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Theoretical efficiency of the pulverising aerator – A case study based on Lake Swarzędzkie

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Abstract: Lakes can be restored by the aeration method with the use of wind driven pulverising aerators. The method allows for moderate oxygenation of hypolimnion waters and it may be part of an integrated surface waters restoration system. The paper attempts to use the author's method of maximum wind speeds to assess the volumetric flow of water through the aerator pulverisation mechanism. The study was conducted in 2018 in windy conditions of Lake Swarzędzkie. The introduction to the paper includes the characteristic of the lake and discusses the construction and operation of the wind driven pulverising aerator. Based on the maximum wind speed model, the theoretical capacity of the machine was calculated, which in the conditions of Lake Swarzędzkie was less than 111,500 m^3 per year. Based on maximum wind speeds, the method of assessing the efficiency of the wind driven pulverising aerator is suitable for determining the volumetric flow rate of the pulverisation unit. This can significantly facilitate the planning of water reservoir restoration.

Keywords: lake aeration, Lake Swarzędzkie, pulverising aerators, wind energy

INTRODUCTION

The life of every organism on the Earth depends on the availability of water (Tong *et al.*, 2014; Wang and Ma, 2016). In the past, access to it was unlimited, despite the fact that it is considered an indisputable right of human to use natural resources (Monchamp *et al.*, 2014; Kuyuk *et al.*, 2019; Skoczkowski, Bielecki and Wojtyńska, 2019). In Poland, the use of water resources is regulated by the Water Law (Prawo wodne, 2017). Water use restrictions are imposed to protect water reserves against pollution and depletion (Kowalczewska-Madura *et al.*, 2018). The amount of water on the Earth is constant and estimated at $1.377 \cdot 10^6$ km^3. However, the vast majority of it is salt water. Fresh water available to human amounts to less than 1% of all resources (Żurek, 2008; Kowal and Świderska-Bróż, 2009). The depleting resources of fresh water are not the only significant problem of the modern world. Another important problem that remains unsolved is the deterioration of water quality. The main causes of water pollution include uncontrolled sewage discharges, fertilisers and plant protection product runoff from agricultural areas (Osuch *et al.*, 2017).

Many lakes in Poland and in the world have reached the poor level of water quality. Cutting off or reducing the inflow of pollutants into reservoirs is not enough to achieve significant improvement in their quality (Chen *et al.*, 2014; Ilnicki, 2014; Osuch *et al.*, 2016; Ajeagah, Abanda and Nkeng, 2017; Ferral *et al.*, 2017; Singh *et al.*, 2018). In many cases, the level of aquatic ecosystems degradation prevents self-purification (Sadecka and Waś, 2008; Gromiec and Gromiec, 2010; Dervaux, Mejean and Brunet, 2015; Xiao *et al.*, 2019). Therefore, it is necessary to implement appropriate restoration and protection methods. These include biological, chemical and mechanical methods. All of them can be implemented in the restored reservoir basin. The main purpose of the methods is to bring the quality of water to the level that allows proper functioning of an aquatic ecosystem. The goal is to improve the quality of water as soon as possible with the use of environmentally sound methods. The choice of an appropriate method or methods depends on many factors characteristic for a given water area. Each aquatic ecosystem can be characterised by various factors that cause pollution (Dondajewska *et al.*, 2019). Thus, it is necessary to conduct water and bottom sediment quality tests.

One of the methods of mechanical lake restoration is the moderate oxygenation of hypolimnion waters with the use of wind driven pulverising aerators (Photo 1).

Photo 1. Wind driven pulverising aerator located on Lake Swarzędzkie (phot.: *A. Osuch*)

This technology was developed by Prof. Stanisław Podsiadłowski from the Institute of Agricultural Engineering at the Agricultural University of Poznan (currently the Institute of Biosystems Engineering at the University of Life Sciences in Poznan). The wind driven pulverising aerators are fully mechanical and resistant to pollution deposited in the overlying area. The aerator is divided into two pulverising chambers which operate on the basis of communicating vessels. Each chamber has three spigots with suction and pressure ducts connected to them. The paddle wheel (pulverising one), which is the main working mechanism, is driven by a rotating motor through a bevel gear and a belt transmission system (Podsiadłowski, 2007; Podsiadłowski, 2008; Konieczny, 2013). A major threat to the good condition of surface waters is their insufficient oxygenation. Under anaerobic conditions, the oxidation-reduction potential decreases, and the decomposition of organic matter accumulated at the bottom of the reservoir is accompanied by the release of harmful gases, such as methane, hydrogen sulphide, carbon dioxide or ammonia. The reservoir is internally supplied mainly with phosphorus, which in turn promotes eutrophication of water. Restoration of proper oxygen conditions can be achieved by artificial aeration (Buśko, Gałczyńska and Milke, 2019). The aerator discharging harmful gases from anaerobic decomposition of organic matter and oxygenation of hypolimnion waters is propelled by wind power only, which is considered to be one of the cleanest energy sources available on Earth. The device allows to maintain oxygen conditions in the bottom area in the range of 0–1 mg $O_2 \cdot dm^{-3}$. There are also other technical solutions to aerate bottom waters. These include forcing compressed air to the bottom of a lake. Solutions of this type require much energy, which significantly reduces their efficiency. Moderate oxygenation of pulverising aerator transfers the place of bottom water oxygenation to the surface, which significantly reduces energy demand. The advantage of moderate oxygenation over the intensive one is that it limits mineralisation of organic matter in bottom sediments and maintains a positive redox potential at the sediment-water interface. This allows phosphorus retention and enables nitrification and denitrification processes, which result in the removal of nitrogen and its discharge to the atmosphere. It also promotes the anammox process and in result ammonium nitrogen is oxidised into N_2 (Sadecka and Waś, 2008). The wind drive can operate at wind speed as low as 2 $m \cdot s^{-1}$ (Gałczyńska and Buśko, 2016). Aeration and oxygenation replace harmful gases with oxygen (Osuch *et al.*, 2020a; Osuch *et al.*, 2020b). Then, water can be completely saturated with oxygen. Figure 1 shows the operation of the pulverising aerator mechanism.

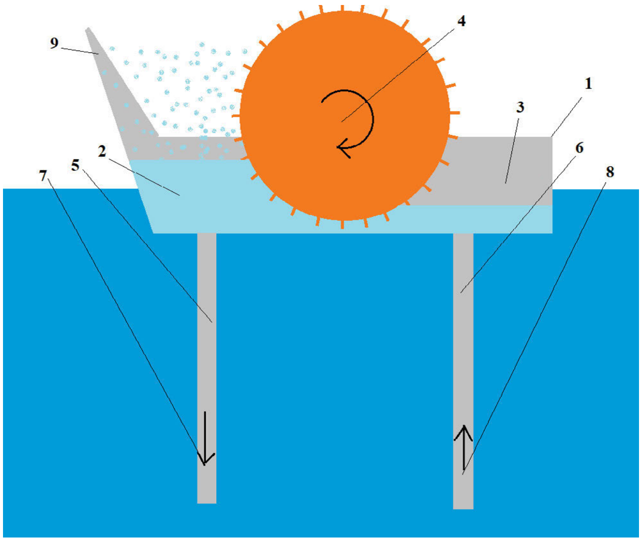

Fig. 1. Pulverising aerator unit: *1* = pulverising segment, *2* = pumping (pulverising) chamber, *3* = water intake chamber, *4* = paddle (splash) wheel, *5* = pulverising chamber spigot, *6* = water intake chamber spigot, *7* = discharge hose, *8* = inflow hose, *9* = splash plate; source: own elaboration

Lake Swarzędzkie (52°24'49" N, 17°03'54" E) is a flow lake of 93.7 ha. In administrative terms, it is located in the northern part of the city of Swarzędz in the Wielkopolskie Voivodeship. It is located in the Natura 2000 area (Cybina Valley) of the Wrzesińska Plain. The maximum depth of this postglacial reservoir is 7.2 m. Two watercourses, Cybina and Mielcuch, flow into the reservoir. The waters of both tributaries are significantly polluted with biogenic substances (Rosińska *et al.*, 2017). Until 1991, all sewage in the area was discharged directly to the reservoir. This eliminated underwater macrophytes and promoted the development of cyanobacteria. In consequence, recreational use of the lake was prohibited (Kowalczewska-Madura and Gołdyn, 2006). In 2011, steps were taken to improve the quality of lake water and reverse eutrophication processes. During the restoration process, three methods were used simultaneously: inactivation of phosphorus in the water column, oxygenation of overlying waters, and biomanipulation. The condition of the reservoir significantly improved in the following years. Currently, the restoration of Lake Swarzędzkie is limited to pulverisation aeration only, which resulted in a drastic deterioration of ecological conditions of the reservoir.

MATERIAL AND METHODS

The aim of the paper was to determine the volumetric flow rate in the wind driven pulverising aerator based on its technical parameters and data regarding maximum wind speeds in the period analysed. The efficiency of the pulverisation unit was determined based on the operation of the aerator in 2018. The tests were conducted in windy conditions on Lake Swarzędzkie. Then, according to Equation (1), the theoretical volumetric flow rate of the pulverisation unit was determined per one rotation of the paddle wheel.

$$Q_r = O_c \cdot P_v \tag{1}$$

where: Q_r = theoretical efficiency of one pulverising wheel rotation (m^3), O_c = pulverisation wheel circumference (m), P_v = area of the pulverisation wheel blade (m^2).

According to Equation (2), the ratio of the wind turbine bevel gear to the aerator pulverisation unit was determined.

$$i_g = \frac{r_{wt}}{r_c} \tag{2}$$

where: i_g = pulverising aerator bevel gear ratio, r_{wt} = wind turbine speed ($\text{rev}\cdot\text{min}^{-1}$), r_c = pulverisation wheel rotation speed ($\text{rev}\cdot\text{min}^{-1}$).

In the next stage, a rotational speed model of the aerator pulverisation wheel was determined based on the maximum wind speeds (Eq. 3). The model was determined using a professional portable weather station and research conducted in spring and summer of 2018. With the help of the weather station, maximum wind speeds in 1-minute periods were determined by counting the number of revolutions of the aerator wind turbine. The results allowed to determine the linear regression equation in the form of 2nd degree polynomial.

$$v_m = y \tag{3}$$

where: v_m = rotational speed of the pulverisation wheel ($\text{rev}\cdot\text{min}^{-1}$), y = determined linear regression equation.

A professional meteorological station located in the area of Lake Swarzędzkie was used to determine maximum wind speeds for each hour and each day of the month, starting from 1st March and ending on 19th November. This is the period of effective pulverising aerator operation throughout the year. The station saves wind speed data and the exact time of the measurement. During each hour, several dozen measurements are made to determine the maximum wind speed for each hour. For this purpose, Equation (4) was used.

$$v_{\max} = \max(v_{i,j}) \tag{4}$$

where: $v_{\max}$ = maximum wind speed for each hour ($\text{m}\cdot\text{s}^{-1}$), $v_{i,j}$ = successive wind speed values per hour.

After substituting the pulverisation wheel rotational speed v_m with maximum wind speeds for each hour $v_{\max}$ in the linear regression equation and multiplying the value by 60 (1 hour 60 minutes), according to Equation (5), rotational speeds of the pulverisation wheel were obtained for each hour of the period analysed.

$$v_h = 60 v_m \tag{5}$$

where: v_h = rotational speed of the pulverisation wheel ($\text{rev}\cdot\text{h}^{-1}$).

Then, using Equation (6), the theoretical efficiency of the aerator was determined for each hour of the pulverisation period.

$$q = v_h Q_r \tag{6}$$

where: q = theoretical efficiency of the aerator ($\text{m}^3\cdot\text{h}^{-1}$).

In the next step of the work, according to the Equation (7), the theoretical efficiency of the pulverisation mechanism was determined for each day of operation in 2018. The results were presented in monthly record sheets.

$$Q_{t_j} = \sum_{q_{ij}}^{24} q \tag{7}$$

where Q_{t_j} = theoretical volumetric flow rate per one day ($\text{m}^3\cdot\text{day}^{-1}$), q = theoretical volumetric flow rate per one hour of the day, i = hour (1, 2, 3, …, 24), j = day of the month.

The present study also compared theoretical volumetric flow rates of the pulverisation aerator unit for individual months of the year (Eq. 8). The comparison was made by comparing Q_t values with each other.

$$Q_t = \sum Q_{t_j} \tag{8}$$

where: Q_t = theoretical volumetric flow rate for one month ($\text{m}^3\cdot\text{month}^{-1}$).

Summing up the analyses, the theoretical volumetric flow rate was calculated for the entire pulverisation season, in total for all 9 months of pulverising aerator operation. The calculations were made in accordance with Equation (9).

$$Q = \sum Q_t \tag{9}$$

where: Q = theoretical volumetric flow rate for the entire year ($\text{m}^3\cdot\text{y}^{-1}$).

RESULTS AND RESEARCH ANALYSIS

The determination of theoretical efficiency of the pulverisation unit during one rotation of the paddle wheel is based on:
- blade width of 0.07 m,
- blade height of 0.07 m,
- pulverisation wheel diameter of 1.8 m.

Substituting the above values into Equation (1), the theoretical efficiency value of one turn of the pulverisation wheel Q_r in the pulverisation unit is approximately 0.028 m^3.

Using Equation (2), the ratio of the wind turbine bevel gear was determined. According to the measurements, the gear ratio is $i_g = \frac{1}{1}$. This means that the number of counted revolutions of the wind turbine during tests is equal to the number of pulverisation wheel revolutions (excluding efficiency of belt transmissions). Therefore, there is no need to count them.

The determination of the rotational speed model for the aerator pulverisation wheel. The test conducted on the lake using the weather station, based on Equation (3), allowed to develop the linear regression equation. The equation together with results obtained are shown in Figure 2.

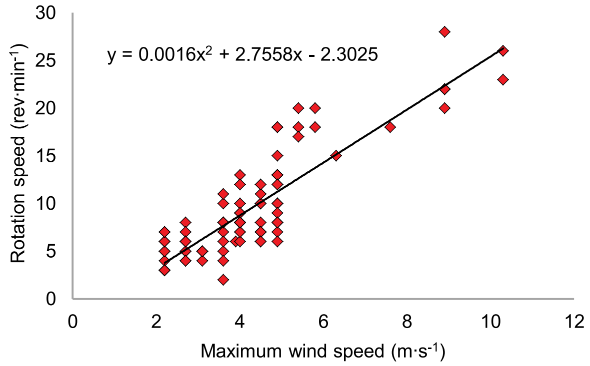

Fig. 2. Rotational speed model for the pulverisation wheel of the aerator in relation to the maximum wind speeds; source: own study

After substituting the massive weather data from the weather station into Equation (4) (tens of thousands of wind speed measurements), maximum wind speeds for each hour of the period were determined. A total of 6600 maximum hourly wind speeds were recorded, respectively in: March – 744, April – 720, May – 744, June – 720, July – 744, August – 744, September – 720, October – 744, and in November – 720.

The values of maximum hourly wind speeds were substituted into the linear regression equation of the model for the rotational speed of the paddle wheel. Then, using the following equations (according to work methodology), the theoretical efficiency of the pulverisation unit was determined for each day of operation in 2018. The results were presented in monthly record sheets (Fig. S1, available at: https://www.jwld.pl/files/Supplementary-material-Osuch.pdf).

Obtained results of the theoretical daily efficiency in monthly records, after their substitution into Equation (8) were compared with each other. As shown in Figure 3, the highest theoretical efficiency per month (exceeding 13,600 m^3) was recorded in July, while the lowest in June (about 11,300 m^3).

Summarising the research and analysis, the theoretical volumetric flow rate for the entire season of the pulverisation operation was calculated based on Equation (9); in total for all

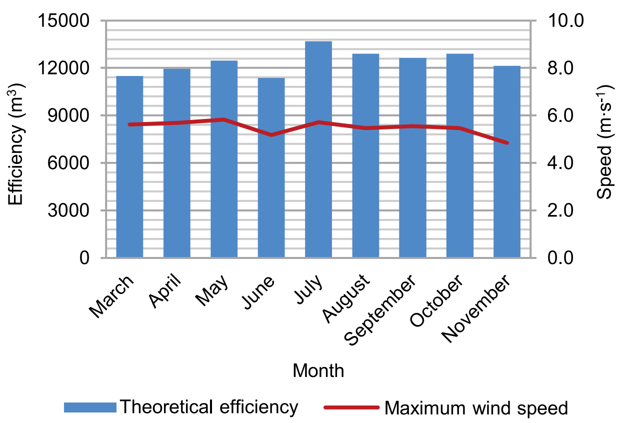

Fig. 3. Theoretical efficiency of the pulverisation unit in 2018; source: own study

9 months of effective operation of the pulverising aerator. The theoretical efficiency of the water flow through the pulverisation unit at Lake Swarzędzkie determined by the maximum wind speeds method in 2018 was over 111,500 m^3.

DISCUSSION

Konieczny (2013) carried out an analysis of operating parameters of pulverisation aeration systems. His aim was to determine nomograms for monitoring aerator operation parameters. The main issue was the monthly operating efficiency of the aerator pulverisation mechanism. The author showed that an increase in the wind speed by one unit ($m \cdot s^{-1}$) corresponds on average to an increase in rotational speed of the pulverisation wheel by an average of 3 $rev \cdot min^{-1}$. Konieczny (2017) highlighted differences in the efficiency depending on the wind conditions on the reservoir, which varied from 5,977.8 to 13,418.4 $m^3 \cdot month^{-1}$. However, the value of the volumetric flow rate according to maximum wind speeds in July, determined under this study, was 13,682.8 $m^3 \cdot month^{-1}$, which exceeded the maximum efficiency estimated by Konieczny.

Podsiadłowski *et al.* (2018) analysed the efficiency of the pulverising aerator on Lake Góreckie. The authors showed that the efficiency of the pulverisation aeration depended on the wind speed. At speeds from 4.2 to 5.2 $m \cdot s^{-1}$, the largest increase in the pulverisation efficiency was noted. This dependency may result from the self-sealing of the paddle wheel, due to higher water volumetric flow rates (Konieczny, 2004). On the other hand, wind speeds above 5.2 $m \cdot s^{-1}$ reduce the aeration efficiency due to the limitation of the volume flow of water through the suction hoses.

Numerous authors indicate, however, an improvement in oxygen conditions in overlying area of waters subjected to pulverisation aeration using wind driven pulverising aerators (Konieczny, 2002; Daniszewski, 2012; Rosińska *et al.*, 2018]. None of the above mentioned studies were based on maximum wind speeds. For this reason, the method presented in this paper seems to be suitable for determining the efficiency of the pulverisation aeration unit in its operating conditions.

CONCLUSIONS

1. As the wind speed increases, the power generated by the wind turbine increases, which significantly increases the efficiency of the pulverisation unit of the aerator.
2. The method of assessing the efficiency based on maximum wind speeds is suitable for determining the volumetric flow rate of the pulverisation unit, which can significantly facilitate planned restoration of water reservoirs.
3. The rotor engine with vertical rotation axis used in the aerator is the only drive for the pulverisation unit, which in connection with even low wind speeds in temperate climate conditions allows to achieve the intended biological effect.

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