Determination of the optimal technological parameters for increasing the oxygen transfer rate of a modified submersible rotating biofilter

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Abstract. The modified submersible rotating biofilter MSRB was developed and patented to improve the efficiency of wastewater treatment in small settlements in Syria by performing structural modifications in the biofilter body without the need for additional aeration elements. 112 experiments were carried out on two types of biomass carriers and, as a result, optimal pairs of technological parameters were obtained to achieve the highest oxygen transfer rate OTR values. The highest values of the OTR when using the first biomass carrier were at the low filling percentage of the drum of 60% and immersion depth of the drum in the liquid 35%, while the highest values of OTR when using the second biomass carrier were at the high filling percentage of the drum 90% and low immersion depth 15%. Comparison of the obtained values of the standard aeration efficiency SAE for the MSRB with the results of similar studies showed that the SAE values of the MSRB increased by 58.29%.

1. Introduction

The method of rotating biological contactors (hereinafter RBC) has been successfully used in various parts of the world for wastewater treatment, in particular in small settlements. However, its applications were not limited to this, as it has been successfully applied for wastewater treatment in medium to large settlements in addition to the treatment of industrial wastewater from various industrial sectors and unique types of wastewater [1], such as removing free cyanide from wastewater of gold mines [2]. In Syria, RBC is considered a method that has a priority for wastewater treatment in small settlements in accordance with the guidelines developed by the Ministry of Water Resources, due to its advantages, such as: relatively small footprint; simplicity in construction and operation, the possibility of industrial manufacturing of the entire structure in site and the electricity consumption which is 3-5 times lower than that of the activated sludge method, etc. [3].

RBC are divided into: disk, drum, tubular, and rotary, the most common of them are disk and drum [1]. However, drum-type RBC have been used as an effective alternative to discs in recent years due to their operational limitations [3; 4]. Although the use of drum filters in recent years has dominated over the other types due to their operational advantages, there are also some negative design factors represented by: represented by the large length of the drum relatively to its diameter; rectangular
supporting walls inside the drum, which prevent regular mixing of the biomass carriers; as well as the restriction of mass transfer between the biomass carriers and the liquid only while the drum is rotating inside the biofilter tank; in addition most of the used biomass carriers have a low specific surface area. All of this leads to a decrease in the OTR of the biofilter and, consequently, the treatment efficiency [3; 5].

Based on the foregoing and to increase the OTR of the biofilter without the need for additional aeration elements, a modified submersible rotating biofilter (hereinafter MSRB) (RF patent No. 2720 150 C1), which is described in detail in the literature [3; 6], was developed and patented. Higher efficiency was achieved by changing the ratio of the drum length to its diameter to 1.5, as well as by creating ventilation gaps in the biofilter body by dividing it into 16 cells. Each cell is filled with a mobile biomass carriers with a large surface area; a rod is installed inside each cell to mix the biomass carriers; along the perimeter of the drum outside on the body there are 16 scoops for lifting and pouring out the purified water during rotation to increase the mass transfer between the liquid and the biomass carriers on one hand and the exchange of oxygen between the liquid and air oxygen on the other hand, which contributes to increasing the OTR and the treatment efficiency.

2. Materials and methods

The article presents the results of determining the optimal technological parameters that contribute to an increase in the OTR of the MSRB, and calculating the standard aeration efficiency (hereinafter SAE).

The pilot plant of the MSRB consists of a drum in the form of two adjacent cylinders, separated by a ventilation gap, drum diameter D = 32 cm and length L = 23 cm. Also, eight ventilation gaps are made diagonally and divide each cylinder into 8 cells. The biofilter frame consists of support rings interconnected by stiffening ribs around the circumference and center. All elements of the biofilter frame are made of acrylic. Drum cylinders and cells are made of plastic mesh (12*12) mm. The biofilter cells are filled with mobile biomass carriers with a large surface area. The first mobile biomass carrier used in the study is XEL-X (HXF13KLL +) which has a cylindrical shape with a diameter of 13 mm and a length of 12 mm, its protected surface area is 806 m$^2$/m$^3$, made from recycled HDPE pellets (black color). The second mobile biomass carrier is XEL-X (HEL-X flake 30) which has a form like biochips with a diameter of 30 mm and a thickness of 1.1 mm, its active surface area is> 5000 m$^2$/m$^3$, made of primary HDPE granules (white color). The drum frame is mounted on a rotation shaft made of aluminum with a diameter of 30 mm. The rotation of the drum is carried out by mechanical motors "G-MOTOR GK44", the rotation of the drum is controlled using an electrical panel, which contains reverse of rotation direction; a potentiometer for speed control; ammeter; voltmeter; an electric meter and an electric switch [3] (figure 1).

![Figure 1. General view of the laboratory pilot plant of the MSRB.](image)
The calculation of the OTR was carried out by the method of unsteady mode of aeration of tap water with the addition of sodium sulfite (Na$_2$SO$_3$), followed by reaeration to the saturation level [7]. Sodium sulfite was added to the water by dissolving it in a separate mixing tank before it was added to the reservoir; after the end of each experiment, the water was completely removed from the reservoir. Oxygen transfer to the water volume is controlled during the re-aeration period by measuring the dissolved oxygen concentration at several points selected to best represent the contents of the reservoir. The data obtained at each point of determination is then analyzed using a simplified mass transfer model to determine the volumetric mass transfer coefficient $k_La$ and the steady-state saturation dissolved oxygen concentration $C^*_\infty$. The mathematical model is given by the formula (1) [3]:

$$C = C^*_\infty - (C^*_\infty - C_0) \exp(-k_La \cdot t)$$

$C$ - dissolved oxygen concentration DO, mg / l;
$C^*_\infty$ - the experimental value of the steady state saturation concentration of DO when the time approaches infinity, mg/l;
$C_0$ - DO concentration at zero time, mg/l;
$k_La$ - experimental value of the volumetric mass transfer coefficient, $t^{-1}$.

The plot of $\ln(C^*_\infty - C)$ versus time has a slope $k_La$ in units of time (min$^{-1}$, hour$^{-1}$ or day$^{-1}$). After the experimental determination of the $k_La$ values and $C^*_\infty$, the OTR (g/m$^3$.h) is calculated by the formula (2):

$$OTR = \frac{\partial C}{\partial t} = k_La(C^*_\infty - C_0)$$

These values are then corrected to standard conditions (formulas (3) and (4)), and the standard oxygen transfer rate SOTR, which is OTR in pure water, when the DO concentration is zero at all points in the volume of water, the water temperature is 20°C, and atmospheric pressure is equal to 1.00 atm (101.3 kPa) is calculated according to the formula (5):

$$k_La_{20} = k_La \cdot \theta^{(20-\tau)}$$

$$C^*_{\infty 20} = C^*_\infty (1/\tau \Omega)$$

$$COC = k_La_{20} \cdot C^*_{\infty 20}$$

$k_La_{20}$ - $k_La$ value corrected for 20°C;
$\theta$ - an empirical temperature correction factor assumed to be 1.024 unless proven to have a different value for the aeration system and tested tank;
$C^*_{\infty 20}$ - steady state DO saturation concentration corrected for 20°C and standard atmospheric pressure 1.00 atm (101.3 kPa);
$\tau$ - temperature correction factor $C^*_u / C^*_{\infty 20}$;
$C^*_u$ - tabular value of dissolved oxygen surface saturation concentration, mg/l, at test temperature, standard total pressure 1.00 atm (101.3 kPa) and relative humidity 100% [8];
$C^*_{\infty 20}$ - tabular value of dissolved oxygen surface saturation concentration, mg/l, at 20°C, a standard total pressure of 1.00 atm (101.3 kPa) and 100% relative humidity [8];
$\Omega$ - pressure correction factor = $P_b / P_s$ for tanks under 20 ft (6.1 m);
$P_b$ - barometric pressure at test site during test, ft$^2$;
$P_s$ - standard barometric pressure of 1.00 atm (101.3 kPa), ft$^2$;
$T$ - water temperature during test, $^\circ$C.

Determination of the SOTR allows one to determine the standard aeration efficiency SAE which is SOTR per unit of total power consumption [8]. This parameter is usually expressed in units of pounds per hour horsepower or kilograms per kilowatt-hour and is obtained by the formula (6) [7]:

$$CEA = \frac{k_La_{20} \cdot C^*_{\infty 20}}{\tau \Omega}$$
In this study, the following variable parameters are used: the drum filling percentage with biomass carriers (60, 75, 90)%; rotation speed (1, 5, 10, 15) rpm, depth of drum body immersion in liquid (15, 25, 35, 45)%, 2 types of biomass carriers. A series of 112 experiments was carried out on each biomass carrier to determine the optimal technological parameters of the MSRB to increase the OTR.

3. Results

MSRB operating mode was compiled to achieve the best values of the OTR for each of the drum filling percentage and the corresponding rotation speed and immersion depth. Tables 1 and 2 show the matrix of the optimal operation conditions of the MSRB for the biomass carrier (1) and (2), respectively (The amount of electricity consumed to treat 1 cubic meter of water in the biofilter reservoir).

Table 1. Matrix of optimal technological parameters of the MSRB operating mode using biomass carrier (1).

| No | filling percentage, % | immersion depth, % | rotational speed, rpm | $k_{L,a}20$, min$^{-1}$ | SOTR, g / m$^3$.h | P/V*, W/m$^3$ | SAE, gO2/k W.h | Correlation coefficient, $R^2$ |
|----|-----------------------|---------------------|-----------------------|-----------------------------|-------------------|----------------|----------------|-----------------|
| 1  | 60                    | 15                  | 1                     | 0.2167                      | 75.96             | 552            | 137.6          | 0.9973          |
| 2  | 60                    | 25                  | 5                     | 0.4549                      | 200.63            | 557.14         | 360.11         | 0.9974          |
| 3  | 60                    | 35                  | 10                    | 0.7677                      | 326.22            | 728            | 448.1          | 0.9986          |
| 4  | 60                    | 35                  | 15                    | 0.881                       | 409.0             | 1050           | 389.53         | 0.999           |
| 5  | 75                    | 25                  | 1                     | 0.1874                      | 75.16             | 597.86         | 125.72         | 0.9904          |
| 6  | 75                    | 15                  | 5                     | 0.4558                      | 185.28            | 720            | 257.34         | 0.9954          |
| 7  | 75                    | 35                  | 10                    | 0.6487                      | 282.65            | 751.67         | 376.03         | 0.9985          |
| 8  | 75                    | 35                  | 15                    | 0.7227                      | 326.2             | 1081           | 301.76         | 0.9948          |
| 9  | 90                    | 25                  | 1                     | 0.196                       | 71.57             | 604.29         | 118.44         | 0.9957          |
| 10 | 90                    | 35                  | 5                     | 0.5694                      | 236.94            | 606.67         | 390.55         | 0.9994          |
| 11 | 90                    | 35                  | 10                    | 0.6612                      | 285.74            | 779            | 366.81         | 0.9999          |
| 12 | 90                    | 35                  | 15                    | 0.793                       | 331.43            | 1143.33        | 289.88         | 0.9985          |

4. Discussion

Tables 1 and 2 show the results of the optimal pairs of technological parameters studied in this work, which allow achieving the highest values of the OTR of the MSRB. Comparing the indicators of the tables, we find that the second material (2) achieved a higher value of the OTR and the volumetric mass transfer coefficient $k_{L,a}20$, compared to the first material (1). The highest value of the SOTR was 518.95 g / m$^3$.h, and the $k_{L,a}20$ value was 1.1194 min$^{-1}$ with the filling percentage, immersion depth and rotation speed (90%, 15%, 15 rpm). At the same time, the highest value when using the biomass carrier (1) was 409 g / m$^3$.h and a $k_{L,a}20$ value was 0.881 min$^{-1}$ with the filling percentage, immersion depth and rotation speed (60%, 35%, 15 rpm).

It was noted that the pairs combination of optimal technological parameters that reached the highest value of SOTR when using the biomass carrier (1) differed from the pairs combination that reached the highest value when using the biomass carrier (2). Also, we note that the highest values of SOTR when using the biomass carrier (1) were at a low filling percentage 60% and an immersion depth of 35%, while the highest values of SOTR when using the biomass carrier (2) were at a high filling percentage 90% and low immersion depth 15%. From the comparison, we conclude that the optimal pairs of technological parameters for one biomass carrier from the optimal technological pairs for another biomass carrier, when the shape and density of the carrier differ.
Table 2. Matrix of optimal technological parameters of the MSRB operating mode using biomass carrier (2).

| No | filling percentage, % | immersion depth, % | rotational speed, rpm | kL,a20, min⁻¹ | SOTR, g/m³.h | P/V², W/m² | SAE, gO₂/kW.h | Correlation coefficient, R² |
|----|-----------------------|--------------------|-----------------------|----------------|--------------|-------------|---------------|-----------------------------|
| 1  | 60                    | 45                 | 1                     | 0.2413         | 96.95        | 449.29      | 215.78        | 0.9988                      |
| 2  | 60                    | 15                 | 5                     | 0.4758         | 196.68       | 907.5       | 216.73        | 0.9981                      |
| 3  | 60                    | 25                 | 10                    | 0.6398         | 291.52       | 998.21      | 292.04        | 0.9988                      |
| 4  | 60                    | 15                 | 15                    | 0.9155         | 398.42       | 1540        | 258.71        | 0.9993                      |
| 5  | 75                    | 15                 | 1                     | 0.296          | 131.06       | 611         | 214.5         | 0.9993                      |
| 6  | 75                    | 15                 | 5                     | 0.5336         | 236.91       | 790.5       | 299.7         | 0.9997                      |
| 7  | 75                    | 15                 | 10                    | 0.7387         | 322.55       | 1131        | 294.63        | 0.9984                      |
| 8  | 75                    | 25                 | 15                    | 0.9377         | 437.93       | 1217.14     | 359.8         | 0.9989                      |
| 9  | 90                    | 25                 | 1                     | 0.3675         | 140.16       | 564.64      | 249.23        | 0.9976                      |
| 10 | 90                    | 15                 | 5                     | 0.5238         | 231.61       | 867         | 267.14        | 0.999                       |
| 11 | 90                    | 15                 | 10                    | 0.8802         | 402.37       | 1008        | 399.17        | 0.9996                      |
| 12 | 90                    | 15                 | 15                    | 1.1194         | 518.95       | 1267.5      | 409.43        | 0.9985                      |

Since the biomass carrier (1) has a cylindrical shape and a density higher than that of water, it helps to capture oxygen from the air and transfer it into the liquid in the biofilter reservoir and mix it with it due to the process of turbulence, which it causes when it is immersed in the liquid during the drum rotations. Although this effect is more obvious at a low filling percentage, it decreases as the filling percentage increases due to a decrease in the movement freedom of the biomass carrier and hence the degree of turbulence and mixing. At the same time, the opposite happens with the biomass carrier (2), which has a density less than the density of water and since its shape, similar to chips, does not help to capture air oxygen and transfer it, but rather the carriers stack on top of each other as a layer on the liquid surface without immersion in water and mixing it especially at a low filling percentage, and thus the OTR is reduced. The highest SAE value when using biomass carrier (2) reached 409.43 g O₂/kW.h, and when using biomass carrier (1) 448.1 g O₂/kW.h. Comparing the SAE in Tables 1 and 2, it can be seen that the SAE values are higher when using the biomass carrier (1) compared to the biomass carrier (2), i.e. biomass carrier (1) makes a large contribution to the transfer of oxygen from the air to the liquid in the reservoir, in addition to its high contribution to mix water in the reservoir compared to the biomass carrier (2).

Comparing the results of SAE for our MSRB filled with biomass carrier (1) and the results of a study published in 2019 [9] for a modified rotary drum type biofilter filled with carriers type (Kaldnes-3, ZHENGJIE, China) at a filling percentage of 60 %, made of stainless steel mesh (diameter 30 cm, length 40 cm, and pore diameter 15 mm), we find that at an depth immersion depth of 33% and a rotation speed of 12 rpm, the SAE reached 225 g O₂/kW.h, and at a rotation speed of 16 rpm it reached 160 g O₂/kW.h. Under similar technological conditions in our study, we find that when the filling percentage of the drum with biomass carrier (1) is 60% and the immersion depth is 35%, the SAE is 448.1 g O₂/kW.h at a rotation speed of 10 rpm, which is about 49.8% higher compared to the value at a rotation speed of 10 rpm. And at a rotation speed of 15 rpm it is 389.53 g O₂/kW.h, which is about 58.9% higher compared to the value at a rotation speed of 15 rpm. This is due to design modifications made to the drum body, which have increased the OTR without the need to consume additional electricity to increase the OTR by increasing the rotational speed or decreasing the immersion depth.

5. Conclusion
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in the biofilter body without the need for additional aeration elements. 112 experiments were carried out on two types of biomass carriers and, as a result, optimal pairs of technological parameters were obtained to achieve the highest oxygen transfer rate OTR values. The highest values of the OTR when using the first biomass carrier (1) were at the low filling percentage of the drum of 60% and immersion depth of the drum in the liquid 35%, while the highest values of OTR when using the second biomass carrier (2) were at the high filling percentage of the drum 90% and low immersion depth 15%. Comparison of the obtained values of the standard aeration efficiency SAE for the MSRB with the results of similar studies showed that the SAE values of the MSRB increased by 58.29%.

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