Technical Whitepaper – Aerzen USA Corporation

AERZEN

Aeration Blowers in the Wastewater Industry in North America

Executive Summary

As the main consumer of electricity in a wastewater treatment plant, the aeration system greatly influences the overall cost of operation, that in the long-term by far exceed the initial investment cost. Several blower technologies can be chosen from and it therefore behooves the engineer to accurately evaluate the characteristics of the aeration blowers and carefully interpret some of the claims made by various manufacturers. The most energy efficient solution must be based on actual conditions that, in reality, will vary over an extended period of time.

The economical operation of a wastewater treatment plant depends largely on the design and the interplay of the aeration and process controls. Moreover, the human factor and the management objectives are at the heart of the plant's reality and should also be taken into consideration. Selection and thoughtful integration of all the subsystems is of paramount importance.

The intent of this paper is to provide information that will help the engineer appropriately define both the design and the evaluation criteria of various blower technologies. The real total costs of ownership over time should guide the selection process.

Taking a pragmatic approach, this paper presents ways to minimizing the energy usage: right-sizing, aeration control, defining the operating range and matching the blower technology to the application, and comparing operating data over time.

The paper presents four types of blowers: two dynamic and two positive displacement machines. Since each technology has its place, a comparison is made specifically based on the treatment of wastewater. Taken into account are the daily and seasonal swings in oxygen demand, fouling and aging of diffusers, air flow control and turndown capabilities, total blower efficiency and energy consumption over time, mode of operation, blower accessories, and plant set-up.

The paper recommends engineers to exercise due professional diligence and to select the most suitable aeration blower technology based on a relevant comparison.

Table of Contents

Selection of blowers for wastewater aeration

Introduction:

As the main consumer of electricity in a wastewater treatment plant, the aeration system weights most heavily on the costs of operation.

Climatic changes, the 2007/08 rise in the costs of energy, and the public support for green initiatives have raised the level of awareness for our use of energy, and this has spread far beyond the circles of the environmentally concerned: energy efficiency has become one of the decisive factors in the selection of process equipment. Rightly so, because the long-term operating costs by far exceed the initial investment. There is, however no better time for impactful marketing then when the sensitivity for a relevant subject is broadly heightened. Falling in love with an appealing technology may make one blind and it behooves the engineer to accurately evaluate the characteristics of proposed aeration blowers and carefully interpret some of the claims made by various manufacturers. The most energy efficient solution must be based on actual conditions that, in reality, will vary over an extended period of time. A comparison made at one hypothetical operating point alone is merely academic and has no practical use.

It is our intent to provide information that will help the engineer appropriately define the design and the evaluation criteria of various blower technologies.

1 General

The economical operation of a wastewater treatment plant depends largely on the design and the interplay of the aeration and process controls, and the selection and thoughtful integration of all the subsystems.

Moreover, the human factor and the management objectives are at the heart of the plant’s reality and should also be taken into consideration.

The real total costs of ownership over time should guide the selection process.

1.1 Right-sizing

Many plants are oversized because the population growth did not occur according to projections, and these plants have been operating very inefficiently since the first day.

A sound approach to minimizing energy usage begins with a right-sizing approach and the selection of equipment that will best match plant’s real demands for most of the operating time. It is not a good practice to largely oversize a plant in order to meet speculative future growth. Machines and systems operating much below their normal range are usually not very efficient and, in some applications, may have a reduced life.

It would be wise for these oversized plants to consider downsizing their existing aeration blowers and, as a result, save energy.

Example:

An older rotary lobe blower package sized originally for 3000 cfm / 8.5 psi used 179 BHP with a traditional belt drive and a standard efficiency motor, if oversized by 30% and replaced by a more efficient and modern rotary lobe blower package with automatic belt tension and premium efficiency motor will produce 20% more cfm per HP than the old machine!

1.2 Matching aeration blowers to plant's demands

A normal operating point should be defined as "the point at which usual operation is expected and optimum efficiency is desired. This point is usually the certified point."[1] In other words, if a plant is designed to operate at 80% of its peak, the performance of the aeration blowers should be optimized for that point.

1.3 Real plant and operating conditions

The reality of a plant is the result of compromises resulting from the many components combined into a system that needs to perform reliably while subjected to the many interdependent variables that characterize a wastewater treatment operation: quantity and composition of the effluent stream, water and air temperatures, actual vs. future capacity, budget, goals, operator competency, environmental and legal constraints, etc…

Most plants operate with the primary goal of meeting the environmental permit requirements. Managing the plant processes for lowest energy usage and lowest life cycle costs may not be the highest priority, and efforts made to design the most efficient plant could be wasted.

Therefore, healthy pragmatism will help prevent spending extra for added complexity that ultimately may become an additional burden to the operations.

1.4 Plug-and-play approach

An increasing number of manufacturers offer machines in a plug-and-play concept. It is an efficient and attractive proposition to buy industrial equipment as easily as a kitchen appliance. But where one size does not fit all, flexibility is required to meet actual needs. For example, electricians prefer working on motor starters and VFD (if needed) located in a clean and air conditioned electrical room than in the machinery blower room; blowers installed outdoors eliminate the need for a machine room; the control of temperature in a machine room must be achieved without raising the operating costs for air conditioning; in addition to the OSHA

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[1] API 619 4th Edition

limits within the plant, continuous and transient[2] noise emissions may cause problems close in a residential area.

1.5 Total costs

Total costs include the investment costs, energy costs based on anticipated operating conditions over time, maintenance, service, spare parts, and repairs. Unfortunately, costs used to compare proposals are frequently based on hypothetical conditions. Some less obvious aspects are sometimes completely neglected but nonetheless important for the costs of ownership. To mention a few: balanced and stable power supply, unused reserves of pressure or air flow, air filter maintenance / replacement frequency, number of machines, etc… [i]

1.6 Technologies compared

We will compare two types of positive displacement and two types of dynamic blowers:

1. Rotary lobe blowers
2. Low-pressure dry screw compressors
3. Special purpose high speed single-stage centrifugal blowers with inlet guide vanes and outlet diffuser vanes to achieve a wide turndown at constant operating speed. These machines can be operated with a VFD to provide additional flexibility while maintaining highest efficiency.
4. Standardized high speed single-stage turbo blowers. These recently introduced machines are direct-driven by a high-speed permanent magnet motor and always require a VFD to meet varying air density and/or pressure needs. The impellers are precision cast or fully machined depending on the manufacturers. Adjustable diffuser vanes are not used and the machines rely on a well integrated elaborate control system to adapt to changing conditions.

   They make use of most modern technology with magnetic bearings or air bearings. Magnetic bearings enable continuous vibration monitoring, while air bearings cannot be monitored.

2 Defining the field of operation

The field of operation that the blower system will be subjected to consists of the following parameters:

Site conditions

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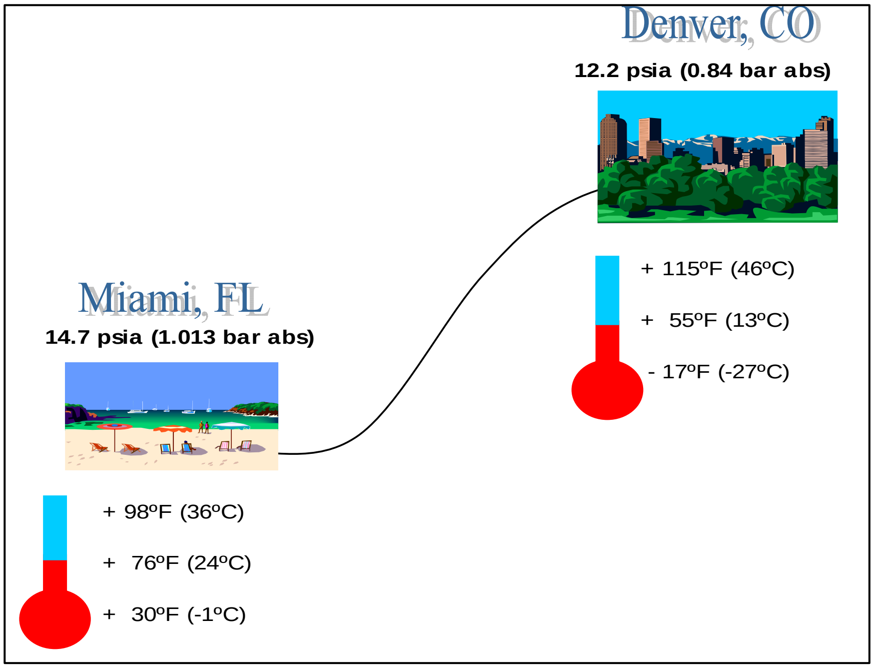
[2] Transient noise is generated by anti-surge control valves, opening of pressure safety or unloading valves

Type of aeration system
Mass flow of air at any moment in time
Other system variables: upstream and downstream

2.1 Site conditions

The altitude above sea level determines the atmospheric pressure, therefore the inlet pressure, and the air density. As a result, the compression ratio (defined as the ratio of the absolute discharge pressure to the absolute inlet pressure) and the discharge temperature of the compressed air will vary accordingly.



Example: If the system pressure to overcome is **8 psi** (550 mbar), considering constant relative humidity of 36% (data source: weatherbase.com)		
Location examples	Miami, FL	Denver, CO
Atmospheric pressure	14.7 psia (1.013 bar abs)	12.2 psia (0.84 bar abs)
Discharge pressure	22.7 psia (1.56 bar abs)	20.2 psia (1.39 bar abs)
Compression ratio @ 8 psid (550 mbar)	**1.544**	**1.655**
Average temperature	76ºF (24ºC)	55ºF (13ºC)
Lowest temperature	30ºF (-1ºC)	-17ºF (-27ºC)
Highest temperature	98ºF (36ºC)	115ºF (46ºC)
Air density at lowest temperature	0.081 lb/ft^3 (1.297 kg/m^3)	0.076 lb/ft^3 (1.225 kg/m^3)
Air density at average temperature	0.074 lb/ft^3 (1.184 kg/m^3)	0.065 lb/ft^3 (1.046 kg/m^3)
Air density at highest temperature	0.071 lb/ft^3 (1.134 kg/m^3)	0.059 lb/ft^3 (0.937 kg/m^3)

Variation of oxygen content per unit of volume of ambient air between the warmest and coldest conditions at constant relative humidity	**14%**	**31%**
The effect of the relative humidity must also be taken into account: a rise in humidity results in a lower air density, all other conditions being equal. Example: at the maximum temperature, the air with 100% RH will have a 3% lower density in Miami, and 2 % in Denver, than 36% RH air.		

<u>Average vs. maximum and minimum conditions:</u>

While it is generally accepted practice to use the site average conditions to compare energy usage, this is only an approximation, since the average power required over the course a year will most likely not equal the power at yearly average conditions. A higher degree of accuracy can be achieved by using monthly minimum, maximum and average data, corresponding air flows and anticipated operating hours.

Similarly, the extreme ambient temperature / moisture atmospheric pressure cannot be used as a point for comparing performance. However, any machine selected must be capable of operating safely under these conditions and at the highest pressure ratio over their entire flow range.

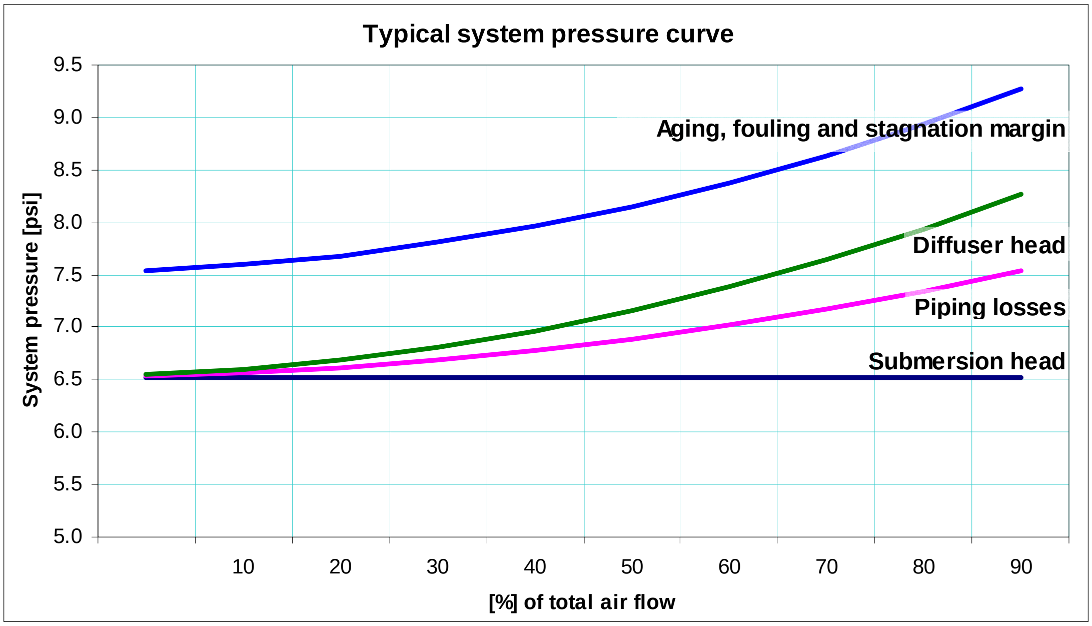
2.2 Type of aeration system; operating pressure

The purpose of this section is not a discussion on the most efficient aeration system. Instead, it provides an overview of how components of the aeration system affect the operation of the aeration blowers.

1. Submergence:

   The depth of submersion of the diffusers determines the hydrostatic head that the blowers must overcome. The submersion ranges typically from 10 ft (3 m) to 26 ft (8m) in municipal wastewater treatment plants, requiring aeration blowers capable of pressures under 15 psig (~1000 mbar), while industrial systems may require 33 ft (10 m) to 66 ft (20 m). For deep aeration applications single stage oil free screw compressors or high-speed centrifugal compressors should be considered.

2. Pressure losses must be added to the aeration depth:



   Piping and air distribution system with check valves, isolating valves, elbows other piping components will engender restrictions that, at maximum flow can reach or even exceed 1.0 psi (70 mbar).
3. The head loss across the diffuser system (typically 0.4 to 0.8 psi (30 to 60 mbar))
4. A safety margin should be added to account for some aging and/or fouling of the diffusers (in the range of 0.5 to 1.0 psi (35 to 70 mbar)).
5. When starting up the aeration system, an elevated stagnation pressure needs to be overcome for a short period of time. Moreover, condensate that may have appeared in the pipe must be driven out.

All these pressure losses and pressure reserve margins must be considered for dependable and stable operation. While this pressure reserve margin can easily reach and exceed 15% of the submersion head at full flow, it will decrease to only a small amount at minimum flow with a clean system. Therefore, a plant can directly benefit from reduced pressure losses if the power needed by the aeration blowers drops in the same proportion.

Any blower system must be capable of operating under all conditions, between day and night, between summer and winter, between the lowest to the highest wastewater loads, from the first day to the last.

If a wastewater treatment plant operates at different submersion depths, a central aeration system must be capable to overcome the highest head. It is then beneficial to use separate blowers for the various depths of aeration. The selection of a common standby machine would need to accommodate both pressure levels.

2.3 Variable oxygen need and air flow range

The right dosage of the quantity of oxygen at each step of the process and the absorption of the oxygen in the wastewater are the most important parameters that influence the amount of energy used by the plant, since the amount of oxygen is directly proportional to the air flow produced by the aeration blowers.

Providing for the correct oxygen level at any moment requires automatic flow adjustments. Blower systems must therefore adapt to these changing conditions in the most efficient and stable way possible, reliably and without surging. This can be accomplished by cycling the blowers, throttling the suction, adjusting outlet diffuser vanes, or using adjustable speed drives.

The amount of air required for the aeration will be expressed in units of measure that are independent of the site conditions. These would be scfm (14.7 psia, 70ºF, 36% RH) or Nm^3/hr (1.013 bar abs, 0ºC, 0% RH). The sizing of the aeration system will require a calculation of the inlet volume flow:

- At maximum temperature and maximum relative humidity
- At average temperature and average relative humidity
- At minimum temperature and minimum relative humidity

As an example, if the mass flow of oxygen must vary between 100% and 40% and the ambient conditions vary from a minimum of 14 ºF (-10ºC) / 80% relative humidity and a maximum of 104 ºF (40 ºC) / 65% relative humidity, the turndown capability of the aeration blower system has to be 100% to 32% of the volumetric flow.

The turndown capability of the system is determined by the number of blowers, their individual turndown capability, the operating mode (variable flow or on/off cycling operation) and which is largely a function of the blower and drive technology.

A wide turndown range is often required to meet the varying oxygen demand: 4:1 to 10:1 are typical.

2.4 Blowers control scheme

The purpose of the control system is to match the air flow to demand in the most efficient manner, therefore running the smallest number of machines and running them in the range of their best efficiency.

The plant control system will be crucial in achieving the most efficient sequencing of the aeration blowers.

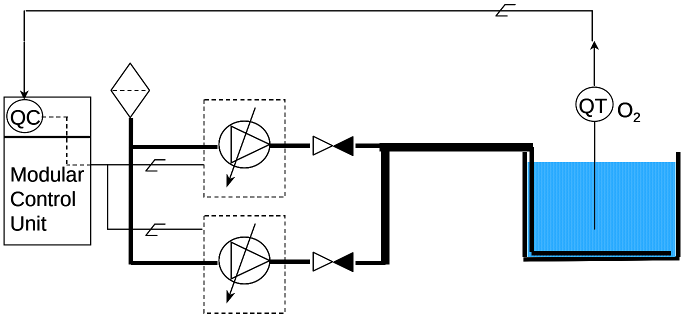
Three principles apply:

1. Run the least number of machines (a blower that does not turn does not use energy)
2. Run the largest number of machines in their most efficient range
3. Avoid idle operation and any bleeding off of air
4. Sequence the operation with longevity and maintenance intervals in mind

2.5 Flow control

Direct flow control: This type of control is only suitable when the aeration blower system is dedicated to one basin and the pressure is equal for all the various aeration sectors.

Direct flow controlled compressor group



Indirect flow control: This type of control is required to adjust the air flow from a common air header to individual basins or individual aeration sectors. A control valve is inserted in the air line to each basin or sector. The pressure loss of such a control valve typically ranges from 0.3 psi (20 mbar) to 0.5 psi (35 mbar). While most of such systems use pressure to control the flow in a reactive manner, a more accurate and more energy efficient method is to anticipate the oxygen need and control the flow by means of flow sensors[3], then vary the control valve setting for each sector accordingly. In addition of being the most efficient, this aeration control system offers an additional advantage: it allows the blower discharge pressure to follow the system back pressure, therefore further lowering the energy usage.

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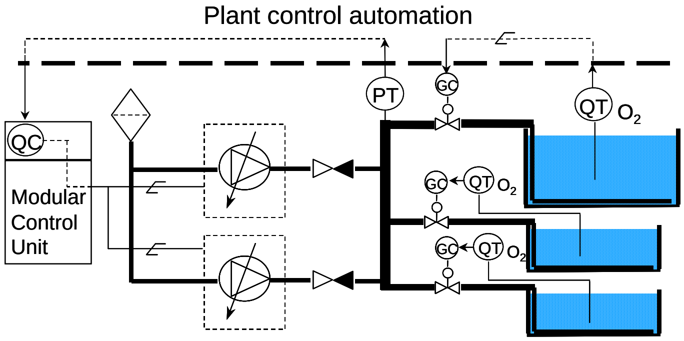
[3] BioChem Technology, Inc. (see http://www.biochemtech.com/)

Typical pressure controlled multi–basin multi–compressor plant



2.6 Blower system turn-down capability

Careful selection of equipment is required to achieve a high degree of flexibility in meeting a wide range of oxygen needs with the highest degree of energy efficiency.

Some aeration systems cycle individual blowers for various lengths of time and use the oxygen retention capability of the wastewater to adjust the oxygen feed. For the purpose of this paper, however, we will discuss the ability of a system to adjust to any flow within the required range of operation. This requirement originates in the desire for highest possible efficiency of the overall wastewater treatment process over time.

A large turndown means that the system will be able to meet the lowest air requirements without wasting energy by bleeding any excess discharge air to the atmosphere.

A larger turndown also provides additional flexibility and enables the blower system to meet the air requirements in a step-less manner with the minimum number of machines and lowest number of frequency inverters (VFD). The turndown of each machine must allow for some overlapping (preferably ≥ 5% of the flow of an individual machine). Therefore, a 55% turndown is required for a stable control system, avoiding steps and wasting power by blowing-off air.

The number of blowers required depends on the turndown capabilities of each machine.

Example: if a system requires a 4:1 turndown ratio, this can be accomplished with two machines with each a 2:1 turndown. For ease of controls, some overlap is preferable and therefore, each machine in this example should be capable of a flow range from 45% to 100% under the worst conditions: highest pressure ratio and lowest air density combined.

The number of identical size blowers can easily be determined with the following formula:

$$n = \frac{S_{MAX}}{S_{\min}} \times \frac{Q_{\min}}{Q_{MAX}}$$ Whereas:

S_{MAX} = total maximum system flow

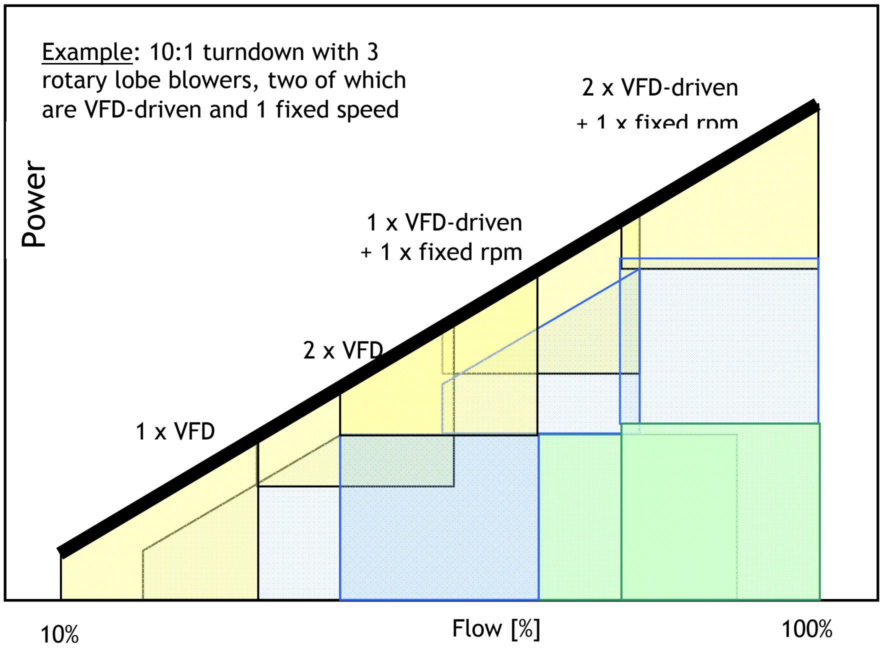
S_{min} = total minimum system flow

Q_{MAX} = Maximum flow of one blower

Q_{min} = Minimum flow of one blower: to achieve a step-less and stable flow control, Q_{min} should never be higher than 45% of Q_{MAX} under the worst operating conditions

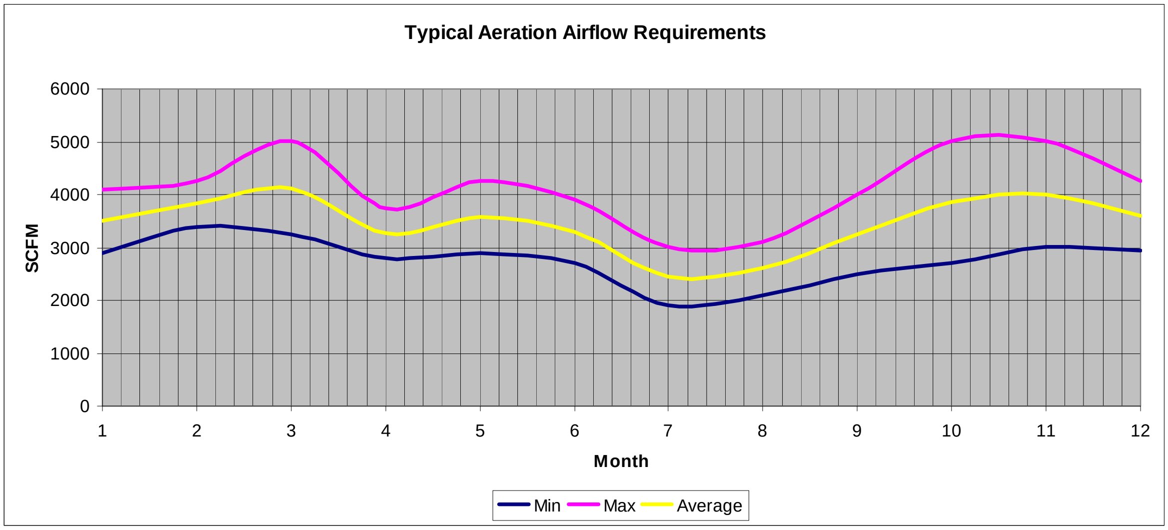
The result will only produce a step-less flow if the minimum flow of two blowers is lower than the full flow of a single one.

<u>Example</u>: a 10:1 system turndown can be achieved (a) 3 blowers of which at least two have an operating range from 30% to 100% while one can have a constant flow, or, (b) 5 blowers would be required, of which at least two must have a safe operating range from ~ 45% to 100% while three could have a constant flow.



<u>Example</u>: 10:1 turndown with 3 rotary lobe blowers, two of which are VFD-driven and 1 fixed speed

In wastewater aeration applications, depending on the aeration control system, the operating pressure will drop slightly as the air flow decreases, but the main portion of this pressure corresponds to the hydrostatic pressure, which remains as constant as the water level. As the flow of a machine is regulated down, its efficiency will vary. At pressure ratios of 1.5 to 1.7 that are frequently encountered in wastewater aeration, efficient rotary lobe blowers and oil-free screw machines can offer turndown capabilities up to 4:1 of the machine's flow capability, while special-purpose high-speed centrifugal blowers offer a turndown up to about 2.2:1 at constant pressure. Standardized high-speed turbo blowers may have a turndown as high as 2.2:1 at constant pressure, but this is largely dependent upon the characteristics of the impeller, the size fit and the pressure ratio. For all the machines that are subject to our comparison, the higher the pressure ratio, the smaller the turndown capability will be.



2.7 Other system variables: upstream and downstream

Inlet air filtration

The filtration of the inlet air is crucial for the durability of the blowers, and the maintenance of the filters, while seemingly of little importance, impacts the energy costs.

The degree of filtration as well as the dust retention capability of the filter elements has to be considered. The filter must be sufficiently fine to protect the blower as well as the diffuser system downstream from air-borne dust particles. On the other hand, a very fine filter will require a large filtration area and/or more frequent cleaning or replacement. Machines with high tip speeds, such as high-speed centrifugal blowers and turbo blowers, are particularly sensitive to particles and droplets in the air stream, and therefore require very fine filtration.

Typical maximum tip speeds	High-speed centrifugal / turbo	Rotary-lobe blowers	Oil free screw machines
Ft/sec	1150	140	400
m/sec	350	45	120

Typical operating speeds	High-speed centrifugal / turbo	Rotary-lobe blowers	Oil free screw machines
RPM	20,000 to 65,000	1,000 to 5,000	3000, to 15,000

If the pressure loss of the clean filter may be negligible, a dirty filter can easily cause an additional 0.5 psi (35 mbar) drop resulting in an increase in the compression ratio (see formula below) of some 3% based on sea level conditions, and a comparably higher use of energy. Inlet pressure losses have a much more important impact on power usage and actual flow than the same pressure drop on the discharge side.

$$\Pi = (p_2 + \Delta p_{Disch.})/(p_1 - \Delta p_{Suction})$$

Filter location:

It is preferable that the filter be the last element touched by the inlet air before entering the blower. This is most important in the case of very high speed machines such as the turbo and centrifugal blowers. We found that most suppliers do not pay much attention to this detail, and there is a danger that loose particles from the silencers or even, as is the case with the standardized turbo blowers, from the acoustic enclosure could enter the blower.

Cleanliness is particularly crucial in the case of high-speed machines and machines with high tip speeds. A few particles can damage an air bearing or cause damage when touching an impeller rotating at 1000 ft/sec tip speed. If the filter element is such that dust particles can fall off during the filter change, it is recommended to pay particular attention to remove the dust prior to installing the clean filter element.

Particles that find their way into the downstream piping will ultimately restrict the air flow in fine bubble diffusers.

Inlet piping:

For various reasons, some engineers prefer to manifold the inlet of multiple blowers to pull air from outside a blower room. The additional inlet pipe pressure losses need to be accounted for. Moreover, frequently forgotten is the fact that inlet air noise is then being ducted out and may require additional acoustical treatment, which in turn causes additional pressure losses.

Pre-heating of the intake air:

Some blower packages use the intake air to cool the electric drive motor and some of the power electronic. The result is a higher amount of energy to be used for the same amount of oxygen: the higher air inlet temperature results in lower air density and proportionally lower mass of oxygen per unit of air volume. For example: a 20ºF increase in inlet temperature results in about 4 % lower mass of oxygen per cubic foot of air, a 4 % lower density, a higher discharge temperature, higher air velocity and higher pressure losses.

Discharge check valve:

While nearly always required, the discharge check valve is one of those components that is frequently not included in a blower package or shipped separately. Whether the pressure loss caused by the check valve has been accounted for is not always clear. The pressure loss of a check valve should be less than 0.15 psi (10 mbar). The selection of the check valve must be such as it has a low opening pressure and will not chatter at reduced flow.

Additional flow control valve:

Some control systems, particularly used in conjunction with centrifugal or turbo blowers, make use of a discharge pressure control valve. This valve receives its signal from the Dissolved Oxygen (DO) control. Should less oxygen be required, the control valve will restrict the total air flow, therefore increasing its upstream pressure. The blower flow control, being set to maintain a constant discharge pressure, will reduce the blower flow until the set pressure is reached again. Not only is the pressure drop across such a control valve not negligible (0.3 to 0.5 psi or 20 to 35 mbar), but with such a control system, the pressure generated by the blowers remains constant, and may therefore not be able to take advantage of any drop in system pressure at partial flow.

2.8 Machine selection: thermodynamic performance

2.8.1 Type of compression

Rotary lobe blowers:

The process of compression in rotary lobe blowers is isochoric (compression at constant volume). There is no internal compression in the absence of system back pressure.

Centrifugal and turbo blowers:

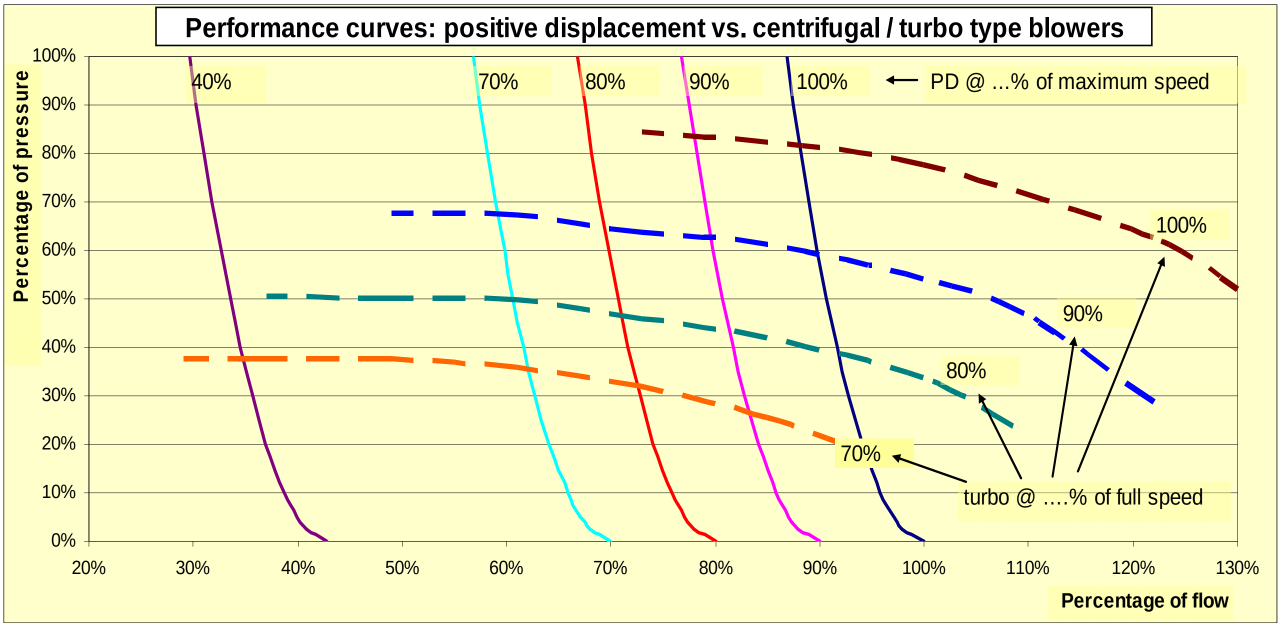
The process of compression in centrifugal and turbo blowers is considered to be adiabatic.

Screw compressors:

The process of compression in dry screw compressors is considered to be adiabatic.

2.8.2 Performance characteristics

The graph below shows the dependence of the dynamic compressing machines on the speed to produce a pressure and its impact on flow control, and conversely, the dependence on speed of the positive displacement machines to produce a given flow, almost regardless of the discharge pressure.


Performance curves: positive displacement vs. centrifugal / turbo type blowers

2.8.3 Compression formulae

Adiabatic power formula (screw compressors, centrifugal & turbo blowers)

SI units [kW]:

$$P_{th} = \frac{10^4 \times V \times p_1}{6000} \times \frac{\gamma}{\gamma - 1} \times \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

V is the volume flow [m^3/min]

p_1 is the absolute inlet pressure [bar abs]

p_2 is the absolute discharge pressure [bar abs]

g is the adiabatic exponent of the air (c_p/c_v = 1.4)

US units [HP]:

$$P_{th} = \frac{144 \times V \times p_1}{33000} \times \frac{\gamma}{\gamma - 1} \times \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

V is the volume flow [icfm][4]

p_1 is the absolute inlet pressure [psia]

p_2 is the absolute discharge pressure [psia]

Isochoric power (rotary lobe blowers)[5]

SI units [kW]:

$$P_{th} = \frac{V_0 \times \Delta p}{600}$$

V_0 is the displacement at the operating speed [m^3/min]

Δp is the differential pressure across the machine [mbar]

US units [HP]:

$$P_{th} = \frac{V_0 \times \Delta p \times 4.361}{1000}$$

V_0 is the displacement at the operating speed [icfm][4]

Δp is the differential pressure across the machine [psi]

Actual power

The shaft power is calculated by dividing the Adiabatic Power by the adiabatic efficiency and then adding internal mechanical losses, i.e., frictional losses from the bearings and seals.

$P_{Actual} = P_{th} + P_{mech}$

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[4] [icfm] stands for "inlet cubic feet per minute" and is used to quantify a volume flow given at the conditions at the blower inlet. Often "acfm" is used instead for "actual cfm," and to clearly understand "actual," the "actual conditions" must be defined.

[5] Note that the power required by a rotary lobe blower does not depend on the properties of the air, therefore, all other things being equal, the same power will be required on a cold and dry day as on a warm and humid day. In other words, at constant pressure and speed, a rotary lobe blower will need less power per pound of oxygen when operating on a cold day than a warm day.

2.8.4 Efficiency

Volumetric efficiency (positive displacement machines)[6]

Volumetric efficiency is an important characteristic of positive displacement machines. At a given set of conditions and rotating speed, it is the ratio of the actual volume flow to the displacement. The volumetric efficiency increases with the size of the machine and the rotor clearances, with the differential pressure and with the inverse of the density.

$$\eta_v = \frac{V_1}{V_0} = \frac{V_0 - V_S}{V_0}$$

V_1 is the actual inlet flow at a given speed
V_0 is the displacement at the same speed as V_1
V_S is the internal slippage[ii]

Adiabatic efficiency

This is the ratio of the adiabatic power to the actual power at the shaft of the compressor or blower.

Typical order of magnitude for machines used for aerating wastewater (standard conditions and a differential pressure of 9 psi or 0.6 bar):

Rotary lobe blowers: 65%

Rotary screw and centrifugal / turbo blowers: 75%

$$\eta_{ad} = \frac{P_{ad}}{P_K}$$

P_{ad} = adiabatic power (can be calculated with the above formula for P_{th})
P_K = power at the drive shaft

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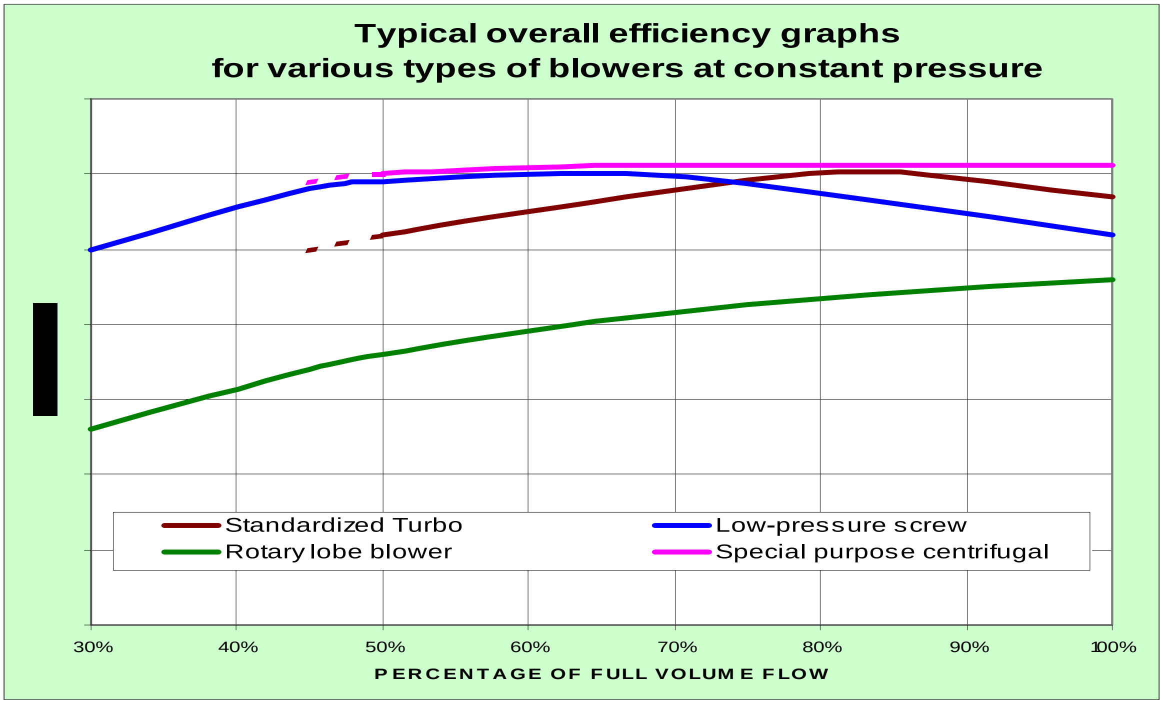
[6] This formula shows that the volumetric efficiency drops as the displacement drops, i.e. at lower speed

Efficiency diagram[7]

For the various types of blowers compared in this paper:



<u>Efficiency range for various manufacturers of the same type of equipment:</u>

There is a relatively wide spread of energy efficiency values – as high as 15%- among products of the same type but from different manufacturers.

The efficiency of positive displacement machines depends largely on the operating clearances between rotors and between rotors and housing.

Screw compressors that are designed for higher pressures will also work at low pressure but they will not be as efficient and their level of vibration will be higher than on screw compressors designed specifically for low pressure.

There are also differences in the efficiency of the standardized turbo blowers, depending on the specific fit of a standardized impeller to a given set of conditions.

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[7] Used for comparison: Aerzen VML and GM blower packages (provided by manufacturer); K-Turbo and Siemens Turbo (based on website information)

The package design also greatly influences the energy usage. In some cases, the intake air is pre-heated by the heat rejected by the motor or even the entire package, resulting in a drop in performance. Belt-drives can feature manual, partially or fully automatic belt tensioning. Needless to say, that the fully automatic belt-drive is the only one that will maintain a higher efficiency constantly without readjustments.

Regardless of the blower technology, the engineer must know that not all manufacturers include all pressure losses across the accessories or mechanical and electrical drive losses in the performance data.

2.9 Drive system

In addition to the thermodynamic characteristics of the machines, the drive system needs to be taken into consideration.

Typical drive systems:

	Rotary lobe blowers Screw compressors	Special-purpose high-speed centrifugal blowers	Standardized high-speed turbo blowers
Motor type	Standard induction	Standard induction	Permanent magnet
Drive	Belt drive	Gear	Direct
VFD	VFD optional	VFD optional	VFD always required

<u>Drive efficiencies</u>

Much is said about drives. Here are some facts:

1) Narrow, cogged V-belt drives:
    a. 98% to 97% efficient when right-sized, constantly properly aligned and tensioned
    b. worst case: 90% efficient, resulting from over-sizing, poor design, lack of tension, poor alignment
    c. Advantage: flexibility of speed selection and motor sizing for best efficiency
2) Speed increasing gears:
    a. 97 to 99 % efficient
    b. Advantage: flexibility of speed selection and motor sizing for best efficiency; reliable and low maintenance

3) Frequency inverter:
    a. 95% to 98% efficient average, however, the efficiency is not constant over the entire range of operation. The total drive efficiency will vary with speed and load
    b. Moreover, the inverter and the motor influence each other, as mentioned in research papers[iii]
    c. Some VFD types and applications may limit the distance between the VFD and the motor. A high speed drive requires a high switching frequency of the inverter and generates a higher level of harmonics, heat generation, necessitates harmonics filters, and precludes the cable length between inverter and motor from being longer than some 20 ft (~ 7 m).
4) Asynchronous induction motors:
    a. > 95% for premium efficiency motors at 100 HP and above
    b. Efficiency drops as the load drops
    c. Power factor drops as the load drops, however the power factor is corrected with the use of a frequency inverter
    d. High-speed induction motors are used by some manufacturers to drive smaller blowers because the cooling of such motors is less critical than for permanent magnet motors. The distance between VFD and motor is limited due to high inverter switching frequency.
5) Permanent magnet motors:
    a. Permanent magnet motors used on high-speed turbo blowers are custom motors. At partial load, their efficiency is slightly better than that of premium efficiency asynchronous motors. Only little information is available on their performance.
    b. Magnetism may be affected at higher temperatures and exposure to magnetic fields; sufficient cooling is critical: some manufacturers require air conditioning of the blower enclosure; some require water/glycol cooling of the motor above a certain power rating or ambient temperature.
    c. The distance between VFD and motor is limited due to high inverter switching frequency.

Drive maintenance

The notion that some machines do not require any maintenance is illusive. Past the obvious oil changes on the more traditional designs and filter changes, consideration must be given to bearings, seals, and electronic components.

1) Bearings: whether they are anti-friction bearings, magnetic, or air bearings, an inspection is recommended at least every 5 years

2) Electronic components, such as VFD may require replacement every 5 to 15. High switching frequency inverters and high ambient temperature will reduce the life expectation of the VFD. It is recommended to add the costs of a replacement inverter in a long-term operating costs analysis.
3) The costs of air filters elements are directly related to the air flow to be filtered. If the cooling air needs to be filtered because the package design dictates it, the air filters will be costly and require more frequent replacement than if the process air flow only needs to be filtered.
4) Belts: the frequency of belt replacement depends on the proper sizing and on the type of belt drive adjustment. Properly designed drives and fully automatic belt tensioning devises normally do not require more frequent belt changes than once every two years. However, the frequency of belts replacement on drives with manual or semi-automatic (spring tension) tension adjustment depends largely on drive design and on the maintenance crew.
5) Speed increasing gears: when properly designed and AGMA 12 or 13 quality, when properly lubricated should have a live expectancy of 20 years.
6) Coupling elements: these should not need frequent replacement unless the coupling is poorly aligned. Waste water treatment plant should be able to operate without replacing coupling element more frequently than every 5 years.

2.9.1 Power Factor

For induction motors, power factor drops with decreasing load and speed; synchronous motors (for example with permanent magnets) operate at improved power factors.

An electric utility may assess a power factor penalty if the plant operates at a power factor that is less than some predefined limit. The power factor penalty is usually billed as an additional demand charge. If penalties become high, plants usually consider adding capacitors to correct (increase) the power factor.

With the use of variable frequency drives, the power factor is corrected to close to unity.

2.10 Other points to consider

2.10.1 Additional accessories

Single-stage high-speed centrifugal blowers feature a speed increasing gear with its high-speed shaft on hydrodynamic bearings. These require pressure lubrication. The oil pump power needs to be added to the blower power.

The power required to drive cooling fans if not included, needs to be added.

Some manufacturers do not include a check valve in their standard package. Its pressure loss needs to be included.

The power loss of gear drives that are integral to a blower are usually included in the blower performance data, while belt drive losses often need to be added.

2.10.2 Tolerance on flow and power

Machining tolerances of blowers and drive components dictate the existence of performance tolerances. ISO 1217 provides guidance for the fields of tolerance on flow and power.

In the USA, ASME PTC 9 is still frequently mentioned as an acceptable standard to measure or verify a positive displacement blower performance. This standard accepts a 1 psi slippage test method that cannot be representative of the operating conditions and cannot be considered accurate. A load test in accordance with a recognized standard should be specified.

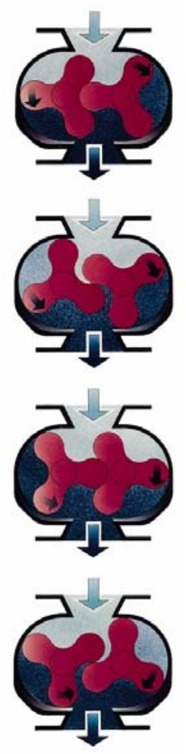
ASME PTC 10 is mostly used in the USA for the testing of dynamic compressors.

The “W2P” or “Wire-to-Process” concept includes all the losses of a package, mechanical and electrical. This all-encompassing solution puts the burden of flow and power responsibility on the supplier and it works best in cases of fully integrated packages. It is not always considered best practice to mount electronics directly on the working machine and many electrical engineers – rightfully- prefer installing VFD and motor starters in a climate-controlled room, while the blowers can be in a less demanding environment or even outdoors. Moreover, some projects benefit from having motor controls to be supplied and installed by a separate electrical contractor.

3 Differences between the blower technologies

3.1 Principle of operation

3.1.1 Rotary lobe blower



We will not describe in detail this technology since it is generally well known in the wastewater treatment industry.

Positive displacement rotary lobe blowers, by nature, develop only a pressure equal to the system pressure; they adapt naturally to changes of backpressure engendered by the system, for example during the daily cleaning of the diffusers, for overcoming momentarily an elevated stagnation pressure or, over time the increased pressure loss across diffusers, without need for any control system.

Flow control to adjust for varying ambient temperature and/or meeting the varying oxygen demand is best accomplished by varying the rotating speed. Systems based on positive displacement machines most simple, dependable, and ideally suited for applications with changing operating conditions.

The power changes proportionally to the pressure rise across the blower and to the rotating speed.

3.1.2 Centrifugal or turbo blower

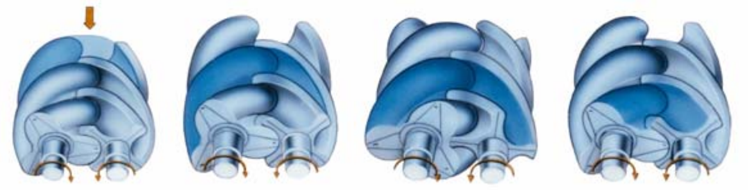
Turbo blowers are dynamic machines that convert the kinetic energy imparted to the air by the impeller into head pressure (potential static energy) in the discharge scroll. The machine must be designed for the worst case conditions defined as lowest air density and highest compression ratio. The turbo blower reaches its best efficiency at its design point. Any deviation from its design point leads to a drop in efficiency: changes in air density due to inlet filter restriction, relative humidity, varying inlet temperatures, changing flow requirements, and changes in discharge pressure, all affect the performance and the efficiency of dynamic blowers.

Ideally, a dynamic blower will be designed and built for a specific application to achieve its highest efficiency under "normal conditions[1]." The special purpose single-stage high-speed centrifugal blowers with outlet diffuser vanes achieve the highest efficiency of all machines subject to our comparison and, when driven with a VFD, they are capable of maintaining a nearly constant thermodynamic efficiency over a 45% to 100% flow range. Controlling multiple VFD-driven machines over the wide range of operating conditions including transient conditions requires however complex controls and a correct set-up.

Standardized single-stage high-speed turbo blowers are not designed for a special purpose. The optimum operating point may not be the normal operating point for the plant. Therefore, the efficiency will change as the operating point moves within the allowable range and the turndown capability may be limited for the same reasons. These machines rely on a well integrated VFD and electronic control system that the user can use to select among operating modes, such as “constant pressure” and “constant flow.”

3.1.3 Rotary screw compressor

The rotary screw compressor technology has been applied successfully since the 1940s for the compression of air or other gases to higher pressures than can be efficiently achieved with rotary lobe blowers. They have for many years been very successfully and efficiently used -with or without VFD- for deep cell aeration and in tower biology systems. These machines feature screw-type rotors that intermesh and, as these rotors turn, the cavity formed by the two screw profiles and the housing (shaded dark blue in picture below) continually diminishes in volume until reaching the discharge port.



There are various designs: oil-free and oil-flooded machines and, in each category various rotor profiles and rates of internal compression can be found. Low-pressure, single-stage oil-free screw compressors are the only ones used for wastewater aeration and combine the high efficiency of internal-compression machines with the simplicity of positive displacement blowers. This is most advantageous for pressures 9 psig (600 mbar) and above.

3.2 Comparison of machines

3.2.1 Rotary lobe blowers

Robust machines; easy to operate; easy to maintain by plant personnel; mean time between overhauls typically 5 to 10 years; only little instrumentation required and controls are vey simple: no pressure ratio controls required for air density adjustments; the blower adjusts naturally to the system backpressure without any controls; at constant speed, the power required is proportional to the downstream pressure at any moment; flow control range up to 4:1[8] using a standard constant torque frequency inverter; at constant pressure, the power is proportional to the speed; the drive uses a standard NEMA or IEC motor; wide turndown range; no surge limitation; requires some more space than an equivalent turbo blower; lower initial costs than a turbo; lower repair costs than a turbo; blower and motor bearings are not a limiting factor for number of starts.

Due to their operating principle, rotary lobe blowers rely on pulsation attenuation at the discharge side to reduce piping noise. Packagers are offering acoustic treatment to meet occupational and environmental noise limits.

3.2.2 Single-stage oil-free screw compressors

Robust machines; easy to operate; easy to maintain by plant personnel; mean time between overhauls typically 5 to 10 years; only small amount of controls required; no controls required for pressure ratio and air density adjustments; the system backpressure determines automatically the pressure generated by the blower without any controls; at constant speed, less energy than rotary lobe blowers above pressure ratio of 1.7 thanks to internal compression; the power drops and adjusts naturally to the downstream pressure at any moment; flow control using a standard constant torque frequency inverter; at constant pressure, the power is proportional to the speed; the drive uses a NEMA or IEC motor; wide turndown range up to 4:1; no surge limitation; may require more space than an equivalent high-speed turbo blower; compressor bearings are not a limiting factor for number of starts. Lower initial and repair costs than a special purpose centrifugal blowers; similar cost to standardized turbo blowers.

Due to their operating principle, screw compressors rely on pulsation attenuation at the discharge side to reduce piping noise. Packagers are offering acoustic treatment to meet occupational and environmental noise limits.

3.2.3 Standardized single-stage high-speed turbo blowers

Simple machines, complex controls made easy in a plug-and-play concept. Must be capable of handling the conditions at the extremes without surging; efficiency advantage compared to positive displacement blowers at or close to the design point and compression ratio above 1.4; complex proprietary controls required to adjust to the interplay of changing conditions of air density, changing pressure ratio, and air flow variations; controls are needed to protect against surging; very sensitive to contamination and sudden pressure swings; low space requirements; high investment costs. Under typical conditions encountered in municipal wastewater treatment plants, a turndown at constant pressure of 55% can be achieved with some loss in efficiency.

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[8] Possibly less, at higher discharge pressure and temperature

An acoustic hood to treat inlet noise and machinery noise is required to meet occupational and environmental noise limits. Increased noise levels are experienced when machines unload.

3.2.4 Special purpose single-stage high-speed centrifugal blowers

Highest efficiency when operating in the design range; robust machines, proven technology adjustable diffuser vanes since the 1980s; high investment and costs of repairs; with proper professional maintenance, long life can be expected. Controls are needed to protect against surging; low space requirements; high investment costs. Under typical conditions encountered in municipal wastewater treatment plants, a turndown at constant pressure of 55% can be achieved without any loss in efficiency. Complex controls required when multiple machines are operated with VFD.

An inlet silencer is required to meet occupational and environmental noise limits. Increased noise levels are experienced when machines unload.

3.2.5 Overview

The table below provides an overview of the most advantageous selections:

Special purpose single-stage high-speed centrifugal blower

Flow control range at constant pressure	100% to 45% of full flow; power required is nearly proportional to the load
Most useful operating pressure range	Compression ratio up to 2.5
Most useful flow range per unit	Standardized packages to 5000 to 70 000 icfm (150 to 2000 m^3/min). The engineer specifying a single machines for an air flow ≥ 10,000 icfm (>300 m^3/min), should consider a special-purpose high-speed centrifugal blower for its high energy efficiency and small space requirements.
Efficiency	Highest thermodynamic efficiency. If equipped with adjustable outlet diffuser vanes and VFD driven, these machines will maintain a nearly constant efficiency over their entire flow turndown range at constant pressure.
Drive	Standard electric motor. Integral gear. Inlet guide vanes are used to adjust to varying compression ratio and inlet conditions. A VFD is not required but can be used instead of inlet guide vanes.

Rotary lobe blowers

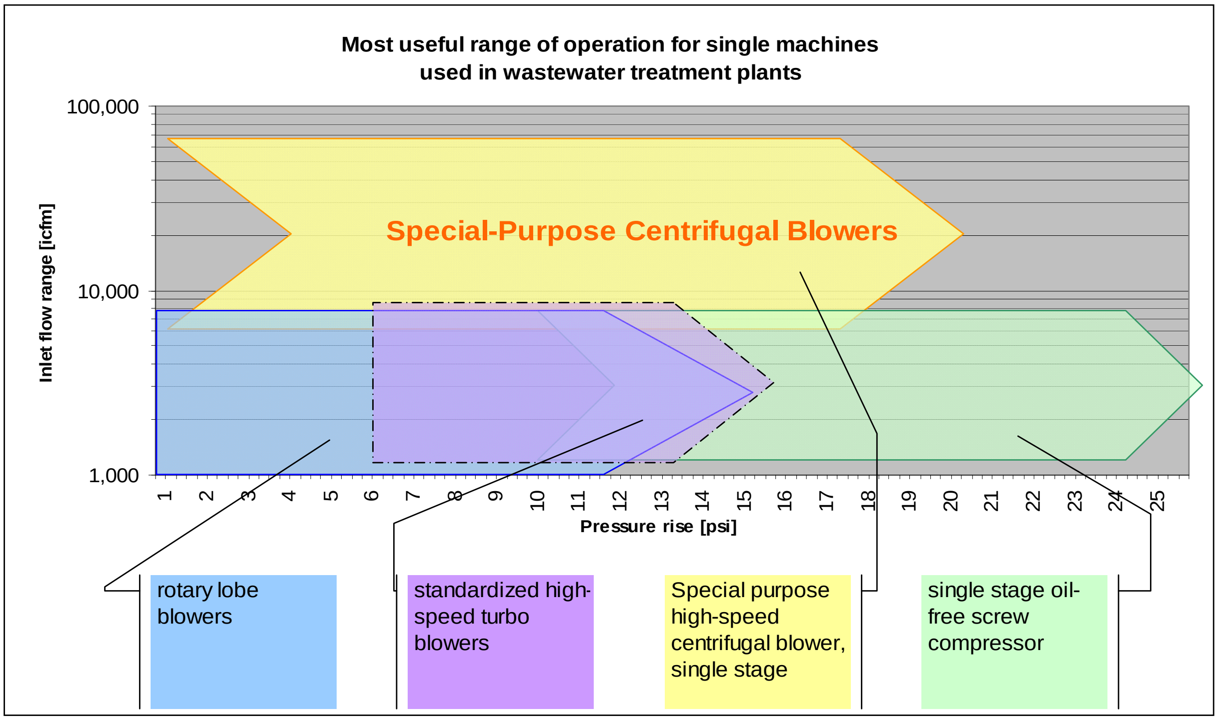
Flow control range at constant pressure	100% to 25%; power required is nearly proportional to the load
Most useful operating pressure range	Compression ratio up to 1.8
Most useful flow range per unit	Standardized packages to ~ 8800 icfm (~250 m^3/min)
Efficiency	Average; increases with lower pressures and lower inlet temperature; drops slightly with increasing turndown.
Efficiency comparison to the special purpose high-speed centrifugal blower	Depends largely on compression ratio: lower efficiency by 5 to 10% at 1.50 and to 20% to 30% at 1.80
Drive	Standard electric motor. Belt drive is typical, providing for flexibility. Standard VFD can be used for flow control but is not required.

Rotary screw blowers and compressors

Flow control range at constant pressure	100% to 25%
Most useful operating pressure range in wastewater treatment applications	Compression ratio 1.70 to 3.0 and higher
Most useful flow range per package	Up to 8800 icfm (~250 m^3/min)
Efficiency	High; drops slightly with increasing turndown
Efficiency comparison to the special purpose high-speed centrifugal blower	Very similar, possibly somewhat lower depending on operating speed and actual pressure ratio compared to built-in compression ratio
Drive	Standard electric motor. Belt drive on small machines 1500 icfm (~ 40 m^3/min), or integral gear drive, providing for flexibility. A VFD is not required. Standard VFD used for flow control.

Standardized high-speed turbo blower

Flow control range at constant pressure	100% to 45% possibly narrower depending on operating vs. design point. Reduced turndown at high ambient temperature or at high pressure ratio.
Most useful operating pressure range	9 psig (~600 mbar) to 18 psig (~1.2 bar g)
Most useful flow range per package	From 350 icfm (10 m^3/min) to 6000 icfm (170 m^3/min)
Efficiency	High at the design point; drops when conditions differ from the design point. Power information includes all electrical and mechanical losses: “wire-to-process”
Typical efficiency difference to a specific-purpose high-speed centrifugal blower	Lower efficiency by 0% to 10% depending on operating point vs. optimum point
Drive	Direct only with high-speed proprietary permanent magnet motor. Cannot be operated without a high frequency VFD.



General rules of thumb for selection:

Selection criteria base on standard conditions at blower inlet and flow per individual machine: T = Standardized turbo blower C = Special purpose centrifugal blower L = Rotary lobe blower S = Dry screw compressor	< 7 psid	7 to 10 psid	10 to 12 psid	12 to 15 psid	> 15 psid
Flow per machine < 1000 cfm / 30 m^3/min	L	LS	LST	ST	ST
Flow per machine 1000 to 8500 cfm (30 to 250 m^3/min) with significant pressure reduction at partial load	L	L	TS	TSC	TSC
Flow per machine 1000 to 8500 cfm (30 to 250 m^3/min) with narrow discharge pressure band	L	TS	TS	TSC	SC
Low operating hours / intermittent operation	L	L	L	L	S
Continuous operation	L	LST	TSC	TSC	TSC
Turndown capability for each machine > 55%	L	LS	LS	S	S
Turndown capability for each machine ≤ 55%	L	LS	TLSC	TSC	TSC
Simplicity of controls	L	LS	LS	S	S

Larger flow per machine > 8500 cfm / 250 m^3/min can best be compressed with a special purpose centrifugal blower or, if the pressure is low or the turndown requirement is low, a multi-stage centrifugal blower.

4 Examples

4.1 Energy usage for three different types of blowers

	14 psig				11 psig				8 psig			
	W2W [kW]			**Yearly energy [kWh/yr]**	W2W [kW]			**Yearly energy [kWh/yr]**	W2W [kW]			**Yearly energy [kWh/yr]**
Air flow [icfm]	3300	2640	1980		3300	2640	1980		3300	2640	1980	
% operating time	10%	60%	30%		10%	60%	30%		10%	60%	30%	
Low-pressure screw (1)	164	129	99	**1,072,905**	141	107	80	**891,765**	116	87	64	**723,862**
Rotary lobe blower (2)	212	176	140	**1,468,798**	165	135	107	**1,130,507**	119	97	76	**805,864**
Standardized turbo (optimized) (3)	167	134	102	**1,108,135**	136	112	89	**938,428**	104	83	65	**693,502**

W2W includes VFD losses and motor losses for all machines as well as transmission losses for the rotary lobe blower and the low-pressure screw compressor

Used for comparison:
(1) Aerzen VML95 (provided by manufacturer)
(2) Aerzen GM150S Delta Blower Package (provided by manufacturer)
(3) K-Turbo TB200-1.0S (based on website information)
(4) K-Turbo TB200-0.8T (based on website information)
(5) K-Turbo TB150-0.6T (based on website information)

4.2 Evaluation in a typical application with multiple machines

Location: .... St Louis, MO
Normal atmospheric pressure: .... 14.32 psia
Normal average temperatures over a year: ....max 66 °F / min 47°F
Temperature max/min: .... + 99°F / - 5°F
Maximum recorded temperature: .... +115°F
RH: yearly average:... day 60% / night 78%

System
Submersion:..15 ft (6.63 psi)
Pressure loss piping: ....0.5 psi
Diffuser head loss: ....0.5 psi
Allowance (diffuser fouling & reserve for emergencies):.....0.75 psi
Inlet filter pressure loss clean / contaminated: ....0.1 / 0.75 psi
Allowance for stagnation ....0.75 psi
Pressure loss discharge check valve.............................0.2 psi
Design pressure: ....9.43 psig
Pressure loss discharge control valve ....0.5 psi
Design compression ratio: 1.73
Operating pressure new / clean system: ....7.72 psig

Operating compression ratio new / clean system: 1.55
Lowest normal air density (99ºF/60% RH): .... 0.069 lb/ft^3
Extreme low air density (115ºF / 36% RH): .... 0.068 lb/ft^3
Highest normal air density (-5 ºF / 36% RH): .... 0.086 lb/ft^3

Maximum annual airflow requirement: .... 5100 scfm
Minimum annual airflow requirement: .... 1900 scfm

Two (2) operating units and one (1) standby unit are desired.

Each blower unit should be designed to handle 2550 scfm at 9.43 psig during the worst case site ambient conditions.

Data Points for Evaluation:

Data Points	Total Flow [scfm]	Flow per Machine [scfm]	Pressure [psig]	Inlet Conditions	Time operating
1	5100 (maximum)	2550 (2 units)	9.43	99 F & 78% RH	10%
2	1900 (minimum)	1900 (1 unit)	7.72	-5 F & 0% RH	10%
3	4080 (80%)	2040 (2 units)	9.43	66 F & 78% RH	20%
4	4080 (80%)	2040 (2 units)	7.72	47 F & 0% RH	20%
5	3060 (60%)	1530 (2 units)	9.43	66 F & 78% RH	20%
6	3060 (60%)	1530 (2 units)	7.72	47 F & 0% RH	20%

	BHP per Machine		
Data Points	PD Blower	Screw Compressor	Standardized Turbo Blower
1	155	137	132
2	71	68	67
3	111	100	98
4	85	81	80
5	85	76	75
6	65	61	62

Annual Energy Costs

Assumptions:

1. Cost of Electricity = $ 0.12 per kW-hour
2. Motor Efficiency = 95% for all machines
3. VFD Efficiency = 97% for all machines
4. Belt Drive Efficiency = 97% for the PD Blower

Rotary lobe Blower	Screw Compressor	Standardized Turbo Blower
$207,569	$184,117	$181,493

5 Conclusion:

Each technology has its place and blanket efficiency statements cannot be taken at face value. With professional due diligence, the engineer will select the aeration blower technology based on a comparison of real operating data over time while being mindful that any machine must be capable of operating safely under extreme site conditions and at the highest pressure ratio over the entire flow range. With pragmatism and common sense, the engineer will also be mindful of the actual operation of the plant and the management of its processes.

NOTES

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[i] The Office of Industrial Technologies of the US Department of Energy has published a useful guide for calculating the Life Cycle Costs of pumps: http://www.eere.energy.gov/industry

[ii] Internal slippage (rotary lobe blowers) formula shows that the slippage is independent of the speed. The volumetric efficiency of a rotary lobe blower will increase as the differential pressure drops.

$$V_S = V_0 - V_1 = V_{S\_ref} \times \sqrt{\frac{\rho_{\_ref}}{\rho_1} \times \frac{\Delta p}{\Delta p_{\_ref}}}$$

VS_ref is the slippage under reference conditions for a specific machine

$\Delta p_{\_ref}$ is the reference differential pressure

$\rho_{\_ref}$ is the density at reference conditions

Δp is the actual differential pressure

ρ_1 is the actual inlet density

[iii] Electric Motor Efficiency under Variable Frequencies and Loads by Charles M. Burt; Xianshu Piao; Franklin Gaudi; Bryan Busch; and N. F. N. Taufik

About Aerzen USA

Aerzen USA is a wholly-owned division of the German manufacturer, Aerzener Maschinenfabrik GmbH, and is a recognized world leader in the production of rotary positive displacement machines since 1868.

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