl-goal}$ kPa (in. w.g.)	SP_{h-goal} kPa (in. w.g.)
1-A	102 (4)	0.155 (328)	0.271 (1.09)	0.274 (1.10)	0.189 (400)	82	0.403 (1.62)	0.408 (1.64)
2-A	127 (5)	0.250 (529)	0.289 (1.16)	0.351 (1.41)	0.189 (400)	132	0.164 (0.66)	0.199 (0.80)
3-B	102 (4)	0.171 (362)	0.329 (1.32)	0.334 (1.34)	0.189 (400)	91	0.403 (1.62)	0.408 (1.64)
4-C	127 (5)	0.261 (554)	0.316 (1.27)	0.383 (1.54)	0.189 (400)	139	0.164 (0.66)	0.199 (0.80)
5-C	127 (5)	0.261 (554)	0.316 (1.27)	0.383 (1.54)	0.189 (400)	139	0.164 (0.66)	0.199 (0.80)
6-D	178 (7)	0.486 (1030)	0.284 (1.14)	0.446 (1.79)	0.189 (400)	258	0.042 (0.17)	0.067 (0.27)
Fan	356 (14)	1.584 (3357)			1.133 (2100)	140		

airflows (Q_{corr}) from that computation were used as target branch airflows in a second set of similar computations using the same loss coefficients, duct lengths, etc. The values of Qt_2 were computed from:

$$Qt_2 = Q_{corr1} \times Q_{fan2}/Q_{fan1} \quad (26)$$

where

1 = value computed in the first spreadsheet

2 = value computed in the second spreadsheet

Q_{corr} = corrected airflow through a branch due to unequal pressure requirements at the junction fitting

This allowed modeling of the effects of adjusting dampers on the fan airflow without encountering the circular reference problems of Excel. Note that early tests demonstrated that it was not necessary to compute a set of Qt_3 in a third of computations.

- The estimated Q_{fan} value was used to compute new values of the spreadsheet target airflow (Qt_2) for each branch.
- Adjustment of damper insertion depths for a given branch was simulated by changing the inputted value of X_{damper} by trial and error until the desired goal or target value was met in the second spreadsheet. For example, to achieve a value of $SP_{h-target}$ for Branch 2 might prove to require an X_{damper} value of 2.9. The value of X_{damper} is independent of airflow levels and thus would not change with subsequent adjustments to other dampers.

The modeled values are somewhat unrealistic in that no measurement errors were included in the simulations. Omitting measurement errors makes it easier to understand what is happening with each step but gives a somewhat false impression of the precision one could expect.

Example for Goal Method

The example application listed here illustrates the use of the Goal Method. This example employed $VP_{cl-goal}$ and did not include adjusting the fan airflow prior to adjusting dampers. Following the steps of the Goal Method, the results would be as follows:

- Determine $Q_{br-goal}$ for each hood. Compute $Q_{fan-goal}$ from Eq. 4. The values of $Q_{fan-goal}$ shown in Table I were selected arbitrarily for this example.
- Open all dampers. . . . In this case, all dampers were opened fully.
- Do Pitot traverses and measure VP_{cl} and SP_h for each branch duct. Compute Q_{open} for each branch. The results are shown in Table I
- Compute the initial Q_{fan} . See value of 3357 ft³/min in Table I
Compute $Q_{fan-ideal}$ using Eq. 10. Noting from Table I that $\%minQ_{br-goal} = 0.82$, the ideal initial fan airflow

would be:

$$\begin{aligned} Q_{fan-ideal} &= \left(\frac{Q_{fan-open}}{Q_{fan-open}/Q_{fan-goal} + (\% \min Q_{br-goal}/100\%)} \right) \\ &= \left(\frac{3357}{\frac{3357/2400+0.82}{2}} \right) = 3026 \text{ ft}^3/\text{min} \quad (27) \end{aligned}$$

Compute FanFactor = $Q_{fan-open}/Q_{fan-ideal} = 3357 \text{ ft}^3/\text{min}/3026 \text{ ft}^3/\text{min} = 1.11$.

- Adjust the fan speed. The value of $Q_{fan-open}$ exceeded $Q_{fan-ideal}$ by only 11%, so the fan output was not adjusted.
- Compute $VP_{cl-goal}$ or SP_{h-goal} for each branch duct using Eq. 13 or Eq. 14, respectively. See Table I for the results. For example, for Branch 6-D $VP_{cl-goal}$ can be computed from Eq. 14 as:

$$\begin{aligned} VP_{cl-goal} &= VP_{cl-open} \left(\frac{Q_{br-goal}}{Q_{br-open}} \right)^2 \\ &= 0.284 \left(\frac{0.189}{0.486} \right)^2 = 0.042 \text{ kPa} \end{aligned}$$

Alternatively, values of SP_{h-goal} can be computed using Eq. 14. For example, for Branch 6-D:

$$\begin{aligned} SP_{h-goal} &= SP_{h-open} \left(\frac{Q_{br-goal}}{Q_{br-open}} \right)^2 \\ &= 0.446 \left(\frac{0.189}{0.486} \right)^2 = 0.0672 \text{ kPa} \end{aligned}$$

- Determine the order to adjust dampers. . . . It is likely that practitioners currently often base order on convenience (e.g., least total effort in moving the ladder).
Adjust each damper in turn. . . .
Each branch airflow in turn was adjusted until it equaled close to 0.189 m³/sec (400 ft³/min) unless it fell below 0.189 m³/sec with the damper fully open. However, pushing in the damper also has the effect of shifting airflow to all other ducts. Thus, after all dampers were adjusted, all branch airflows would have risen to values above 0.189 m³/sec except Branch 6-D, the last to be adjusted. There is no point in doing Pitot traverses yet, but if they were done the results would be the values of $\%Q_{br-goal}$ shown in Table II. Note that the fan airflow would have fallen from 1.584 m³/sec (3357 ft³/min) to 1.421 m³/sec (3011 ft³/min) at the end of Round 1. Note also that the values of X_{damper} are greatest for the ducts that were most excessive in airflow before any dampers were adjusted.
- Repeat Step 8 (i.e., second round). As in the first round, each branch airflow was adjusted in turn until it reached $VP_{cl-goal}$, but as each damper was adjusted, the airflows in previously adjusted branches rose increasingly above $Q_{br-goal}$ levels, except the last damper adjusted, Branch 6. As shown in Table II, Branch 1-A now had a 21% excess

TABLE II. Order of Adjustment and Results at the End of Rounds 1, 2, and 3

Duct	Order	X _{damp}	Q _{br} m ³ /s (ft ³ /min)	%Q _{br-goal}	VP _{cl}	SP _h kPa (in. w.g.)
End of Round 1						
1-A	1	0.0	0.233 (493)	1.233	0.613 (2.46)	0.620 (2.49)
2-A	2	2.7	0.234 (560)	1.401	0.324 (1.30)	0.393 (1.58)
3-B	3	0.0	0.247 (523)	1.307	0.687 (2.76)	0.697 (2.80)
4-C	4	3.6	0.251 (532)	1.329	0.291 (1.17)	0.354 (1.42)
5-C	5	4.4	0.236 (501)	1.252	0.259 (1.04)	0.314 (1.26)
6-D	6	41	0.190 (402)	1.006	0.042 (0.17)	0.067 (0.27)
Fan			1.421 (3011)	1.255		
End of Round 2						
1-A	1	1.7	0.229 (486)	1.214	0.593	0.600 (2.41)
2-A	2	10.0	0.213 (451)	1.128	0.209	0.254 (1.02)
3-B	3	3.0	0.207 (438)	1.095	0.483	0.488 (1.96)
4-C	4	12.0	0.199 (422)	1.055	0.184	0.224 (0.90)
5-C	5	13.0	0.193 (408)	1.021	0.172	0.209 (0.84)
6-D	6	60	0.189 (400)	1.001	0.042	0.067 (0.27)
Fan			1.229 (2605)	1.085		
End of Round 3						
1-A	1	2.3	0.224 (475)	1.190	0.568	0.575 (2.31)
2-A	2	14.0	0.192 (406)	1.010	0.169	0.207 (0.83)
3-B	3	4.4	0.191 (404)	1.010	0.411	0.416 (1.67)
4-C	4	14.5	0.189 (401)	1.000	0.167	0.202 (0.81)
5-C	5	14.5	0.189 (401)	1.000	0.167	0.202 (0.81)
6-D	6	64	0.189 (400)	1.000	0.042	0.067 (0.27)
Fan			1.174	1.040		

in flow, and the fan airflow now had only 8.5% in excess above goal values. As that may be considered excessive by many practitioners, a third round is begun in Step 9.

9. *If necessary, repeat Step 8 (i.e., third round).* As shown in Table II, at the end of the third round, the total excess flow through the system is about 4%.
10. *Do a full Pitot traverse for each branch duct. . . .* The resulting %Q_{br-goal} values are shown after Round 3 on Table II.
11. *If the lowest value of %Q_{br-goal} (i.e., %minQ_{br-goal}) is less than 1.0, increase the fan speed based on (Safety Factor = 0):*

$$\omega_2 = \frac{\omega_1}{(\% \min Q_{br-goal} / 100\%)^2}$$

In this case the lowest %Q_{br-goal} had a value of 1.0, which should always be the case if the fan speed exceeded ideal levels. No fan adjustment is needed.

Results: After the second round of adjustments the excess airflow was about 8.5%. After the third round of adjustments, the excess was about 4% (see Table II), which is probably acceptable to most practitioners. Note also that the values of X_{damp} are as high as 63.5. To obtain that much resistance the damper must be nearly completely closed. In that case, even the slightest change in insertion depth would have large effects

on airflow, making it very difficult to set the damper so that the airflow equaled Q_{br-goal}. Finally, a byproduct of such high resistances is a fan total pressure estimated in the simulation to be 3.59 kPa (14.4 in. w.g.), a relatively high value.

Example for the Target Method

The same example used for the Goal Method is used here to demonstrate the use of the Target Method procedure. The step-by-step solution is as follows:

- Steps 1–4. Same as the example for Goal Method.
5. *Consider adjusting the fan speed. . . .* In this case the SP_h values were all well above (0.05 kPa) (0.2 in. w.g.), so it was not necessary to adjust the fan output prior to balancing to produce values high enough to measure accurately.
6. *Determine the order to adjust dampers. . . . Determine the value of k for each duct using Eq. 15.* The order for the first round of adjustments is shown in Table III under the Order column.
7. *Compute VP_{cl-goal} and VP_{cl-target} or SP_{h-goal} and SP_{h-target} for each branch duct.* The goal values were computed and are shown in Table I. The target parameter results are shown in Table III. Note that the target values are greater than the goal values in Table I

TABLE III. Computation of First Round Target Parameters

Duct	Order	%k	Fan Factor (%)	Qt m ³ /s (ft ³ /min)	VP _{cl} kPa (in. w.g.)	SP _h kPa (in. w.g.)
1-A	6	100	111	0.210 (444)	0.500 (1.99)	0.500 (2.02)
2-A	4	98	111	0.206 (436)	0.200 (0.79)	0.240 (0.96)
3-B	5	99	111	0.208 (440)	0.490 (1.96)	0.490 (1.98)
4-C	3	97	111	0.203 (431)	0.190 (0.77)	0.230 (0.93)
5-C	2	95	111	0.200 (423)	0.180 (0.74)	0.220 (0.90)
6-D	1	92	111	0.193 (410)	0.040 (0.18)	0.070 (0.28)

because the fan airflow is excessive. For example, for Branch 2-A:

$$\begin{aligned}
 SP_{h-goal} &= SP_{h-open}/(\% Q_{br-goal}/100)^2 \\
 &= 3.51/1.32^2 = 0.200 \text{ kPa} \\
 SP_{h-target} &= \left[\left(\frac{\%k}{2x\%Q_{br-goal}} \right) \left(\frac{Q_{fan-open}}{Q_{fan-goal}} + \frac{\% \text{ min } Q_{br-goal}}{100\%} \right) \right]^2 \\
 &\quad \times SP_{h-open} \\
 &= \left[\left(\frac{98\%}{2(132\%)} \right) \left(\frac{1.58 \text{ m}^3/\text{s}}{1.13 \text{ m}^3/\text{s}} + 0.82 \right) \right]^2 \cdot 0.351 \\
 &= 0.239 \text{ kPa}
 \end{aligned}$$

- Beginning with the branch with the greatest value of %Q_{br-goal} and continuing through to the damper with the least value of %Q_{br-goal}, adjust each damper in turn until VP_{cl} = VP_{cl-target} or SP_h = SP_{h-target}. Leave the damper open for Branch 1-A, for which %Q_{br-ratio} initially was the least.
- After the first round is complete, measure SP_h or VP_{cl} for each branch again. The results are shown on Table IV. Note that the values are still somewhat larger than the goal values.
- Compute for each branch the resulting ratio of SP_h to SP_{h-goal} or the ratio of VP_{cl} to VP_{cl-goal} and determine

the median value for each set of ratios. Compute the new target value of SP_h or VP_{cl} using Eqs. 22 or 23. As shown on Table IV, the range of %SP_{h-goal} values is 1.22 to 1.81 with a median %SP_{h-goal} value of 1.50. The new target values computed from Eqs. 22 or 23 are also shown on Table IV. For example, for Branch 1-A:

$$\begin{aligned}
 SP_h &= SP_{h-goal} \times \text{median } \% SP_{h-goal}/100\% \\
 &= 0.408 \times 1.501 = 0.613 \text{ kPa}
 \end{aligned}$$

- Adjust each branch damper so that its measured value equals the target value SP_h or VP_{cl} determined in the previous step. Note that the order of adjustments should probably be different from the first round. Begin with the duct whose ratio of SP_h/SP_{h-goal} or VP_{cl}/VP_{cl-goal} is the greatest, followed by the least, and alternate between the next highest and the next lowest until roughly one-half of dampers have been adjusted a second time. If necessary, adjust all dampers.
In this case all of the dampers were adjusted during the second round.
The results are shown in Table V.
- Do a Pitot traverse for each branch duct to determine the final observed airflows. The results are shown in

TABLE IV. Results After Round 1 and Computation of Round 2 Targets

Duct	Order	X _{damper}	Results from Round 1			Computation of Round 2 Targets				
			Q _{br} m ³ /s (ft ³ /min)	%Q _{br-goal}	VP _{cl} kPa (in. w.g.)	SP _h kPa (in. w.g.)	SP _{h-goal}	Order	VP _{cl} kPa (in. w.g.)	SP _h kPa (in. w.g.)
1-A	1	0.00	0.254 (538)	1.344	0.727 (2.92)	0.737 (2.96)	1.807	1	0.605 (2.43)	0.613 (2.46)
2-A	2	7.40	0.210 (444)	1.109	0.204 (0.82)	0.247 (0.99)	1.231	4	0.247 (0.99)	0.301 (1.21)
3-B	3	1.60	0.203 (441)	1.104	0.491 (1.97)	0.496 (1.99)	1.218	2	0.605 (2.43)	0.613 (2.46)
4-C	4	6.20	0.224 (475)	1.188	0.234 (0.94)	0.284 (1.14)	1.412	6	0.247 (0.99)	0.301 (1.21)
5-C	5	5.20	0.238 (504)	1.261	0.261 (1.05)	0.319 (1.28)	1.590	5	0.247 (0.99)	0.301 (1.21)
6-D	6	27.5	0.241 (510)	1.276	0.070 (0.28)	0.110 (0.44)	1.627	3	0.065 (0.26)	0.100 (0.40)
Fan			1.374 (2913)	1.214			1.501			

TABLE V. Results for Round 2 Before and After Fan Speed Adjustment

Duct	Order	X _{damp}	Q _{br} m ³ /s (ft ³ /min)	%Q _{br-goal}	VP _{cl} kPa (in. w.g.)	SP _h kPa (in. w.g.)
Prior to adjusting fan speed						
1-A	1	0.60	0.227 (480)	1.200	0.580 (2.33)	0.588 (2.36)
2-A	4	5.30	0.232 (491)	1.228	0.249 (1.00)	0.301 (1.21)
3-B	2	0.77	0.230 (487)	1.217	0.598 (2.40)	0.605 (2.43)
4-C	6	5.50	0.232 (492)	1.229	0.249 (1.00)	0.304 (1.22)
5-C	5	5.60	0.231 (489)	1.222	0.247 (0.99)	0.299 (1.20)
6-D	3	30.0	0.230 (487)	1.219	0.065 (0.26)	0.100 (0.40)
Fan			1.381 (2926)	1.219		
After multiplying airflows by 1/(minimum %Q _{br-goal})						
1-A		0.60	0.189 (400)	1.000	0.403 (1.62)	0.408 (1.64)
2-A		5.30	0.193 (409)	1.020	0.172 (0.69)	0.209 (0.84)
3-B		0.77	0.192 (406)	1.010	0.413 (1.66)	0.418 (1.68)
4-C		5.50	0.193 (410)	1.020	0.172 (0.69)	0.209 (0.84)
5-C		5.60	0.192 (407)	1.020	0.172 (0.69)	0.207 (0.83)
6-D		30.0	0.192 (406)	1.020	0.045 (0.18)	0.070 (0.28)
Fan			1.151 (2438)	1.016		

Table V. Note that values of %Q_{br-goal} range from 120% to 123%. Because the values are all about the same, the branch airflows have been adjusted to the correct relative distribution. Hence, adjusting the fan speed appropriately could bring all branch airflows close to 100% of their Q_{br-goal} values.

13. *Adjust the fan speed based on Eq. 12 so that the lowest value of %Q_{br-goal} (i.e., %minQ_{br-goal}) equals 1.0.* For this example, the minimum value of %Q_{br-goal} was 1.20 (see Table V), so the fan rotation rate should be reduced so that:

$$\omega_2/\omega_1 = 100\%/ \%minQ_{br-goal} = 100\%/120\% = 0.833$$

Note that after the fan speed is adjusted (see Table V) the excess airflow for the system is 1.6%, a low level that required only two rounds of adjustments.

DISCUSSION

For this example problem, the simulations predicted that the Goal Method would have excess flows of 25.5% after one round of damper adjustments, 8.5% after two rounds of damper adjustments rounds, and 4% after three rounds (Table II). The example for the Target Method predicts an excess of 1.6% after two rounds of damper adjustment followed by adjusting the fan speed (see Table V). For those examples the Target Method required fewer damper adjustments and therefore fewer measurements. On the other hand, the Target Method required adjustment of the fan speed and the Goal Method (in this case) did not.

Note also that the maximum X_{damp} value for the Goal Method example was 63.5 (Branch 6-D), while the maximum for the Target Method example was 30. That is a dramatic

difference that is due to the use of dampers to “choke down” the fan with the Goal Method. As results, the fan total pressure (TP_{fan}) was 3.59 kPa (14.44 in. w.g.) for the Goal Method (computations not shown) and 1.20 kPa (4.82 in. w.g.) for the Target Method (computations not shown). Hence, the power requirement for the fan motor would be three times higher using the damper adjustments set in the Goal Method. As stated previously, the simulated examples did not include simulations of measurement errors. It is plausible that the excess airflows would have been higher for both methods if they had.

The advantages of the Goal Method as presented here are:

1. It is conceptually simple.
2. The required computations are relatively simple and straightforward (e.g., VP_{cl-goal} and SP_{h-goal}).
3. If the initial fan airflow is adjusted to Q_{fan-ideal} prior to damper adjustments, it should produce excess airflows and system pressures only marginally higher than those obtained using the Target Method.

The advantages of the Target Method as presented here are:

1. It requires no more than two rounds of adjustment to achieve an excess system airflow of less than 3% when no branch airflow is below its Q_{br-goal}.
2. It minimizes the resistance of each damper, thereby minimizing pressures throughout the system as well as the total system resistance.
3. The minimal system resistance minimizes the fan pressure and the fan motor operating cost.

CONCLUSIONS

Despite their disadvantages and limitations, dampers appear to be a necessary part of many ventilation systems

but adjusting them is often time-consuming and tedious. Both of the methods discussed here can achieve a well-balanced airflow distribution. Both have advantages and disadvantages. The Goal Method requires the least understanding and the fewest computations. However, if it does not include initial adjustment of the fan airflow, the Goal Method will fail if the initial fan output was too low and will produce high pressures if the fan airflow was too high.

The Target Method presented here is more complicated than the Goal Method. Compared with the Goal Method, it should require fewer damper adjustments, achieve lower fan pressures and less wasted airflow, and it requires only one fan output adjustment. It should not fail unless the fan output cannot be adjusted to necessary flows after damper adjustments.

The experimental and simulated validations for both methods were based on one duct/fan system and only two airflow distributions. Further testing is needed on a diverse array of systems and fans. In addition, the effects of random measurement errors were not considered in the simulations. More uncertainty in observed values would produce less precise damper adjustments. For that reason, it is likely that the excess airflows would be higher for both of the methods if done in working ventilation systems, especially for systems with poor measurement conditions

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