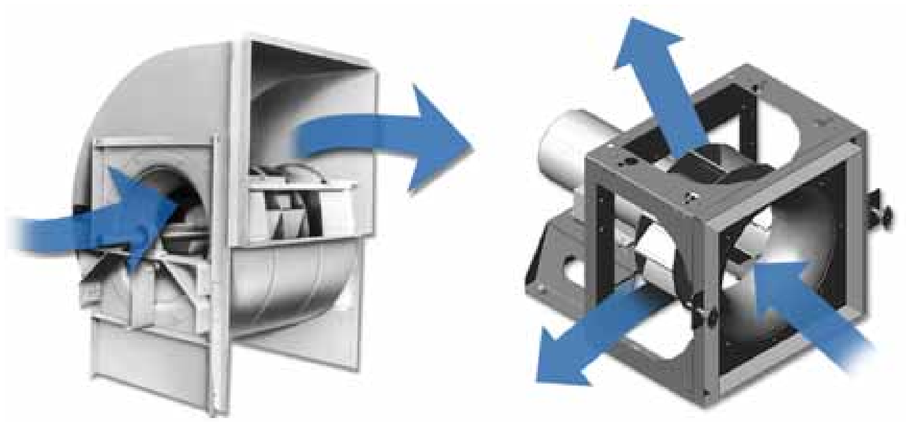
engineers newsletter

volume 39–1 • providing insights for today's hvac system designer

Direct-Drive Plenum Fans and Fan Arrays

Air-handling units are typically available with several choices of fan types and sizes. This affords the opportunity to select a fan that optimizes the balance of energy efficiency, acoustics, and cost. This EN will explore two fan technologies that have become increasingly popular over the past several years: direct-drive plenum (DDP) fans and fan arrays.

Figure 1. Housed fan versus direct-drive plenum fan



housed centrifugal fan   direct-drive plenum fan

Direct-Drive Plenum Fans

A housed fan contains a scroll, or housing, that directs the air leaving the fan in one direction (Figure 1). A plenum fan consists of a centrifugal fan wheel without the surrounding housing. The fan wheel pressurizes the surrounding plenum, allowing air to discharge in multiple directions.

Historically, most large fans used in HVAC systems have used a drive kit, consisting of one or more belts and associated sheaves, to connect the motor to the fan shaft. However, as variable-frequency drives (VFD) have become more cost effective and reliable, direct-drive fans have become more popular, primarily with plenum fans.

With a direct-drive plenum fan (Figure 1), the fan wheel is mounted directly on the motor shaft. With no belts or sheaves, and fewer bearings, direct-drive fans are more reliable and require less maintenance than belt-drive fans. Since there are fewer moving parts,no belt-related drive losses, and less inlet or outlet obstructions, direct-drive plenum fans are typically more efficient, quieter, and experience less vibration than belt-drive plenum fans.

Because the motor is in line (or parallel) with the direction of airflow through the air-handling unit, the motor mounted behind the fan wheel does not restrict airflow, protrude from the side of the unit, or increase unit width. However, the air-handling unit may need to be slightly longer to accommodate the motor mounted behind the fan wheel. (This can be offset partially by using a fan array, which is discussed later in this EN.)

Depending on the location of the fan within the air-handling unit, a plenum fan may be more or less efficient than a housed fan (see Table 1).

Example 1: Draw-thru fan discharging directly into a straight section of duct. A housed fan is specifically designed to discharge into a long, straight section of duct that is about the same size as the fan outlet. This minimizes energy loss as velocity pressure is converted to static pressure, and turbulence dissipates into laminar flow. With this discharge configuration, a housed airfoil (AF) fan will typically require less power than a plenum fan.

As an example, consider a typical VAV air-handling unit with a draw-thru supply fan that discharges into a straight section of duct. Operating at 13,000 cfm, the housed AF fan requires 11.8 brake horsepower (bhp), compared to 14.0 bhp for the belt-drive plenum fan and 12.8 bhp for the direct-drive plenum fan (Table 1).

While the housed fan requires less power in this discharge configuration, the plenum fan will typically have significantly lower discharge sound levels (Figure 2). The reduced sound levels occur partly because air velocity dissipates more quickly as the air pressurizes the plenum surrounding the fan, and because the plenum provides an opportunity for some of the sound to be absorbed before air discharges from the unit.

Note: Figures 2 and 3 compare discharge sound power levels. On the inlet side, plenum fans will usually have higher sound levels than housed fans. Depending on the location of the fan within the air-handling system, either discharge or inlet sound may be more important, so the quietest fan choice depends on the application.

Example 2: Draw-thru fan discharging into a plenum with multiple outlets. A discharge plenum is often added downstream of a housed fan to reduce discharge sound levels or allow for discharge flexibility (e.g., multiple duct connections or an abrupt change in direction). As mentioned previously, however, a housed fan is at its best when discharging into a straight section of duct. When a housed fan discharges into a plenum, the energy losses result in increased fan power.

Using the same example, adding a discharge plenum increases the brake horsepower of the housed AF fan from 11.8 to 13.2, compared to 14.0 bhp for the belt-drive plenum fan and 12.8 bhp for the direct-drive plenum fan (Table 1).

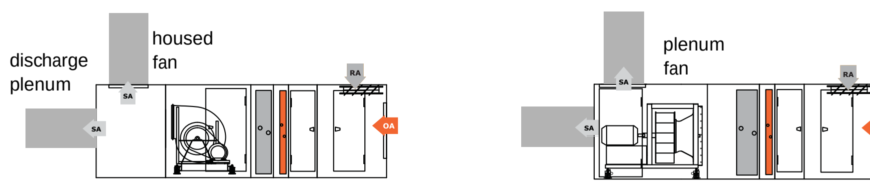
While adding the discharge plenum increases fan power and increases the length of the overall air-handling unit, it does enable the housed AF fan to achieve similar discharge sound levels as the plenum fans (Figure 3). In this example, the direct-drive plenum fan is still the quietest choice, especially in the low-frequency octave bands that are difficult to attenuate.

Table 1. Comparison of housed versus plenum fans[1]

Example 1: Draw-thru fan discharging directly into a straight section of duct[2]

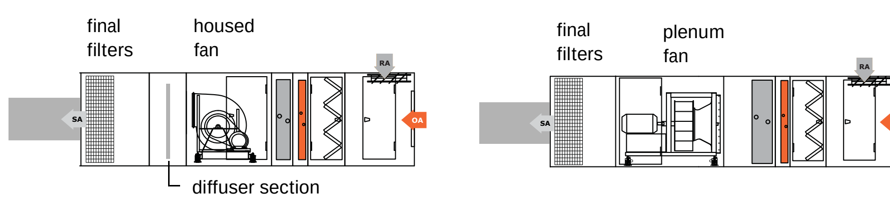
Fan type and wheel diameter	Input power,[5] bhp	Rotational speed, rpm
Housed AF, 25 in.	11.8	1320
Belt-drive plenum AF, 35.56 in.	14.0	1050
Direct-drive plenum AF, 30 in.	12.8	1320

Example 2: Draw-thru fan discharging into a plenum with multiple outlets[3]



Fan type and wheel diameter	Input power,[5] bhp	Rotational speed, rpm
Housed AF, 25 in. + discharge plenum	13.2	1380
Belt-drive plenum AF, 35.56 in.	14.0	1050
Direct-drive plenum AF, 30 in.	12.8	1320

Example 3: Final filters[4]



Fan type and wheel diameter	Input power,[5] bhp	Rotational speed, rpm
Housed AF, 25 in. (with diffuser section)	15.0	1450
Belt-drive plenum AF, 35.56 in.	15.4	1090
Direct-drive plenum AF, 30 in.	14.1	1370

[1]Based on a typical VAV air-handling unit configuration (OA/RA mixing box, filters, hot-water heating coil, chilled-water cooling coil, and supply fan) operating at 13,000 cfm with 2 in. H_2O of external static pressure drop.

[2]Draw-thru supply fan has a single discharge opening off the fan section, discharging into a long, straight section of duct that is about the same size as the fan outlet.

[3]AHU with the housed fan has a downstream discharge plenum with two openings. AHU with the plenum fans has two discharge openings in the fan section, no discharge plenum is used.

[4]A diffuser section is required between the housed fan and final filters. This is not required between a plenum fan and final filters.

[5]Brake horsepower values include 5 percent belt-related drive losses for the belt-drive housed or plenum fans.

When multiple supply duct connections are desired, a housed fan requires a discharge plenum to allow for the multiple connections. If a plenum fan is used, however, multiple duct connections can be made to the fan section itself, eliminating the need for a discharge plenum, and resulting in a shorter air-handling unit (smaller AHU footprint).

Example 3: Final filters. In some applications, final filters are included as the last section in the air-handling unit. When a housed fan is used, a diffuser section (which contains pressure-equalizing baffles) must be added to provide even airflow through the downstream filters. This is not a requirement for a plenum fan, since it pressurizes the surrounding plenum and provides even airflow through the final filters with minimal downstream distance.

In this configuration, the input power for the housed fan increases due to the added pressure drop of the diffuser section and the fact that the housed fan is no longer discharging into a straight section of duct. In this example, the direct-drive plenum fan requires the least power—14.1 bhp compared to 15.0 bhp for the housed AF fan and 15.4 bhp for the belt-drive plenum fan (Table 1).

When downstream sections are present, such as a discharge plenum, final filters, gas heating section, or even a blow-thru cooling coil, a direct-drive plenum fan will likely require less input power than either a housed fan or a belt-drive plenum fan.

Figure 2. Draw-thru fan discharging directly into a straight section of duct (example 1)

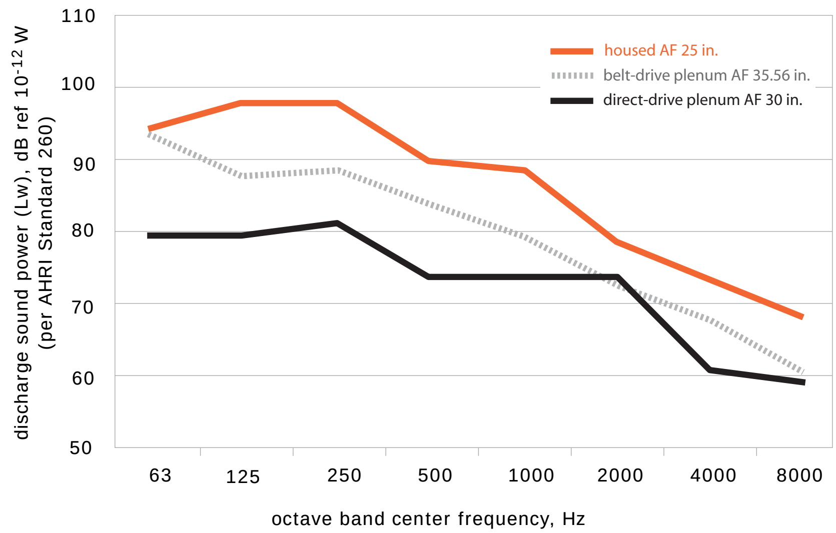
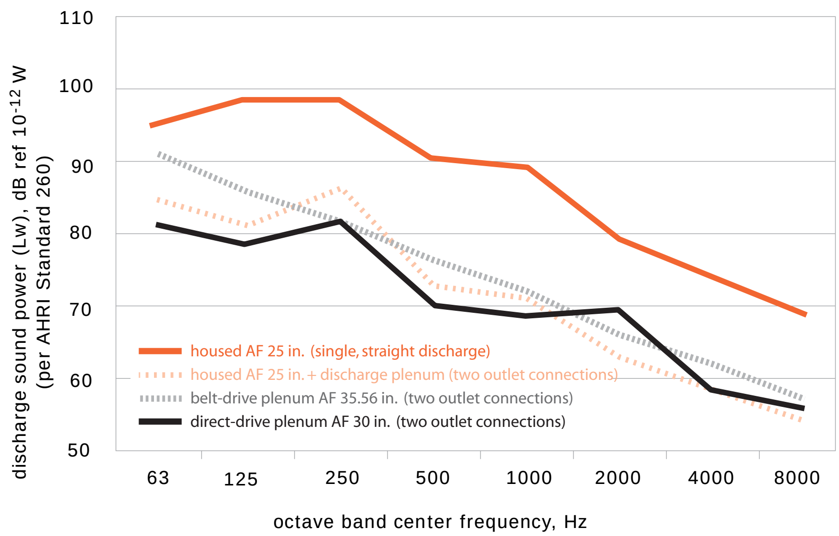


Figure 3. Draw-thru fan discharging into a plenum with multiple outlets (example 2)



Synchronous-speed versus flexible-speed selections. The use of direct drive (rather than belt drive) for a plenum fan has allowed for some changes to traditional paradigms when selecting the fan. Historically, the diameter and width of the fan wheel would often be pre-determined by the manufacturer of the air-handling unit. The variable open to change was the rotational speed (rpm) of the fan shaft, which was adjusted using belts and sheaves.

Today, direct-drive plenum fans are available in various wheel diameters and wheel widths. Even though there are no belts and sheaves to adjust rotational speed, the fan can be operated at various speeds through the use of a variable-frequency drive (VFD). In a sense, the VFD on a direct-drive plenum fan replaces the drive kit that would be used for a belt-drive fan.

Most people think of a VFD as being used to reduce the speed of the fan from the synchronous speed of the motor to some minimum turndown limit of the VFD. However, the VFD can also be used to operate the motor above synchronous speed. This provides the opportunity to use one of two selection approaches:

- In a **synchronous-speed selection**, the motor operates at its synchronous speed (typically 1800 or 1200 rpm) and the diameter and/or width of the fan wheel are changed to achieve the desired performance.
- In a **flexible-speed selection**, the width of the fan wheel is held constant and the diameter and/or speed of the fan are changed to achieve the desired performance.

Flexible-speed selection is a relatively new concept in the industry, but it typically results in a more efficient and quieter DDP fan selection.

Using the same example VAV air-handling unit, Table 2 compares two selections for a 30-inch diameter, direct-drive plenum fan. The first row shows the synchronous-speed selection, and the second row shows the flexible-speed selection.

For the first selection, the nominal speed of the motor is 1800 rpm. To deliver the desired airflow and static pressure, the width of the fan wheel is trimmed down to 57 percent of nominal width for this particular wheel diameter and the motor operates at its synchronous speed of 1780 rpm.

For the flexible-speed selection, however, the fan wheel is kept at its nominal width. To deliver the same desired performance, the fan wheel need only rotate at 1320 rpm. A 1200-rpm motor is operated above synchronous speed by running the VFD at approximately 66 Hertz (rather than the nominal 60 Hertz) to achieve the desired 1320 rpm.

Note: As an example, the VFDs and motors that Trane uses for direct-drive plenum fans in air-handling units can operate up to at least 90 Hz, which equates to about 2700 rpm for a nominal 1800-rpm motor.

The resulting input power drops from 15.4 bhp for the synchronous-speed selection to 12.8 bhp for the flexible-speed selection. Also, because the fan operates at a reduced speed with a wider wheel, the flexible-speed selection will typically result in lower sound levels.

As with anything, there are drawbacks to using the flexible-speed selection process. 900- and 1200-rpm motors are less common than conventional, "off-the-shelf" 1800-rpm motors, so they can be more expensive. (This drawback can often be avoided by using a fan array, which is discussed later in this EN.)

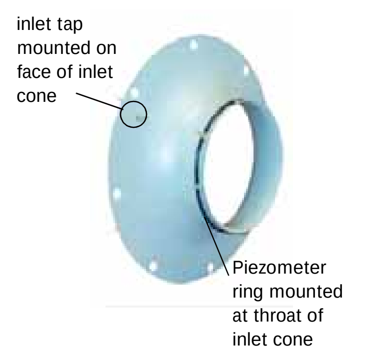
Also, these 900- to 1200-rpm motors are often less efficient, so be sure to include motor efficiency (not just brake horsepower) when comparing fan selections.

Piezometer ring for airflow measurement

In an air-handling system, measurement of actual fan airflow can be very useful for troubleshooting and ensuring proper system operation, especially in a VAV system.

A piezometer ring (Figure 4) is a device that can be mounted within the inlet cone for many types of fans. It measures the pressure drop from the inlet side of the fan to the throat, which is then used to estimate airflow. The total accuracy of the piezometer ring measurement system (device and transmitter) is typically within plus or minus 5 percent.

Figure 4. Piezometer ring



Perhaps the biggest advantage of this technology is that it does not obstruct airflow, so it does not affect the airflow or acoustic performance of the fan. It is very simple and low cost, and can easily be installed in the factory. Finally, periodic cleaning, if necessary, is easy. It is as simple as disconnecting the tube from the transmitter and sending compressed air backwards through the tube.

Table 2. Example synchronous-speed versus flexible-speed selections[1]

Fan type and wheel diameter	Wheel width, % of nominal	Fan rotational speed, rpm	Motor nominal speed, rpm	Input power, bhp
Direct-drive plenum AF, 30 in. (synchronous-speed selection)	57%	1780	1800	15.4
Direct-drive plenum AF, 30 in. (flexible-speed selection)	100%	1320	1200	12.8

[1]Based on a typical VAV air-handling unit configuration (OA/RA mixing box, high-efficiency filters, hot-water heating coil, chilled-water cooling coil, and draw-thru supply fan with two openings off the fan section) operating at 13,000 cfm with 2 in. H_2O of external static pressure drop.

Fan Array

Historically, most air-handling units have used a single fan wheel, although the use of a few fans in parallel has been somewhat common. Over the last several years, however, the use of four or more fans in an array has increased in popularity.

A fan array uses multiple, smaller fan wheels arranged in parallel airflow paths. Typically, direct-drive plenum fans are used in the array. The example pictured in Figure 5 shows four stacked DDP fans in an array.

Fan arrays have some advantages over using a single fan wheel, but they also have drawbacks. The primary benefits of using a multiple-fan array are a possible reduction in the overall length of the air-handling unit and providing some level of redundancy in the event of a fan failure.

Reduction in overall AHU length. The distance, or spacing, required both upstream and downstream of a fan is typically a function of the fan wheel diameter. Therefore, if multiple, small-diameter fan wheels are used, the upstream and downstream spacing required will usually be less than if a single, large-diameter fan wheel is used. In many cases, this can shorten the overall length of the air-handling unit.

Figure 5. Example fan array using four, direct-drive plenum fans

However, there is a bottom threshold to this length reduction:

- First, there is a certain amount of space needed upstream or downstream to allow the fans to be serviced or replaced, if necessary. This includes space for a person, and for a fan motor and/or wheel if the fans are stacked in multiple levels. It may also require space for a ladder and possibly a mechanical hoist.
- Next, for applications where an inlet connection is made to the top, bottom, or side immediately upstream of the fan section, or where a discharge connection is made to the top, bottom, or side of the fan section itself, additional space may be required to properly load or unload all fans in the array.
- Finally, motorized control or backdraft dampers are sometimes used to prevent backflow through an inactive fan or to allow a fan to be serviced or replaced while the other fans remain operational. These components will typically add length to the unit.

As an example, Table 3 depicts an air-handling unit selected to deliver 15,000 cfm. In this case, the fan is located upstream of the cooling coil.

When a single, 33-inch-diameter fan wheel is used, the minimum spacing required upstream is 19.8 in. If two smaller fan wheels are used in an array, the upstream spacing is reduced to 14.7 in. As the number of fan wheels increases, this upstream spacing continues to decrease, but notice that the incremental benefit is greatest going from one to two fans, and is less significant as the number of fans continues to increase.

Table 3. Example of AHU length reduction using a fan array[1]

		Upstream			Downstream			
Number of fans	Fan wheel diameter, in.	Minimum spacing required, in.	Service clearance, in.	Upstream total,[2] in.	Minimum spacing required,[3] in.	Length of fan + motor, in.	Service clearance, in.	Downstream total,[4] in.
1	33	19.8	12	19.8	50.5	54.3	0[5]	54.3
2	24.5	14.7	12	14.7	38.8	42.0	0[5,6]	42.0
3	20	12.0	12	12.0	33.1	35.3	18	53.3
4	18.25	11.0	12	12.0	29.9	31.4	18	49.4

[1]Based on a typical VAV air-handling unit with supply fan located upstream of the cooling coil, operating at 15,000 cfm and a 4.0 in. H_2O total static pressure drop.

[2]The upstream distance required is the larger of the upstream spacing required for airflow distribution or the upstream service clearance.

[3]The minimum downstream spacing required is equal to the length of the fan (to the leaving-edge of the impeller) plus any downstream spacing required for airflow distribution.

[4]The total downstream distance required is equal to the downstream spacing required or the sum of the length length of fan + motor plus the downstream service clearance, if required (whichever is largest).

[5]Use of an inward-swinging access door may require additional service clearance.

[6]Assumes access doors located on both sides of the fan section.

As mentioned previously, however, there is a certain amount of space needed to allow the fans to be serviced. The typical recommendation for upstream clearance is 18 in., but for this example the absolute minimum of 12 in. was used. As shown in Table 3, when four fans are used, the upstream spacing required is dictated by the need for service access rather than by fan wheel diameter, so there is no further upstream length reduction benefit by using more fans.

Looking at the downstream side of the fan, for a single fan wheel the minimum spacing required downstream is 50.5 in. Similar to the upstream side, as the number of fans increases, the required downstream spacing decreases. But notice that the length of the fan plus a direct-drive motor mounted at the end of the fan shaft is longer than the downstream spacing required. For this example, downstream spacing for airflow distribution is not a limiting factor: it's the length of the fan plus motor.

When multiple fans are used, the smaller fan wheels and smaller motors are shorter, so the downstream length is lessened. Again, the benefit is greatest going from one to two fan wheels, but the incremental benefit is less as the number of fans continues to increase.

The typical recommendation for downstream service clearance is 24 in., but for this example the absolute minimum of 18 in. was used. Also, it was assumed that the fan section has access doors on both sides. If it has a door on only one side, additional access space would be required downstream to allow the opposite-side fan to be serviced or replaced in the two-fan array. When three or four fans are used, however, this extra downstream space is needed to access the middle or upper fans.

The total downstream length is dictated by the length of the fan plus motor plus any downstream service clearance required. The length reduction is greatest going from one to two fans, but due to the need for service access, the downstream length might actually increase when more than two fans are used.

Figure 6 depicts the result of adding the upstream and downstream distances. When a single fan wheel is used, the overall length of the fan section is 74.1 in. If two smaller fan wheels are used in an array, the overall length is reduced to 56.7 in. (assuming doors on both sides of the fan section).

While the length can be reduced significantly by changing from one to two fans, the potential length reduction diminishes as the number of fans continues to increase. And, as shown in this example, due to the need for service access, the length may actually increase when more fans are used.

When more than about four or six fan wheels are used in an array, the upstream and downstream spacing requirements begin to be dictated by the need for service access rather than by fan wheel diameter, so there is typically little further length reduction benefit.

Redundancy. Another benefit of using more than one fan in an array is that it can provide some level of redundancy. If one fan fails, the other fans are still able to provide some (or all) of the airflow. Table 4 shows the redundancy that can be achieved by using two, three, or four fans in an array.

Figure 6. Example length reduction due to using a fan array (see Table 3)

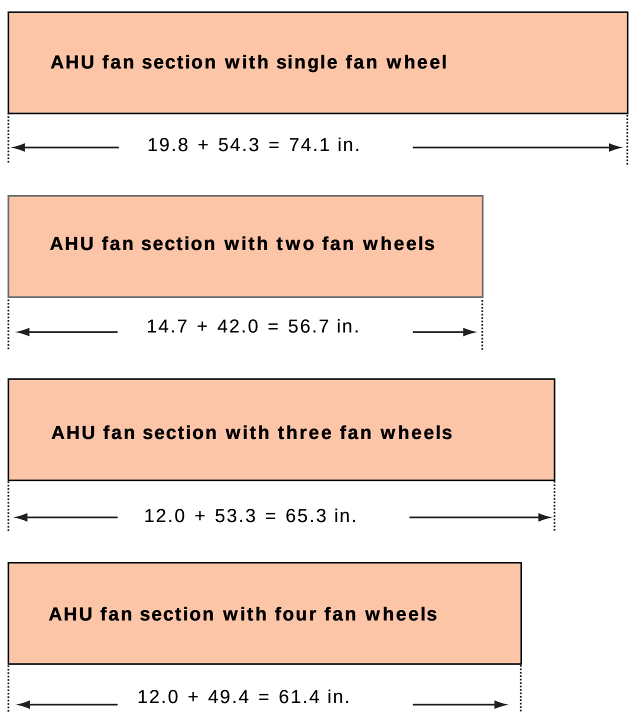


Table 4. Example of providing redundancy with a fan array[1]

Number of fans operating	Fan wheel diameter, in.	Level of redundancy	Airflow (each fan), cfm	Input power (each fan), bhp	Input power (total), bhp	Motor size (each fan), hp	
Two-fan array							
2	24.5	design	7500	6.55	13.10	7.5	
1	24.5	100%	15,000	16.13	16.13	20	(requires change from 7.5 to 20 hp motors
1	24.5	70%	10,500	7.13	7.13	7.5	(no change in motor size)
Three-fan array							
Number of fans operating	**Fan wheel diameter, in.**	**Level of redundancy**	**Airflow (each fan), cfm**	**Input power (each fan), bhp**	**Input power (total), bhp**	**Motor size (each fan), hp**	
3	20	design	5000	4.68	14.04	7.5	
2	20	100%	7500	7.43	14.86	7.5	(no change in motor size)
Four-fan array							
Number of fans operating	**Fan wheel diameter, in.**	**Level of redundancy**	**Airflow (each fan), cfm**	**Input power (each fan), bhp**	**Input power (total), bhp**	**Motor size (each fan), hp**	
4	18.25	design	3750	3.53	14.12	5	
3	18.25	100%	5000	4.71	14.13	5	(no change in motor size)

[1]Based on an air-handling unit designed to operate at 15,000 cfm and a 4.0 in. H_2O total static pressure drop.
[2]Operating at 10,500 cfm and 2.8 in. H_2O total static pressure drop.

For the two-fan array, the first row shows the selection at design conditions with both fans operating. Each fan delivers 7500 cfm and requires a 7.5 hp motor. In order to provide 100 percent redundancy, if one fan was to fail, the other fan must be able to deliver the design airflow by itself. As shown in the second row, for either one of the fans to deliver 15,000 cfm, it must be equipped with a 20 hp (not 7.5 hp) motor. For this example, a two-fan array can provide 100 percent redundancy, as long as each fan is provided with a larger motor. The drawbacks of increasing motor sizes are reduced motor efficiency and increased size of the electrical service.

As a side note, if the motor sizes are not increased, the two-fan array is capable of providing up to 70 percent of design airflow if one fan fails. If 70 percent is an acceptable level of redundancy (which is not a design day), the two-fan array might be the best choice for this example because it results in the lowest total input power when all fans are operating—13.10 bhp compared to 14.04 bhp for the three-fan array, and 14.12 bhp for the four-fan array.

For the three-fan array, at design conditions with all three fans operating, each fan is selected to deliver 5000 cfm and requires a 7.5 hp motor. As shown in the second row, if any one of the fans was to fail, the remaining two fans could still deliver the full 15,000 cfm—each able to deliver 7500 cfm using the same 7.5 hp motor.

The same is true for the four-fan array. If any one of the fans was to fail, the remaining three fans could deliver the design airflow without the need to increase the size of the fan motors.

For this example, if 100 percent redundancy is required, any of the configurations depicted in Table 4 can work:

- The two-fan array requires the lowest total power when all fans are operating, but requires equipping each fan with a larger motor.
- Either the three- or four-fan array can provide 100 percent redundancy without changing motor sizes.
- The four-fan array requires the lowest total power when one fan has failed, but it requires the most power when all fans are operating. Assuming that a fan will be fixed or replaced when it fails, evaluating fan power when all fans are operating would seem to be more important than when one fan has failed.

Advantages and drawbacks of a fan array (Table 5). While fan arrays have some advantages, there are also drawbacks compared to using a single fan wheel. When a fan array is used, there are advantages of using fewer, larger fans (like 2, 4, or 6) versus many, smaller fans (like 9, 12, 24 or even more) in the array.

- A fan array will typically reduce the overall length of the air-handling unit (Table 3). The length reduction achieved by going from one to two fans can be very significant, but the incremental length reduction benefit is not as significant as the number of fans increases. Eventually a minimum threshold dictated by service clearance is reached.
- When multiple fans are used, the air-handling unit can provide some level of redundancy. This requires proper selection, however, to ensure that when one fan fails the remaining fans are able to provide the required airflow (Table 4). Typically, an array of three or four fans is able to provide the same level of redundancy as an array that consists of many, smaller fans.

- When multiple smaller fans are used in an array, the individual fans and motors are lighter and easier to replace, if necessary.
- Using a single fan wheel (rather than a fan array) will typically result in the lowest-cost air-handling unit. When a fan array is desired, using fewer, larger fans will typically cost less than using many, smaller fans.
- Using a single fan will typically require less input power than an array of multiple fans. When a fan array is desired, using fewer, larger fans will typically require less power than using many, smaller fans.
- Since the fans are operating at a slower speed and the larger fans are more efficient, the fewer the number of fans, typically the better the acoustics.
- Fewer moving parts (and, therefore, fewer fans) generally results in better reliability. Of course, the redundancy provided by using multiple fans in an array partially offsets the concern over a fan failing.

Note that these are generalized conclusions. For example, depending on the length of the air-handling unit and nominal motor speed (900- and 1200-rpm motors can be more expensive than 1800-rpm motors), a unit selected with fewer fans may cost less than a unit selected with a single fan. As another example, using a larger number of fans could lower the sound level in a difficult-to-attenuate octave band by changing the blade pass frequency to an easier-to-attenuate octave band. The optimum number of fans depends on the application.

Summary

When an air-handling unit contains a draw-thru fan that discharges directly into a sufficiently long, straight section of duct that is about the same size as the fan outlet, a housed airfoil fan will typically require less input power than a plenum fan, but a plenum fan will likely have lower discharge sound levels. However, when discharge conditions are not so ideal or when downstream sections are present (such as a discharge plenum, final filter, gas heater, or a blow-thru cooling coil), a plenum fan will likely require less input power and have lower discharge sound levels than a housed fan.

Direct-drive plenum fans are more reliable and require less maintenance than belt-drive fans. And because there are no belt-related drive losses, direct-drive fans are typically more efficient, quieter, and experience less vibration than belt-drive plenum fans. When selecting a direct-drive plenum fan, consider flexible-speed selection, which typically results in a more efficient and quieter fan selection.

Fan arrays may reduce the overall length of the air-handling unit, can provide redundancy for critical applications, and allow the fans and motors to be more easily replaced. However, they typically increase the cost of the air-handling unit, require more input power, and have higher sound levels. When a multiple-fan array is desired, using fewer, larger fans—like 2, 4, or 6—will typically be a better overall solution than using many, smaller fans—like 9, 12, 24 or even more.

For more information on direct-drive plenum fans or fan arrays, refer to the Trane engineering bulletin titled "Direct-Drive Plenum Fans for Trane Climate Changer™ Air Handlers" (CLCH-PRB021-EN).

By Dustin Meredith and John Murphy, applications engineers, and Jeanne Harshaw, information designer, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/engineersnewsletter. To comment, e-mail us at comfort@trane.com.

Table 5. Single fan versus fan array

Characteristic	Single DDP fan	Multiple DDP fans (fan array)	
		Fewer fans	More fans
AHU footprint	+	++	+++
Redundancy	none	+++	+++
Serviceability	+	++	+++
AHU cost	+++	++	+
Efficiency	+++	++	+
AHU acoustics	+++	++	+
Fan reliability	+++	++	+

Trane,
A business of Ingersoll-Rand

For more information, contact your local Trane office or e-mail us at comfort@trane.com