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EFFICIENCY OF WASTEWATER TREATMENT IN HYBRID BARBOTAGE REACTORS WITH MOVING BEDS

Barbotage reactors extensively used in various branches of industry and bioengineering have been investigated in numerous studies. Recently the moving bed has become a popular solution in sewage and water treatment processes. Purification and transportation of small amounts of sewage from households and industrial plants is a hydraulic and technological problem for the sewage system and sewage treatment plants. A hybrid barbotage reactor (HBR) may be applied to transport small wastewater volumes while simultaneously aerating sewage. This study was conducted on a prototype hybrid barbotage reactor equipped with a pipe element for sewage circulation and aeration, which was packed with a moving bed to 20% of its volume. Based on the results of measurements, oxidation curves have been plotted and the efficiencies of sewage treatment have been calculated for the reactor aerated in the continuous and intermittent modes. The amount of energy used to treat and transport sewage has been established.

1. INTRODUCTION

Barbotage reactors based on the flow of liquid and gas are extensively used in various branches of industry and bioengineering. A simple and reliable design of reactors facilitates their modification and adaptation to the requirements of specific processes. Treatment and transport of sewage generated by households and industrial facilities, particularly in small towns, continue to be problematic and have not been comprehensively solved. Small wastewater volumes in conventional gravity sewerage systems very often undergo putrefaction, leading to a deterioration of their quality. This increases the costs of their treatment and hurts sewerage infrastructure. Inadequately treated wastewater poses a serious threat to the quality of both surface and underground waters, as

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well as the entire catchment. Modernization of combined sewerage systems and combined small sewage treatment plants is very costly and for small communes constitutes a considerable financial burden. Airlift may be applied to transport small sewage volumes at simultaneous oxidation of sewage. In recent years, the moving bed has become a popular solution both in biological sewage treatment and water treatment.

This study aimed to determine the efficiency of pollutant removal in a prototype hybrid barbotage reactor with a moving bed. A modified airlift design facilitated aeration of reactor contents and transport of pretreated sewage. The discussed hybrid barbotage reactors are combinations of airlift reactors (ALR) and bubble column reactors (BCR). The prototype reactor was used to analyze aeration processes, efficiency, and costs of treatment for small sewage volumes pretreated in a septic tank.

Barbotage reactors are classified into two main categories: bubble column reactors (BCR) and airlift reactors (ALR). These reactors have no moving parts, they are composed of a cylindrical or rectangular tank with a gas distributor at the inlet. The primary difference between the discussed solutions is connected with a special zone of the mixture lift separated by a partition or pipe installed in ALR-type reactors. Depending on the mechanism of their operation and the flow of the medium, ALRs may have different designs. In terms of adopted modifications of the barbotage column system with forced medium circulation, two basic designs are available: a) with internal medium circulation, and b) external medium circulation. In each design variant of ARL reactors, we may distinguish four hydrodynamic zones: lifting, degassing, fall, and bottom [1]. ALRs are considered an alternative to stirred tank reactors (STR), particularly in the case of such numerous bioprocesses as plant and animal cell cultures, but also as a solution to purify streams of contaminated fluids (sewage, exhaust gases) [2–5]. Industrial applications of ALRs have been limited due to a lack of certain data required for their appropriate design, construction, operation, and scaling, as well as reliable models and empirical correlations capable of predicting key operating parameters in various ALR design variants and operating conditions. Many authors have investigated the application of ALRs in sewage treatment as an alternative to conventional systems (a hybrid STR reactor and a bubble column reactor – BCR) [6, 7]. Analyses showed greater efficiency of ALRs in terms of the efficacy of removal for various contaminant types compared to STRs, as well as comparable or superior results compared to BCRs. The main advantages of ALRs are particularly useful in the conventional sewage treatment process, although certain problems may appear during advanced sewage treatment processes. Increased efficiency of sewage treatment is connected with combined technologies (multi-phase ALRs with biofilm carriers, sequential bioreactors, the biofilm system, membrane bioreactors, ultrasound reactors, oxidation ditches, photobioreactors, electrocoagulation/electrochemical systems, etc.) [8, 9].

Hybrid reactors are a technology that applies activated sludge coupled with the moving bed to treat sewage. This modification combines both methods, which greatly enhances their advantages and practically eliminates their drawbacks. In hybrid reactors, biomass is found in two forms: as a biological membrane attached to a carrier and as activated sludge suspended in sewage. Profiles with a large surface area serve as biomass carriers. Studies on hybrid reactors are being conducted in Europe and worldwide, on the pilot plant and commercial scales. Their applications and advantages have been extensively described in numerous publications [10, 11].

As a result of the development of hybrid technologies, various profile shapes have become commercially available as moving bed solutions. They are used in many aerated systems, water treatment stations as well as municipal and industrial sewage treatment plants. Numerous studies have confirmed the high efficiency and reliability of treatment processes using such profiles [12–14]. The main characteristics required for reactor packing materials include large surface area (in m^2/m^3), hydrophobicity, and density of the material used to produce the carrier (to ensure good circulation of the bed) close to the density of the liquid, in which it is found. Profiles constituting the moving bed are made from plastic (PP, PE, PU), less frequently from various types of natural ceramics or highly granulated aggregate. Most such materials have a surface area of 240–1000 m^2/m^3 [15]. The body of literature on the subject includes many publications presenting characteristics of moving beds. Comparative studies on the application and operation of moving beds were conducted, e.g., by Qiqi et al. [16]. At the reactor packing rate below 20% of the reactor volume, the efficiency of oxygen transport and pollutant removal decreases considerably. A lack of resistance to motion results in a faster release of air bubbles to the surface. At the packing rate exceeding 70% of the reactor volume, oxidation is no longer cost-effective due to the high consumption of energy required for mixing and oxidation. Many authors assumed 60–70% of the reactor capacity as an adequate bed packing level. It guarantees complete circulation of profiles inside the reactor, facilitates small bubble aeration, ensures sufficient oxygen retention period, and eliminates bed clogging [15].

Sewage treatment costs are dependent on many factors such as the size of the treatment plant, applied technology, and sewage quality [17, 18]. Removal of 1 kg BOD_5 load from municipal sewage requires 1.9–2.5 kWh, while the treatment of 1 m^3 sewage consumes ca. 0.35–0.45 kWh (at BOD_5 300 mg O_2/dm^3). Masłoń [19] reported that energy consumption depends on the adopted technology: for SBR 4.64 kWh/kg BOD_5 and 1.5 kWh/m^3, the Imhoff tank + biological bed 1.46 kWh/kg BOD_5 and 2.5 kWh/m^3, the hybrid system, activated sludge + biological beds 5.18 kWh/kg BOD_5 and 3.2 kWh/m^3.

Effective removal of nitrogen compounds from sewage requires alternate aerobic and anaerobic conditions. In conventional systems, two reactors with sewage recirculation are required to obtain a similar result. An intermittent solution is provided by a reactor with intermittent aeration cycles operating in the batch or continuous sewage inflow mode. In such a reactor, at specified time intervals, the aerobic and anaerobic phases (up to complete oxygen depletion) alternate, which facilitates nitrification and denitrification in one tank.

2. EXPERIMENTAL

Description of the benchmark test. Current solutions used for holding tank, onsite wastewater treatment plant, sewage systems. Wastewater treatment in a sewage network (pretreated in a septic tank) is a novel solution. Analyses were conducted using hybrid barbotage reactors as equipment to treat sewage coming from households, pretreated in a septic tank. The design allows storage, aeration of wastewater (wastewater treatment); lifting, and transporting them. The device has no advanced controls or mechanical components. The configuration of the hybrid barbotage reactor (D, H, Q_p) was determined based on detailed hydraulic and aeration tests. It is a prototype device for wastewater treatment in a small-diameter sewage network or pre-treated in a septic tank. The hybrid bubble rector has ALR and BCR features. The device was registered in the patent office under the number P.414127.

For this purpose a field reactor installation was constructed at a testing station of the Department of Hydraulic and Sanitary Engineering, Poznań University of Life Sciences based in Tadeuszewo (the Środa Wielkopolska commune), composed of a hybrid reactor and a clarifier-settler. The reactor is fed by pretreated sewage from the sewerage system, to which 8 farms in the village were connected. Effluents were collected from the settling tank chamber of the TURBOJET EP-50 treatment plant, to which sewage from the farms was discharged. Potentially suspended solids were separated on a filter installed at the pressure conduit of the metering pump.

The purpose of this work was to determine the efficiency of removing impurities in a prototype hybrid barbotage reactor with a moving bed. Two modes of operation of the hybrid rector were studied: continuous and intermittent aeration 30/30 min. The following processes were analyzed: aeration, efficiency, and costs of purifying small amounts of wastewater pre-treated in a septic tank in a prototype reactor.

Elements of field model installations and measuring apparatus. Figure 1 presents a diagram of the barbotage reactor used in the experiments. A tank of 1 m^3 in volume was equipped with an airlift with an aeration pipe element of 2 × 15 cm and 2 × 45 cm arm lengths, installed at a height of 84 cm from the bottom. The position of the pipe element was established based on the conducted hydraulic tests [20]. The clarifier-settler tank of 0.2 m^3 was an additional element of the system.

Analyses were conducted in two stages: in the first stage, the reactor was operating with continuous aeration, while in the second one, it was with intermittent aeration – 30-min aeration and 30-min break (Table 1). In the first stage of the study, sewage was fed to the reactor in the continuous mode at the rate of delivery $Q_s = 0.7$ dm^3/min, while in the second stage it was in 24 batches within 24 h (one batch per hour) using a TH-25 metering pump at 40 dm^3 per batch. Within 24 h, a total of 0.974 m^3 sewage was fed to the reactor tank. The hydraulic sewage retention time in the reactor was 24 h.

Inside the reactor, the moving bed amounted to 20% operating volume of the tank. According to the available literature data, it is the minimum recommended volume of bed packing. The rate of air fed to the reactor was constant and amounted to $Q_p = 5.0$ m^3/h. Measuring probes (2, 4, 6) were used to record oxygen concentration, temperature, and level of effluents. Treated effluents were collected for analyses from the sampling point No. 8 at the outlet from the reactor leading to the settling tank. The flow rate Q_{s1} measured using an electromagnetic flowmeter was 5.81 m^3/h.

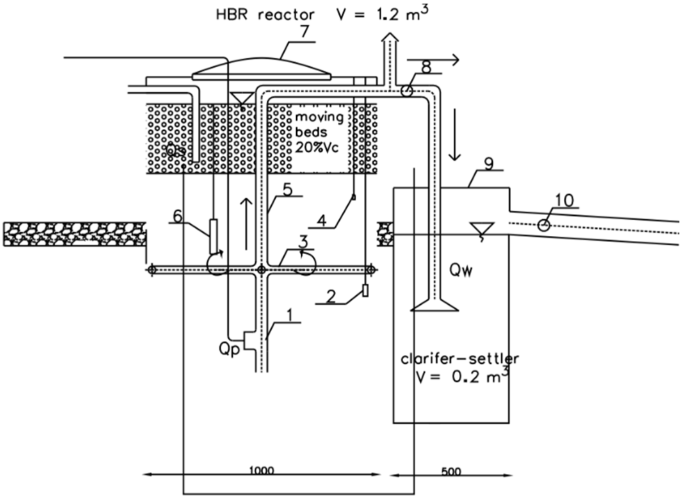

Fig. 1. A diagram of the field model: 1 – diffuser, water-air mixer, 2 – liquid level sensor, 3 – nozzle, 4 – temperature sensor, 5 – airlift with pipe element, 6 – LDO oxygen probe, 7 – reactor cover, 8 – collection point for effluents discharged from the reactor, 9 – clarifier-settler cover, 10 – collection point for effluents discharged from the clarifier-settler, 11 – vent, Q_s – sewage inflow, Q_p – air inflow

Table 1

Operating parameters of the hybrid barbotage reactor

Stage	Q_p	Q_s	HRT	Aeration time	W	Physical measurements	Chemical measurements
1	5 m^3/h	0.7 dm^3/min	1 day	continuous aeration	20%	temperature, level of effluent, pH, redox potential, DO	BOD$_5$, COD, N-NH$_4$, N-NO$_2$, N-NO$_3$, P-PO$_4$, TSS
2		24 × 40 dm^3		intermittent aeration 30/30 min			

The intensity of flow rate for air supplied by a blowing fan to the reactor was measured using a PSM–21 cone and float meter by Tecfluid. An electronic system was also constructed to control the operation of the bioreactor and recorded data from sensors based on a BeagleBone Black microcontroller. The microcontroller at times controlled blowing fan operation time and at times also the rate of delivery of the pump with the regulated rate of sewage delivery to the reactor ranging from 0 to 3.6 dm^3/min. It recorded data from the effluent level gauge and three thermometers.

The recording system by Hach Lange equipped with an LDO probe was installed to measure the concentration of dissolved oxygen in the reactor, pH, and redox potential. Figure 2 shows the plan of the experiment.

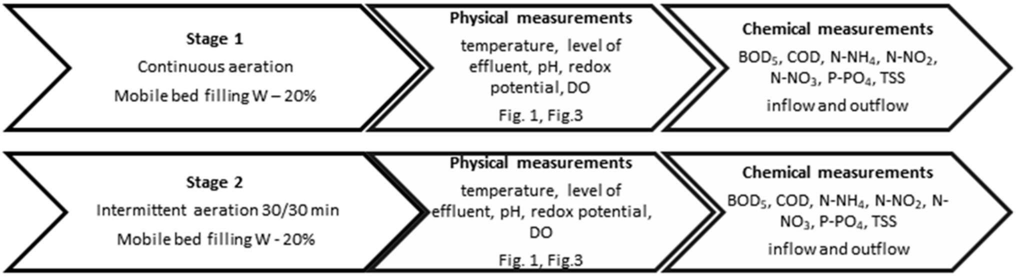

Fig. 2. Plan of the experiment

Measurements and calculations. In the course of field studies, the following parameters were measured:

- external ambient temperature, temperature of influents and within the reactor, °C,
- continuous measurement of effluent level in the reactor, cm,
- pH in influents and effluents in the reactor,
- redox potential in influents and effluent in the reactor, mV,
- dissolved oxygen concentration (DO) in the reactor, mgO_2/dm^3.

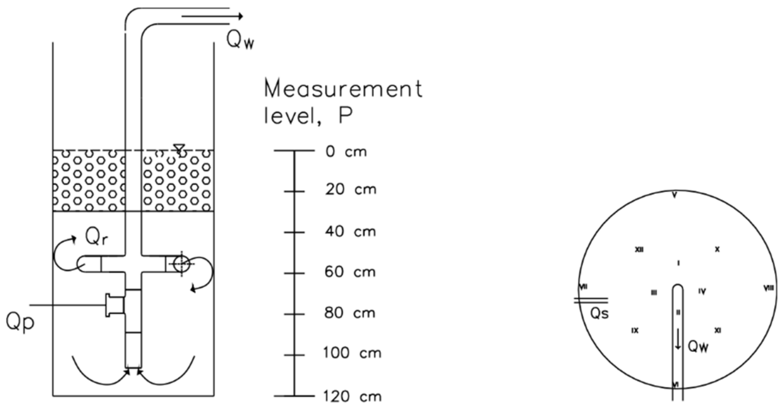

Fig. 3. A diagram for oxygen concentration measurements in the barbotage reactor

In the course of continuous aeration of effluents in the reactor, the concentration of dissolved oxygen was measured as presented in Fig. 3, at twelve measuring points at different depths *P*. During the operation of the reactor with intermittent aeration cycles within the planned 30/30 minute phase cycles, the recording of measurements at twelve points was hindered. For this reason, the oxygen probe was installed at the reactor axis at various depths *P*. Oxygen concentration was recorded every 5 min. Measurements of the above-mentioned parameters were taken using an HQ40d multimeter or a multirecorder.

To monitor the efficacy of pollutant removal in the reactor, the quality of influents and treated effluents leaving the reactor were analyzed. Contents of organic compounds were assayed as BOD_5 and COD, contents of nitrogen compounds were recorded as ammonia nitrogen ($N\text{-}NH_4$), nitrite nitrogen ($N\text{-}NO_2$) and nitrate nitrogen ($N\text{-}NO_3$), while contents of phosphorus compounds were assayed as phosphates ($P\text{-}PO_4$). For this purpose, a spectrophotometer and cuvette tests along with the BOD_5 OXI-TOP measuring system were used. Total suspended solids (TSS) and organic suspended solids were determined by the direct gravimetric method using a drier and a muffle furnace (at 105 and 550 °C, respectively).

To assess the condition of sewage sludge in the reactor a 30-minute sedimentation test was conducted in a cylinder of 1 dm^3. The sewage sludge index IO, cm^3/g, was determined from the formula:

$$IO = \frac{V_{30}}{x_{ZO}} \tag{1}$$

where: V_{30} – sewage sludge volume after 30-minute sedimentation, cm^3/dm^3, x_{ZO} – mean concentration of activated sludge at the test *u*, g/dm^3.

Based on the results concerning the quality of influents and treated effluents, as well as consumption of electric energy, the following aspects were analyzed:

- efficacy of pollutant removal from sewage η,
- biological treatability of sewage based on respective indexes COD/BOD_5, $COD/N\text{-}NH_4$, $BOD_5/N\text{-}NH_4$,
- the effect of ammonia on nitrification [21],

$$S_{\mathrm{NH_3}} = \frac{17}{14} \times \frac{S_{N\text{-}NH_4} 10^{\mathrm{pH}}}{\exp\left(6344/T\right) + 10^{\mathrm{pH}}} \tag{2}$$

where: $S_{N\text{-}NH4}$ – concentration of ammonia nitrogen in sewage, mg/dm^3, pH – value in the reactor, *T* – temperature in the reactor, K.

- The amount of energy consumed to treat 1 kg of the BOD_5 load in the reactor,
- The effect of aeration method on sewage treatment results (analysis of variance).

3. RESULTS

3.1. AEROBIC CONDITIONS

Values of dissolved oxygen concentration – minimum, maximum and mean – as well as redox potential recorded during continuous aeration of the reactor (stage 1) according to the measurement diagram presented in Fig. 3 are given in Table 2. Measurements were taken at the absence of raw sewage inflow in order to eliminate the confounding factor.

Table 2

Dissolved oxygen concentration and redox potential in a barbotage reactor at measurement levels *P* at continuous aeration and sewage inflow

Measurement level *P* [cm]	Dissolved oxygen [mg O_2/dm^3]			Potential red-ox [mV]		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
0	3.5	9.4	6.2	–787.0	399.3	–61.6
20	1.7	8.8	5.8	–707.0	918.0	–67.0
40	2.2	7.7	5.7	–555.4	224.0	–80.4
60	3.1	7.4	5.6	–326.0	220.0	–57.4
80	1.9	7.3	5.5	–202.0	212.0	–41.8
100	1.3	7.2	5.0	–832.0	381.1	–62.1
120	1.1	5.9	2.9	–239.0	224.0	–99.1

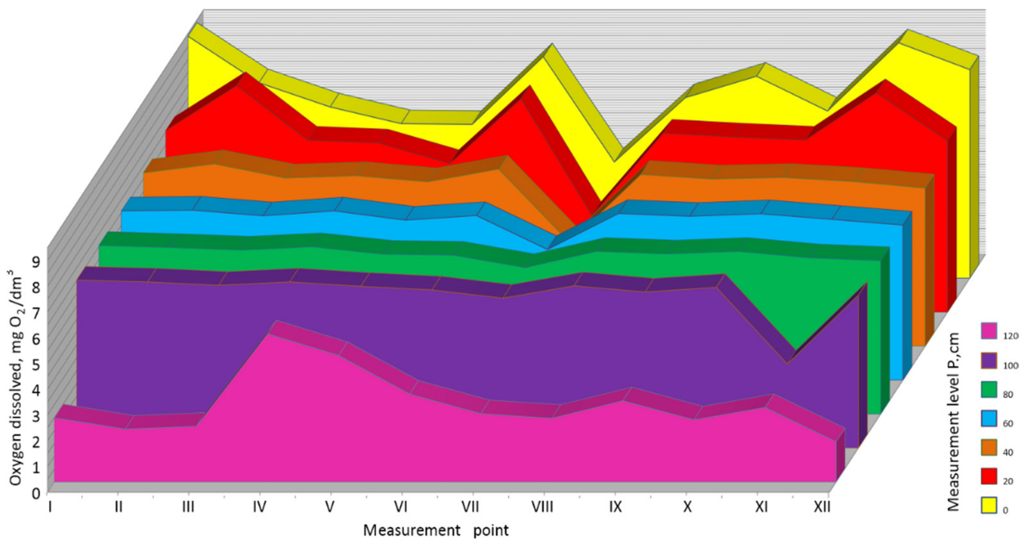

Fig. 4. An exemplary graph for dissolved oxygen concentration in a barbotage reactor at continuous aeration and sewage inflow; sewage temperature of 12.1 °C

Concentration of dissolved oxygen decreased with the depth of the reactor from 6.2 to 2.9 mg O_2/dm^3, which indicates inferior aerobic conditions at the reactor bottom. The redox potential decreased depending on oxygen concentration at a given level P and due to the inflow of sewage and internal circulation in the reactor. Figure 4 presents an example distribution of concentrations of dissolved oxygen at individual measurement levels.

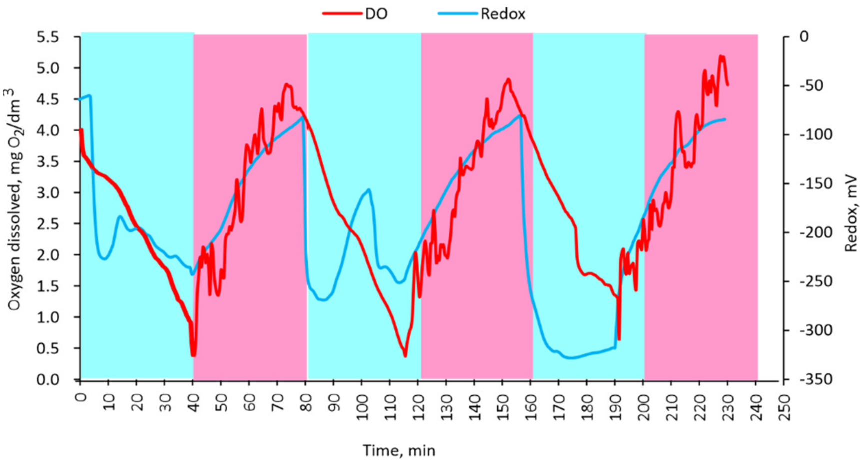

Fig. 5. Concentration of dissolved oxygen and redox potential in the field barbotage reactor at variable aeration at the measurement level *P* = 0; blue – no aeration, red – aeration; sewage temperature of 16.2 °C

In the second stage of the study during intermittent aeration of the reactor, the concentrations of dissolved oxygen in the reactor were lower than those recorded at the stage with continuous aeration. The distributions of oxygen concentration in the reactor at depths *P*0, *P*20, and *P*40 were comparable, while the maximum value was recorded at the sewage surface level amounting to ca. 4.5 mg/dm^3 (Fig. 5). At depths of *P*60, *P*80, *P*100, and *P*120 the measured concentrations of dissolved oxygen in sewage were 0 mg/dm^3, which was caused by the oxygen deficit at the stage with no aeration and high temporary oxygen consumption by microorganisms in the reactor. The value of redox potential during intermittent aeration also fluctuated: it was decreasing at the stage with no aeration and during sewage inflow, while at the stage of aeration it was increasing, which indicates advantageous conditions for oxidation of the substrate introduced with sewage. The DO gradient for stage 2 is much higher than in stage 1. The oxygen transfer increases, and gas holdup. This is consistent with the literature data [22].

3.2. SEWAGE QUALITY

During the operation of the barbotage reactor in the continuous mode (stage 1) and intermittent aeration (stage 2), several analyses were conducted concerning sewage quality to assess the efficacy of pollutant removal. The mean values of pollutant indexes are given in Fig. 6.

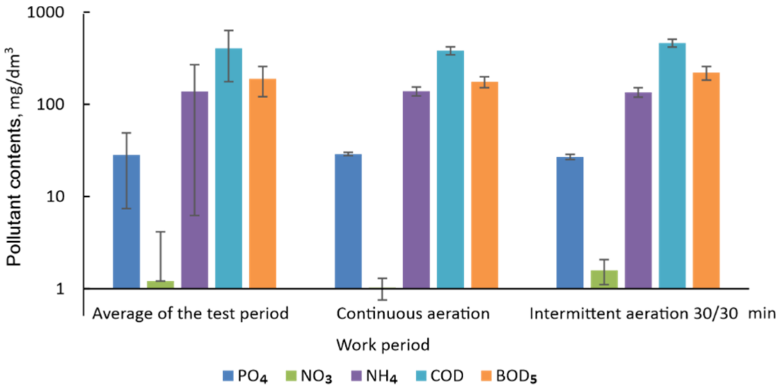

Fig. 6. Mean values of pollutant indexes in influents

The content of organic compounds and phosphates corresponded to amounts characteristic of effluents leaving the septic tank, while contents of nitrogen compounds were higher than in typical domestic wastewater. Calculated reactor loads with organic compounds were small and ranged from 0.01 to 0.05 g BOD_5/g d.m., indicating that the reactor was working at a small load.

Pollutant concentrations in treated effluents varied in the course of the study; however, in the series with continuous aeration (stage 1), the content of organic compounds expressed as BOD_5 and COD fell within the range of requirements for effluents discharged to receiving waters following the currently binding regulations.

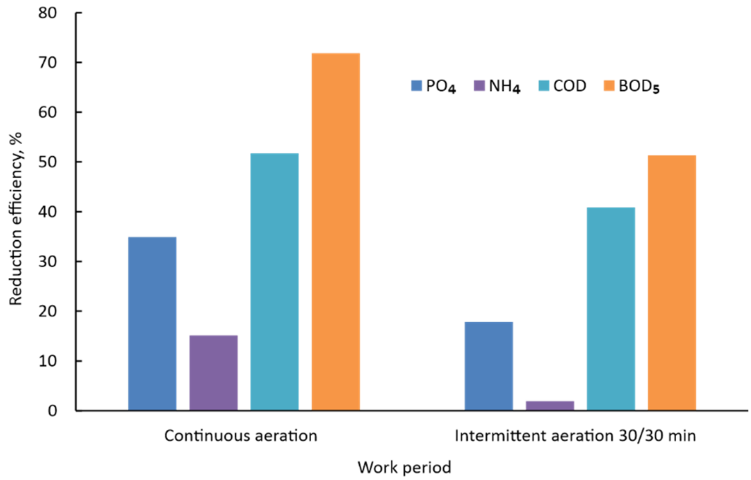

Fig. 7. The degree of pollutant reduction in the tested hybrid barbotage reactor

The degree of reduction for carbon compounds expressed as BOD_5 was ca. 70%, while for COD it was ca. 50%, which showed that readily degradable organic compounds were removed more effectively. A markedly inferior effect was obtained for ammonia nitrogen. All the pollutants contained in treated effluents were removed to a greater degree at the stage with continuous aeration than it was at stage 2 with intermittent aeration (Fig. 7).

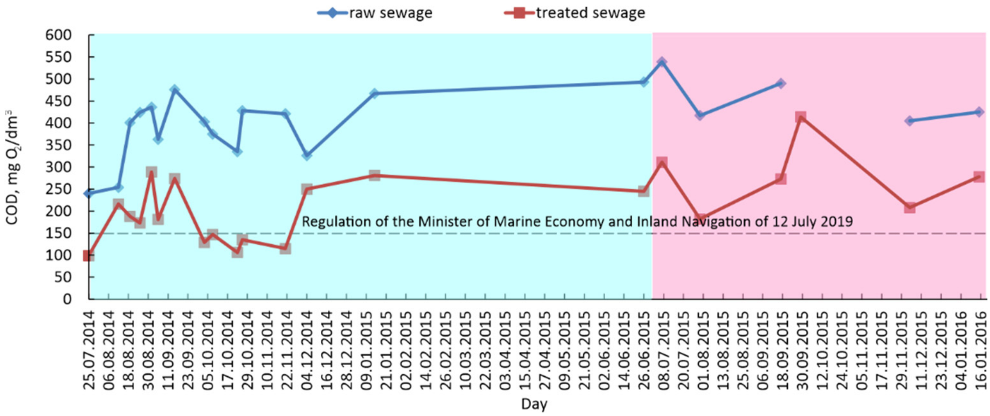

Fig. 8. Contents of organic pollutants in raw and treated sewage expressed as COD; blue – continuous aeration stage 1, red – 30/30 min intermittent aeration stage 2

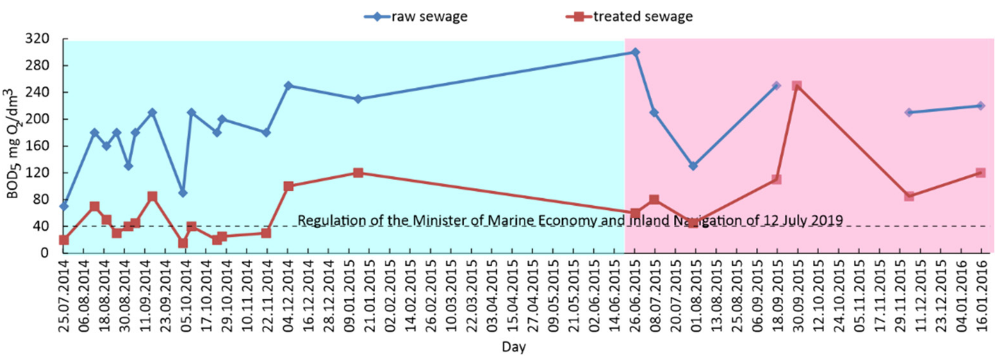

Fig. 9. Contents of organic pollutants in raw and treated sewage expressed as BOD_5; blue – continuous aeration stage 1, red – 30/30 min intermittent aeration stage 2

Figures 8 and 9 present contents of organic pollutants in raw sewage and treated effluents in the reactor, expressed as COD and BOD_5. In the course of the study, the degree of COD reduction in the period of continuous aeration (stage 1) was highest (52%), while in the case of 30/30 min intermittent aeration(stage 2) it was lowest (41 %). Values of BOD_5 were slightly higher, in the period of continuous aeration, it was 72% and in the period of intermittent aeration – 51%. In the course of reactor operation in the continuous aeration mode from 5.10.2014 to 21.11.2014, the COD and BOD_5 for treated effluents reached values facilitating their direct discharge to receiving waters, following the currently binding *Regulation of the Minister of Marine Economy and Inland Navigation of 12 July 2019* (*RLM* < 2000).

Based on the results of the analyses, biological treatability of influents was determined (Table 3)

Table 3

Factors affecting biological treatability of influents

Period	COD/BOD_5	BOD_5/COD	COD/NH_4	BOD_5/NH_4
Mean for the entire period of analyses	2.1	0.5	3.3	1.6
Continuous aeration	2.2		2.8	1.3
Intermittent aeration 30/30 min	2.1		3.4	1.6

Proportions between COD and BOD_5 of raw sewage introduced to the barbotage reactor ranged from 1.3 to 3.6, at a mean value of 2.1. These values indicate the contents of readily degradable organic compounds in influents and slight amounts of slowly degradable compounds. Occasionally, the value of 2.5 (the boundary value of COD/BOD_5 reported for sparsely degradable substrate) was exceeded. The proportion between BOD_5 and NH_4 was on average 1.6, with the values falling in the 0.5–3.0 range characteristic of a high share of nitrifying bacteria in the total biomass of activated sludge [23].

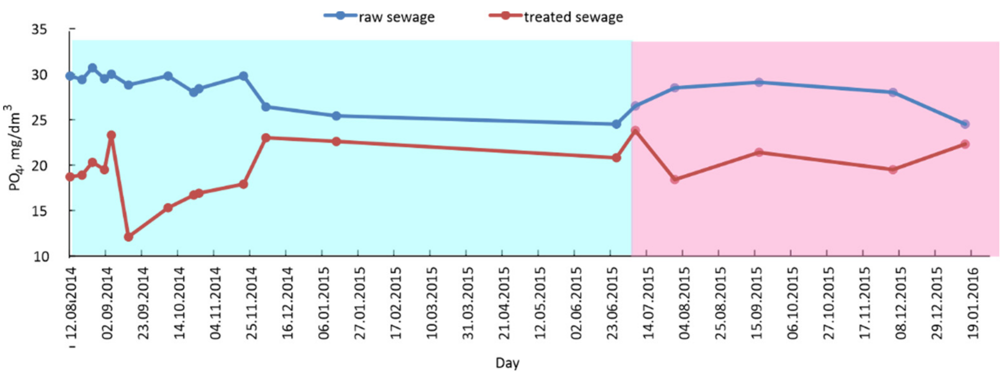

Fig. 10. Phosphorus contents in raw and treated sewage;
blue – continuous aeration stage 1, red – 30/30 min intermittent aeration stage 2

Concentrations of phosphorus compounds in influents ranged from 24.5 to 30.7 mg/dm^3 (Fig. 10). The mean degree of reduction for phosphorus compounds in the investigated period was 31%; in the period of continuous aeration, it was 35%, while in the case of intermittent aeration – 18%. These results are consistent with literature data, showing that during its development biomass absorbs phosphorus compounds, reducing their level by as much as 30% [24]. During continuous aeration (stage 1), the amount of sewage sludge flowing out of the reactor with treated effluents was greater than in the case of intermittent aeration (stage 2), thus the difference in the degree of reduction amounted to 17%.

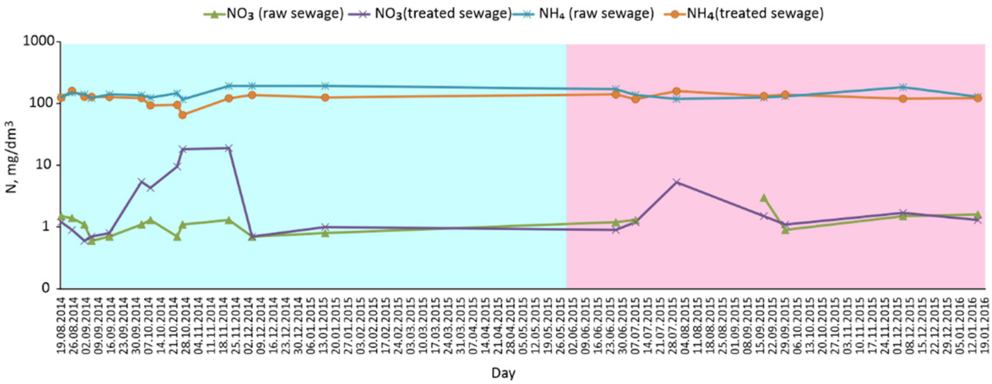

Fig. 11. Nitrogen compounds in raw and treated sewage;
blue – continuous aeration stage 1, red – 30/30 min intermittent aeration stage 2

The efficacy of the removal of nitrogen compounds from sewage was influenced by two factors. One of them was related to a high concentration of ammonia nitrogen (on average 137 mg/dm^3) and pH 7.5–8.1, which caused substrate inhibition of undissociated ammonia. Table 4 presents the calculated concentrations of ammonia nitrogen found in an undissociated form according to formula (2). A high concentration of ammonia N-NH_3 (from 1.3 to 4.5 g/m^3) considerably slowed down the rate of nitrification. A slight reduction of nitrogen was connected only with its consumption in the biosynthesis of microbial cells (Fig. 11).

Table 4

Concentration of undissociated ammonia nitrogen in influents

Aeration	Day	T [°C]	S_{NH_4} [mg/dm^3]	pH	S_{NH_3} [mg/dm^3]
Continuous	15.09.2014	12.5	136	8.1	4.47
	26.10.2014	11.7	192	7.7	2.76
	31.10.2014	11.8	170	7.7	2.24
	21.11.2014	11.9	170	7.7	2.21
Intermittent	10.11.2015	11.6	128	7.6	1.29
	29.07.2015	16.2	128	7.7	2.31

Another factor was connected with the low contents of organic compounds concerning the amount of nitrogen in influents (Table 3).

Table 5 presents the biomass concentration in the reactor together with the calculated sludge volume index (*SVI*) proposed by Mohlman. It was found that *SVI* falls within the admissible limits and sludge had good sedimentation properties.

Table 5

Mean biomass parameters in a barbotage reactor

Aeration	Total suspended solids [mg/dm^3]	Mineral solids [mg/dm^3]	Organic solids [mg/dm^3]	Sludge volume index [cm^3/g]	Sedimentation test [cm^3/dm^3]
Continuous	4835.7	970.7	3865.0	103.5	260–800
Intermittent 30/30 min	6114.0	1372.5	4741.5	77.7	250–330

Table 5 also presents readings of sludge volume after a 30-minute sedimentation test. Sludge from the reactor chamber was collected using an organic glass pipe. The amount of sludge was increasing starting from the beginning of reactor operation, after the incorporation of biomass, the sludge volume was 500–600 cm^3/dm^3. During the period of reactor operation in the intermittent aeration mode, the sludge showed better sedimentation properties.

To compare results obtained in both stages of the study, statistical calculations were performed using the analysis of variance (Table 6). The efficacy of pollutant removal in both stages was compared to determin092e whether the adopted aeration regime affected sewage treatment.

Table 6

Analysis of variance for treatment efficacy

Analysis	BOD_5	COD	NH_4
Stage 1 CON vs. stage 2 INTER	yes	yes	no

CON – continuous aeration, INTER – intermittent aeration, yes – statistically significant effect, no – statistically non-significant effect.

It was found that the degree of pollutant removal from organic sewage in both stages of the study differs significantly, whereas the efficacy of ammonia nitrogen removal was independent of the adopted aeration regime.

Costs of sewage treatment and transport were calculated based on mean values of the degree of BOD_5 reduction for both stages of the experiment. In the case of continuous aeration treatment of 1 kg BOD_5, the load requires 20 kWh; 1 kg COD load requires 12.7 kWh, while the costs of transport amount to 2.16 kWh/m^3. In intermittent aeration (stage 2), these costs are lower at 11.1 kWh/1 kg BOD_5; 6.7 kWh/1 kg COD and 1.08

kWh/m^3, respectively. Changes in the reaction feed system to a batch mode and the aeration method to 30/30 min intermittent cycles resulted in a reduction of sewage treatment costs by 30% and provided a stable reactor operation. Nevertheless, it needs to be remembered that the used rotameter considerably limited the air flow by ca. 30%, for this reason under commercial scale conditions the degree of pollutant reduction may be increased, and as a result costs of energy may consequently be reduced.

4. DISCUSSION

In the course of studies conducted under semi-commercial scale conditions, the hybrid barbotage reactor operated as a sewage treatment facility produced by private farms. In the continuous aeration system, the distribution of oxygen concentrations at the same depths at various locations was very similar; it varied at different reactor depths. Maximum values of oxygen concentrations were recorded at the level of sewage surface (frequently over 6 mg/dm^3), while minimum – at the bottom (ca. 1 mg/dm^3). Mean oxygen concentration in the reactor in the continuous aeration system considerably exceeded the values reported in the literature required to reduce nitrogen compounds in the nitrification process [4]. For intermittent aeration(30/30 min) (stage 2), the distribution of oxygen concentrations at various depths was analogous. The aeration time reduced by half resulted in a decrease in the concentration of dissolved oxygen in the reactor at the measurement depths *P*100 and *P*120 practically to zero. The intermittent aeration system for five out of seven measurement depths (from *P*0 to *P*80) produced good aerobic conditions for sewage treatment, which was also shown by the measured redox potential [4]. Mean values of pollutant indexes (COD, BOD_5, PO_4) in raw sewage corresponded to values for effluents discharged from the septic tank. Values of COD/BOD_5 and BOD_5/NH_4 in influents were characteristic of readily degradable substrates and a high share of nitrifying bacteria in the total biomass of activated sludge [23]. The reactor operated on pretreated sewage. The degree of COD and BOD_5 reduction in the reactor was higher for the continuous aeration system compared to the intermittent aeration. A low C/N ratio in influents and a high concentration of ammonia nitrogen (mean 137 mg/dm^3) and pH 7.5–8.1 harmed the efficacy of removal of nitrogen compounds (ammonia substrate inhibition) [21]. The degree of reduction in the case of phosphorus compounds in the period of the study was 31%; nitrogen and phosphorus were utilized only for the development of microbial cells.

The change of the sewage aeration and feed system to the intermittent aeration variant generates lower treatment costs at a stable reactor operation, which is consistent with literature data [8, 25].

Based on the conducted analyses, it was found that hybrid barbotage reactors, particularly when operating in the continuous aeration system, may be used to pre-treat domestic sewage. The composition of treated sewage, typical of the outflow from the septic tank (a low C/N ratio), may lead to problems in the nitrification process. However, the obtained degree of sewage treatment facilitates their drainage in the ground or potentially further transport to a collective treatment plant, thanks to the reactor design. Under advantageous conditions (sewage composition, reactor operating parameters) wastewater may the treated to a degree sufficient to its discharge to receiving waters.

5. CONCLUSIONS

Based on the conducted technical studies and aeration in a hybrid barbotage reactor, it was found that:

- The reactor is suitable for transport and treatment of small amounts of sewage in the small-bore sewerage network.
- In the continuous aeration mode in the hybrid reactor, the efficiency of pollutant removal from sewage expressed as BOD_5 and COD indexes is over 20% better than for the 30/30 min intermittent aeration cycle, for phosphorus compounds this difference was almost 50%.
- The change in the aeration system made it possible to reduce costs by 44% expressed for the treatment of 1 kg BOD_5 load and 48% for COD.
- At stage 1 of the study in the continuous aeration system, the concentration of dissolved oxygen in sewage was much higher than in the intermittent aeration stage 2.
- HBR is an alternative to sewage aeration in sewage and pumping stations.

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