Evaluating and Comparing Aeration Blower Power Requirements

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Abstract
Evaluation of energy requirements is an important part of optimizing blower selection for aeration applications. In order to calculate blower power it is important to use actual process requirements and appropriate ambient conditions. A methodology is developed to establish the air flow, pressure, and ambient conditions that are reflective of operational energy use without excessive engineering time.

Keywords
Blower power, energy evaluation, aeration energy requirements, blower control, aeration air flow rates

Problem Definition
Providing power for aeration blowers is the greatest single use of energy in most municipal wastewater treatment plants (WWTP). In systems employing diffused aeration suspended growth activated sludge or aerobic digestion the power for aeration is consumed by the blowers supplying air to the diffuser system. Any attempt to optimize energy usage must necessarily include an analysis of the blower power requirements.

It is common practice during facility design to evaluate alternate blower types and configurations for energy efficiency. The type of blowers commonly used fall into three broad categories: Positive Displacement (PD), Multistage Centrifugal (MS), and Single Stage Centrifugal (SS). The selection of blower type is dependent on many factors, including flow rate and discharge pressure, maintenance requirements, operator preference, initial equipment cost, and energy use. In many cases more than one type of blower will satisfy the design criteria. In all cases selection of the type of blower should include an evaluation of comparative power requirements.

The number and capacities of blowers selected to satisfy the air flow rates is another important factor in optimizing the aeration system design. Most municipal WWTPs are required to have standby equipment to insure operation during failure or service of blowers, which necessitates at least two blowers sized to provide 100% of design flow. In order to provide greater operational flexibility, however, arrangements with three or more blowers are typical. Alternate designs include with three blowers sized at 50% of design flow, four blowers at 33% of design flow, and two blowers at 50% plus two blowers at 25% design flow. The impact of equipment cost for alternate arrangements is usually not as great as the impact of power requirements on life cycle cost.

The need for power comparisons doesn't end when equipment design is finalized. Multiple suppliers are usually competing for each project. Equipment cost is obviously a consideration, but not necessarily the most significant one. In the final selection of equipment is advisable to include an evaluation of energy in equipment selection to insure that higher energy expense doesn't negate lower first cost.

The evaluation of power at a single set of operating parameters is not particularly difficult. Evaluation of energy requirements for alternate selections would be a simple task if aeration systems required a constant flow rate at a single set of inlet and discharge conditions. Unfortunately, a large number of factors affect air requirements and aeration power consumption in a typical WWTP.

These factors include varying process requirements, blower operating characteristics that change with ambient and discharge conditions, and control strategies that significantly affect power at a specific set of operating parameters. Add the different types of blowers, different sizing strategies, and alternate suppliers, and the number of possibilities become almost overwhelming!

Background

The evaluation methodology for energy consumption needs to meet a number of criteria. First of all, it is necessary to reflect the energy use expected in normal operation. That means that reasonable variations in flow rate and discharge pressure must be accommodated. Second, since blower power is a function of the ambient air conditions, normal values must be determined and used in the evaluation. Finally, the evaluation methodology must be manageable so that calculations can be performed in a time frame to allow the required number of comparisons to be made.

Most evaluation methods in current use are arbitrary in nature and either very simplistic or complex and unwieldy. For example, a common method is to simply compare blower power at design conditions. Since design parameters are usually based on worst case expectations, this evaluation will not accurately reflect the actual power used during the fluctuations experienced in normal operation. Worse, selection of equipment based solely on peak efficiency at design conditions means that most of the operational life of the blower will occur at conditions resulting in lower efficiencies, resulting in a selection that may not be optimized.

Another common methodology utilizes energy evaluation for each blower option at several flow rates and varying inlet conditions with a constant discharge pressure. There are several shortcomings inherent in this method. Many systems actually operate at variable discharge pressures, particularly in cases where Most-Open-Valve (MOV) techniques are employed specifically to minimize discharge pressure. Since discharge pressure has a significant impact on power requirements, the assumption of constant discharge pressure results in inaccurate evaluations. Furthermore, in current methodology the flow rates and inlet conditions are at best arbitrary and at worst specifically selected to provide favorable values for a specific blower option. The results of an evaluation based on these criteria clearly will not provide results that reflect energy use expected in actual aeration system operation.

Additional techniques employed include average air flow and discharge pressure or air flow and discharge pressure at design aeration system loading conditions. Since experience shows that aeration basins seldom operate at these conditions for extended periods the results of this evaluation do not provide a sound basis for system comparisons.

Very elaborate criteria are sometimes developed for specific treatment facilities to reflect the expected spectrum of flows, discharge pressures, and inlet conditions. In some cases ten or more evaluation points are used to model the expected air flow range, with seasonal and diurnal factors considered. Both the development of the evaluation spectrum and the actual energy evaluations are time consuming, and the level of engineering effort required from both the design engineer and the potential equipment suppliers is extremely burdensome. Since the evaluation criteria are inherently based on assumptions, the accuracy of the results is frequently not commensurate with the effort and expense involved.

A need exists for an evaluation methodology that is process based, provides energy comparisons sufficiently accurate for optimizing equipment selection, and avoids unnecessary detail.

It is important to remember that even the best evaluation is a model and is unlikely to exactly duplicate the actual system performance. Assumptions are required to establish the evaluation criteria. Variability in hydraulic and organic loads, diffuser oxygen transfer efficiency (OTE), diffuser condition and fouling, mixed liquor temperature, and actual dissolved oxygen concentration all have an effect on air flow and pressure requirements. Further assumptions are involved in the actual energy analysis. Most blower manufacturer's published performance data is accurate to approximately ±4%. Actual utility supply voltage, motor performance characteristics, and maintenance considerations such as inlet filter condition also impact actual operating energy requirements. Consequently, the evaluation methodology should identify major factors in energy consumption without creating excess detail that is not justified by increasing the value of the results.

Objectives

There were three objectives for developing the analysis methodology:

1) Identify the parameters significant to energy comparisons, including normal ranges of variation for each
2) Differentiate between parameters critical for equipment specification and parameters critical for energy evaluation
3) Provide an evaluation methodology based on typical process requirements, with sufficient detail to provide realistic comparisons but without excessive requirements for engineering time

It is important to distinguish between design criteria for blower selection and the criteria used for energy comparisons. Design criteria must account for worst case conditions to insure that the system will provide adequate process performance at all times. This means that extremes in ambient conditions, air flow requirements, and discharge conditions must be included in the design specifications.

The energy comparison, on the other hand, should be based on typical operating parameters. These are generally much less severe than the specified design conditions. Further, design parameters represent a single set of values, while typical operation covers a range of conditions. To accurately assess the impact of various blower system design characteristics on energy consumption the evaluation should include consideration of the variations expected in normal operation. A design that optimizes energy at worst case design conditions may not provide the best energy efficiency in day to day operation.

Blower Performance Parameters

Blower power requirements as a function air flow for any blower may be calculated from inlet and discharge conditions and air flow. The generalized formula is:

$$hp = 0.01542 \cdot \frac{Q \cdot p_i \cdot X}{\eta}$$

Where:

hp = brake horsepower at blower shaft
Q = blower inlet volumetric flow rate, ICFM (Inlet Cubic Feet per Minute)
p_i *= blower inlet pressure, psia*
η *= blower efficiency, decimal*
X = blower adiabatic factor:

$$X = \left(\frac{p_d}{p_i}\right)^{0.283} - 1$$

p_d *= discharge pressure, psia*
p_i *= inlet pressure, psia*

The two most significant parameters affecting the power requirement of any blower system are air flow rate and discharge pressure.

Air flow rate can be defined as a volumetric flow rate or a mass flow rate. The volumetric flow rate is usually expressed as CFM (Cubic Feet per Minute). Blower inlet volumetric flow rate is expressed as ICFM (Inlet Cubic Feet per Minute) and is generally used as the default unit by blower manufacturers. The aeration process requirements are generally based on mass flow rate and usually expressed as SCFM (Standard Cubic Feet per Minute).

The units of SCFM appear to represent a volumetric flow, but SCFM is defined as 68 ˚F, 14.7 psia, and 36% RH. This results in a density of 0.075 lbs./cu. ft. and contains 23% oxygen by weight. The relationship of ICFM to SCFM is:

$$ICFM = SCFM \cdot \frac{14.58}{p_i - (RH \cdot PV_i)} \cdot \frac{460 + T_i}{528} \cdot \frac{p_b}{p_i}$$

Where:

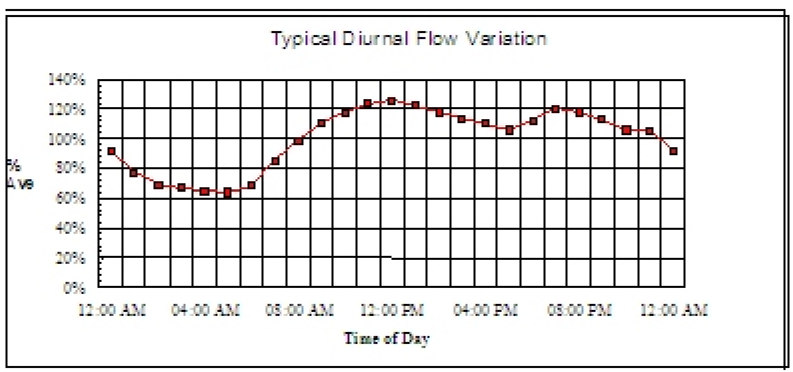
RH = ambient air relative humidity, decimal
PV_i *= saturated vapor pressure of water at inlet temperature, psi*
T_i *= inlet air temperature, ˚F*
p_b *= barometric pressure, psia*

Determining Air Flow Variations

The flow rate for an aeration system is essentially determined by the organic loading, type of process, and the diffuser oxygen transfer characteristics. Organic loading includes the mass of oxygen required to support metabolism and conversion of the BOD_5 (Biochemical Oxygen Demand). If the process includes nitrification the oxygen requirement also includes the conversion of ammonia to nitrate. If the process includes denitrification the oxygen released decreases the overall air demand. In many plants additional air is used for channel aeration, aerobic digestion, post-aeration, and so on. These air flow requirements are usually superimposed on the demands of the aeration process.

The aeration system organic load is affected by many factors, such as normal hydraulic variations, internal side stream flows from sludge thickening or digestion, industrial slug loads, septage haulers, etc. All of these parameters vary daily and seasonally, causing the air requirements to vary. If the actual loading spectrum is quantified it can be used to determine oxygen demand variations and air flow variations.

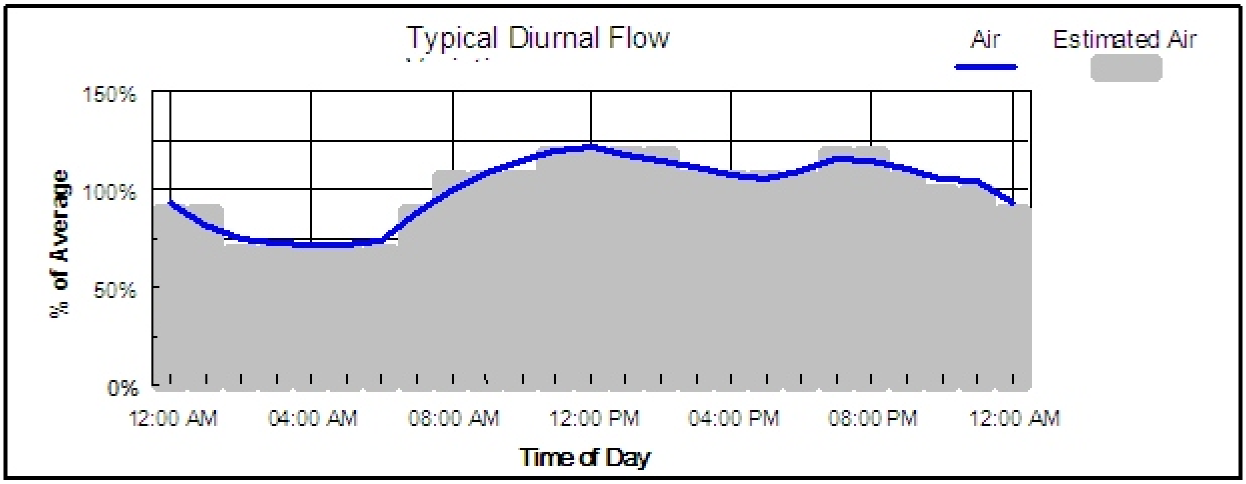
In most cases, however, most of these parameters are not monitored and recorded, and they are subject to considerable variation in degree and schedule as the result of operational decisions. In the case of channel aeration, sludge holding tanks, post aeration, and similar flows the impact on blower air flow can be adequately characterized by adding a constant air flow to the biological process requirements.



The dominant change in air flow rate typically results from variations in hydraulic and organic loading at the plant influent. In most municipal treatment facilities this flow follows a consistent diurnal pattern. In most facilities the organic loading pattern, oxygen demand, and air flow required is not exactly proportional to hydraulic loading changes. However, for the purpose of establishing a reasonable range of air flow for blower evaluation sufficient accuracy is achieved by making that assumption unless more precise site specific data is available. There are also seasonal variations, infiltration and inflow from rain, internal side streams, and industrial contributions superimposed on this pattern. In general, however, air flow variations follow a pattern consistent with the diurnal hydraulic variations.

Note that the ratio of minimum to maximum aeration air flow is approximately 2:1. This wide variation emphasizes both the need to evaluate the turndown capabilities of the aeration blowers and the need to evaluate blower energy requirements over the range air flows.

Evaluation of the air flow rates on a continuous or hourly basis is unnecessarily cumbersome. From inspection it is apparent that the spectrum of air flows can be modeled with sufficient accuracy by selecting several air flows that reflect the total volume of air required and represent the extreme high and low flow rates. A set of five flow rates was chosen as a reasonable compromise between convenient modeling effort and accuracy of results.



Hours/Day	Duty Cycle Weighting Factor (% of Time)	Flow Factor (% ADF)	Totalization Factor (%Time x %ADF)
5	20.8%	70.0%	14.58%
3	12.5%	90.0%	11.25%
2	8.3%	100.0%	8.33%
8	33.3%	107.5%	35.83%
6	25.0%	120.0%	30.00%
24	100.0%		100.00%

In some applications air requirements for post aeration, channel aeration, sludge holding, etc. may represent a significant percentage of total air flow rate. Adding a constant air flow rate to the diurnal variation of the aeration process can account for these requirements.

Selection of the air flow rate at Average Daily Flow (ADF) can be a complex task. There is often a large difference between the loading at commissioning and final design capacity. Peak monthly and average monthly flows may be significantly different. The selection of the appropriate ADF is ultimately up to the judgment of the design engineer. It is important to remembering that the purpose of the evaluation is to select an energy efficient system, not to attempt an exact prediction of air requirements under all conditions. Using air flow rates for an ultimate design condition based on twenty year growth projections will not be indicative of actual energy needs. The use of ADF at either current measured air flows or at the average of current and final design conditions is more likely to result in a cost effective design.

Blower turndown capability and efficiency at reduced flow is critical to matching air flow to process requirements and minimizing energy requirements. The flow profile identified above is based on actual process requirements and will provide a performance profile indicative of actual energy consumption under operating conditions..

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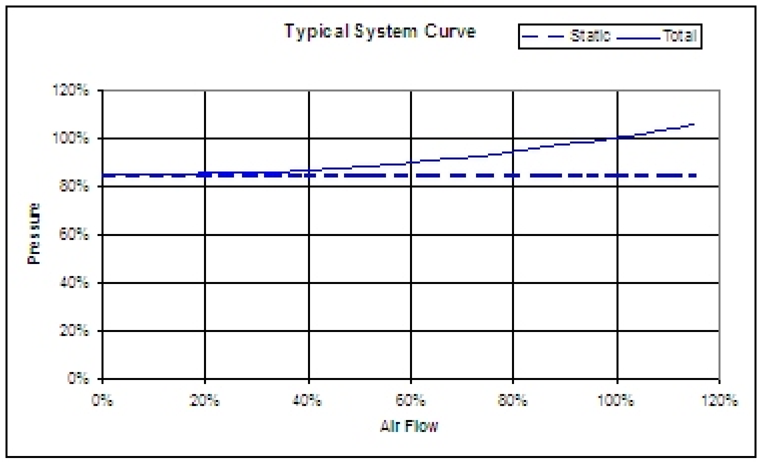
Discharge Pressure

After air flow rate, the next most significant variable affecting aeration blower power is discharge pressure. Actual operating pressure is generally much lower than design pressure. Many blower systems employ automatic controls that are designed to maintain constant pressure, but for most WWTPs discharge pressure varies with air flow rate. Determination of the most energy efficient blower system must include anticipated variations in pressure.

The discharge pressure for aeration systems has two components. The first, and generally the largest component, is the static pressure from diffuser submergence. The second component is friction loss resulting from air flow through valves, piping, and diffusers. The sum of the two components is represented by the system curve.



$$p_{total} = D \cdot 0.433 + k \cdot Q^2$$

Where:

p_{total} = *total discharge pressure, psig*
D = depth of water at top of diffusers, feet
k = constant determined from calculated pressure drop at design air flow

$$k = \frac{\Delta P}{Q^2}$$

Q = flow rate, SCFM
P = average pressure drop at design air flow

The specified blower design pressure is generally calculated at worst case conditions: maximum air flow rate, worst case assumptions for pipe roughness, fouled diffusers, and partially throttled valves at the aeration basins. This is necessary to insure reliable operation under all conditions.

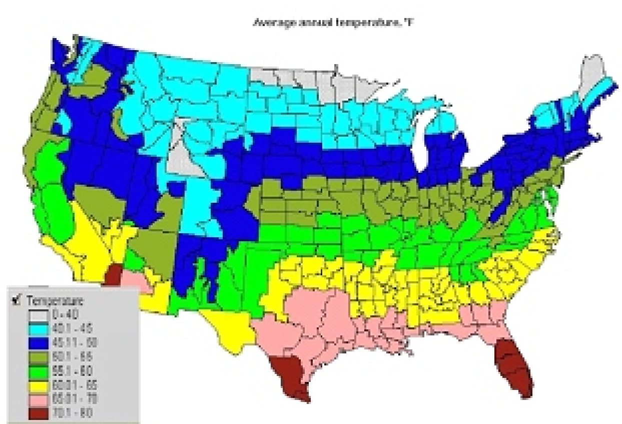
During normal operation the actual discharge pressure is usually 0.5 to 1.0 psi below the design pressure. For evaluating the energy difference between alternate blowers using the design discharge pressure may not provide a reasonable comparison. If a constant discharge pressure control system is being used, good practice requires an allowance of 0.5 to 1.0 psig for pressure drop across basin air flow control valves. The design discharge pressure should include this allowance. With constant discharge pressure control or with manual blower and aeration basin air flow control the evaluation of blower power should be based on the design pressure for each flow rate tabulated.

MOV logic is employed in many automated blower and aeration control systems. This logic, when properly implemented, insures that the air flow control valves at each aeration basin operate as close to full open as possible. The result is minimizing blower discharge pressure to match the static pressure and the pressure drop requirements of the piping and diffusers. The blower discharge pressure will equal the system curve calculated above. If most open valve control is included in the control strategy the discharge pressure at each tabulated air flow rate should equal to p_{total} , the pressure calculated from the system curve equation.

Ambient Conditions and Ranges of Variation

The process requirements are essentially a mass flow rate, SCFM, based on pounds of oxygen required to meet the demands of biological activity. Variations in ambient and blower inlet conditions create corresponding variations in blower inlet air density and increase or decrease the ICFM needed to provide the mass flow rate corresponding to process requirements.

The critical variations in inlet conditions are inlet temperature, inlet pressure, and relative humidity. Inlet pressure and temperature affect air density. Relative humidity, reflective of the amount of water vapor contained in the ambient air, changes both inlet density and displaces the other gases with a corresponding increase in volumetric flow rate needed to equal the mass air flow rate defined by standard conditions.



Inlet temperature for most locations exhibits significant daily and seasonal variations. The typical extreme variations have been tabulated by the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE). These tables are widely available, and include relative humidity (wet bulb) corresponding to the temperature extremes.

These temperature variations substantially affect blower performance as well as ICFM requirements. The highest anticipated temperature is typically used to determine the blower selection and insure the blower can provide adequate discharge pressure at worst case conditions. This is particularly significant for centrifugal blowers. The lowest anticipated temperature is usually critical to determining blower motor power, with centrifugal blowers more sensitive to this variation than PD blowers. An exception is variable speed centrifugal blowers, where the maximum power required occurs at the highest inlet temperature.

Although the extremes of inlet temperature range are used to specify blower design characteristics, they are encountered rarely during normal operation. Use of extreme temperatures for energy evaluations will result in an inaccurate comparison of alternate blower systems. Further, there is no direct correlation between extreme ambient temperatures and the required flow rate.

Using a single inlet air temperature for evaluating power at varying air flow rates is no more arbitrary than a random selection of temperatures or using annual extreme temperatures. There are two equally logical temperatures that can be used for evaluation. One choice would be to use the standard temperature of 68 ˚F, which has the advantage of being the temperature used by most manufacturers for standard performance data. This makes performance data readily available. Another appropriate temperature would be the average annual temperature. This data is illustrated in the map above. The average of the annual maximum and minimum temperatures in the ASHRAE tables provides approximately the same result. Use of annual average temperature has the advantage of providing a closer approximation to expected energy use in actual operation.

Inlet pressure variations reduce the density of the air supply to the blower. There are a number of factors that reduce ambient pressure below the standard 14.7 psia (30" H_g). Standard pressure is based on average sea level barometric pressure. As altitude increases the barometric pressure decreases predictably. The barometric pressure at various altitudes is available as tabulated data from most blower manufacturers, and may be approximated as 1.0 psi decrease in pressure for each 2,000 feet altitude above sea level (ASL).

Inlet pressure is also affected by pressure drop, or suction losses, through inlet filters and piping. Actual suction losses vary considerably in any given application as the filters get dirty. The typical range of variation is 0.1 to 0.4 psi (2 to 12" H_2O). A value of 0.2 psi (5.5" H_2O) is normally included in design specifications, and may be used as a default for inlet filter losses.

Barometric pressure is not constant, but varies with weather conditions. Normally this variation is 0.25 psia (0.5" H_g) or less. Because actual barometric pressure variations are indeterminate and not related directly to flow rate or ambient conditions this variation may be ignored in the energy comparisons between blower systems.

The final factor affecting blower ICFM requirements is relative humidity. The humidity value used for evaluating blower power for comparative purposes is inherently arbitrary and indeterminate. Therefore, for convenience, the standard value of 36% may be used for the calculations.

Control Strategies
The impact of control strategy on blower energy requirements is significant. It is important that the actual control strategy for each alternate system be used for the power calculations.

The control method for modulating blower flow is one factor for consideration in the evaluation. With PD blowers variable speed is the accepted technique. Other methods, such as constant air flow and using blow-off valves are not energy efficient, but if used the energy requirements should be calculated accordingly.

There are numerous alternates for controlling centrifugal blowers. They include variable speed, inlet guide vanes, variable discharge diffuser vanes, inlet throttling, and discharge throttling. The actual method to be supplied should be used for power calculations.

The method of aeration basin air flow control should also be defined for each alternate system and used to evaluate power required. The most important variable to be considered is whether discharge pressure control is used with M-O-V logic or as a constant discharge pressure system.

Analysis Method
The effect of each parameter discussed above was tabulated and used to establish the evaluation technique. The most critical variables are SCFM required and discharge pressure. The other parameters are defined to provide blower energy calculations reflective of actual requirements during typical operating conditions.

The design engineer should establish the design air flow rate at average daily flow, the discharge pressure, and inlet conditions. The blower supplier should provide the actual blower power based on the evaluation criteria, control system, and blower characteristics. A typical evaluation is shown below.

Parameter	Value	Units
Discharge Pressure @ Design Flow	**8.5**	psig
Blower Design Flow	**12,000**	SCFM
Qty. Operating Blowers @ Design	**2**	n/a
Total Blower Design Flow	24,000	SCFM
Barometric Pressure	**14.20**	psia
Suction Loss:	**0.20**	psi
Blower Inlet Pressure	14.00	psia
Diffuser Submergence	**17**	ft.
Static Pressure	7.36	psig
Friction Factor	1.9711E-09	n/a
Average Annual Air Temperature	**55**	˚F
Average Annual Relative Humidity	**36.0%**	
Specific Gravity @ Inlet	**0.979**	n/a
Average Aeration Air Flow at ADF	**12,000**	SCFM
Miscellaneous Air Flow	**2,000**	SCFM
Total Air Flow @ ADF	14,000	SCFM

Percent of Design Aeration Flow	Aeration SCFM	Miscel. SCFM	Total SCFM	Disch. Press. psig	Qty. Blowers Running	SCFM per Blower	bhp per Blower	Total Blower bhp	Evaluation Factor (% Time)	Pro-Rated bhp
70.0%	8,400	2,000	10,40	7.58	1	10,400	**418.6**	418.6	**20.83%**	87.2
90.0%	10,80	2,000	12,80	7.69	2	6,400	**260.7**	521.4	**12.50%**	65.2
100.0	12,00	2,000	14,00	7.75	2	7,000	**287.1**	574.2	**8.33%**	47.9
107.5	12,90	2,000	14,90	7.80	2	7,450	**307.3**	614.5	**33.33%**	204.8
120.0	14,40	2,000	16,40	7.89	2	8,200	**341.5**	683.1	**25.00%**	170.8
									Total Evaluated bhp:	**575.9**

Conclusion

The analysis method defined above represents a process based approach to calculating aeration blower power. The factors that appreciably affect blower power consumption are defined, and extraneous factors are excluded to simplify the analysis. The most critical parameters, air flow rate and discharge pressure, are directly related to the process requirements of the aeration system. Other parameters are defined as required to provide energy consumption calculations that are representative of the actual operating conditions.

This methodology distinguishes between blower and aeration system design conditions and the conditions used to compare energy requirements of alternate blower system designs. Parameters that are not significant for energy comparisons may be significant in insuring the installed equipment will operate satisfactorily under worst case site conditions. However, using design parameters for comparison of energy requirements will not accurately reflect the relative efficiency of alternate systems or suppliers.

One significant difference between the process based analysis and most other energy comparison techniques is that the duty cycle of the blowers is skewed in the process based evaluation. The weighting factors indicate that the aeration system operates at or near average flow rate for a small percentage of the time. Particularly when automatic Dissolved Oxygen control is employed, aeration blowers will operate near the limits of the air flow range more hours per day than they operate at average flow. Most current evaluation schemes, even those that employ some kind of weighting factor for duty cycle and flow rate, tend to emphasize air flow at or near average daily flow. The factors identified by this analysis more accurately reflect actual diurnal blower energy variations without adding excessive complexity.