Influence of weather conditions on energy consumption of controlled blowers at WWTP

Andrei Ustiuzhanin¹, Konstantin Chizhik¹ and Victor Bazhenov²

¹Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia
²Closed Joint Stock Company "Water and Waste Water" 1, Polkovaya street, Moscow, 127018, Russia

Abstract. The object of analytical research are controlled air blower units of wastewater treatment plants (WWTPs) for wastewater utilities with pneumatic aeration systems for biological processes, based on oxygen consumption. The goal of analytical research is accounting and estimation values of temperature, relative humidity, atmospheric pressure for energy consumption by controlled air blowers. The system of equations is proposed for the joint solution: 1st equation - according to the Guide to Meteorological Instruments and Methods of Observation; 2nd equation - modification for determining the energy consumption for the blower unit P wire in kW. These form the analysed mathematical model with the following results of study. Fluctuations in the full range of operating temperatures leads to a change in power consumption in the range –14.9 to 19.9%. Fluctuation of atmospheric pressure in the full range leads to a change in power consumption in the range from –3.4 to 3.7%. Relative humidity affects power consumption only in combination with high temperature (between 20-40°C the maximum influence of relative humidity is 0.6-3.3%). The combined influence of all three parameters in the full range is from –9.2 to 11.2%. All presented data are supplied also for the range of average values.

1. Introduction

The object of analytical research are controlled air blower units of wastewater treatment plants (WWTPs) for wastewater utilities with pneumatic aeration systems for biological processes, based on oxygen consumption.

The subject of analytical research is necessity and estimation accounting value of weather conditions (temperature, relative humidity, atmospheric pressure) for energy consumption by controlled air blowers (duty units and reserve involved in control sequence of operation).

Aeration is the most important process, which accounts of the wastewater treatment plants (WWTP’s) energy ranging 45-75% [1, 2]. Due to seasonal and daily control of air supply to the aeration tanks, it is possible to save about 30-40% of the power consumption, which becomes achievable when using air blowers with a range of performance control more than 50-100% [3, 4]. The method of estimating the dynamics of technological loads fluctuation (by flows and concentrations) plays a key role in the formation of initial data [5, 6].

Mathematical modeling of processes in this area of knowledge is the only tool, that can reflect the complexity of phenomena according to the scheme "energy consumption – dynamics of fluctuation" in a short period of time for issuing the design. The forecast of the overall system for regulating
technological methods is complicated by a significant number of system equations and the need to assign design parameters for optimization of WWTP’s [7]. The regulating methods of air blowing units are [2, 3]: variable inlet guide vanes (IGVs), variable diffuser vanes (VDVs), inlet-outlet throttling controls, variable frequency drive.

In the context of classical mass transfer equations, regulation is the maintenance of balance between phase changes in oxygen in aeration tank: demand side - consumption of OUR (oxygen uptake rate) and supply side - oxygen transfer of OTR (oxygen transfer rate). In dynamic conditions OTR ≠ OUR for an unregulated system at any time, and OTR → OUR for regulated systems [8]. Ultimately, regulation results in saving the energy consumed by blowers. Combination of efficient equipment aerators, blowers and monitoring system can significantly improve total energy and cost savings [9, 10].

Therefore, the list of key aspects to be modelled is presented [11, 12]: blower performance curves and it’s variations (prediction of performance: delivered air flow, discharge pressure, power consumption); pressure drops in the piping network (diffusers, fittings, valves with/without positioning); design and hydrodynamic parameters (design dimensions and parameters); operating conditions (present of surfactants, mixed liquor viscosity); controllers for adjusting of valve positioning and blower operating duty points. Anyway, these aspects are traditionally under consideration by modern classical issues, like [1-4, 13], taking into account special conditions for airflow (standard, or normal, or mass), supplying oxygen to aeration tanks.

Not directly written, but obvious is, that weather conditions affect blowers and their power consumption in two different ways, figure 1: affecting the performance curve and changing the compression start conditions. For controlled blowers, the first path is the main one, in which the mass of the supplied oxygen of air and the discharge pressure change only under the influence of weather conditions. This mode is characterized by a decrease in power consumption when the intake air temperature increases.

![Figure 1](image)

**Figure 1.** Two ways influence of weather conditions on the energy consumption of blowers

When automatic control is implemented, the air supply corresponds to the oxygen demand of the aeration tanks, and the discharge pressure is also stabilized by the control strategy [14-16]. Thus, the impact of weather conditions occurs in the second way - through changing the conditions of the beginning of compression. In this mode, the opposite pattern is observed: when the intake air temperature increases, the power consumption increases.

The goal of analytical research is accounting and estimation values of temperature, relative humidity, atmospheric pressure for energy consumption by controlled air blowers.

2. Materials and methods

The power [kW] required to compress the air is determined by the mass flow of air and the isentropic head [17]:

\[
P = \frac{M_{\text{air}} L_{\text{in}}}{3.6 \times 10^8 \eta_{\text{is}}} = \frac{Q_{\text{air}} p_{\text{air}} L_{\text{in}}}{3.6 \times 10^8 \eta_{\text{is}}}
\]  

(1)
where $M_{	ext{air}}$ is a humid air mass flow rate [kg/h], $L_n$ is an isentropic head [J/kg] and $\eta_n$ is an isentropic efficiency [-]. $Q_{	ext{air}}$ is a volumetric humid air flow rate [m$^3$/h] and $\rho_{	ext{air}}$ is a density of humid air [kg/m$^3$]. Coefficient $3.6 \times 10^6$ is required to convert units from joules to kilowatts. It should be noted that instead of isentropic head and efficiency, polytropic head and efficiency can be used without loss of calculation accuracy. Equation (1) is fundamental to determine the power used to compress air. Isentropic efficiency is the internal efficiency of the compressor and takes into account only the loss of the compression process.

In general, to determine the pressure at the inlet and outlet of the blower, it is necessary to take into account the full pressure balance, starting from atmospheric pressure and ending with the pressure of the liquid column in the pneumatic aeration system. The specified balance depends on the configuration of air filters, pipelines, control valves and aerators, as well as on the performance curves of blowers.

Weather conditions have a significant impact on the performance curves of blowers and consumers, changing the position of the operating point. However, with automatic control of the pressure sensor, the pressure drop at the inlet and outlet of the blower remains constant, and the air supply meets the oxygen requirements of the aeration tanks at each time point.

Thus, when considering the influence of weather conditions on the energy consumption of blowers, we assume that the suction pressure corresponds to atmospheric pressure, and the pressure difference at the inlet and outlet of the blower is constant. In this case, the isentropic head is determined as follows:

$$L_n = \frac{k}{k-1} \frac{10^5 \rho_{\text{air}}}{\rho_{\text{air}}} \left[ \left( \frac{p_{\text{am}} + \Delta p}{\rho_{\text{air}}} \right)^{\frac{k-1}{k}} - 1 \right]$$

where $k=1.4$ is a specific heat ratio of air [-]. The pressure difference at the inlet and outlet of the blower $\Delta p$ [kPa] includes the hydrostatic pressure of the water column in the aeration tank and all speed losses in the piping system, control valves, aerators, etc.

Gases have different densities and volumes depending on temperature and pressure. In the same system under consideration, the gas can be in different conditions (for example, the conditions at the inlet and outlet of the blower differ significantly). Therefore, for an unambiguous determination of gas parameters, it is necessary to indicate the conditions for which the values used are true.

Parameters (density, volume and accordingly volume flow) of the same gas can be recalculated for any predetermined pressure and temperature conditions. In the case of air, a third condition is added - relative humidity, which is more complicated. The problem is that, when the air humidity changes, its specific gas constant R changes, and such air can no longer be called the same gas under other conditions. When recalculating air from one humidity value to another, we remove or add a certain amount of water vapor in the mixture. But this does not raise questions only if water vapor does not affect the processes under consideration. For example, for biochemical processes in the aeration tank, only the amount of dry air supplied (which contains 23.15% oxygen by mass) is important, while water vapor is important for the air compression process, since water vapor compression requires additional energy.

There are a large number of standards defining ‘standard conditions. When using standard conditions, it is necessary to strictly indicate the standard according to which the conditions are defined. In natural science ‘normal conditions’ term is often used as a less strict substitute for ‘standard conditions’. Some standards define ‘standard conditions’ and ‘normal conditions’ at the same time. Some standards define only pressure and temperature as conditions, while others also determine relative humidity. The application of certain specific conditions and standards depends on the industry, country, etc.

In this study, we will traditionally use the following ‘normal conditions’ for the wastewater utility or industry: temperature 0 ° C, pressure 101.325 kPa, relative humidity 0%. It should be noted that these conditions coincide with the definition of ‘standard conditions’ according to DIN 1343:1990 [18]. For these normal conditions, the following equation is correct [12]:
\[ Q_{\text{air}} = Q_N \frac{(T+273.15)}{273.15} \frac{101.325}{p_{\text{atm}} - p_w} \]  

where \( Q_N \) is a normalized air flow rate [Nm\(^3\)/h], \( p_w \) is a water vapour partial pressure [kPa], and \( T \) is an air temperature [°C].

The amount of water vapor in the air depends on temperature, atmospheric pressure and relative humidity. The higher the temperature, the more water vapor can be dissolved in air. Relative humidity shows how much water vapor is actually in the air relative to the maximum amount possible at given temperature and pressure. The partial pressure of water vapor in the air [kPa] at a relative humidity \( \text{RH} \) [%] is determined according to the Guide to Meteorological Instruments and Methods of Observation [19]:

\[ p_w = \frac{\text{RH}}{100\%} \left( 100160 + 3.15 p_{\text{atm}} - \frac{740}{p_{\text{atm}}} \right) \times 10^8 \exp \left( \frac{17.627}{243.12 + T} \right) \]  

During compression, the air parameters change (significant heating and pressure increase occurs), however, the amount of water vapor in the air remains unchanged. Therefore, the partial pressure of water vapor is considered only for atmospheric conditions without taking into account further compression.

3. Essence of study and Results

Isentropic efficiency is internal to the blower and characterizes the energy loss directly during compression. Losses not directly related to the compression process are called external. The most significant external losses include losses in the transmission (this also includes losses in the frequency converter if used) and the electric engine. These losses should also be taken into account when calculating energy consumption.

In addition to the main electric engine blower units can include various auxiliary devices, such as cooling pumps and fans, oil pumps, various controllers cabinets, etc. The share of energy consumed by these devices is small, but it should also be taken into account when calculating energy consumption.

In view of the above, combining equations (1) - (3) and making simplifications, we obtain the final equation for determining the energy consumption for the blower unit \( P_{\text{wire}} \) [kW]:

\[ P_{\text{wire}} = \frac{Q_N (T+273.15)}{9704.811 \eta_{\text{en}} \eta_{\text{tr}}^{(k-1)}} \left( \frac{k}{k-1} \right) \left( \frac{p_{\text{atm}}}{p_{\text{atm}} - p_w} \right) \left( \frac{p_{\text{atm}} - \Delta p}{p_{\text{atm}}} \right)^{\frac{k-1}{k}} - 1 \right) + P_{\text{aux}} \]  

where \( \eta_{\text{tr}} \) is a transmission efficiency [–], \( \eta_{\text{en}} \) is an engine efficiency [–] and \( P_{\text{aux}} \) is a power consumption by auxiliary devices [kW].

Equations (4) and (5) together form the mathematical model for studying the influence of weather conditions on the power consumption of blowers under automatic control by a pressure sensor. The values of the parameters used in the calculation as constants are given in table 1. The variable parameters are air temperature \( T \), atmospheric pressure \( p_{\text{atm}} \) and relative humidity RH.

| Table 1. Parameters used in the calculation as constants |
|---------------------------------|---------------------------------|-------------------------------|
| Parameter | Description | Value |
| \( Q_N \) (Nm\(^3\)/h) | Normalized air flow rate | 40000 |
| \( \Delta p \) (kPa) | Differential pressure | 44.13 |
| \( \eta_{\text{en}} \) (–) | Engine efficiency | 0.96 |
| \( \eta_{\text{tr}} \) (–) | Transmission efficiency | 0.97 |
| \( \eta_{\text{is}} \) (–) | Isentropic efficiency | 0.82 |
| \( P_{\text{aux}} \) (kW) | Power consumption by auxiliary devices | 2 |
Weather parameters fluctuate randomly over short periods of time, for example, during the day. At the same time, there are some average values inherent for the seasons of the year in accordance with climatic conditions. There are also annual average values of the parameters. Therefore, it is advisable to divide the values of the variable calculation parameters into two ranges: the range of average values and the full range, taking into account possible random extreme values. The range of fluctuations of average values should be used to predict the influence of weather conditions on energy consumption, and the full range to check the technical parameters when choosing equipment.

For practical calculation, the ranges of variable parameters are conditionally selected, but are typical for the middle latitudes of eastern Europe, western and middle Siberia. The ranges of parameters presented in table 2.

| Table 2. Typical range of average values and full range of weather parameters |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Average value                      | Range of average values | Full range |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| $T \ (^{\circ}C)$               | 0               | -20             | 20              | -40     | 40 |
| $p_{\text{atm}} \ (kPa)$         | 100             | 98              | 102             | 96     | 104 |
| $RH \ (%)$                       | 65              | 40              | 90              | 30     | 100 |
Thus, in this study, power consumption is a function of three variable weather conditions. The figure 2 presents the dependence of power consumption as a function of temperature at various values of atmospheric pressure and relative humidity (a). Similarly, power consumption is presented as a function of atmospheric pressure (b) and relative humidity (c) for different values of the other two parameters.

The magnitude of the influence of each of the three parameters can be estimated from the slope of the graphs, which are partial derivatives of the function of power consumption. As can be seen, the greatest influence on the power consumption of the blowers has the temperature of the intake air. With its increase, the power consumption also increases regardless of other parameters. The second most influential weather parameter is atmospheric pressure. With its increase, power consumption decreases regardless of other parameters. The least influence is exerted by relative humidity, the influence of which is the higher, the higher the temperature.
More accurate numerical values of power consumption for the full range of weather conditions are presented in table 3.

| T (°C) | p_atm (kPa) | RH (%) | P_wire (kW) | T (°C) | p_atm (kPa) | RH (%) | P_wire (kW) |
|-------|-------------|--------|-------------|-------|-------------|--------|-------------|
| -40   | 96          | 30     | 504.69      | 104   | 30          | 510.76 | 65          |
| -40   | 100         | 504.76 | 30          | 104   | 511.19      | 65     |
| -40   | 100         | 486.94 | 0           | 96    | 592.03      | 104    | 65          |
| -40   | 100         | 486.98 | 65          | 93.35 | 100         | 594.69 | 65          |
| -40   | 100         | 487.01 | 65          | 93.35 | 65          | 594.69 |
| -40   | 104         | 470.42 | 100         | 30    | 571.16      | 40     | 65          |
| -40   | 104         | 470.45 | 100         | 30    | 572.39      | 65     |
| -40   | 104         | 470.48 | 100         | 30    | 573.62      | 65     |
| -20   | 96          | 547.99 | 104         | 30    | 551.73      | 100    | 65          |
| -20   | 96          | 548.25 | 65          | 552.87 | 100         | 668.10 |
| -20   | 96          | 548.50 | 100         | 554.01 | 100         | 712.75 |
| -20   | 100         | 528.71 | 20          | 96    | 638.68      | 104    | 65          |
| -20   | 100         | 528.95 | 65          | 644.20 | 100         | 661.63 |
| -20   | 100         | 529.18 | 100         | 649.83 | 100         | 679.33 |

Table 3. Numerical values of power consumption

Table 4. The influence of weather conditions on the energy consumption

| Power variation over a range of average values (%) | Power variation over a full range values (%) |
|--------------------------------------------------|---------------------------------------------|
| Min     | Max   | Min   | Max   |
| T       | -7.6  | 8.5   | -14.9 | 19.9  |
| p_atm   | -1.7  | 1.8   | -3.4  | 3.7   |
| RH      | 0.2   | 0.2 (0.6) | -0.2  | 0.1 (3.3) |
| Joint influence | -9.2 | 11.2 | -17.8 | 28.2 |

Power consumption 572.39 kW corresponds to the average values of weather conditions. The results of the analysis of the influence of weather conditions for the range of average values and the full range are presented in table 4. Since the influence of relative humidity increases with increasing temperature, its effect is also calculated for the upper value of the temperature range (value in brackets).

4. Conclusions

The system of equations is proposed for the joint solution: 1st equation (4) - according to the Guide to Meteorological Instruments and Methods of Observation; 2nd equation (5) - modification for determining the energy consumption for the blower unit P wire in kW. These form the analyzed mathematical model with the following conclusions:

- The energy consumption of controlled blowers, at constant values of the mass air flow and differential pressure, is most affected by the temperature of the intake air. The higher the temperature, the higher the power consumption in controlled mode. Temperature fluctuations in the range of average values leads to a change in power consumption in the range from -7.8 to 8.5%. Fluctuations in the full range of operating temperatures leads to a change in power consumption in the range from -14.9 to 19.9%.

- The second most important parameter is atmospheric pressure. Fluctuations in atmospheric pressure in the range of average values leads to a change in power consumption in the range from -1.7 to 1.8%. Fluctuation of atmospheric pressure in the full range leads to a change in power consumption in the range from -3.4 to 3.7%. Moreover, an increase in atmospheric
pressure reduces power consumption, provided that the differential pressure of the blowers is constant.

- Relative humidity affects power consumption only in combination with high temperature. At a temperature of 20 °C, the maximum influence of relative humidity is 0.6%, while at a temperature of 40 °C the influence of relative humidity increases to 3.3%. The higher the relative humidity, the higher the energy consumption of the blowers.

- The combined influence of all three parameters in the range of average values is from –9.2 to 11.2%. In the full range from –17.8 to 28.2%.

References
[1] Stenström M.K. and Rosso D. *Aeration and Mixing*. Biological Wastewater Treatment: Principles, Modelling and Design (London: IWA Publishing) chapter 9 pp. 245-272 (2008)
[2] Rosso D. (Ed.) *Aeration, Mixing and Energy: Bubbles and Sparks*. London: IWA Publishing. (2018)
[3] Liptak B.G. Instrument Engineers Handbook. Volume Two: *Process Control and Optimization*. London: Taylor & Francis. (2005)
[4] Jenkins T.E. *Aeration control system design: a practical guide to energy and process optimization*. John Wiley & Sons. (2014)
[5] Schraa O., Rieger L. and Alex J. Development of a model for activated sludge aeration systems: linking air supply, distribution, and demand. *Water Science & Technology*, 75.3, pp. 552-560 (2017)
[6] Emami N., Sobhani R. and Rosso D. Diurnal variations of the energy intensity and associated greenhouse gas emissions for activated sludge processes. *Water Science & Technology*, 77.7, pp. 1838-1850 (2018)
[7] Fernández-Arévalo T., Lizarralde I., Maiza M., Beltrán S., Grau P. and Ayesa E.. Diagnosis and optimization of WWTPs using the PWM library: full-scale experiences. *Water Science & Technology*, 75.3, pp. 518-529 (2017)
[8] Bazhenov V.I., Ustiuzhanin A.V., Koroleva E.A. Aeration for wastewater biological treatment: updating foreign terms and abbreviations. *Water supply and sanitary technique*, No 9, pp. 46-56 (2019)
[9] Stamatelatou K., Konstantinos P.T. (Eds.) *Sewage Treatment Plants: Economic Evaluation of Innovative Technologies for Energy Efficiency*. Integrated Environmental Technology Series. London: IWA Publishing. (2015)
[10] Bazhenov V., Ustiuzhanin A. Life Cycle Cost management of blower station construction for wastewater utility. *MATEC Web of Conferences*, 170, 04021 (2018)
[11] Amaral A., Schraa O., Rieger L., Gillot S., Fayolle Y., Bellandi G., Amerlinck Y., Mortier S. T. F. C., Gori R., Neves R. and Nopens I. Towards advanced aeration modelling: from blower to bubbles to bulk. *Water Science & Technology*, 75.3, pp. 507-517 (2017)
[12] Amerlinck Y., Keyser W. D., Urchegui G. and Nopens I. A realistic dynamic blower energy consumption model for wastewater applications. *Water Science & Technology*, 74.7, pp. 1561-1575 (2016)
[13] Mueller J.A., Boyle W.C., and Popel H.J. *Aeration: Principles and Practice*. CRC Press LLC. (2002)
[14] Åmand L., Olsson G. and Carlsson B. Aeration control – a review. *Water Science & Technology*, 67.11, pp. 2374-2398 (2013)
[15] Schraa O., Rieger L., Alex J. and Miletic I. Ammonia-based aeration control with optimal SRT control: improved performance and lower energy consumption. *Water Science & Technology*, 79.1, pp. 63-72 (2019)
[16] Du X., Wang J., Jegatheesan V. and Shi G. Dissolved Oxygen Control in Activated Sludge Process Using a Neural Network-Based Adaptive PID Algorithm. *Applied Sciences*, 8, 261 (2018)
[17] Tchobanoglous G., Burton F.L., Metcalfe & Eddy, Inc. & Stensel, H.D. *Wastewater Engineering*
Treatment and Reuse. New York: McGraw-Hill (2004)

[18] DIN 1343:1990 Reference conditions, normal conditions, normal volume - concepts and values. German Institute for Standardisation (Deutsches Institut für Normung). Published 01-01-1990.

[19] Guide to Meteorological Instruments and Methods of Observation. World Meteorological Organization, WMO-No. 8 (2012)