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Energy Efficient Design for Wastewater Treatment Plants

A System Splitting Approach

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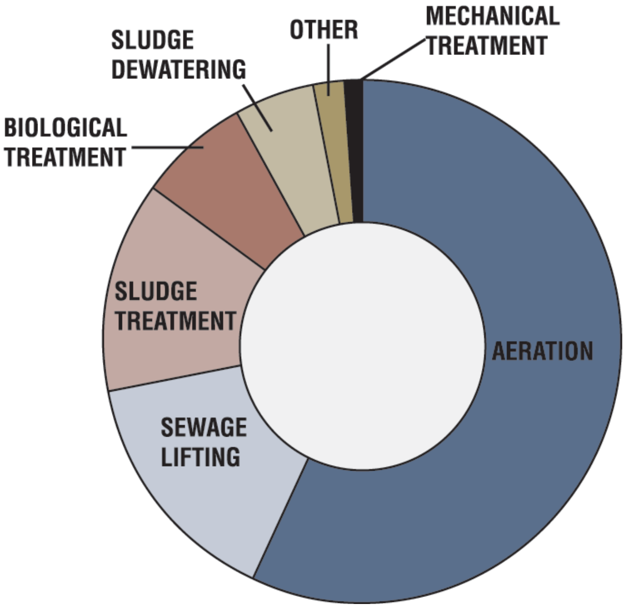
Abstract

Energy is the single highest operating cost in a wastewater treatment plant. More specifically, the energy to operate blowers for aeration is the single highest energy consumer. Fortunately, blowers and blower systems are becoming more energy efficient as system engineers pay more attention to this critical cost factor. It is no longer enough to only consider the individual equipment's efficiency. With energy costs on the rise, it is now more important than ever to carefully examine the entire system's efficiency and understand how each piece of equipment works with one another and how this interaction impacts the overall plant energy efficiency. This paper will outline the traditional approach to wastewater treatment plant design, the efficiency problems associated with this approach, and explain system splitting, an alternate design approach with key efficiency gains. The paper will include guidance on how to calculate specific power for an individual unit as well as an entire system and provide calculation examples for comparing system specific power between traditional and system splitting design approaches.



Of all the energy costs at a waste-water treatment plant, energy for aeration is by far the highest.

Nature of WWTP Planning

Unlike commercial systems, municipal wastewater treatment plants are often designed and built based on projected populations and demand 10, 20, and even 30 years in the future. Because project funding is available now and may not be available later on, system engineers are tasked with building a system that will continue to serve the community's growing needs, and in the most cost-effective, energy-efficient way possible. This is no simple task. Although the volume of air needed changes seasonally, day to day, even hour to hour, the general practice is to design the plant's capacity for the worst case/maximum load. This results in oversizing the blowers. Because the blowers are oversized, they do not operate at their most efficient design point, spending as much as 90% of their operating time wasting costly energy. This traditional design approach continues to waste money, until decades into the future.

Wire-to-air efficiency

System engineers do their best to combat wasted energy by selecting energy efficient equipment. This has led to an increased focus on energy and has helped spur innovations in blower technology. Blower manufacturers are taking advantage of the increasing interest in "wire-to-air efficiency" to promote these new technologies, which can produce more efficient blowers for certain performance points. Wire-to-air efficiency is simply the total energy used to provide the specified flow and pressure and is expressed as a ratio of the power to the flow. While this metric is relatively new to the blower market, it is widely used for industrial compressors and compressed air systems and is often referred to as *specific power.*

Whether using the term wire-to-air or specific power, it is important to differentiate between each individual piece of equipment's efficiency and the overall system efficiency. The traditional system design approach for wastewater treatment plants focuses on individual blowers instead of considering how each piece will work with one another. However, even if the most energy efficient blowers are selected, if they are not properly applied and controlled, they will not yield the anticipated energy savings. This is why system specific power is crucial in system design.

Specific Power Explained

In its most basic form, specific power is a product of input kilowatt to the machine divided by cubic feet per minute of air at standard conditions.

$$\text{Specific Power} = \frac{\text{Input kW}}{\text{SCFM}}$$

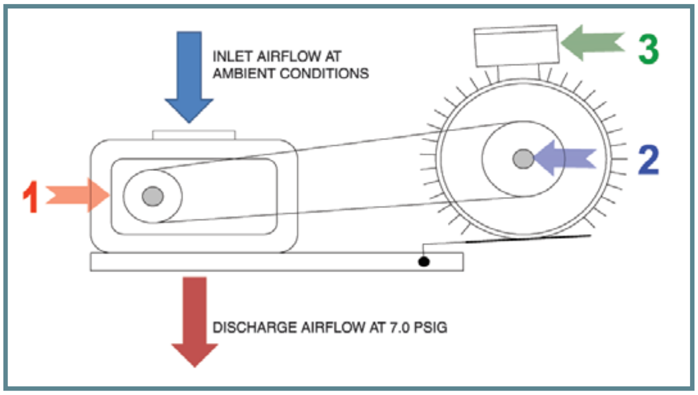
Today, manufacturers publish CAGI data sheets for blowers. These data sheets indicate the machine's complete performance for the set of conditions indicated on the data sheet. These sheets come in two forms. One is for fixed speed machines which provide a single performance point for the stated pressure. The other, for VFD machines, provides data for a total five data points at a given pressure.

On these CAGI data sheets, the manufacturers have declared the components on the machines and the power numbers must reflect the effects of these components in the reported figures. The reported figures must be guaranteed to the tolerances stated on the data sheets and guaranteed in accordance to the BL300 standard.

In the absence of the CAGI data sheets, the burden of deciphering the supplied data is on the engineer or end-user. To calculate specific power, it is possible to measure the input kW at the package control panel and install a flow meter at the outlet of the package to determine flow. However, when specifying equipment, this is obviously not possible since the equipment is not on hand. This necessitates understanding how to calculate specific power for the entire package and how each component will affect the overall efficiency. Looking at the specific power of only a blower block from one manufacturer versus that of an entire package from another will not give a true efficiency comparison. The following calculations are a tool to evaluate information provided by the supplier.

To start, consider a fixed speed machine producing 1,000 cfm at 7.0 psig as stated by the manufacturer. For simplicity, in this example, the machine is a bare blower without cooling fans, silencers, preheated air, or other sources of power consumption, and is operating at standard conditions (14.7 psia, 68°F, 0% RH). In this configuration, the only consideration is blower consumption (1), drive losses (2), and motor efficiency (3).

To calculate specific power, first the flow rate needs to be determined. For positive displacement blowers, this is a function of the blower's displacement per revolution, blower slip, operating RPM, ambient conditions, and operating pressure.



Blower consumption (1), drive losses (2), and motor efficiency (3), all impact specific power.

$$\dot{V}_1 = V_0 \left(n - n_{slip} \cdot \sqrt{0.0371 \cdot \frac{T_1 \cdot \Delta p}{p_1 \cdot 1K}} \right)$$

V_1 = Suction Volume

V_0 = Displacement/Revolution

n = Block Speed

n_{slip} = Slip Speed (basis 100mbar)

T_1 = Inlet Temperature in Kelvin [K]

Δp = Pressure Differential

p_1 = Inlet Pressure

Next, we need the required blower power (1) which is a function of mechanical design and pressure differential. Since in this example ambient conditions are the same as standard conditions, icfm and scfm are equal. Now we have blower power (1), but this is not what the user is paying for. The user is paying for electrical input at the motor (3). To calculate motor input power (2), we need to determine the losses associated with the drive. For most v-belt slide base designs where the motor can be moved to adjust center distance and apply tension, we can expect a 5% loss. For more advanced tension systems, these losses can be reduced to 2-3%. Finally, we need the rated motor efficiency as given on the motor nameplate. Therefore, input kilowatt (3) is given by;

$$\frac{\text{Blower Horsepower} \times (1 + \text{Drive Efficiency})}{\text{Motor Efficiency}} \times 0.746$$

For our example (1,000 scfm at 7.0 psig), the blower shaft power is approximately 40 hp. If we expect drive losses of 5%, we would need a 50 hp motor to avoid operating in the service factor without reserve. A 2-pole 50 hp motor would typically have an efficiency rating of approximately 95%. Putting this data into the input kW equation, we get the following number;

$$\frac{40\ hp \times (1 + 0.05)}{0.95} \times 0.746 = \mathbf{32.98\ kW}$$

With input kW, we are finally ready to solve for specific power;

$$\text{Specific Power} = \frac{\text{Input kW}}{\text{SCFM}}$$

Therefore;

$$\text{Specific Power} = \frac{32.98}{1000}$$

$$\text{Specific Power} = 0.03298\ \text{kW/scfm}$$

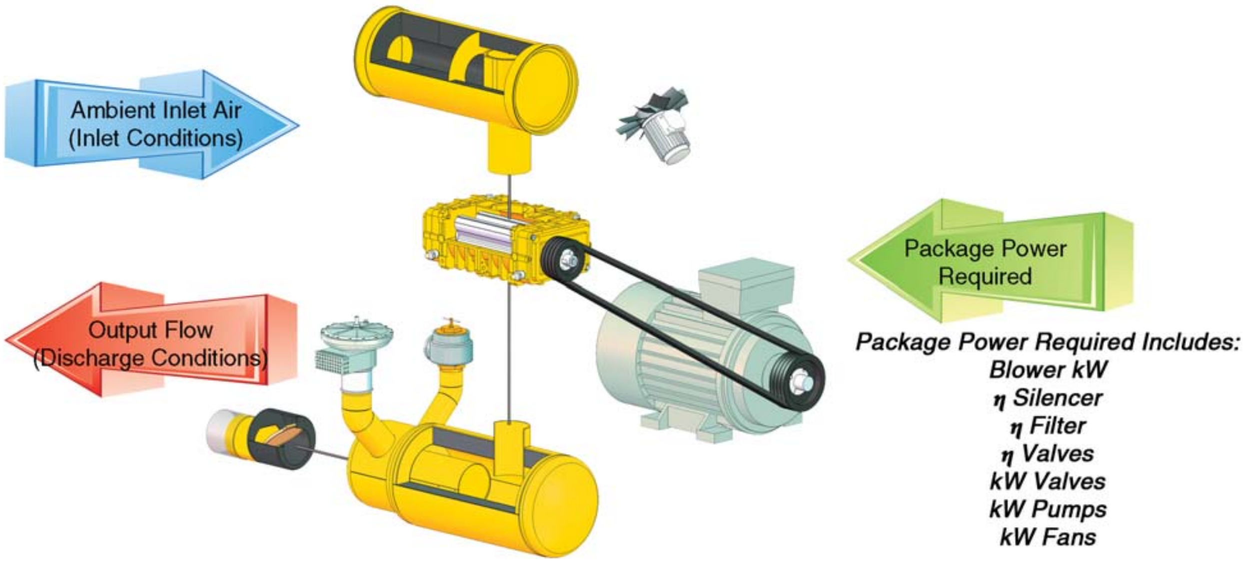
To facilitate an easy to read number, low pressure applications are often measured in kW/100 scfm;

$$\text{Specific Power} = 3.298\ \text{kW/100 scfm}$$

The lower the specific power value, the more efficient the blower is. This was a very basic example for the purposes of defining specific power and how different variables should be considered. Here we only evaluated the blower, belt drive, and motor, and we assumed ambient conditions to be the same as standard conditions, which helped simplify the flow values and calculations.

In reality, most blower systems include accessory components such as silencers, filters, and valves, which all present flow restrictions. Flow restrictions result in a greater pressure differential across the blower and result in more power consumption. In addition, other package designs utilize cooling fans (shaft or separate), pumps for cooling, or some other electrical or mechanical device, which add to the power requirements of the machine.

For the best accuracy, input kilowatt should be measured at the input of the machine's control panel. This takes into account all losses associated with the package as well as other relevant components. In addition to system losses and power consumers inside the package, power consumers in the control panel also need to be considered. The sum of each of these gives the total package input kilowatt consumption.



So far we have evaluated the elements of a blower package, power transmission, and accessory power consumers to represent the performance of the physical package. For a fixed speed machine, the specific performance of the machine is mostly constant (excluding the effects of ambient conditions). However, the vast majority of modern wastewater systems utilize variable frequency drives and the demand is split between the units.

Variable Frequency Drive

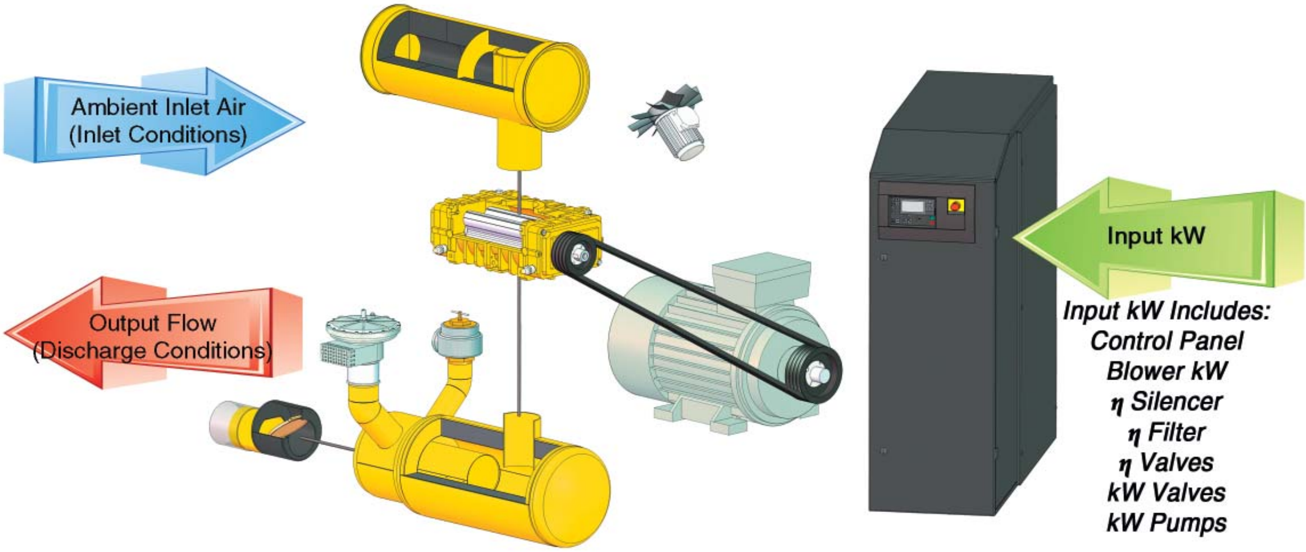
Variable frequency drives (VFDs) allow equipment to operate at different speeds by adjusting the voltage and frequency delivered to the motor. This gives the machine versatility by varying blower performance to match system demand; however, this does come at a price. Most variable frequency drives have an efficiency rating just like motors. The 97% VFD and 95% motor efficiency do not apply when the unit is running at ¼ or ½ speed. At these reduced speeds, the efficiency is decreased; therefore, VFD usage should be limited to applications where the demand actually fluctuates. VFDs are beneficial in handling fluctuations in demand, especially when compared to blowing off excess air to atmosphere. What should be avoided, however, is using a VFD on an oversized machine.

ICFM vs. SCFM

For the sake of simplicity, the calculation examples included used systems with ambient conditions identical to standard conditions, namely 14.7 psia, 68°F, 0% RH. It is from these standard conditions that "scfm" values are based. However, in the real world, there are of course, very few plants that operate at or near these conditions. This is why it is important to understand the difference between sfcm and icfm.

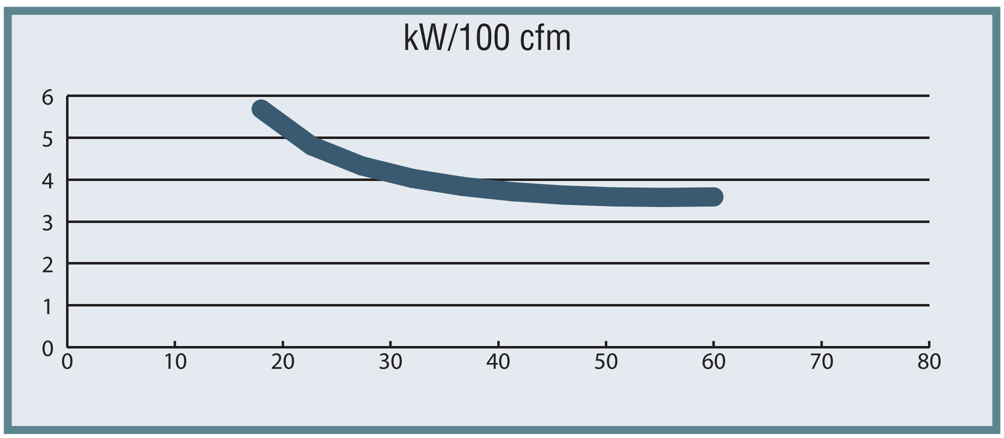
Equipment is tested and rated according to standard conditions. A 1,000 scfm blower would produce that amount of air at 14.7 psia, 68°F, and 0% RH. Icfm, however, is measured at the blower inlet and is adjusted for ambient conditions of temperature, pressure, and relative humidity. Differences in these three variables can have a large impact on the blower's capacity and may necessitate upsizing in order to meet demand.

For example, when our 1,000 scfm blower is at 750 ft. above sea level, 85°F, and has 85% RH, it is actually producing 1099 scfm. That same blower would produce 978 scfm at 550 ft. above sea level, 45°F, and 25% RH.



Let's consider our 1,000 cfm example from before, but at a reduced capacity of 30% or 300 cfm at the same standard conditions. If the 1,000 cfm unit is now a VFD and we evaluate the specific power from minimum speed to maximum speed, we find our specific power (kW/100 cfm) now ranges from 5.7 to 3.8. At 30% (300 CFM) capacity, we have 4.8. Again, a lower specific power value indicates better efficiency. In this instance, the difference in efficiency between the variable frequency drive (4.8 kW/100 cfm) and the fixed speed unit (3.3 kW/100 cfm) is dramatic.

This increase in kW consumption is a function of the losses in the motor and VFD which are greater at lower speeds or demand. If the value of 4.8 kW/100 cfm is compared to an appropriately sized fixed speed machine at 300 cfm, which has a specific power value of 3.4 kW/100 cfm, we find a difference of 4.2 kW or 5.6 hp. This is more than 10% of our 50 hp motor. If the demand is being shared by multiple machines running at the same speed, the impact is multiplied. If there is no real method of control over the VFDs, the situation is even worse.



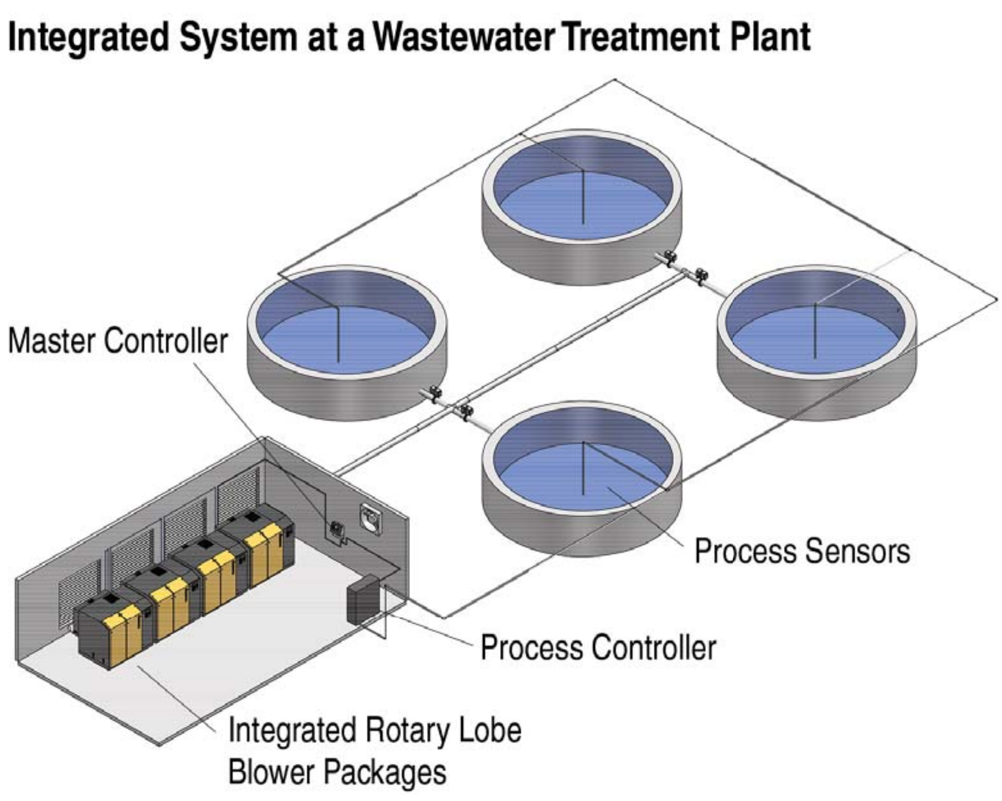
Graph 1: Running at reduced capacity greatly impacts the energy efficiency of a variable frequency drive unit.

Focus on the System

For a multiple blower system, the focus must be on system efficiency. It is not enough to simply use the most efficient blowers. Well-designed blowers are a great start but to operate as an efficient system, they must be applied correctly and controlled properly. Now that we have examined how to calculate efficiency for individual units, we can apply those concepts to understanding the overall efficiency of the entire system and further, how sizing and selection affects the efficiency of the system. As explained earlier, conventional aeration system designs include two large blowers. For versatility, they are often large variable speed blowers with an identically sized back up unit. Basic control systems are set to share the demand and the blowers operate at the same speed. This is very costly, since not only do variable frequency drive units cost more to purchase, their drive losses must be factored into the unit's efficiency.

Furthermore, they will be running at part load for the vast majority of their operating time. We have already seen how variable frequency drive units running at reduced capacity are significantly less efficient than properly sized fixed speed units. However, it is not prudent to simply eliminate variable frequency drive units from the system altogether.

An alternate method of system design is system splitting. With system splitting, the maximum load is split among several cycling online/offline fixed speed machines to cover the large portion of the demand and a variable frequency drive (VFD) machine to cover the trim load. This method of system design allows much more efficient control without sacrificing the ability to meet the occasional periods of higher demand.



Adaptive Control

For system splitting, only one or two machines are VFD units. If there are two VFDs in the system, only one runs at a time, with the second acting as back-up. The remaining blowers are fixed speed units. By limiting the number of VFD units in the system, initial investment costs are considerably lowered. The final component of system splitting is controls. Adding an adaptive master controller makes it possible to find the best combination of units to meet the current demand. Since the fixed speed units run on auto-dual control, the units can run idle for a defined period of time before shutting down. This gives the adaptive master controller enough time to observe the system's response and signal the units to reload if needed. The VFD is sized no larger than required, reducing the initial investment cost while covering the supply gaps that occur when the fixed speed machines are offline.

Calculation example

A typical plant with an air requirement of 3,000 cfm will utilize three blowers each sized for 1,000 cfm. As is the case with most plants, it is sized for anticipated demand 30 years in the future and grossly oversized for the current demand of only 1200 cfm. These blowers are then controlled by VFD's and operated in parallel to maintain the desired DO levels in the basin(s). If we evaluate Graph 1 at ten data points from minimum speed to maximum speed, we can derive an average specific power performance of each individual 1000 cfm unit.

For this unit, it will average to 3.7 kW/100 cfm. If this is then done for the entire 3,000 cfm system accumulating all three units, the average specific power for the entire system is 3.8 kW/100 cfm.

While this examines the complete system, it assumes that the system operates at each level from min to max for the same period of time. In practice, 70% of plant operation occurs over the middle third of the plant capacity. This would require the majority of operating time spent at partial load or reduced speed.

With the system splitting method, demand is divided between a combination of fixed speed and variable

Adaptive Master Controller

With the wide range of master controllers available today, it is important to keep in mind these key criteria when selecting a controller for your wastewater treatment facility.

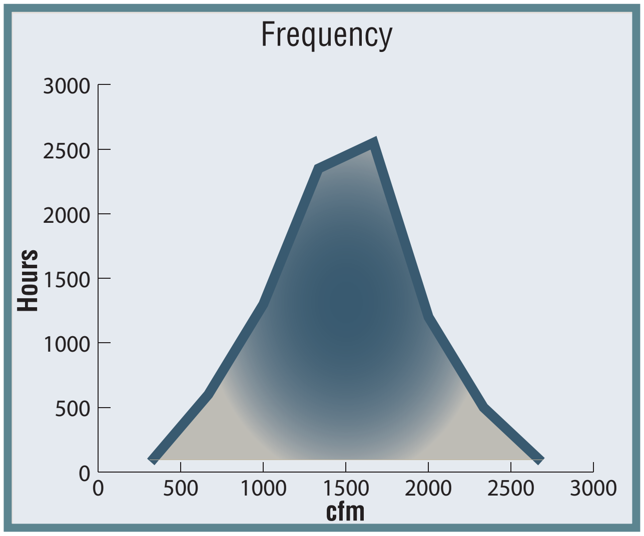
Adaptability: Wastewater treatment plants see fluctuating demand. A master controller that learns the system and adapts to these fluctuations can better respond and choose the most efficient combination of units to meet the demand and improve pressure stability.

Integration: Chances are you have a plant SCADA system for monitoring. Look for a master controller with communications capabilities that will easily integrate into what you already have.

Back-up: Since most plants are designed with built-in back-up, you can help reduce your maintenance costs with the right master controller. Some master controllers can rotate like-sized machines to equalize run times and spread out maintenance intervals. Additionally, some will also let you specify certain units to run as back up only. This is ideal if you have older, less efficient units that you would only want to come on if one of the other units has a failure.

speed machines. The VFD machine is utilized to trim the fluctuations in plant demand, while the fixed speed machine(s) are cycled on and off to fill the remaining demand. In this scenario, a single 1300 cfm VFD unit is utilized with two 850 cfm on/off machines. When these units are evaluated across the entire 3,000 cfm, the average specific performance is 3.6 kW/100 cfm, but the real gains can be seen at the reduced plant loads where the system spends 70% of the time.

When evaluating the specific performance in this 70% range, we find a 13% improvement. Depending on the size of the equipment selected and the effectiveness of the control, this improvement could be as high as 30%.



The darker part of the graph indicates where the system operates more than 70% of the time.

Summary

Clearly, wastewater treatment is a critical utility and the system must be designed to reliably meet its highest expected load. But when it comes to the blower system, bigger is not always better. The best air system design is a holistic one that takes into account the range of demand, future growth, the entire system's specific power, and optimized energy efficiency. System splitting and using an adaptive control scheme can provide reliable supply without unnecessarily burdening the community with higher energy costs. Spending a little more time today to understand the dynamics of your system can save initial costs as well as maintenance and power costs for many years to come.

About the Author

Stephen Horne *is the US Product Manager for Kaeser's blower product line, and has over 10 years of experience with the design and function of blower systems in wastewater aeration applications. Stephen has also served as Kaeser's in-house engineer for machine modifications and system design. He is a primary blower product and application instructor in Kaeser's Factory Certified Training program. Stephen holds a Bachelor's degree in Mechanical Engineering from Virginia Polytechnical Institute and State University.*

Technology Meets Tradition

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This tradition of excellence also drives new technology development. Advances in airend design, controls, and system design ensure our customers can meet the daily challenges of their manufacturing operations.

Each Kaeser product is designed with the future in mind, but we never lose sight of our roots. Technology needs may change from year to year, but the need for quality and reliability will always remain.

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