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ACCURATE OXYGEN TRANSFER EFFICIENCY MEASUREMENTS BY OFF-GAS METHOD - TANK COVERAGE DILEMMA

POMIAR SPRAWNOŚCI TRANSFERU TLENU METODĄ OFF-GAS - PROBLEM STOPNIA POKRYCIA REAKTORA

Abstract: The off-gas method is one of two primary aeration efficiency examination methods. In off-gas method, exhaust air from aeration tank is collected by a floating hood and conveyed to a measurement module. In this part of the installation, gas flow is measured, collected air is dried, stripped of CO₂ and subsequently oxygen concentration is measured. The hood area is usually few square meters or even less and is a very small part of the aeration tank area. The main advantage of the off-gas method is that it offers measurement without disturbances to reactor routine work, which are necessary in the case of alternative, absorption method. Thereby, the off-gas method can be used in any circumstances and is free from uncertainty about the influence of reactor disturbances on the obtained results. However, a question remains about the number of measurement points required to obtain representative results for the whole reactor. According to The Environmental Protection Agency (EPA) guidelines, coverage of 2% of the tank area is sufficient, but this number seems insufficient. This article presents an analysis of the influence of tank coverage on the obtained oxygen transfer efficiency values. The presented analysis is based on real data.

Keywords: wastewater treatment, aeration, oxygen transfer efficiency, off-gas method

Introduction

Oxic biological treatment processes has been key element of modern wastewater treatment for decades and are used in every single activated sludge based wastewater treatment plant (WWTP). Optimization of wastewater aeration is very important as the process plays a vital role advanced nitrogen and phosphorus removal, while being also very energy-intensive. According to research reports [1], aeration process is responsible for around 50% of total electricity consumption in the wastewater treatment plant. Having such significant share in the energy balance of wastewater treatment, aeration process optimization has been the object of scientific research for a long time, especially due to the growing energy prices. Therefore, good understanding of the mechanisms involved in oxygen transfer from gaseous to liquid phase and in the subsequent role of oxygen in biochemical reactions seems vital. One of the basic indicators of aeration process quality is oxygen transfer efficiency (OTE, $\text{g O}_2 \cdot \text{Nm}^{-3} \cdot \text{m}_{\text{depth}}^{-1}$) which is the measure of oxygen transfer efficiency in process conditions.

While other measurement methods exist that allow the OTE calculation, the off-gas method, which consists in the analysis of the exhaust air from the reactor, proved to be particularly useful. It is the only method which allows taking measurements during regular operation of the aeration tank and hence allows the elimination of interference caused by deviating from normal operating conditions. Unfortunately, despite its obvious

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Contribution was presented during ECOpole'16 Conference, Zakopane, 5-8.10.2016

advantages, the method is not very popular worldwide; the team from Wrocław University of Science and Technology is the only one in Poland to make use of it. This is probably due to the need to possess specialist measuring apparatus, which is of limited commercial availability. Another important reason is that taking measurements and analyzing the data requires skilled and experienced personnel.

Aim of work

Finding the average value of oxygen transfer efficiency in the aeration tank necessitates taking measurements in an adequate number of points on the aeration tank surface, which will translate into the area of the aeration tank covered with the hood capturing the exhaust air. According to the American Environmental Protection Agency guidelines [2] and to German ATV M 209E 1996 standard [3], coverage of 2% of tank area is sufficient to obtain reliable results that are needed to assess the aeration efficiency in an investigated system. However, some reports [4] indicate that detailed information on the condition of the aeration system can be provided only by measurements that would cover a larger area of the reactor. The influence of the number of measurement points on the accuracy of the results is not known either. This paper presents the analysis of the relationship between the number of measurement points, which corresponds to reactor's area covered by hood during the off-gas test and the quality of the obtained results, based on a measurement series performed with off-gas method in one of Polish municipal WWTPs.

Off-gas method - an outstanding method for the diagnostics of aeration systems

Wastewater aeration systems examinations which are performed with the off-gas method have unique features as compared to other available measurement methods. The measuring apparatus may be situated in practically any location on the reactor surface and this feature allows finding spatial variation of oxygen transfer efficiency (e.g. resulting from progressive biodegradation present in the sewage, as it passes through the plug flow reactor) as well as finding OTE time variation that results from varying wastewater composition (e.g. surfactants) and reactor loading [4-6]. Such information enables optimization of the aeration system by adapting the control system to reduce aeration at those locations where and those times when the process would be less effective, and to increase aeration intensity in more advantageous conditions, thus saving electric energy. As mentioned before, one of the indisputable advantages of the off-gas method is that it allows measurements without the need to interrupt normal operation of the reactor, as is the case with the competing method that consists in oxygen absorption. According to some research [7], flow velocity of the aerated medium has significant impact on the values of oxygen transfer, and this factor is extremely difficult to be included in calculations when a reactor is not operated normally. Another important advantage of the off-gas method is that it allows finding the localization of leaks in the air distribution system, which is situated at the bottom of the reactor, by identifying spots characterized by high exhaust air flow and low oxygen transfer [8].

The off-gas method was developed in 1983 in the United States [9]. The method is based on the fact that the exhaust air from the aeration tank is a good source of information on the oxidic processes that occur inside the reactor. The exhaust air from the bioreactor has lower level of oxygen as compared to atmospheric air, because the oxygen is used by activated

sludge in biochemical processes, and contains impurities that are the result of those processes, e.g. nitrogen oxides and dinitrogen monoxides, volatile organic compounds etc. It has been shown that information obtained from exhaust air composition may be effectively used to diagnose and control such biological processes as nitrification and to determine the amount of emitted gases that influence the condition of the atmosphere [10-15]. This technique has also been proven as a useful tool in plant energy usage optimization process as it can be used for aeration systems diagnosis [16-19]. In off-gas measurement apparatus, exhaust air is collected in an airtight hood floating on the surface of wastewater. The hood may have an area of up to several square meters. From the hood, the air is sent, via a duct, to a measurement module in which humidity is removed, air flow is measured, and oxygen and carbon dioxide levels are monitored. The module may be further equipped with practically any type of sensors (e.g. nitrogen oxide sensors) or the measured gases may be limited to oxygen only - in such case a CO₂ binding agent must be introduced into the installation directly upstream of the oxygen sensor. Figure 1 shows a schematic diagram of the off-gas method.

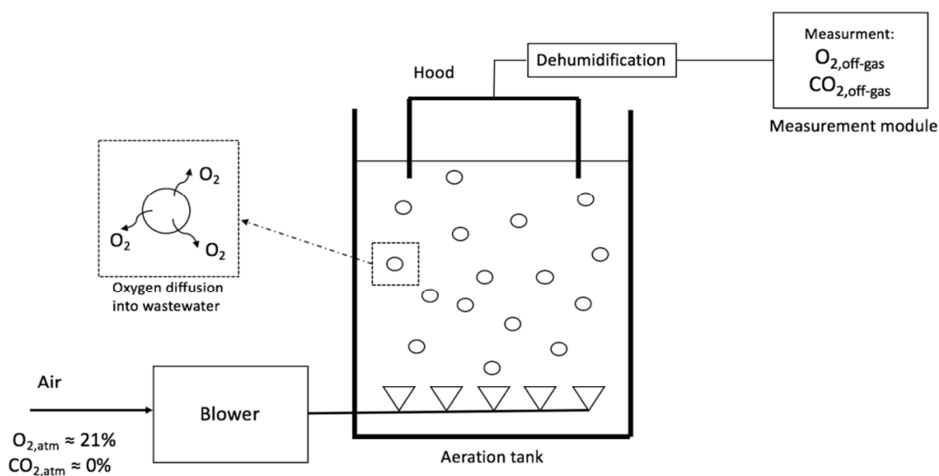


Fig. 1. Schematic diagram of oxygen transfer efficiency measurement using the off-gas method

Materials and methods

Description of the off-gas apparatus

Because solutions for off-gas measurement apparatus are commercially unavailable, the team from Wrocław University of Science and Technology developed a series of measurement instruments in accordance with the guidelines provided by literature [2, 3]. The presented tests were performed with the third, upgraded development version of the apparatus (both the hood and the measurement module). This version did not contain some design flaws identified in previous measurements that could have some impact on the results. Figure 2 shows the hood and the measurement module used during the tests described in this paper.

The hood used in the apparatus had the area of 2 m² and its design allowed it to float on the surface of wastewater. During tests, the hood was fastened with ropes to prevent its

movement on the reactor surface. The measurement module comprised a Testo 6641 flowmeter, which monitored the stream of off-gas air flow captured by the hood. The installation further comprised 2 sorption columns in which the analysed air was dried and the CO_2 in it was bound. The last stage comprised an oxygen concentration analyser in the form of an AMI 65/ O_2 zirconium probe. Furthermore, Hach LDO[®] dissolved oxygen probes were located at suitable depths directly below the hood. The measurement error was calculated using total differential method on the basis of the data which were available on the accuracy of the equipment used. Apart from the earlier described parameters, measurement uncertainty in the off-gas method was calculated including measurement uncertainty for sewage depth and temperature. The calculated measurement uncertainty is $0.9 \text{ g O}_2 \cdot \text{Nm}^{-3} \cdot \text{m}_{\text{depth}}^{-1}$ and corresponds to a few percent of the measured value [20].

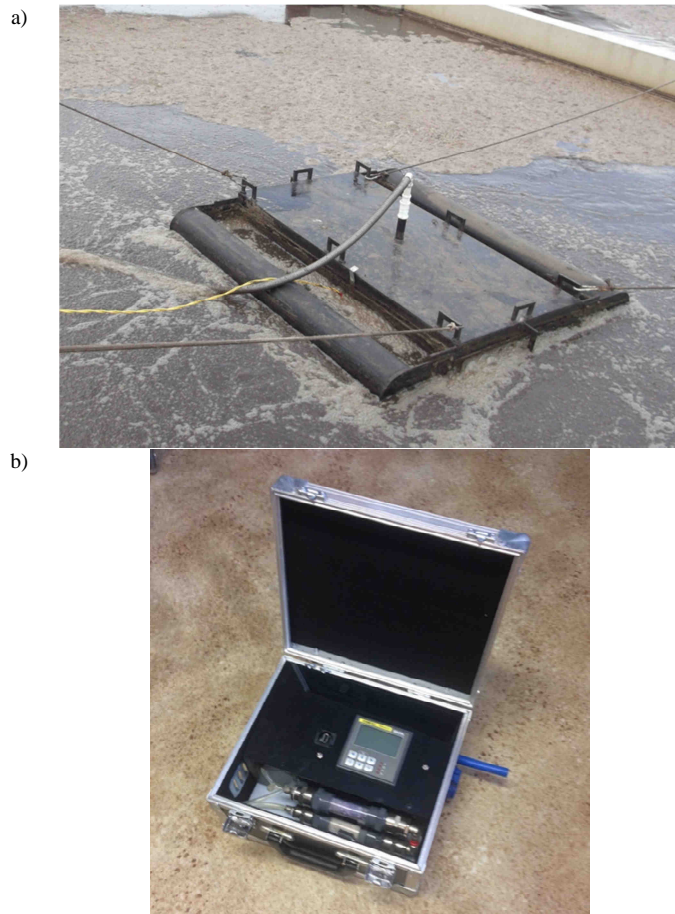


Fig. 2. Measurement hood (a) and measurement module (b) [20]

WWTP description

The tests were performed in one of Polish municipal wastewater treatment plants with population equivalent PE > 100 000. The sewage process line comprises 2 identical technological lines equipped with identical aerated CSTR bioreactors (BR I and BR II). Each chamber's volume is 6905 m³ and the total area of the diffuser section in the chamber is 564 m². The tests were performed during normal, stable operation of the facility.

The measurement methodology

Prior to measurements, a virtual grid is established on the surface of the reactor to facilitate finding the coordinates of the measurement points. In the next step, a number of points (usually between ten and twenty measurements for aeration tanks) are randomly selected that will ensure reliable results for oxygen transfer efficiency measurement, i.e. a minimum of 2% coverage of the tank area. In this case, 24 measurements were performed in Biological Reactor I (BR I) and 33 measurements were performed in BR II, which translates into the coverage of 8.8 and 12.0% of the area of each of the tanks, respectively. Single measurement lasts for about 30 minutes, and after that time the apparatus is moved to the next point, according to the schedule. The data collected using this method allow finding spatial variation of oxygen transfer efficiency for the analyzed reactor. Due to the significant impact of time variation of oxygen transfer efficiency, all results were standardized against the parallel measurements of this variation performed with an identical apparatus with the hood secured in one measurement point.

Data preparation

The results gathered with the off-gas method were used to prepare an MS Excel spreadsheet that allows the user to randomly choose (sample) a selected value number from the set of oxygen transfer efficiency results for each chamber as in Monte Carlo method. The number of the results for each sampling corresponds to the selected percentage of the tank area with the hood area of 2 m². The sampling was performed for the numbers of measurement points that correspond to the tank area between 4 points (1.3% of the area) and 20 points (6.7% of the area) with an interval of 2 measurement points. The set of values that was obtained after each sampling served to calculate the average oxygen transfer efficiency in the reactor. This value was then recorded. After 30 sampling rounds were performed, the recorded data served to calculate the average for each variant, which was presented with maximum and minimum values and standard deviation for the created set. Each chamber was also described with a histogram that presented the accuracy of the results with 2% coverage of the tank area.

Results

Biological Reactor I (BR I)

Table 1 shows the results obtained from a simulation performed for the set of real measurement results of oxygen transfer efficiency in Biological Reactor I (BR I) that was tested in accordance with the methodology here presented. Figure 3 shows a histogram of

average α FSOTE values obtained from 6 randomly selected measurement points (2.0% of the tank area).

Table 1

Simulation results for BR I

BR I						
-	Number of measurement points	Tank coverage area	Average avSOTE [g O ₂ ·Nm ⁻³ ·m _{depth} ⁻¹]	Standard deviation	Max avSOTE [g O ₂ ·Nm ⁻³ ·m _{depth} ⁻¹]	Min avSOTE [g O ₂ ·Nm ⁻³ ·m _{depth} ⁻¹]
Variant	4	1.3%	20.71	1.45	24.60	18.60
	6	2.0%	20.44	1.44	23.20	17.80
	8	2.7%	20.95	0.80	23.20	19.70
	10	3.3%	20.54	0.82	22.60	19.30
	12	4.0%	20.5	0.67	21.90	19.10
	14	4.7%	20.56	0.56	21.30	19.40
	16	5.3%	20.30	0.46	21.20	19.50
	18	6.0%	20.58	0.35	21.10	19.60
Measurement results	20	6.7%	20.54	0.30	21.00	19.70
	24	8.8%	20.50	-	-	-

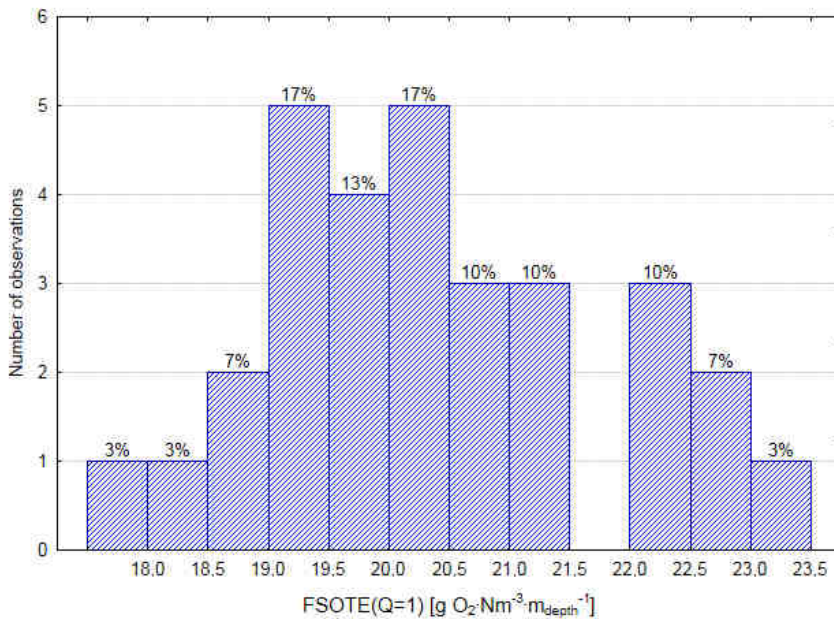


Fig. 3. Histogram of average α FSOTE for BR I with 2% hood coverage of the tank, obtained by randomly selecting measurement points

Biological Reactor II (BR II)

Table 2 shows the results obtained from a simulation performed for Biological Reactor II that was tested in accordance with the methodology here presented.

Table 2

Simulation results for BR II

BR II						
-	Number of measurement points	Tank coverage area	Average avSOTE [g O ₂ ·Nm ⁻³ ·m ⁻¹ _{depth}]	Standard deviation	Max avSOTE [g O ₂ ·Nm ⁻³ ·m ⁻¹ _{depth}]	Min avSOTE [g O ₂ ·Nm ⁻³ ·m ⁻¹ _{depth}]
Variant	4	1.3%	16.71	1.34	19.60	14.50
	6	2.0%	16.71	1.02	18.40	14.60
	8	2.7%	16.89	1.23	19.00	15.00
	10	3.3%	16.66	0.90	18.90	14.90
	12	4.0%	16.96	0.70	18.00	15.60
	14	4.7%	16.66	0.51	17.50	15.20
	16	5.3%	16.87	0.55	18.10	15.60
	18	6.0%	16.92	0.63	18.60	15.90
20	6.7%	16.89	0.37	17.70	16.20	
Measurement results	33	12.0%	16.8	-	-	-

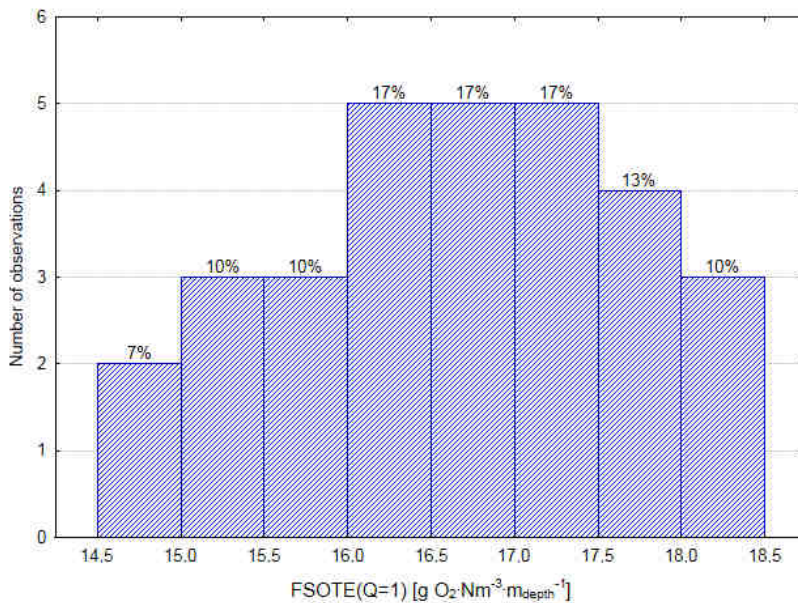


Fig. 4. Histogram of average αFSOTE for BR II with 2% hood coverage of the tank, obtained by randomly selecting the measurement points

Figure 4 shows a histogram of average α FSOTE values obtained from 6 randomly selected measurement points (i.e. 2.0% of the tank area).

Results

The results of the simulation performed for both biological reactors in the analyzed WWTP indicate that covering only 2% of the tank area with the measurement hood may be insufficient. Hood coverage according to the recommendations of EPA and ATV standards was already achieved after measurements performed in just 6 points of the reactor. Such a limited number of measurement points increases the significance of spatial variation in the reactor, thus introducing error to the average oxygen transfer efficiency values for the tested aeration tank.

In the case of BR I, the difference between α FSOTE value for 2% coverage and for 8.8% coverage may reach up to 15% and the number of simulations leading to such differences exceeds 10% of gained results. The percentage of the area covered with the hood during tests performed in accordance with the current recommendations entails low probability of obtaining accurate results - about 50% (with $\pm 1 \text{ g O}_2 \cdot \text{Nm}^{-3} \cdot \text{m}_{\text{depth}}^{-1}$ error).

Similar results were also observed in the case of simulations performed for the results from OTE measurements in BR II. Maximal discrepancies between the obtained values reached about 15% of the real value. As in the case of BR I in the same WWTP, the spread of values with 2% hood coverage of the tank area allows a conclusion that the currently recommended degree of tank coverage is not sufficient, and leads to low probability of obtaining accurate results at about 64% (with $\pm 1 \text{ g O}_2 \cdot \text{Nm}^{-3} \cdot \text{m}_{\text{depth}}^{-1}$ error).

Conclusions

In Poland, off-gas measurements are a novel method for diagnosing the condition of aeration systems in wastewater treatment. Insufficient number of national publications and a limited number of international ones results in imperfect methodology for both the measurements and the results analysis. The above analysis allows the formulation of the following conclusions:

- the value provided by the measurement methodology described in ATV209E and referred to as the minimum percentage of the tank area covered by the measurement points is insufficient to obtain reliable results of the average oxygen transfer efficiency in the tested aeration tank,
- the minimum coverage area with the measurement hood needs further verification for plug-flow reactors.

The conclusions from the analysis here presented will serve as the basis for an attempt at revising the methodology of oxygen transfer efficiency measurements using the off-gas method and at improving the accuracy of the results.

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POMIAR SPRAWNOŚCI TRANSFERU TLENU METODĄ OFF-GAS - PROBLEM STOPNIA POKRYCIA REAKTORA

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Abstrakt: Pomiary off-gas są jedną z dwóch dostępnych metod określenia stopnia wykorzystania tlenu w systemach napowietrzania oczyszczalni ścieków. Największą zaletą prezentowanej metody jest możliwość prowadzenia pomiarów w warunkach procesowych bez ingerencji w funkcjonowanie układu oczyszczania ścieków. Na podstawie danych zebranych podczas pomiarów wykonanych na jednej z komunalnych oczyszczalni ścieków w Polsce przeprowadzono analizę wpływu ilości punktów pomiarowych na uzyskiwane wartości stopnia wykorzystania tlenu. Analizę przeprowadzono, wykorzystując wyniki uzyskane z pomiarów zapewniających dużo wyższe pokrycie powierzchni reaktora (odpowiednio 12 i 8,8%) względem wytycznych literaturowych mówiących o 2% stopniu pokrycia reaktora.

Słowa kluczowe: oczyszczanie ścieków, napowietrzanie, stopień wykorzystania tlenu, metoda off-gas