providing insights for today's hvac system designer

Engineers Newsletter

volume 43–3

FANtastic!
A Closer Look At Fan Efficiency Metrics

This EN will explore two of the most talked-about fan efficiency metrics (Fan Efficiency Grade and Performance Based Efficiency Requirement), and identify their benefits and limitations. It will conclude with a summary of where and how these metrics are currently being applied in standards and codes.

Types of Fan Efficiency Metrics

Fans are at the heart of every air-distribution system so it makes sense that improvements to fan system design coupled with higher efficiency fans can provide substantial HVAC energy savings. The Air Movement and Control Association (AMCA) estimates that fans consume between 30% and 40% of commercial HVAC energy.* Improving fan efficiency is therefore an important next step towards reducing global, overall energy use.

Before diving in, we need to explain some terminology to better understand the usefulness and limitations of each fan efficiency metric.

Application-Independent vs. Application-Dependent. The subject of dependency on the fan's operating point is an important one. Depending on the authority of the organization utilizing fan efficiency metrics, they may have influence over the manufacturer, the designer, or both. Let's therefore broadly characterize the metrics based on whether the fan's operating point is being considered:

- Application-Independent: An efficiency metric in which the fan's actual operating point **is not** considered.
- Application-Dependent: An efficiency metric in which the fan's actual operating point **is** considered.

As we will see, some metrics function better as one dependency type over another.

Product Efficiency vs. System Efficiency. The next subject segregates the fan (product) itself and the overall system:

- Product efficiency: The efficiency metric considers the fan alone
- System efficiency: The efficiency metric considers the overall system, including fan system effects, duct leakage, duct design, etc.

Even if a fan has a high peak efficiency, how one applies that fan in a system will ultimately determine how much energy will be used. The impact of the **system** on fan energy use heavily outweighs the impact of the fan alone.

Total Pressure Versus Static Pressure. Fan efficiency metrics tend to be defined in terms of *total* pressure. Fan **total** pressure is the total pressure (static pressure plus velocity pressure) at the fan outlet minus the total pressure at the fan inlet. It is a measure of the total mechanical energy added to the air by the fan.

On the other hand, *static* pressure is total pressure minus velocity pressure. By definition, fan **static** pressure is the total pressure at the fan outlet minus the total pressure at the fan inlet *minus* the velocity pressure at the fan outlet. This can be a source of confusion. When the fan **inlet** is *unducted*, the *inlet velocity pressure* is zero and the total pressure equals the static pressure. However, when the inlet is *ducted*, care must be taken in the field to measure the total pressure at the inlet rather than just the static pressure. When the **outlet** is *unducted*, the *outlet velocity pressure* is zero, in which case the change in fan total pressure will equal the change in fan static pressure.

To ensure all forms of energy are accounted for, the total pressure should be considered for ducted systems. Note that many engineers will design their systems using only static pressure. They are still accounting for any velocity pressure changes and, therefore, total pressure changes by ensuring the duct connection to the fan matches the intent (e.g., 3 duct diameters of straight duct sized the same as the fan outlet) and by using dynamic loss coefficients ("Kt" factors).

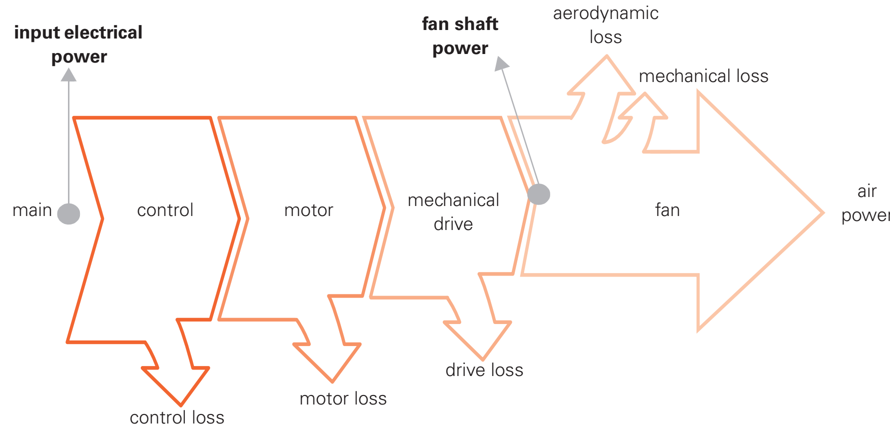
* W. Smith, "2012 Fan Market Data Defines the Path to Higher Efficiency" AMCA International *inmotion* August 2014.

Extended Product (i.e., wire-to-gas). Let's briefly explore an important topic that's not addressed in today's codes and standards. The metrics currently being discussed tend to address only the power applied to the fan shaft. AMCA will soon release AMCA Publication 207, "Fan System Efficiency and Fan System Input Power Calculation," which will provide guidance, a method, and tabulated data to calculate fan system input power and overall efficiency of the complete fan system (see Figure 1). This will include the fan efficiency, the electric motor efficiency, and the efficiency of the power transmission and/or motor controller, if present.

Direct measurement of input kW is preferred, but this publication will at least give manufacturers and other interested parties a common basis for calculation and comparison.

The Air-Conditioning, Heating & Refrigeration Institute (AHRI) recently published another important step towards an accurate, calculated system input power: AHRI Standard 1210, "Performance Rating of Variable Frequency Drives." This standard will provide a uniform method of measuring and comparing Variable Frequency Drives by establishing testing and rating requirements.

Figure 1. Overall efficiency of a complete fan system



Note: There is a version of the Fan Efficiency Grade (FEG) metric that incorporates input power: Fan Motor Efficiency Grade (FMEG). The metric is not widely used in the U.S., where the fan is often sold separate from the motor and/or motor controller, but it is an important metric in the European Union, where fan-motor-drive combinations are more commonly sold.

The first question we need to ask is: Why can't we use the simple fan efficiency calculation, rather than something more complicated like FEG? Let's look at the impact of fan diameter on efficiency.

Larger Fans vs. Smaller Fans. Increased turbulence and tolerance magnification result in smaller fans operating at a reduced efficiency when compared to a larger fan. As shown in Figure 2, this change can be rather dramatic as the diameter is increased – even for the same type of fan. Consider the area in the shaded box. A single-number efficiency limitation (such as > 65%) would either a) effectively eliminate the use of smaller diameter fans or b) require a limit so lenient (such as > 45%) that it would have little impact on reducing building energy use.

FEGs solve this small fan diameter dilemma by accounting for the impact diameter has on fan efficiency.

The FEG classification number alone is an application-independent metric, based on the peak aerodynamic efficiency of a ducted fan separate from its motor and drive. It's important to note, however, that the fan's peak aerodynamic efficiency will not ultimately determine how much

Fan Efficiency Grade (FEG)

Many of the latest energy codes and standards, including the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 90.1-2013, reference a fan efficiency classification system known as Fan Efficiency Grade (FEG). The FEG metric was defined when AMCA published Standard 205 in 2010. It was first adopted into ASHRAE Standard 90.1 through Addendum u to the 2010 version, and is now included in ASHRAE 90.1-2013. It has also been adopted by the International Green Construction Code (IgCC) and is being considered for a number of other model construction and energy codes. FEG is by far the most commonly applied fan efficiency metric in use today.

Figure 2. Fan size versus total efficiency comparison

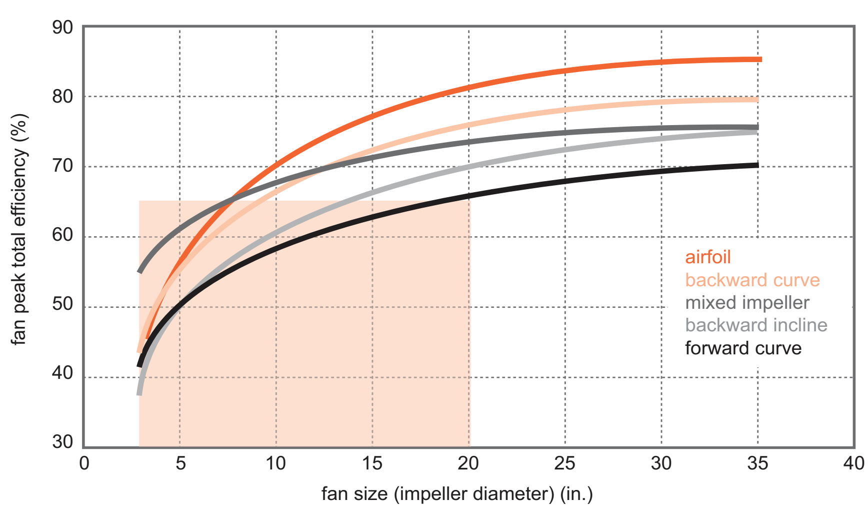


Image courtesy of AMCA International.

Figure 3. Fan minimum efficiency window

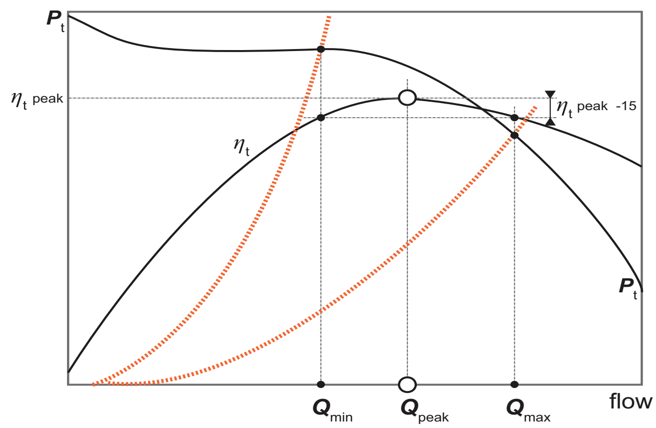


Image courtesy of AMCA International. ANSI/AMCA Standard 205-12, Energy Efficiency Classification For Fans.

energy is used. Even with a highly efficient fan, that fan could be selected to operate at a point far from this peak efficiency.

To use FEG as an application-dependent metric, the FEG classification number can be accompanied by an allowable selection range or "window". This is accomplished by defining a number of percentage points from peak efficiency; as shown in Figure 3.

Note that the selection window is in terms of percentage points; not a percentage. For example, if the peak efficiency is 70%, a 15-point window means that the fan must be selected with an efficiency of at least 55% (not 0.85 x 70% = 59.5%).

Since FEG ratings are an indicator of peak fan efficiency, and not actual operating efficiency, their main value is in segregating fans during selection. Once an engineer has narrowed a list of available fans to only those that meet the minimum FEG rating – and has filtered those outside of the allowable selection window – the focus should turn to other selection parameters, such as actual power consumed, sound power levels, size, and cost.

When published, AMCA Publication 206, "Fan Efficiency Grade (FEG) Application Guide," will provide an overview of issues associated with fan energy consumption and offer guidance for using FEG in codes, standards and regulations as a means to increase the use of energy-efficient fans.

How to determine the FEG classification. To determine the FEG classification for a particular fan, a calculation is not required. Instead, the fan's peak aerodynamic efficiency based on **total** pressure is compared to the chart published in AMCA 205.

For example, consider a 25-inch diameter fan with a peak total efficiency of 68 percent. Using the chart in Figure 4, 68 percent falls above the FEG71 curve, but still below the FEG75 curve. Therefore, this fan would be labeled FEG71.

By definition, an FEG label is assigned based on fan **component** performance data in accordance with a standard like AMCA 210. If an equipment-mounted fan is being evaluated (see sidebar p.6), the equipment manufacturer will need to provide two data sets: a fan component performance data set and an equipment performance data set. The former is used to determine whether a given operating point would meet an application-independent FEG selection window while the latter is used to provide in situ performance data.

Note that the shape of these curves is generally intended to ensure that an entire product line of geometrically similar fans can meet the same FEG. However, several factors could cause some diameters or variations to have different FEG labels.

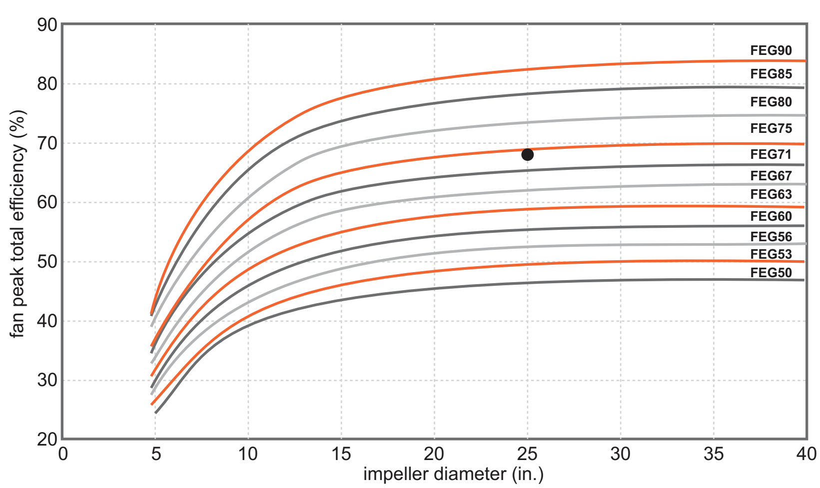
The FEG classification is determined by the fan manufacturer, so the system designer need only filter the available fan selections by the minimum FEG level prescribed by the appropriate code or standard. As described earlier, the designer is then expected to determine whether the desired fan operating point meets the allowable selection window requirement.

How does FEG differ from ASHRAE Standard 90.1 fan power limitation?

The fan power limitation in Standard 90.1 is an overall system design limitation, not a requirement of the fan as a component. There are many examples of equipment (such as those listed in Section 6.4.1.1) or components (such as motors) which contribute to the overall system power, while still having a separate limitation on the component.

To meet the requirements of 90.1, a system designer should consider only those fans that meet the application-

Figure 4. FEG classification for a 25-in. diameter fan with peak total efficiency of 68 percent



independent (FEG level) and application-dependent (allowable selection window) requirements. If the fan power limitation still cannot be met, the entire system needs to be analyzed to reduce fan power.

FEG Shortcomings. FEG is an elegant metric that solves the small diameter dilemma and provides users with a simple classification system to segregate fans based on peak aerodynamic efficiency. However, FEG is not without limitations.

First, it's important to note that FEG is best suited for ducted applications. The application-dependent selection region will often eliminate some fans from consideration in unducted or low pressure applications. Even lower pressure applications (such as return or exhaust fans) will suffer as the minimum FEG limit would force the use of a larger diameter fan or a different fan type altogether (an axial fan in lieu of a centrifugal fan, for example). This could make retrofits more expensive and difficult. Keep in mind: these lower pressure fans typically use less energy than their supply counterparts.

Second, the requirement to use total pressure and total efficiency complicates the selection of an unducted fan. Fan **static** pressure is the only useful work in an unducted application, but FEG requires the use of **total** pressure. To accomplish this, artificial outlet areas must be defined in an attempt to quantify energy that's ultimately unused.

Within the fan community however, there is a metric that is being considered that could address some, if not all, of these shortcomings.

An Alternative Fan Efficiency Metric: Performance-Based Efficiency Requirement (PBER)

An alternative fan efficiency metric currently under consideration is the Performance Based Efficiency Requirement or PBER (sometimes referred to as Fan Efficiency Ratio or FER). Specifically formulated to address the unducted or low pressure fan dilemma, the PBER metric yields a minimum required efficiency based on the useful work performed at a given operating point (airflow and pressure). Alternatively, maximum power in lieu of a minimum efficiency could be output. This type of metric would continue to allow fans with lower peak efficiencies, or fans selected at an inefficient operating point, to be used as long as their energy use is relatively low.

How to calculate PBER. The procedure to determine PBER is a little more complicated than FEG. We first start with a target efficiency and apply a series of factors to adjust that efficiency for those operating points where actual energy use is relatively low:

$$\text{Required Efficiency} = \left(\text{Target Efficiency}\right) \times \left(\text{Flow Factor}\right) \times \left(\text{Pressure Factor}\right)$$

Where:

Target Efficiency: The minimum, peak aerodynamic efficiency allowed. (Note that the required efficiency of the fan will never exceed this Target Efficiency.)

Flow Factor: An adjustment to reduce the target efficiency for a fan operating at lower airflows. (Note that FEG has an implicit flow factor, which is how smaller diameter fans are handled.)

Pressure Factor: An adjustment to reduce the target efficiency for a fan operating at lower pressures. (Unlike FEG, PBER considers the pressure capability of the fan.)

Determining which pressure to use is dependent on whether the fan is ducted or unducted:

- For ducted fans, use total pressure.
- For unducted fans, use static pressure.

The formula would be the same for either pressure type; only the constants would change. For example, the target efficiency could be set to 66 percent for ducted fans and 60 percent for unducted fans.

Let's consider a PBER calculation example assuming an unducted fan. We first need to assume some flow and pressure factors:

$$\text{Required Efficiency} = \left(60\%\right) \times \left(\frac{CFM}{250 + CFM}\right) \times \left(\frac{P}{0.40 + P}\right)$$

It's important to note that the 60 percent, 250, and 0.40 values are for illustrative purposes only. Different code bodies may choose to use different values. The 250 value in particular was chosen here to closely approximate the implicit FEG flow factor.

Assuming 10,000 CFM and 3.0 in. H_2O static pressure, the required fan static efficiency for an unducted fan would then be:

$$\text{Required Efficiency} = \left(60\%\right) \times \left(\frac{10{,}000}{250 + 10{,}000}\right) \times \left(\frac{3}{0.40 + 3}\right) = 52\%$$

Therefore, any unducted fan with a static efficiency of 52 percent or higher at this operating point would be accepted.

PBER compared to FEG. As fans become more efficient, the shape of the allowable PBER selection region will more closely match the shape of the allowable FEG selection region. Consider the two fans illustrated in Figure 5. The region bounded by the dashed black line (surge region), the dashed gray line (peak efficiency - 15 points), and the solid black line (maximum RPM) is the allowable FEG selection region. The region bounded by the orange solid line is the allowable PBER region. The two regions are quite dissimilar for the inefficient fan but are very similar for the more efficient fan.

Therefore, both metrics will allow similar operating points for highly efficient fans. But unlike FEG, the PBER metric does not actually eliminate any fan from being considered – rather, it reduces the valid operating region for less efficient fans.

As mentioned previously, some standard/code bodies or regulators may need to consider an application-independent metric. How can PBER be used as an application-independent metric and would an application-independent PBER still provide advantages over the FEG metric?

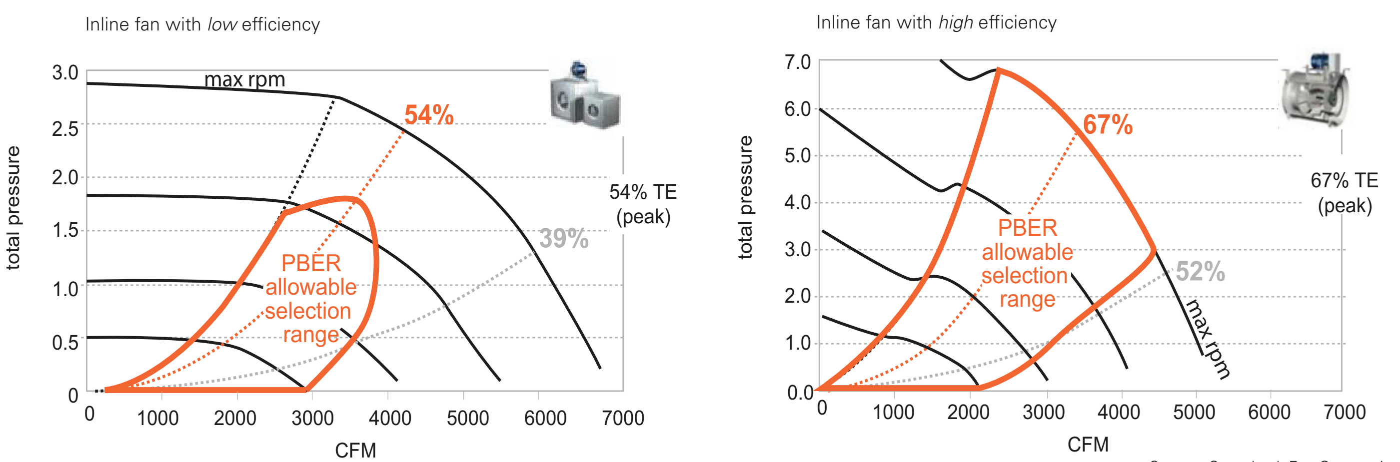
One option is to determine the input airflow and pressure based on a known intersection: peak aerodynamic efficiency and maximum *cataloged* fan speed, for example. This calculation wouldn't be the system designer's responsibility. Instead, the calculation could be used to determine a maximum *allowable* fan speed. Designers would then simply compare their operating RPM with the maximum as defined by the code or standard being considered.

As illustrated in Figure 6, a maximum allowable RPM would permit some selections outside of the PBER range but unlike FEG, it would significantly reduce those operating points at which the fan would consume the highest amount of energy.

Note that PBER, unlike FEG, would also close any loopholes associated with a steep efficiency curve. Typical of axial fans in particular, a steep efficiency curve is one where the fan may have a very high peak efficiency, but low operating efficiency off peak.

We see how a metric like PBER can maximize energy efficiency by considering the selection point or by trimming the most energy-intensive regions off the fan's valid selection window. In addition to these very important benefits, PBER also considers actual input power as a factor, thus allowing alternative fan types, like forward-curved (FC) fans, to be used even if they may have a lower peak efficiency (see sidebar p.7). The alternative would be to assign a unique FEG limit for FC

Figure 5. Allowable selection range comparison examples



Source: Greenheck Fan Corporation

Figure 6. PBER versus FEG application independent comparison

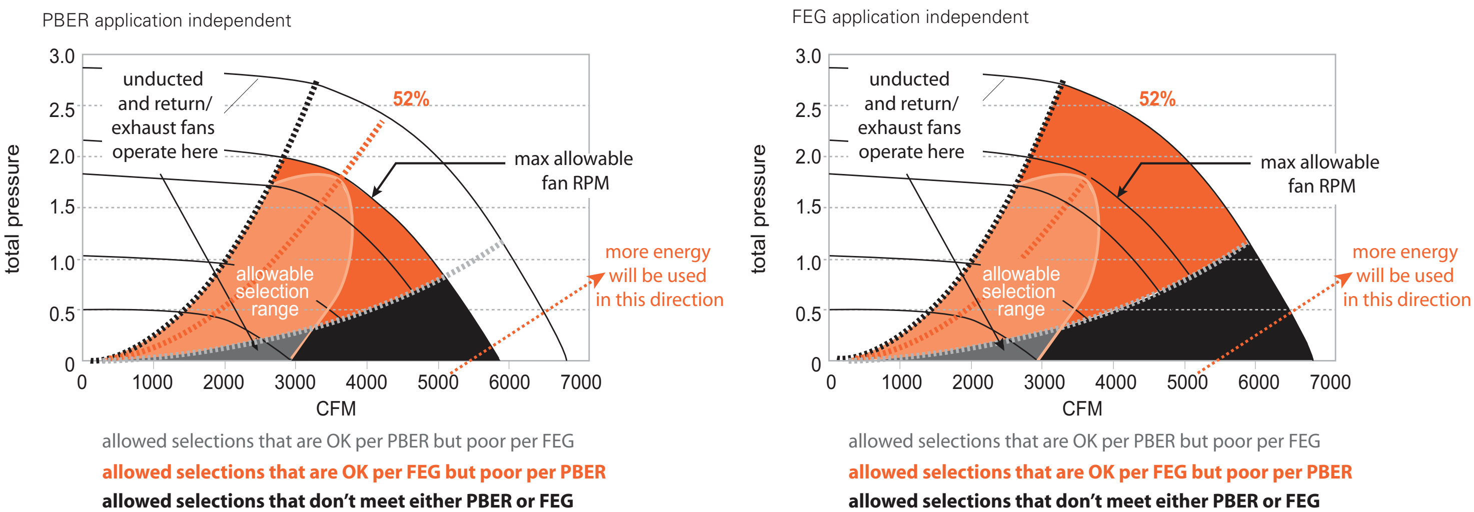


Table 1. Fan efficiency requirements in published codes

	AMCA Standard 205-12 Annex B (recommendations)	2012 International Green Construction Code (IgCC)	ASHRAE Standard 90.1-2013	ASHRAE Standard 189.1-2014	2015 International Energy Conservation Code (IECC)
Minimum	Not specified	Minimum: FEG71	Minimum: FEG67	Minimum: FEG67	Minimum: FEG67
Selection window	within 15 percentage points of peak total efficiency	within 10 percentage points of peak total efficiency	within 15 percentage points of peak total efficiency	within 10 percentage points of peak total efficiency	within 15 percentage points of peak total efficiency
Details	Standard scope: • An impeller diameter of 5 in. or greater • Operating with a shaft power 1 HP and above • Total efficiency calculated according to one of the common fan test standards (such as AMCA 210)	Scope: • For "standalone supply, return and exhaust fans" over 1 HP	Notable exceptions: • Single fans with a motor nameplate of 5 HP or less • Fan arrays with a combined motor nameplate of 5 HP or less • Fans contained in equipment listed under Section 6.4.1.1 • Fans included in equipment bearing a third-party certified seal for air or energy performance of the equipment package	Notable exceptions: Same as ASHRAE Standard 90.1-2013	Notable exceptions: Same as ASHRAE Standard 90.1-2013

fans. However, this FEG approach wouldn't prevent an FC fan from being used in an inappropriate, high energy-use application. The same can be said for return/exhaust fans. The PBER approach would require supply fan selections to be more efficient than return/exhaust fan selections.

Current Requirements

Table 1 details the latest fan efficiency requirements in published codes, standards, or publications.

Note: As mentioned previously, the selection window is in terms of percentage points; not a percentage. For example, if the peak efficiency is 70 percent, a 15-point window means that the fan must be selected with an efficiency of at least 55 percent (not 0.85 x 70% = 59.5%).

Peak total efficiency is based on component performance data. If evaluating an equipment-mounted fan, care must be taken to ensure the correct data set is being used.

Component fans can now be certified in accordance with AMCA publication 211 as an FEG-rated fan and will carry a specific label. To date, this is the only certification program for component fan energy efficiency.

Product Affected

Based on the current requirements detailed in Table 1, the following exceptions are common:

- Fans that are part of equipment listed in Section 6.4.1.1 of ASHRAE Standard 90.1
- Fans included in equipment with a third-party certified seal for air or energy performance of the equipment package

Section 6.4.1.1 (Minimum Equipment Efficiencies) addresses the following equipment which contain fans: DX air conditioners (packaged rooftops, split systems, and self-contained units), air-cooled condensing units, water-source heat pumps, air-cooled chillers, PTACs, furnaces, cooling towers, and VRF systems. Therefore, the fans in these products are currently exempt from having to also meet the minimum FEG and selection window limitations.

Equipment mounted fans

Test and rating standards are created to ensure uniformity amongst manufacturers thus affording system designers and equipment manufactures consistent data for evaluation. ANSI/AMCA Standard 210 (ANSI/ASHRAE Standard 51), "Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating," was created for fans which are used as a standalone **component** and is undoubtedly the industry standard for fan airflow performance.

Once a fan is installed in a cabinet (such as an air-handling unit), however, a number of factors can influence performance. Known generally as "system effects," many of these factors can be approximated, but the combinations must be tested for accurate performance. Some common "system effects" include:

- Cabinet proximity
- Component proximity (coils, filters, internal control enclosures, etc.)
- Motor proximity
- Bearings, sheaves, and other drive components
- Discharge orientation

Equipment test and rating standards are created to include these effects. For example, AHRI Standard 430 describes the test and rating requirements for central station air-handling equipment. An equipment standard will provide the most accurate estimate of final, in situ performance. In the absence of an equipment standard, a fan that has been tested and rated in accordance with AMCA Standard 210, coupled with any appropriate systems effects (reference Publication 201 from the AMCA Fan Application Manual), should be used.

The cabinet's effect on a fan can be quite significant. Addressing these effects can have as much, if not more, influence on overall energy use than addressing fan efficiency itself. By considering the equipment a fan is mounted in, additional energy savings can be realized.

Most air-handling products bear a "third-party certified seal" from AHRI. Catalogued air handlers and blower coils are certified to AHRI Standard 430, which evaluates the air handler on the basis of airflow, static pressure, fan speed, and brake horsepower. Likewise, fan-coils and unit ventilators are certified to AHRI Standard 440. Therefore, the fans in these products are currently exempt from having to also meet the minimum FEG and selection window limitations.

Custom air-handling units do not typically carry an AHRI seal. However, most custom manufacturers will incorporate fans that are certified in accordance with AMCA Publication 211, and it's likely they will now carry the new FEG seal.

Looking Ahead

FEG, and metrics like PBER, are certainly a step in the right direction. But where will the industry go from here?

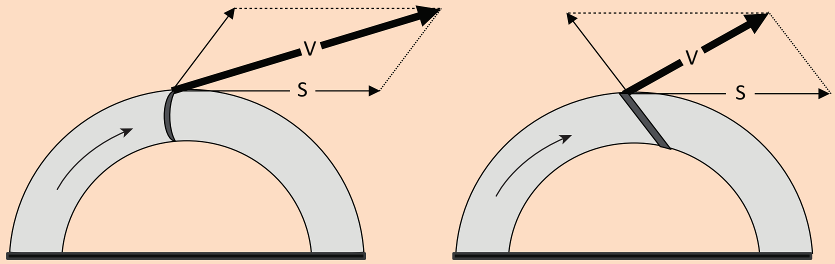
Considering the substantial amount of energy that can be saved at part-load, a metric to encourage speed control (e.g., VFDs) would seem to make sense. The regulation activity for other components (pumps, in particular) seems to suggest such a metric might be forthcoming. Similarly, a metric to account for efficiency at part-load operation would be beneficial. Endeavors like AMCA 207 and AHRI 1210 are helping to get us there.

Direct-driven fans are becoming more and more prominent. Having a way to encourage their use would make sense. For example, PBER could include a drive factor (in addition to the existing flow and pressure factors) to encourage the use of direct-driven fans. The drive factor could also provide a method to incorporate a wire-to-gas consideration.

Other possible changes to fan efficiency regulations could include:

- Raising the minimum FEG requirement (from FEG67 to FEG71, for example)
- Narrowing of the allowable selection window (from 15 percentage points to 10 points, for example)

A Special Fan Type: Forward-Curved (FC) Fans.



forward curved   backward inclined

FC fans are unique in that they can be used in two different ways. They can be used as a low cost, less efficient option for an application where a more expensive, more efficient airfoil (AF) fan should be used. They can also be used for their unique characteristics as described further below. Alternatively, backward-inclined (BI) fans are generally used for one purpose only: as a low cost, less efficient alternative to an AF fan.

As mentioned previously, AF or BI fans are most efficient when selected close to the surge region. Moving towards the surge region along a constant speed (RPM) curve, the severity of stall is gradual for an FC fan. Therefore, they can be operated at peak efficiency with less concern about crossing into the surge region.

Consider that some products are simply selected out of a catalog and in this instance, little may be known about the system resistance. Additionally, the user might not be as experienced in fan selection. If they were to select the more efficient fan with an appropriate safety factor, the fan could very well end up not being as efficient as the more tolerant FC fan.

Advantages of using FC fans (versus other housed fan types)

- FC fans have a relatively flat acoustical spectrum without an objectionable blade tone. They are particularly suited for lower pressure applications where the fan is in close proximity to occupied spaces.
- FC fans are most efficient at low pressure. They are particularly suited for lower static supply fan applications and return or exhaust fan applications.
- FC fans are compact and often result in a smaller unit footprint.
- FC fans typically operate at a lower RPM, which improves bearing life and results in higher reliability.
- FC fans are very forgiving. The onset of objectionable stall is very subtle and the fans can be operated at much lower airflows.
- FC fans are overloading, meaning the input power naturally decreases as system pressure increases (i.e., filter loading).
- FC fans are easier to assemble and install - the inlet cone/impeller gap is not critical.

Drawbacks of using FC fans (versus other housed fan types)

- Lower peak efficiency than BI or AF fans.
- Lower fan static pressure capacity - generally due to structural limitations.
- Low frequency noise is higher than BI or AF fans.
- The relatively flat CFM vs. pressure curve will cause larger changes in CFM when system pressure changes.
- FC fans are overloading, meaning the input power increases as flow increases and system pressure decreases (i.e., filter change out).

- Eliminating or reducing some of the exceptions (from a 5 HP threshold to 1 HP, for example)
- Assigning different FEG requirements for different fan types (FEG67 for FC fans and FEG71 for AF fans, for example)
- Switching from the FEG metric to the PBER metric, or using some combination thereof

Whatever the future holds, it's obvious that fan efficiency will continue to be one of the critical design parameters for tomorrow's system designers.

By Dustin Meredith applications engineer, and Jeanne Harshaw information designer, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/engineersnewsletter. To comment, send e-mail to ENL@trane.com.

October Engineers Newsletter LIVE program

Chilled-Water Terminal Systems.

Trane applications engineers will discuss system design and control strategies for various types of chilled-water terminal systems, including fan-coils, chilled beams, and radiant cooling. Topics include: types of terminal equipment, variable-speed terminal fan operation, dedicated OA system design, chilled-water system design, and complying with ASHRAE 90.1 requirements.

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LEED v4.

LEED v4 officially launch at Greenbuild 2013. Trane applications engineers will discuss changes in the newest version of LEED and how they impact HVAC practitioners.

Applying Variable Refrigerant Flow.

All HVAC systems have their own set of application challenges. This program will discuss some of the challenges when applying a variable refrigerant flow (VRF) system, such as complying with ASHRAE Standards 15 and 90.1, meeting the ventilation requirements of ASHRAE Standard 62.1, zoning to maximize the benefit of heat recovery and the current state of modeling VRF.

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Variable-Speed Compressors on Chillers.

This program discusses the operational, performance and application differences for the various compressor types, particularly centrifugal (dynamic compression) and screw and scroll (positive displacement compression). Attendees will leave with an understanding of which technologies bring real value to different system applications.

Coil Selection and Optimization.

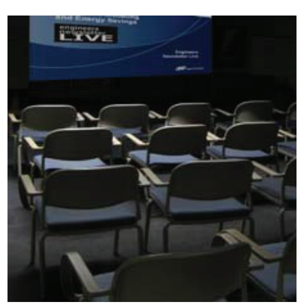
Presents several topics related to selection and application of coils, including the effects of temperature and flow rates on both chilled- and hot-water cooling coils, proper piping for steam heating coils, proper condensate trapping, andcommon problems caused by improper coil selection or application.

Acoustics: Evaluating Sound Data.

Focuses on clarifying sound data terms and weighting methods so that the designers can identify the differences in sound data presented by manufacturers to evaluate more accurately.

Small Chilled-Water Systems.

Presentation considers when and where various system strategies should be used, and on which types of chillers. Topics include: variable primary, primary secondary, constant flow, series chillers, chilled water reset, pump pressure optimization, flow rates and turndown, heat exchanger types, and air versus water-cooled systems.



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Chilled-Water VAV Systems. Focuses on chilled-water, variable-air-volume (VAV) systems; includes discussion of advantages and drawbacks of the system, review of various system components, solutions to common design challenges, system variations, and system-level control.
(SYS-APM008-EN, updated May 2012)

Water-Source and Ground-Source Heat Pump Systems.

Examines WSHP systems components, configurations, options, and control strategies. (SYS-APM010-EN, updated November 2013)

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