Cost aspects of membrane bioreactors for wastewater treatment

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Abstract. There is a tendency of more and more intensive annual growth of popularity of membrane process reactor technology. Membrane bioreactors (MBRs) have become serious competitors to other methods on the part of the quality of water cleaning. This is the new and perspective technology; however it is still rather expensive, although not so complicated to operate it. The choice of such a technology demands taking into account all its advantages and disadvantages. Nowadays customers are able to choose between different varieties of configurations of MBRs, smart choice of which may provide economic efficiency.

1. Introduction
One of the most advanced and dynamically developing technologies in the field of wastewater treatment is the technology of a membrane biological reactor (MBR). Membrane bioreactors combine the processes of microfiltration and ultrafiltration with traditional biological purification of active silt. As it follows from the very name of the technology, the main elements of MBR are membranes, which serve as a powerful barrier against viruses and bacteria, resulting in a high degree of purification.

At the moment two main types of MBRs are distinguished:
• Immersion membrane bioreactor – with this configuration, the membrane module is immersed in the aerotank and filtration is provided by the influence of a vacuum. In the aeration tank the mixture in the form of activated sludge and waste water is filtered through the surface of the membranes, after what the purified water is removed from the aeration tank, and the active sludge and the delayed substances are suspended. Immersion MBRs are compulsorily equipped with aeration systems.
• External membrane bioreactor – in this version of the technological design, the membrane module is placed outside the aeration tank and carries the functions of the secondary settler and post-treatment systems and does not participate in the biological treatment itself. A mixture of activated sludge and waste water is diverted to an external membrane module, which is represented by a set of tubular membranes through which this mixture passes.

2. Materials and methods
The membrane module, as well as the type of membrane, in its turn, is the main pricing factor of MBR. Currently, there are 2 types of membrane modules used in MBR: external (pressure) and submersible. Each of them from the economic and operational point of view has both its advantages and disadvantages. Let us consider which of the types of membrane modules can be preferred due to an economic point of view.
According to its design type, the undisputable favorite is the immersive MBR module, since it has a simpler assembly configuration. This parameter is extremely important, as it implies a number of other significant advantages that greatly simplify, as well as reduce the cost of servicing the operated MBR. With a simpler type of construction, such a parameter as the possibility of modernizing the bioreactor is substantially increased, and at the same time the labor intensity demanded for the service of the aggregate is reduced. All these factors positively affect both the initial cost of ICBMs and the depreciation costs that are unavoidable during the operation of equipment.

Of course, the gain in simplicity of design entails certain costs. In this case, this is the specific productivity of the membrane bioreactor. For pressure MBRs this indicator is several times higher (3–4 times). Usually it amounts about 40–100 l/m² * h, while for immersive membrane modules of bioreactors it does not exceed 10–30 l/m² * h. Loss in performance can be a serious drawback if such parameter, as the volume of filtered water per unit of time is highly important. Moreover, it is critical in cases with large volumes of wastewater that require urgent filtration. However, in some cases, when the time for which the filtration is performed is not so important, it can be neglected.

Pressure and immersive MBR modules also differ in methods of reducing membrane contamination. In pressure MBR are used special technology Cross Flow (what means transverse flow), air flushing, backwashing and chemical cleaning, whereas in immersive modules air mixing, backwashing and chemical cleaning are practiced. However, we should mention that reverse flushing is not always possible due to design parameters, which makes the immersive MBR modules less universal.

It should also be added that by virtue of the simpler design of the immersive modules of membrane bioreactors, it is possible to achieve a higher packing density of membranes in comparison with pressure modules. In the case of pressure MBRs, it is rather low and amounts to only 50–200 m²/m³, while in submerged bioreactors this parameter is brought to 600 m²/m³, what is from 3 to 12 times higher. Unfortunately, such a huge gap in packing density of membranes partially causes the loss of immersive MBRs before the pressure ones in specific productivity.

On the other hand, simplicity of design and low specific productivity allow to reduce energy consumption, which plays an important role in the long-term commercial operation of membrane bioreactors. The consumption of power by pressure modules of MBRs exceeds 0.5 kW*h/m³, while the operation of immersive bioreactors requires no more than 0.2–4.4 kW*h/m³.

Based on the parameters discussed above, we can draw a preliminary conclusion about the economic expediency of each particular system. After comparing the characteristics of pressure and immersive modules of membrane bioreactors, we come to the conclusion that the installation and subsequent operation of immersive MBRs is much less costly both in terms of mounting and in terms of use. Of course, in cases requiring high specific power, it is necessary to use MBRs of pressure type. Particularly, for servicing large urban settlements and municipal centers.

In membrane modules are used different types of membranes. It can be hollow fibers, flat or tubular, each of which are installed depending on the quality of the contaminated water and the economic efficiency. These membranes are made of a polymeric material, but in individual cases, tubular sheath may consist of ceramics.

The hollow fiber membranes surpasses their competitors in terms of fiber packing density, which directly affects the quality of the water being purified. Their density differs between 300 m²/m³ and 600 m²/m³, which is much higher than the density of flat (50–150 m²/m³) and tubular (<300 m²/m³) membranes. It is also worth mentioning that the hollow fiber membranes are the leaders not only in this parameter, but also in terms of the material consumption, which will influence the increase or decrease in the cost of the construction.

Another important characteristic of membranes is their specific productivity. The more water with a suspension can pass through membrane fibers, while passing a benign cleaning, the more efficient the structure will work, and therefore, save resources. In this issue, flat grids will undoubtedly be dominant with their high specific productivity, leaving hollow fiber and tubular membranes far behind.
The membranes have tendency to become clogged by the formation of sediments on them. There is such conception as a "critical flow", what means the highest permissible flow, surplus of which leads to the unacceptably intensive growth of sediment, that becomes a serious obstacle for the normal functioning of the membrane module. It is obvious that all kinds of membranes are clogged with varying intensity. Flat membranes are inclined to becoming clogged faster than any others. This fact indicates that they will demand more frequent cleaning, what will significantly increase the cost of operation, so that the quality of the treated water and the efficiency of cleaning do not decrease. Tubular membranes will be clogged longer than their competitors due to their structure. The hollow fiber membranes in this category occupy an average position, what makes them the most balanced option.

There is an effective way to fight with sludge formation, that historically came from ultrafiltration plants for the purification of natural waters. It is flushing with a return stream of the filtrate, what requires additional energy costs. Usually modules with flat membranes do not allow backwashing, due to possible damage and, Consequently, its further replacement. But with the use of hollow fiber and tubular membranes, hydraulic flushing takes place. Because of it, the membranes will stay at service longer, before they will have to be removed and cleaned. The intervals between backwashes and their duration settle within 10–60 minutes and 15–300 seconds, respectively.

In the course of operation, sooner or later the question of replacing individual membranes due to damage and rupture of the used ones arises. In this issue the hollow fiber membranes are inferior to the tubular and flat membranes, which, if necessary, can be replaced by separate elements, and the structure will be brought back into operation, ensuring high-quality throughput. In the same case, it is absolutely unavoidable to completely change the membrane module, if the damage is critical indeed, but if not, then probably places of fractures will clog up with sludge and the module will continue to function. If we rely on the parameters of the membranes that we have listed above, we can conclude that preference will be given to the hollow fiber membranes, which are used in both pressure and submersible modules due to the advantages of its characteristics. In addition to most of its positive qualities and negative minima, in comparison with other options, hollow fiber membranes have the lowest cost.

While analyzing the available basic parts of the membrane biological reactor, we can conclude that we have 6 different modernizations. By combining the types of membrane modules with membrane types, we can achieve not only effective cleaning, but also economic benefits when taking into account all the weak and strong sides of these technologies.

During the operation of membrane biological reactors, a number of serious problems arise on the grounds of the construction of this technology. Excluding the subtleties of the functioning of the biological treatment itself, we can distinguish the following characteristic problems by priority:

- Contamination of membranes and mesh filters;
- Damage to membranes or severe contamination;
- Failure of communication lines of automation systems;
- Failure of membrane blowing systems;
- Failure of blowers and aerators;
- Contamination of nets or grids;
- Refusal of recycling;
- Failure of auxiliary membrane equipment.

In order to restore the permeability of membranes in the course of operation, treatment with solutions of reagents is carried out, usually with oxidants. In other words, chemical washing takes place. As reagents are generally applied solutions of sodium hypochlorite with a concentration of 0.2–1 % or citric acid with concentrations of 0.2–0.3 %. The frequency of this procedure makes up on average 1 time in a few months, depending on the amount of contamination and the rate of clogging of membranes. As a preventive measure, treatment with sodium hypochlorite solution can be carried out more often. For example, several times a month. The pressure modules are washed by circulating the reagent solution supplied by the pump from a separate tank, when the immersive modules are either
moved to a separate special container or washed right at place. This procedure takes several hours by duration.

In a number of cases where it is not possible to achieve the necessary degree of membrane cleaning from clogging, it becomes necessary to extract membrane blocks for their further mechanical washing with water jets from deposits that have already accumulated on the membrane. Contamination of membranes and mesh filters are the consequences of poor pre-cleaning, what means there is an accumulation of hair, scraps of rags and other fibrous materials on the membrane fibers and in the cavities of the membrane blocks. Considering this fact, it is necessary to provide a quality preliminary cleaning in order to minimize the frequency of membrane contamination, what in other case would lead to a corresponding increase in the cost of their operation.

If the operation of aerators and blowers fails, the process of reducing the permeability of membranes occurs and the precipitate is formed more quickly. Such a problem will not affect the quality of purified water until a certain point, but this will affect energy consumption, because of the need to remove excess sediment. Repair of aerators and blowers is rather expensive and time-consuming.

If we look at the cost of operation in figures, here are the indicators we can observe, during the cost analysis: the capital costs for the construction of a wastewater treatment plant with MBRs range from 475703.4 thousand rubles to 79283.9 thousand rubles (6000–1000 Euros) for 1 m³/day depending on the system's productivity. The cost of the membrane plant itself with all the auxiliary equipment amount 30–60 %, which is an impressive part of the total sum. The cost of membrane blocks varies from 5946.29 thousand rubles to 11892.59 thousand rubles (75–150 euro/m²) with an average specific productivity of 15–30 l/h per 1 m² of membrane area. The cost of treating domestic waste water on membrane modules ranges from 6.34 rubles to 11.89 rubles (0.08 to 0.15 Euros) per 1 m³, and besides, lower values are obtained with the use of hollow fiber modules. Total operating costs amount 19.03–19.85 rubles (0.24–0.25 Euros) per 1 m³.

If we compare the technological scheme with the membrane biological reactor with the traditional technological scheme of wastewater treatment, a number of serious differences will become noticeable, such as cleaning efficiency and economic benefits. Evidently, both of these parameters are inextricably connected with each other. The advantages of a scheme with an MBR over a traditional designed one are determined by such features as:

- Full retention of all suspended solids and microorganisms, and as a result, achievement of the maximum effect of purification from suspended substances, increase of the effect of purification by COD (chemical oxygen demand) and BOD (biochemical oxygen demand), disinfection of purified water without the use of reagents, low sensitivity to fluctuations in flow and quality of source water;
- Minimum residence time of water in the zone of separation of the solid phase;
- Complete retention of microorganisms in the reactor that significantly changes the conditions for auto-selection of microorganisms of activated sludge.

All this can allow to change the parameters of the reactor (aerotank) operation: at high hydraulic loads on the reactor can be increased the age of the activated sludge, including accumulating slowly growing kinds of microorganisms (nitrifying agents, microorganisms, oxidizing bioresistant compounds); we are able to prolong the time of suspension of suspended substances in the reactor until their complete biological destruction; we also have possibility to exclude the influence of sedimentation characteristics of activated sludge on the quality of purified water; and to increase the stability of the system to fluctuations in the concentrations of contaminants in the source water due to good adaptation of biocenoses.

However, if we would pay attention to the economy, we can face a number of problems, caused by the costs at all stages of using the technology with MBR, rather than the traditional technological scheme. Among them are high capital costs, and the specific cost of the membrane units themselves is practically independent from productivity. There is also the problem of inevitable contamination of membranes and consequent subsequent costs, waste for electricity and membrane replacement,
a more complex process control and automation system, the difficulty in providing a sufficient aeration level at high active sludge concentrations specific for MBRs.

In order to graphically see the price difference between the technological scheme with MBR and the traditional technological scheme of wastewater treatment, their technical and economic indicators are demonstrated in Table 1.

**Table 1. Technical and economic indicators are demonstrated**

| Variants of schemes                                | Costs of construction and assembly works (thousands of rubles) |
|----------------------------------------------------|---------------------------------------------------------------|
| **Variant 1:**                                    |                                                                |
| Primary clarifiers, type design 902-2-363.83       | 23190.04                                                      |
| Aerotank-mixer, type design 902-2-211              | 33028.34                                                      |
| Secondary clarifiers, type design 902-2-347        | 15730.82                                                      |
| Filters for post-treatment, type design 902-4-11.84| 27601.56                                                      |
| **Total:**                                         | 99550.77                                                      |
| **Variant 2:**                                    |                                                                |
| Aerotank-mixer, type design 902-2-211              | 10307.34                                                      |
| Submerged Membrane Blocks                          | 88043.48                                                      |
| **Total:**                                         | 98350.82                                                      |

### 3. Results

This assessment of technical and economic characteristics of the possible scheme with MBRs and the traditional scheme of treatment facilities showed that, despite the high cost of MBRs, generally, the total cost of construction of such schemes does not differ from each other (Fig. 1). The savings in the second variant of construction is achieved due to the fact that there is no need to operate additional facilities that differ from one another in technical and technological features. It is also should be mentioned that, with the second option, fewer personnel are required, which contributes to a reduction in payroll payments and social deductions that are quite complicated to calculate. There is a decrease in costs at the stage of capital construction due to a reduction in the construction area, and under the traditional construction scheme, the cost of the land plot reaches 45–50 % of the cost of construction and installation works.

![Figure 1](image_url)

**Figure 1.** A conventional purification scheme (a) and a membrane bioreactor scheme (b)
4. Conclusions
A description of the types of membrane modules and the types of membranes themselves was given, which are the main elements of membrane biological reactors that require proper operation to maintain normal functioning of the system and save on repairment and replacement works of individual parts for prolonging the service life of the equipment.

The emphasis was on the cost of capital construction, the cost of consumables and other consequent elements, and an analysis of possible savings by selecting the necessary configuration of the system was conducted.

During the comparison of the technological scheme with MBRs and the traditional scheme of wastewater treatment the pros and cons of both systems were revealed. We can now conclude that subsequently in terms of economic efficiency both these schemes will be equal to each other and the choice should be made on the basis of the quality of treatment and the individual requirements imposed by treatment facilities.

Acknowledgement
The reported study was funded by The Head Regional Shared Research Facilities of the Moscow State University of Civil Engineering

References
[1] Kulakov A and Makisha N 2017 MATEC Web of Conf. 112 10019
[2] Gogina E and Gulshin I 2016 Procedia Eng. 153 189–94
[3] Ruzhitskaya O and Yantsen O 2016 Int. J. of App. Eng. Res. 11(5) 3496–98
[4] Kuzina O 2016 Matec web of conf. 73 07013
[5] Gulshin I 2017 IOP Conf. Series: Earth and Env. Sci. 90(1) 012198
[6] Pervov A G 2015 Desalin. 368 140–51
[7] Makisha N and Panteleeva I 2017 MATEC Web of Conf. 106 70015
[8] Pervov A G and Andrianov A P 2015 Petrol. Chem. 55(5) 373–88
[9] Volkov A, Kuzina O 2016 Procedia Eng.153 838
[10] Pervov A G, Andrianov A P, Gorbunova T P and Bagdasaryan A S 2015 Petrol. Chem. 55(10) 879–86
[11] Galkina E 2017 Sci. rev. 8 131