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Selecting Fans for Minimum Energy Consumption

By Michael Brendel, Ph.D. Member ASHRAE

Introduction

Fan selection has largely become an automated process that matches system flow and pressure requirements to a pool of candidate fans. It is intuitive that the most energy-efficient fan is the selection having the lowest power consumption. But trade-offs between first cost and power consumption often drive selections to the smallest fan, rather than to the most efficient. Energy codes and regulatory agencies are introducing new requirements that will force greater emphasis on operating costs and push fan selections toward peak efficiency. However, not all is crystal clear when design and selection practices ignore the underlying physics that govern fan performance and air-distribution system design. This article discusses the fan selection process with emphasis on how fan pressures and selection practices influence the result.

Air-Distribution System

All mechanical systems require energy to produce a desired outcome. Air moving in an air-distribution system encounters resistance due to the action of viscosity between the air and its surroundings, among other factors. The resistance introduced by the air-distribution systems' HVAC components is fairly well understood and can be calculated using modern computational or graphical tools.

An energy grade diagram is useful to illustrate the flow through an air-distribution system (*Figure 1*).^{*} Air enters from the left and travels through the system and is discharged back into the space. The total energy per unit volume of air transported must decrease everywhere as energy is consumed – except of course at the fan. This total energy can be separated into potential and kinetic energy contributions, the sum of which must always equal the total energy at any point in the system.

The fan must produce a certain energy output (per unit airflow volume) to exactly balance energy consumed by the system resistance to maintain continuous delivery of air at the specified rate.

In more familiar terms, the energy per unit volume is equivalent to the total pressure (prove this by comparing the basic units of pressure with energy per volume). Likewise potential and kinetic energies are analogous to static and dynamic pressures.

So the total pressure must decrease everywhere in the air-distribution system with the exception of the fan. The static and velocity pressures can be traded

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^{*} Energy (pressure) grade diagrams are a nice way to illustrate pressures in an air-distribution system. Actual installations will be much more complex and likely include duct connections and other system restrictions upstream of the fan. These only add to the system pressure that the fan must overcome and do not change the basic ideas presented here.

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Matching Fans to Systems

Matching the fan to the system is the goal of fan selection. Many different fan types are available offering a range of benefits and attributes. In theory, the fan laws tell us that any fan can be scaled (size and speed) to any operating condition. Yes, any operating condition. Why not, then, take the most efficient fan and scale it to any arbitrary operating point? Unfortunately, the resulting fan might have an impractical size and/or speed. This is why we have different fan technologies to keep size and speed within reasonable limits. For example, a housed forward-curved fan

operating at peak efficiency is actually more efficient than the same size housed airfoil fan.

This may seem counterintuitive, but it is a result of the different aerodynamic characteristics of the two designs and long-forgotten fan metrics: specific diameter and specific speed. Of course the housed airfoil can achieve a higher peak efficiency, but requires a larger size than the forward-curved fan. Size is an unavoidable constraint in many cases due to equipment footprint or mechanical room space (especially retrofits).

back and forth as a design strategy, but their sum must always equal total pressure. A gradual duct expansion, for example, results in increasing static pressure, but the total pressure must decrease – there is no free ride. Component pressure drops from ducts, filters, coils, dampers, among others, combine to form the system's total pressure drop.

Let's not forget that the pressure drop associated with air penetrating into a space downstream of a grille or diffuser is also part of the system pressure drop. Viscous action at the interface of the jet and its surroundings must be overcome by the total energy produced by the fan. It's the velocity pressure that does the work here, and this will factor into our discussion later.

Calculating the pressure drop through the air-distribution system is a critical step in properly selecting the fan. Many design strategies, such as static regain or constant friction, are available for the ductwork. Manufacturers' data and models are used for individual component pressure drops. The designer will often trade off duct size, cost, noise, and other factors when designing

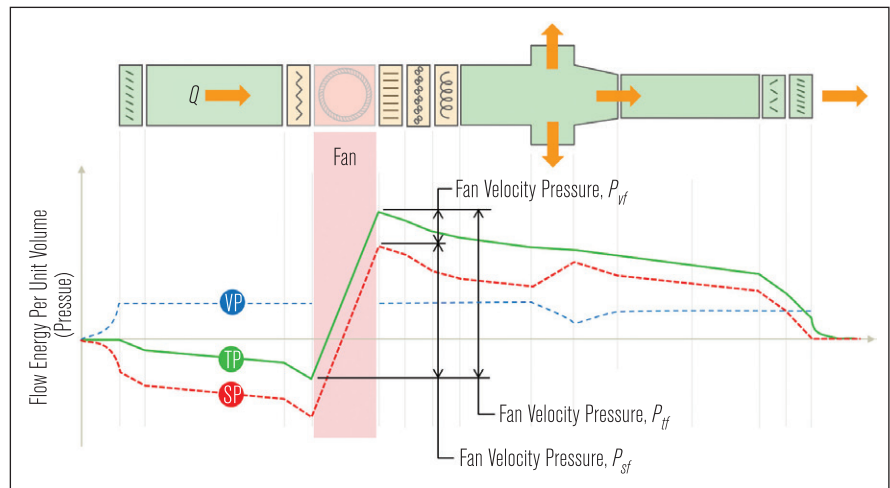


Figure 1: Energy grade diagram, typical air-distribution system

a system. Regardless of approach and tools used, the result is always the total pressure (total energy) required of the fan. This simple fact is often overlooked and leads to incorrect fan selection practices and fan energy consumption estimates.

Fan Characteristics

Fans are characterized by their ability to produce pressure across a range of flow conditions. The pressure ultimately responsible for overcoming the system resistance is the fan total pressure, P_{tf} , the total pressure at the fan outlet less the total pressure at the fan inlet ($P_{tf} = P_{to} - P_{ti}$).

Two other fan pressures will figure in our discussion. The fan velocity pressure, P_{vfr} is the dynamic pressure based on the average velocity at the fan discharge. Finally, the fan static pressure, P_{sfr} is the fan total pressure less the fan velocity pressure ($P_{sf} = P_{tf} - P_{vfr}$). These three fan pressures are shown relative to the energy grade diagram in Figure 1.

The fan total pressure represents the total pressure rise through the fan. However, the fan

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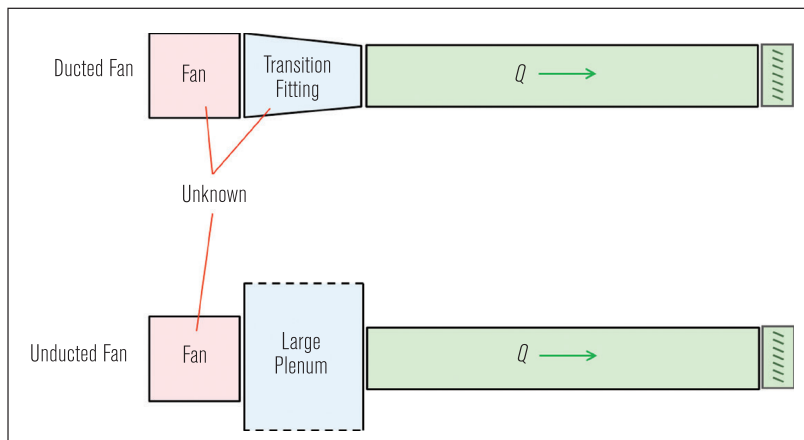


Figure 2: Ducted and unducted fan configurations

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static pressure is not the static pressure rise through the fan since the inlet velocity pressure is not considered in its definition. This is often a key source of confusion when making fan selections. The fan static pressure does not have any real physical significance with regard to fan energy consumption except in special circumstances as will be revealed below.

So the pressure drop resulting from the duct and system calculations is the fan total pressure. To this point there can be no debate. The total energy per unit volume consumed by the system must be balanced by that produced by the fan.

Fan Selection

In general, the air-distribution system pressure drop (fan total pressure) and physical characteristics (duct size) are known in advance of fan selection. The next step is to select a fan that produces the desired flow with the minimum energy consumed. Typically, this is done with computerized selection tools that take the prescribed flow rate and fan pressure and produce a list of candidate fans.

Obviously, the fan consuming the least power is the most energy efficient. It would seem that our story is over. Simply plug in the flow rate and fan total pressure, and pick the most efficient fan. The relationship between fan total pressure and fan selection cannot be understated, especially when energy consumption is of concern. This problem is not new by any means.

Cermak and Murphy,¹ London,² Brake,³ and Graham⁴ have all shown the importance of fan total pressure from various perspectives.

Fan selection, in the simplest form, requires the desired flow rate and fan total pressure. Practical considerations may lead to system designs where the fan outlet is connected directly to ductwork (ducted fans) or connected indirectly through a plenum chamber (unducted).[†] The ducted vs. unducted discharge configuration is important regarding how we interpret and use fan pressures when making fan selections with automated tools.

Many are based on fan static pressure, not fan total pressure. Consequently, using a fan total pressure with a fan static pressure selection tool will lead to incorrect fan selections and performance expectations. Matching the correct fan pressure to that used by the automated selection tool is critical.

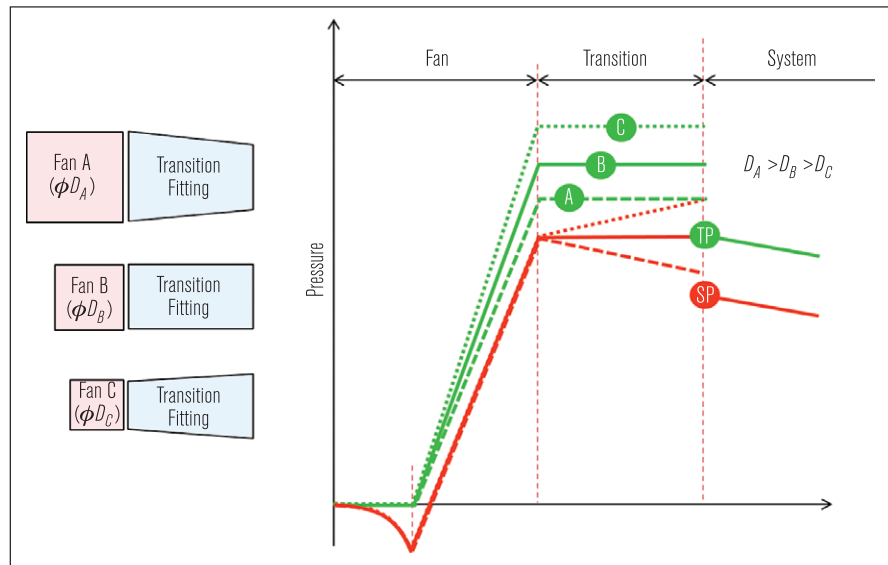


Figure 3: Fan pressure mismatch using fan static pressure (FSP) selection tool with fan total pressure (FTP)

Table 1: Comparison of fan static pressure (FSP) and fan total pressure (FTP) selection tools (ducted)

Fan	Size (In.)	Q (cfm)	P _{sf} (in. w.g.)	P _{tf} (in. w.g.)	H (hp)	N (rpm)
Ducted Fan Selections Using Fan Total Pressure in Fan Static Pressure Selection Tool (Incorrect)						
A	25	12,000	6.00	6.13	15.5	1,469
B	24	12,000	6.00	6.19	14.9	1,648
C	22	12,000	6.00	6.29	15.4	1,950
Ducted Fan Selections Using Fan Total Pressure in Fan Total Pressure Selection Tool (Correct)						
A	25	12,000	5.87	6.00	15.1	1,454
B	24	12,000	5.81	6.00	14.4	1,626
C	22	12,000	5.71	6.00	14.7	1,918

Ducted Applications

Figure 2 shows the important differences between ducted and unducted applications. In the ducted application, the fan has a fitting for direct connection to the ductwork. We know the size of the ductwork in advance, but we do not know the size of the fan. We must anticipate a transition section placed between the fan and ductwork. The upstream size of this transition section is also unknown because we have not selected the fan yet. Typically, however, the transition will have very little total pressure drop compared to that of the system, and we can assume it's zero.

It is common to take the required fan total pressure and use it in a fan selector tool based on fan static pressure. This is incorrect. We do not know the fan static pressure in

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[†] The distinction between ducted and unducted fans described here is in the context of a fan embedded in equipment (roof top unit, air handler, etc.) that is attached to an air-distribution system. A housed airfoil supply fan would be ducted, while a plenum supply fan would be considered unducted. But the unducted configuration also applies to a fan that is not connected to any plenum chamber at all. An exhaust, circulating, or condenser fan discharging into a very large space, or directly outside are examples. The fan inlet configuration is of no importance in the present discussion.

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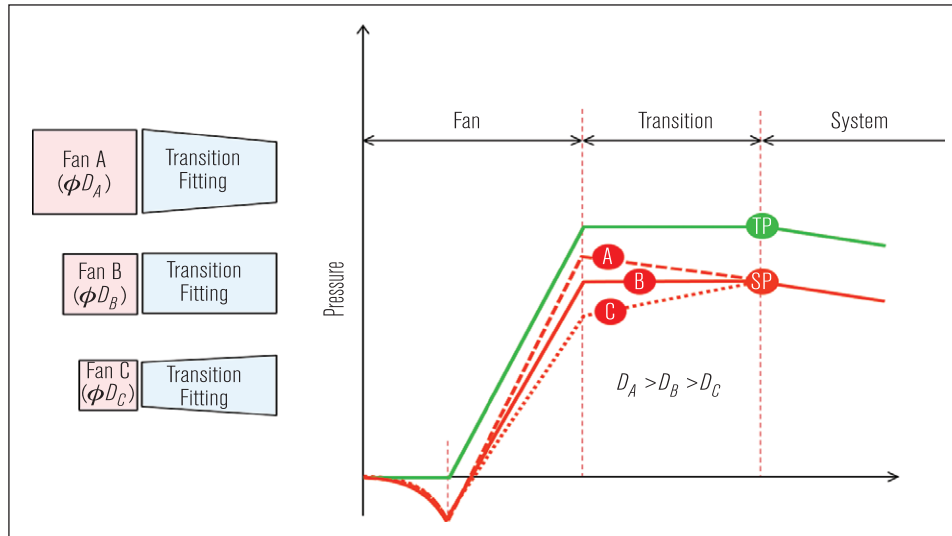


Figure 4: Fan pressure using fan total pressure (FTP) selection tool with fan total pressure (FTP) values

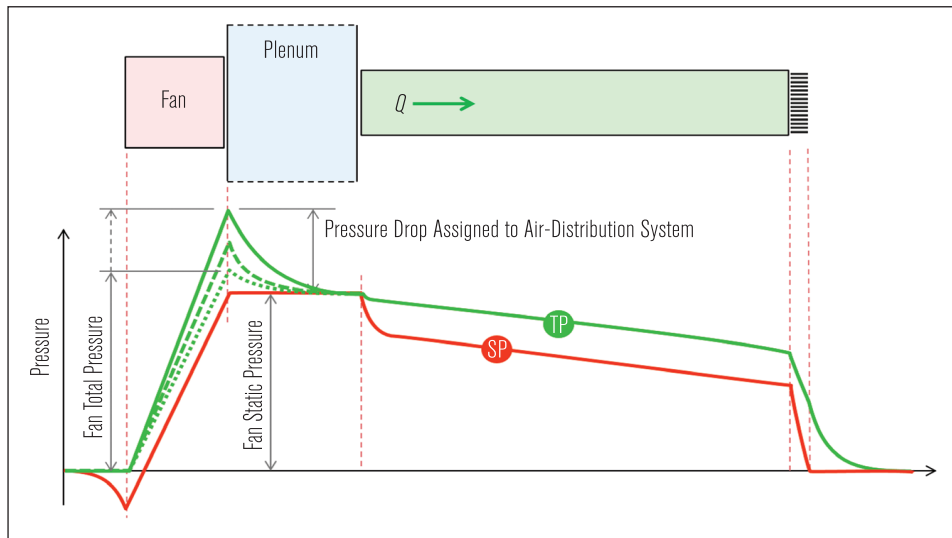


Figure 5: Energy grade diagram, unducted fan configuration

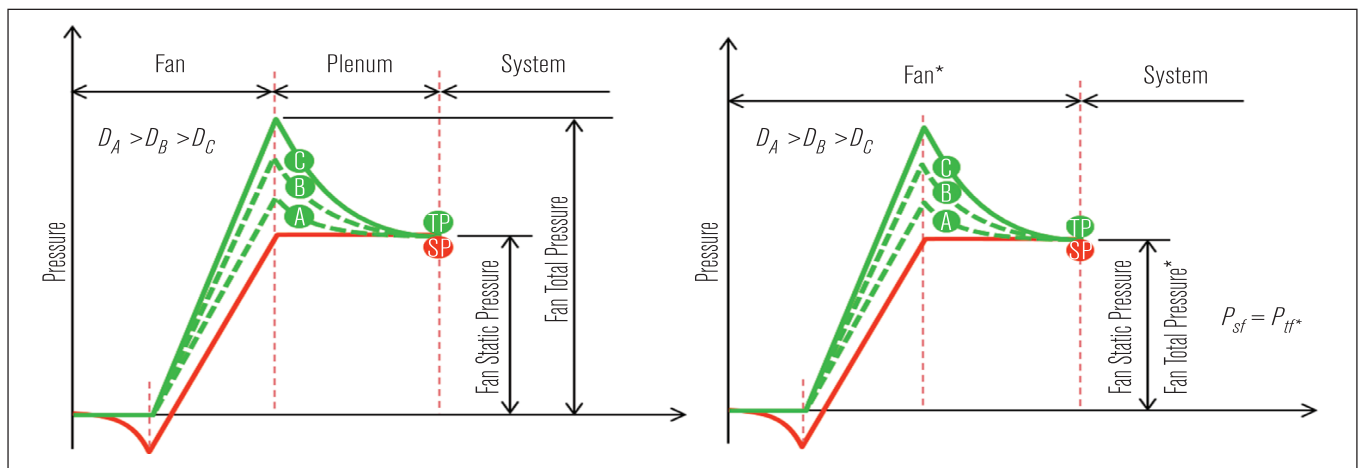


Figure 6: Energy grade diagram, unducted fan configuration, original and redefined fan boundaries

advance. The fan static pressure is different for each fan size as a result of the area change in the transition section. We could make fan selections using the fan static pressure selector tool by calculating the fan static pressure for each candidate fan, but this is cumbersome and does not lend itself to automated selections. The correct approach is to use a fan selector tool based on fan total pressure. Some manufacturers offer this option, but not all. So ask.

If fan total pressure is not available, selections must be made one at a time, each with a different fan static pressure. For each candidate fan, the fan velocity pressure would be calculated from the required flow rate and fan outlet area. Then $P_{sf} = P_{tf} - P_{vf}$. Not much fun.

What sort of error is introduced by using fan total pressure in a fan static pressure selector tool? By using the calculated fan total pressure in a fan static pressure selector tool, we are mismatching the fan to the system requirement. Figure 3 shows three different size fans selected using fan total pressure in a fan static pressure tool and the resulting misalignment with system conditions. Table 1 compares fan static pressure and fan total pressure selection tools in

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ducted systems. In red are three selections for a housed centrifugal fan with a system requirement of 12,000 cfm and 6.0 in. w.g. (5663 L/s and 1500 Pa) fan total pressure. The resulting selections all produce fan total pressure that exceeds the fan total pressure requirement. Therefore, the selections will indicate a higher power consumption than needed.

By contrast, the results of using a fan total pressure selector tool (the correct tool) is shown in Figure 4 and in green in Table 1. Note that the power consumption is lower than that predicted using the fan static pressure selector tool.

The differences illustrated here are small and you could argue that air balance will ultimately set matters straight by way of a speed adjustment. That is true. But increased scrutiny of energy consumption and operating costs are evaluated in advance of installation. A misstep here could be the difference between winning and losing a job based on energy calculations at the submittal stage.

Unducted Applications

Unducted fan selection presents a somewhat different problem. The system pressure drop calculation proceeds as usual up to the plenum chamber as shown in Figure 5 and results in a total pressure drop from that point. What is often overlooked is that the airflow must be delivered into the plenum chamber, and this does not come free.

Despite the lack of a duct, the air penetrating into the plenum chamber (or exhausting into open air) experiences resistance.¹¹ The resulting pressure drop, for a large plenum chamber, is identical to the fan velocity pressure. Therefore, the correct fan total pressure for selection purposes must be the

Table 2: Comparison of fan static pressure (FSP) and fan total pressure (FTP) selection tools (unducted).

Fan	Size (in.)	Q (cfm)	P _{sf} (in. w.g.)	P _{tf} (in. w.g.)	H (hp)	N (rpm)
Ducted Fan Selections Using Fan Total Pressure in Fan Static Pressure Selection Tool (Incorrect)						
A	30	12,000	5.81	6.00	16.5	1,459
B	27	12,000	5.71	6.00	16.1	1,712
C	25	12,000	5.60	6.00	16.2	2,028
Ducted Fan Selections Using Fan Total Pressure in Fan Total Pressure Selection Tool (Correct)						
A	30	12,000	6.00	6.19	17.0	1,478
B	27	12,000	6.00	6.29	16.8	1,739
C	25	12,000	6.00	6.40	17.2	2,067

system pressure drop up to the plenum, plus the fan velocity pressure.

Of course the fan velocity pressure is not known in advance because we have not selected the fan yet. Selecting on the basis of fan total pressure becomes cumbersome because we have to calculate a different fan total pressure for each fan size. But there is a way out.

We recognize that the pressure drop associated with airflow penetrating into the plenum chamber is part of the system. Technically, this is correct. But we can alternatively assign the pressure drop to the fan, in effect redrawing the control boundaries and redefining the fan relative to the system. The redrawn fan boundaries give nearly zero fan velocity pressure at the new fan outlet, so the fan static pressure is the same as fan total pressure as shown in Figure 6. Now the total pressure drop in the system equals the redefined fan total pressure (P_{tf}^* in the diagram). Most importantly, we can use a fan static pressure selector tool to make the fan selection because $P_{tf}^* = P_{sf}$. This is the common practice, although the technical reasons why it

works are rarely considered. So for unducted fan applications, it is appropriate to use the calculated system resistance applied in a fan static pressure selection tool.

To illustrate, Table 2 shows a typical plenum installation with a flow rate of 12,000 cfm and 6.0 in. w.g. (5663 L/s and 1500 Pa) total pressure requirements. The red section shows that selections using the fan static pressure with a fan total pressure selection tool (this rarely happens) would produce selections that underestimate the power requirement of the fan. The green portion shows fan selections using the fan static pressure with a fan static pressure selection tool.

		Ducted Fan	Unducted Fan
		Constant Fan Total Pressure	✓
Selector Tool	Constant Fan Static Pressure	Overpredicted Power and Speed	✓

Figure 7: Selector matrix - ducted versus unducted configurations

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¹¹ Often a subject of debate. The resistance is proportional to velocity squared – just like in a duct. Except that there are no walls, only shear layers that have exactly the same effect. In this case, the kinetic energy is converted to heat. Reducing this resistance (and energy consumed) means reducing the velocity. A larger outlet area (bigger fan), an outlet cone or diffuser, are options. From a practical standpoint, the velocity can never go to zero. You have to deliver the air!

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Whether we are using fan total pressure for a ducted fan selection, or fan static pressure for an unducted fan selection, it is important that the fan data used by the selection tool are appropriate for those configurations. For instance, fans having an outlet duct fitting are generally tested with an outlet duct and are indicated by the AMCA installation type, for example – Type B and D for ducted outlet, and Type A and C for unducted outlet.⁵ Selections for an unducted installation using fan data from a ducted test would not be valid, so make sure the selection tool uses the same outlet configuration as in the application.

Summary

Worldwide, energy codes and regulatory actions continue to target fan energy consumption. It is clear that fans need to be selected closer to their peak efficiency to meet energy reduction goals. But this cannot be achieved without proper selection practices that recognize the correct relationship between system pressure drop, fan pressures, and the tool used to make selections. This is especially important when submittal-based fan performance is used to evaluate competing options for energy efficiency.

The system pressure drop always results in a total pressure requirement of the fan (P_{tr}). *Figure 7* is a matrix for the type and selector tool used and results. In ducted fan arrangements, selections using fan total pressure in a fan total pressure selection tool produce the correct result. Using a fan static pressure tool for selections will over-predict energy consumption and lead to operating cost estimates that are too high. A fan static pressure tool can be used for selection, but the fan static pressure would have to be adjusted for each fan size considered – not very convenient.

On the other hand, an unducted fan can be selected using a fan static pressure selector tool due to offsetting factors in the interpretation of fan and system pressures and still satisfying the total pressure drop in the air-distribution system.

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