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Wastewater treatment in a hybrid barbotage reactor with continuous aeration

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ABSTRACT

Barbotage reactors are the subject of many research papers and have gained prominence in industrial and bioengineering applications. Hybrid barbotage reactor solutions can be used for transport and treatment of small volumes of pretreated wastewater. The subjects of the present study were two hybrid barbotage reactors featuring wastewater circulation and aeration nozzles, which were packed with a moving bed to 20% of their volume. The nozzles were installed at two different heights of 34 and 84 cm. Based on the results, reactor oxygenation curves were prepared, the reactor's wastewater treatment efficiency was calculated, and the amount of energy used for wastewater treatment and transport was determined. The impact of hydraulic conditions on the reactor's contaminant removal efficiency was determined as well. The position of the nozzle affects the efficiency of contaminant removal in the reactor and mixture circulation velocity. The degree of reduction for biodegradable carbon compounds expressed as 5-day biochemical oxygen demand was approx. 49% (H34W20) and 32% (H84W20), while for chemical oxygen demand it was approx. 31% and 20%. The nozzle submergence affects gas holdup and oxygen conditions in the reactor. The gas holdup ratio for the H34W20 model was significantly higher compared to H84W20. The difference in the reactor's bubble column reactor zone was 46% while in the airlift reactor zone it was 31%.

Keywords: Wastewater treatment; Oxygenation; Barbotage reactor; Moving bed; Airlift reactor; Bubble column reactor

1. Introduction

Barbotage reactors that utilize liquid and gas flow have become commonplace in industrial and bioengineering applications. Their simple and reliable design makes it easy to adjust them to the requirements of a given process. These advantages are exploited in such processes as water and wastewater treatment. Today, the treatment and transportation of wastewater from households and industrial plants, particularly in small towns, is still a relevant and not completely resolved issue. Due to the small amounts of water in traditional gravity sewer systems, wastewater is often subject to putrefaction, which results in the deterioration of its quality. This increases its treatment costs and adversely affects the sewer infrastructure. Inadequately treated wastewater poses a major threat to both surface and groundwater quality, as well as the entire catchment area. A common sewage collection system and the small wastewater treatment plant modernization efforts required due to the increase in contaminant volume are very costly and pose a significant financial burden for small municipalities. The airlift pump solution can be used to transport small volumes of wastewater while performing its simultaneous biological treatment.

Barbotage refers to the flow of multiple gas bubbles through a liquid layer. There are two main barbotage reactor types: bubble column reactors (BCRs) and airlift reactors (ALRs). Such reactors have no moving mechanical parts and consist of the main tank (cylindrical or rectangular) and a gas distributor. ALRs include a special mixture lifting zone (in the form of a baffle or tube) that greatly improves the circulation of the medium inside the barbotage

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reactor. Depending on their operation mechanism and medium flow, ALRs can have various designs. In terms of the adopted modifications of the barbotage column system with forced medium circulation, two basic designs can be distinguished: (a) with internal medium circulation; (b) with external medium circulation. Each ALR variant contains four hydrodynamic zones: lifting, degassing, fall, and bottom [1]. ALRs are used in such bioprocesses as plant and animal cell cultures, as well as for purifying streams of contaminated fluids (wastewater, exhaust gases). ALR reactors are considered an alternative to stirred-tank reactors (STRs) [2–5].

Many authors have examined the application of ALRs in wastewater treatment as an alternative to conventional systems (STR hybrid reactors and BCRs). Due to the lack of certain data (scaling, mathematical models, and operating conditions) and design difficulties, their industrial applications are rather uncommon. Nevertheless, many authors have studied the use of such reactors in wastewater treatment as an alternative to conventional systems [6,7]. Study analyses showed that ALRs have improved removal efficiencies for various types of contaminants compared to STRs, as well as comparable or better results than BCRs. Their good internal circulation and simultaneous aeration make ALRs particularly useful in conventional wastewater treatment, even though improvements in wastewater treatment efficiency are associated with hybrid technologies (multiphase ALRs with biofilm carriers, sequential bioreactors, biofilm system, membrane bioreactors, ultrasound reactors, oxidation ditches, photo-bioreactors, electrocoagulation/electrochemical systems, etc.) [8–10].

Using airlift reactors (activated sludge, fixed biomass) for wastewater treatment usually concerns biological removal of organic compounds, but they are increasingly used in advanced wastewater treatment in such processes as nitrification–denitrification [11,12], intense oxidation [13], biodegradation of some refractory organic compounds [14,15], electrocoagulation, and electro-flocculation [16,17].

Compared to traditional stirred-tank reactors, ALRs are safer for shear-stress-sensitive microorganisms, provide an adequate oxygen transfer rate and have relatively low energy consumption [18]. In terms of mass transfer capability, BCRs are slightly better than ALRs due to their higher gas holdup capacity under the same conditions [19,20].

Roy and Joshi [21] compared the mixing characteristics of BCRs and ALRs with external circulation. Computational fluid dynamics (CFD) methods were used for the analysis. The calculation results showed that ALRs provide better mixing results than BCRs with the same energy consumption, reactor volume and dispersion height. For the same BCR volume, changing the ratio of height to diameter makes it possible to improve the reactor's mixing capacity. ALRs achieve 2.5 to 4 times better mixing results than BCRs with the same gas flow conditions and reactor diameter. This is related to the feedback effect between the height and intense directional fluid circulation.

The use of moving beds to support purification and aeration processes has become very popular in recent years, as confirmed by numerous studies [22–26]. Moving beds should be characterized by a large surface area and should provide hydrophobic packing and proper circulation inside the reactor. Currently, most moving beds are made of plastics (PP, PE, PU). It is assumed that the maximum reactor packing that ensures bed mobility and a large impact on the treatment process efficiency is 60%–70% [27,28]. Qiqi et al. [29] tested various packing types of reactors with moving beds. The use of moving beds significantly improves the efficiency of pollutant removal. It is important to properly select the dimensions of the bed and its quantity in relation to the dimensions of the reactor.

Wastewater treatment costs depend on many factors, such as the scale of the wastewater treatment plant, the wastewater treatment technology, the efficiency of the installed equipment and the quality of the intake wastewater. Removing 1 kg of 5-day biochemical oxygen demand (BOD_5) from municipal wastewater requires 1.9–2.5 kWh while treating 1 m^3 of wastewater requires 0.35–0.45 kWh (with BOD_5 in raw sewage 300 mg O_2 dm^{-3}) [30]. Masłoń [31] reported that the system's energy consumption depends on the technology adopted Table 1.

It follows that more advanced system consumes more energy.

This study aims to determine the effect of hydraulic conditions in hybrid barbotage reactors with a moving bed and an aeration tube on the contaminant removal efficiency in the post-mechanical treatment wastewater. The subjects of the study were two hybrid barbotage reactors featuring

Table 1
Energy consumption costs for different technologies

Location of the object	Characteristics of the object	Energy consumption (wastewater treatment) (kWh $kg_{BOD_5}^{-1}$)	Energy consumption (transport) (kWh m^{-3})
Biecz [31]	Sequencing batch reactors (SBR) reactor	5.2	1.7
Dynów [31]	Imhoff tank with a biological bed	3.02	–
Hyżne [31]	Hybrid system, activated sludge + biological bed	5.18	3.2
Krzeczowice [31]	Imhoff tank with a biological bed	1.46	2.5
Nowy Żmigród [31]	Sequencing batch reactors (SBR) reactor	4.64	1.5
Poznań [7]	HBR reactor with a biological bed (the nozzle location 84 cm) and continuous aeration/Intermittent aeration 30/30 min	20/11.1	2.16/1.08

wastewater circulation and aeration nozzles, which were packed with a moving bed to 20% of their volume. The nozzles were installed at two different heights of 34 and 84 cm. The hybrid biological reactor (HBR) is an original solution, a combination of a BCR and ALR reactor. A modified airlift can transport and clean sewage at the same time. Several devices have been used so far.

2. Experimental

2.1. Description of the test bench

For this study, a hybrid barbotage reactor was used as a device for treating small amounts of mechanically pretreated wastewater; it was assumed that the device could simultaneously prove its usefulness as a small pumping station operating in a small-diameter sewer system.

A field reactor system was set up at the research station of the Poznań University of Life Science's Department of Hydraulic and Sanitary Engineering, located in the Left-bank Sewage Treatment Plant building in Poznań. The system included a buffer tank with pumps, a hybrid reactor and a secondary settling tank. The hybrid reactor was fed by mechanically pretreated wastewater. The wastewater was drawn from the outflow of the municipal wastewater treatment plant's sand trap. Since it was necessary to remove suspended solids, a small basket filter was installed at the reactor inflow. A modified airlift pump design enabled the aeration of the reactor contents and transport of the treated wastewater. Two designs were tested as part of the study in sequence: H34W20 and H84W20 hybrid barbotage reactor (tube position at 34 and 84 cm height, respectively, with 20% moving bed packing). This hybrid barbotage reactor is a combination of an ALR (airlift reactor) and a BCR (bubble column reactor), which combines wastewater transport and treatment functionalities. The aeration processes, as well as cost and efficiency of treating small volumes of mechanically pretreated wastewater in the prototype reactor were analyzed. The impact of hydraulic conditions on the wastewater contaminant removal efficiency is discussed as well. In 2020, the Polish Patent Office granted patent No. 236340 for the solution discussed [32].

The reactor start-up for each series of studies took 4 weeks. Research in each series took about 6 months.

Activated sludge used for reactor start-up was from the aeration tank of the Left-bank Sewage Treatment Plant in Poznan. The moving bed consisted of corrugated cylindrical polyethylene elements, with dimensions of 16 mm × 16 mm.

2.2. Field model system components and measurement apparatuses

Fig. 1 shows a schematic diagram of the hybrid barbotage reactor used for the study. The reactor was equipped with an airlift pump with an aeration nozzle (3) with 2 cm × 15 cm and 2 cm × 45 cm arms. The proper position for the nozzle was determined through hydraulic testing [33].

Additionally, the system featured a secondary settling tank with a capacity of 0.2 m^3.

The testing involved two stages: in the first stage (T_1), the position of the nozzle (3) was H = 34 cm above the bottom, and the active volume of the reactor (V_{r1}) was 660 dm^3; in the second stage (T_2), the position of the nozzle (3) was H = 84 cm above the bottom, and the operating volume of the reactor (V_{r2}) was 974 dm^3. The hybrid barbotage reactor was operated under continuous aeration throughout the

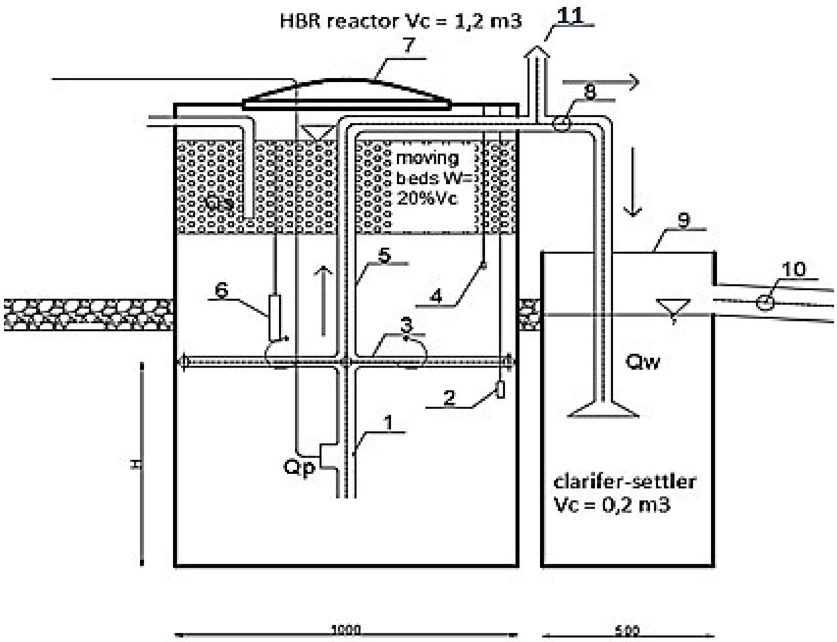

Fig. 1. A diagram of the field model: 1 – diffuser, water-air mixer, 2 – liquid level sensor, 3 – nozzle, 4 – temperature sensor, 5 – air lift with pipe element, 6 – LDO oxygen probe, 7 – reactor cover, 8 – collection point for effluents discharged from the reactor, 9 – clarifier-settler cover, 10 –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

entire study period. Wastewater was fed in 24 batches per day (one batch every 1 h) using a TH-25 dosing pump, in the amount of 27.5 dm^3 per batch in stage T_1 and 40.6 dm^3 per batch in stage T_2. The hydraulic wastewater retention time for both stages was 24 h. The hybrid reactor was packed with a moving bed up to 20% of the tank's operating volume. The rate of air fed to the reactor was constant at Q_p = 5.0 m^3 h^{-1}. Measurement probes 2, 4, and 6 (Fig. 1) were used to record oxygen concentration, temperature and wastewater level. The outside temperature and the temperature of the intake wastewater fed into the reactor were also measured. Raw wastewater for analysis was collected from the reactor intake marked Q_s, whereas treated wastewater was collected from the location marked 8 in the tank, on the outlet line leading from the reactor to the settling tank.

A Tecfluid model PSM – 21 tube flow-meter was installed to measure the airflow rate of the air fed by the blowing fan to the reactor (Q_p). Additionally, an electronic system based on the BeagleBone Black micro-controller was created to control the bioreactor's operation and record sensor data. The micro-controller controlled the timing of the blowing fan and the output of the pump feeding wastewater into the reactor and collected and recorded data from the thermometers and the wastewater level probe.

A Hach Lange recording set with a luminescent dissolved oxygen (LDO) probe was used to measure dissolved oxygen concentration in the reactor, as well as pH values and redox potential. Table 2, Figs. 2 and 3 show the experiment's plan.

The following measurements were taken during the study:

- temperature – measurements of outside temperature, as well as the temperature of the intake wastewater fed into the reactor and wastewater inside of it (°C),
- wastewater level – continuous measurement of the wastewater level in the reactor (cm),
- pH – pH value in the intake wastewater and inside the reactor,
- redox potential – the value of the redox potential in the intake wastewater and inside the reactor (mV),
- DO – dissolved oxygen concentration inside the reactor (mg O_2 dm^{-3}).

Instantaneous measurements of the dissolved oxygen concentration and redox potential were performed according to the scheme in Fig. 3, in four measurement profiles, at different depths P and with continuous aeration of the reactor during wastewater inflow. Additionally, the dissolved oxygen concentration and redox potential were measured over several hours. At that time, an oxygen probe was installed at the hybrid reactor's axis, at various depths P. Oxygen concentration was recorded every 5 min. Measurements of the above parameters were performed with an HQ40d multimeter or an HQ1000 multi-recorder.

To evaluate the contaminant removal efficiency in both stages of the hybrid reactor's operation, the quality of the intake wastewater and the wastewater treated in the reactor

Table 2
Operating parameters of the hybrid barbotage reactor

Stage	Q_p (m^3 h^{-1})	Q_s (dm^3)	HRT – hydraulic retention time (d)	Aeration time	Moving bed filling W (%)	Physical measurements	Chemical measurements
T_1	5	24 × 27.5	1	Continuous aeration	20	Temperature, level of effluent, pH, redox potential, DO, mixture velocity	BOD_5, COD, N–NH_4, N–NO_2, N–NO_3, P–PO_4, TSS
T_2		24 × 40.6		Continuous aeration			

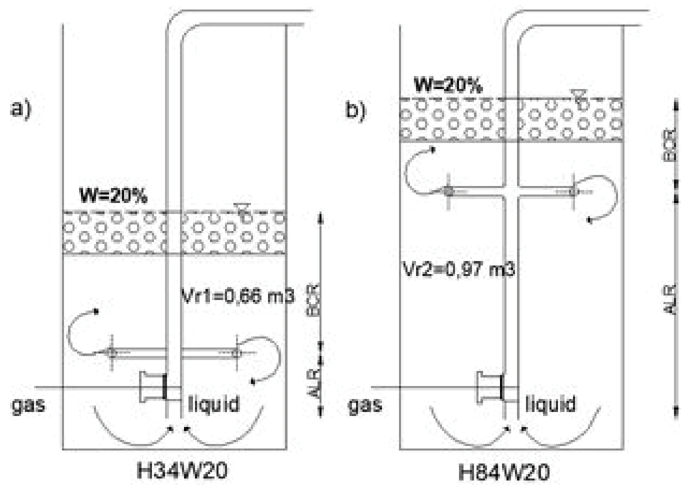

Fig. 2. Reactor design: (a) testing stage T_1 and (b) testing stage T_2.

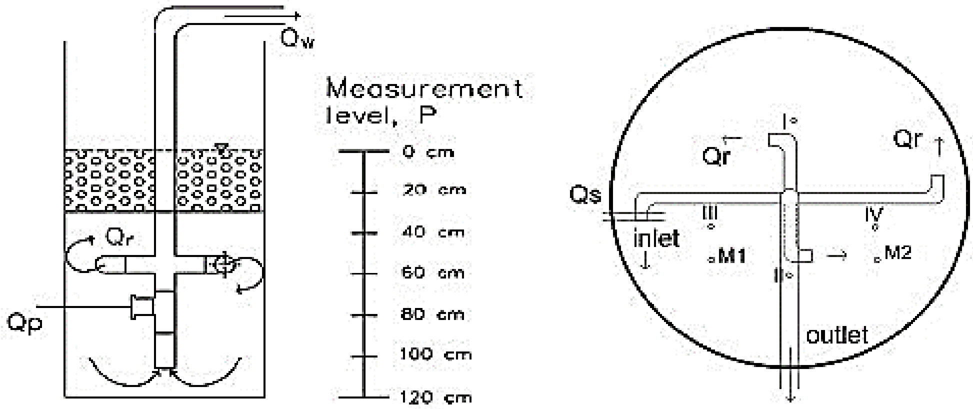

Fig. 3. Measurement scheme of the oxygen concentration and velocity in the barbotage reactor: Q_s – sewage inflow, Q_p – air inflow, Q_w – sewage outflow, Q_r – nozzle outflow M1 and M2 – measurement profiles.

was analyzed. The organic compound content expressed as BOD_5 and chemical oxygen demand (COD), as well as the ammonium nitrogen ($N–NH_4$), nitrite-nitrogen ($N–NO_2$) and nitrate-nitrogen ($N–NO_3$), and phosphorus compound content ($P–PO_4$) was determined. For this purpose, a spectrophotometer and cuvette tests along with an OXI-TOP BOD_5 measurement system were used. The total suspended solids and organic suspended solids were determined by the direct gravimetric method using a dryer and muffle furnace (at 105° and 550°, respectively). The fractions of organic compounds expressed as COD were determined using the ATV method [34].

To evaluate the condition of the sediment in the hybrid reactor, a 30-min sedimentation test was performed using a 1 dm^3 cylinder, and the sludge volume index (SVI) was calculated using the following Eq. (1):

$$\text{SVI} = \frac{V_{30}}{X_{\text{ZO}}}, \text{cm}^3 \cdot \text{g}^{-1} \quad (1)$$

where V_{30} – sediment volume after 30 min of sedimentation, cm^3 dm^{-3}, X_{ZO} – mean activated sludge concentration at the onset of the test, g dm^{-3}.

The activated sludge was collected from the reactor chamber using an organic glass tube. The reactor's power consumption was read from an electricity consumption meter. The following factors were analyzed based on the measurement of oxygen concentration and redox potential, as well as the results of analyses of the quality of intake and reactor-treated wastewater and electricity consumption:

- oxygen conditions inside the reactor,
- wastewater contaminant removal efficiency η,
- susceptibility of the wastewater to biological decomposition using COD/BZT_5, $COD/N–NH_4$, $BOD_5/N–NH_4$ indicators,
- the amount of energy used to treat a 1 kg BOD_5 load in the reactor,
- the impact of hydraulic conditions on the results of the wastewater treatment process (analysis of variance method).

The mixture circulation velocity in the reactor was determined using an electromagnetic measuring probe. The testing was performed with the application of two profiles designated M1 and M2 at different depths P (Fig. 3). The measurements were averaged across the ALR and BCR zones. The detailed methodology for mixture circulation velocity measurements in the BCR and ALR parts of the hybrid reactor were discussed previously [33].

3. Results

3.1. Oxygen conditions

Table 3 shows the minimum, maximum and average dissolved oxygen concentration values, as well as the redox potential values, obtained during continuous aeration of the hybrid reactor in the T_1 and T_2 stages. The testing was performed according to the measurement scheme shown in Fig. 3. The measurement was conducted while the raw sewage intake was shut off to eliminate the interfering factor.

The average concentration of dissolved oxygen in the wastewater in the hybrid reactor decreased along with the reactor's depth in both stages of the study, which indicated poorer aerobic conditions near the bottom of the reactor. At the T_1 stage, the aerobic conditions occurring in the reactor were slightly better than at the T_2 stage. The oxygen concentration ranged from 1.19 to 0.06 mg O_2 dm^{-3}, and from 0.51 to 0.06 mg O_2 dm^{-3}, respectively. The value of the redox potential decreased due to the oxygen concentration at each P level. At the T_1 stage, the redox potential assumed a positive value, indicating that organic compounds could be oxidized. Figs. 4 and 5 present an examples of distribution of dissolved oxygen concentration at each level of measurement.

Measurements lasting several hours revealed an oxygen concentration distribution that is analogous to the one resulting from the instantaneous measurement. The distribution of oxygen concentration in the reactor at depths P0, P20, and P40 depths was analogous. The maximum value occurred at P = 0 cm and for the H34 design was approximately 0.58 mg dm^{-3} (Fig. 6), while for the H84 design it

Table 3
Dissolved oxygen concentration and redox potential in a barbotage reactor at P measurement levels under continuous aeration and wastewater inflow

Measurement level P, (cm)	Dissolved oxygen						Redox potential					
	Minimum (mg O_2 dm^{-3})		Maximum (mg O_2 dm^{-3})		Average (mg O_2 dm^{-3})		Minimum (mV)		Maximum (mV)		Average (mV)	
	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
	H34W20	H84W20	H34W20	H84W20	H34W20	H84W20	H34W20	H84W20	H34W20	H84W20	H34W20	H84W20
0	0.28	0.27	2.99	0.82	1.19	0.51	71	–329	78	–238	76	–235
20	0.12	0.24	0.64	0.73	0.30	0.41	71	–334	78	–290	75	–247
40	0.05	0.08	0.25	0.36	0.12	0.20	71	–342	77	–305	75	–255
60	0.03	0.07	0.15	0.17	0.08	0.09	71	–345	77	–320	75	–263
80	0.02	0.05	0.11	0.07	0.06	0.05	71	–338	77	–322	75	–262
100	0.02	0.06	0.09	0.08	0.05	0.06	70	–335	77	–290	75	–256
120	0.03	0.06	0.09	0.09	0.06	0.06	71	–330	78	–314	74	–215

was approx. 0.68 mg dm^{-3} (Fig. 7). At depths of P60, P80, P100, and P120, the measured concentration of dissolved oxygen in the wastewater was 0 mg dm^{-3}, which resulted from the oxygen deficit in the influent wastewater and the high temporary oxygen consumption by microorganisms in the reactor. The redox potential value rapidly decreased during the inflow of wastewater, which indicated high oxygen consumption during the inflow of fresh wastewater. For the T_1 stage, values of the oxygen concentration were nearly doubled, which reflects favorable conditions for oxidation of the substrate introduced with the wastewater. The measurements were conducted in two different periods, spring and summer, which translated into a significant difference in wastewater temperature in the hybrid reactor and different biomass activity. The data in Table 3 indicate that the better conditions for aerobic processes were in the T1 test series. As a result, a higher removal rate of organic compounds was obtained in this series.

3.2. Wastewater quality

During the operation of the hybrid barbotage reactor at the nozzle position of H = 34 cm (T_1 stage) and H = 84 cm (T_2 stage), several tests of wastewater quality were performed to evaluate the efficiency of contaminant removal. The mean values of contaminant indicators are presented in Fig. 8 and Table 4.

As can be seen from the figure, the content of organic compounds and phosphates in the wastewater introduced into the reactor corresponded to the quantities characteristic of mechanically pretreated wastewater, while the content of total suspended solids was higher than in the case of average domestic wastewater. The calculated reactor loads with organic compounds were small and were 0.032 BOD_5 g^{-1} dissolved organic matter (DOM) for the H84W20 version and 0.015 BOD_5 g^{-1} DOM for the H34W20 version, which indicates that the working reactor was not significantly loaded.

The susceptibility of wastewater introduced into the studied reactor to biological treatment was determined by calculating the COD/BOD_5, COD/NH_4, BOD_5/NH_4 indicators (Table 5).

Proportions between COD and BOD_5 of raw wastewater introduced into the barbotage reactor ranged from 2.1 to 3.4 with an average of 2.8. Those values indicate that the wastewater introduced into the reactor contains organic compounds that are hard to decompose and a small amount of slowly decomposable compounds. Occasionally a value of 2.5 which constitutes the limit value of COD/BOD_5 reported for a substrate that is hard to decompose was exceeded. Proportions between BOD_5 and NH_4 were in the range of 2.4 to 3.7 (average 2.8); the said value falls within the range between 0.5 and 3.0. The temporary excessive loading of the reactor with BOD_5 compounds might have influenced the reduction of ammonium nitrogen in the wastewater.

The ATV method was used to calculate fractions of organic compounds occurring in the wastewater that in total constitutes 100% of COD. The content of dissolved fraction was 81.1% (of which easily decomposable S_s compounds accounted for 46.8% while indecomposable S_i compounds amounted to 34.3%). The content of the suspended fraction

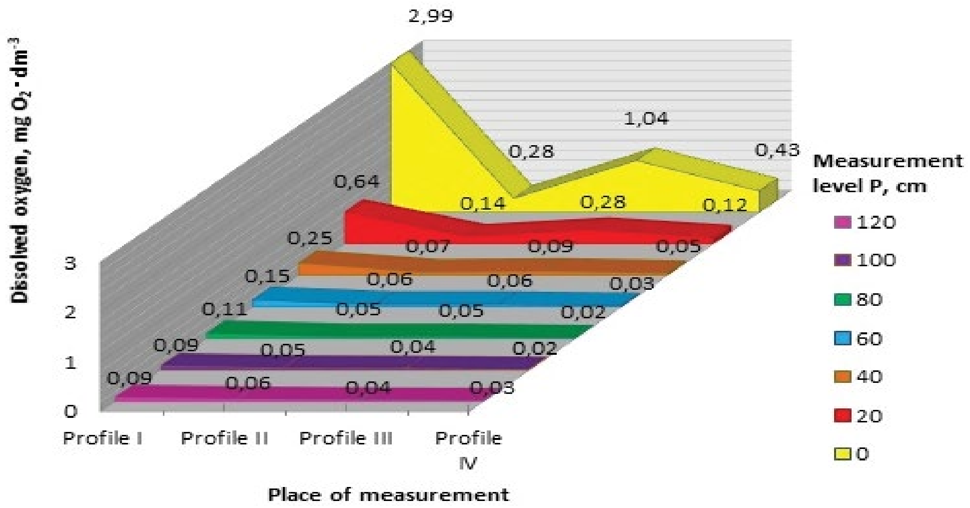

Fig. 4. An exemplary chart of oxygen concentration dissolved in a hybrid barbotage reactor; location of the H34 nozzle, continuous aeration, wastewater temperature of 21.3°C.

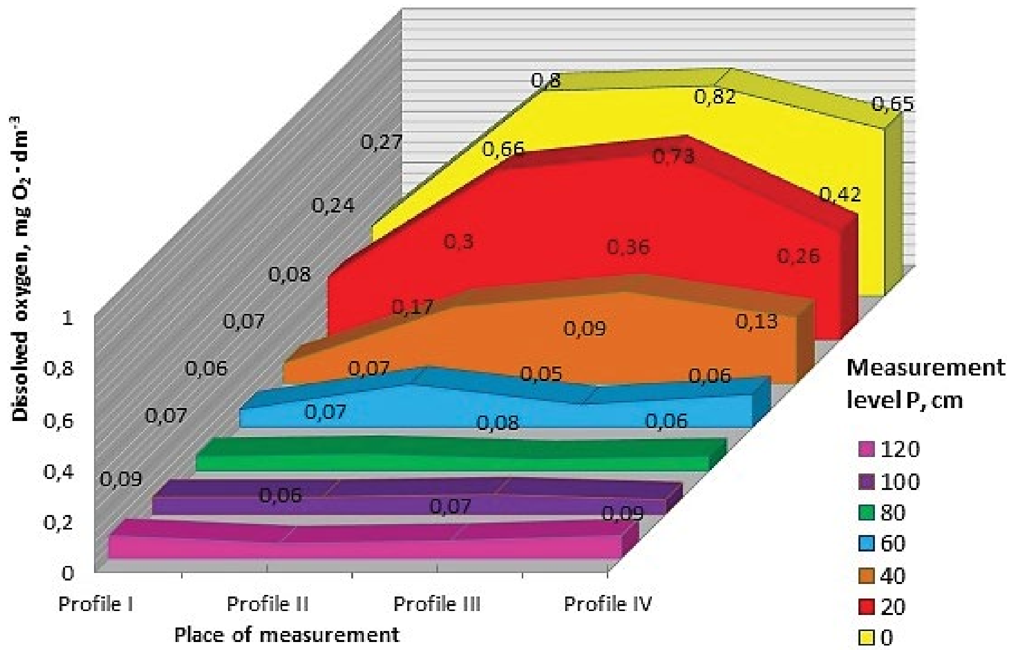

Fig. 5. An exemplary chart of oxygen concentrations dissolved in a hybrid barbotage reactor; location of the *H*84 nozzle, continuous aeration, wastewater temperature of 16.6°C.

was 18.9% (of which slowly decomposable X_s compounds comprised 14.2% while indecomposable X_i compounds amounted to 4.7%.

The degree of reduction of contaminant indicators was calculated for both analyzed designs of the hybrid reactor (Fig. 9). For the organic contaminant indicator, a higher degree of reduction was found in the case of the H34W20 design. The degree of reduction for biodegradable carbon compounds expressed as BOD_5 was approx. 49% (H34W20) and 32% (H84W20), while for COD it was approx. 31% and 20%. In both variants, ammonia nitrogen was removed at a similar level of approx. 15%–16%. The reduction of phosphorus compounds occurred only in the H84W20 design and amounted to 11%.

Values of biomass concentration and the result of the 30 min sedimentation test performed in the reactor together with the calculated Mohlman's sludge volume index are provided in Table 6. It was found that the SVI falls within acceptable limits and the sludge was characterized by good sedimentation properties.

In order to compare the results obtained in both stages of the study statistical calculations were performed

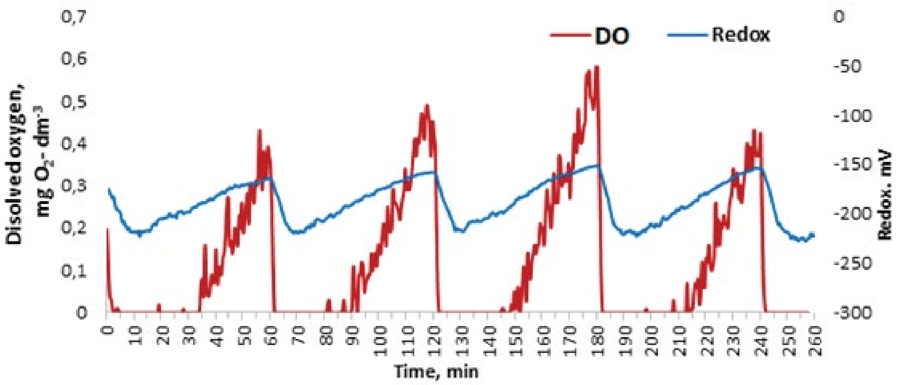

Fig. 6. Example diagram of concentration of dissolved oxygen and redox potential in the field barbotage reactor during aeration; location of the *H* nozzle – 34 cm; measurement depth of *P* = 0 cm; wastewater temperature of 21.5°C (summer).

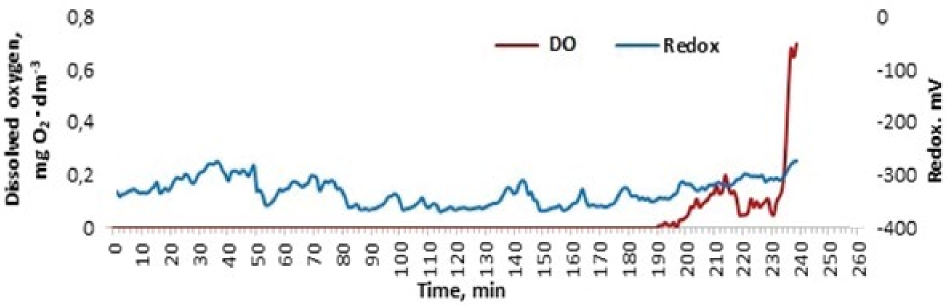

Fig. 7. Concentration of dissolved oxygen and redox potential in the field barbotage reactor during aeration; location of the H84 nozzle; measurement depth of *P* = 0 cm; wastewater temperature of 15.0°C (spring).

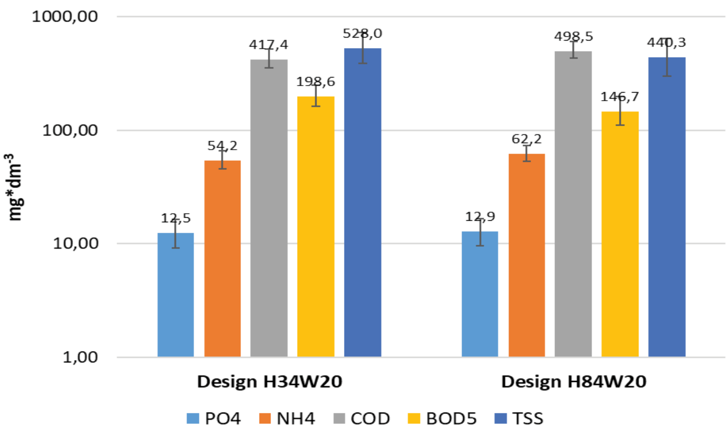

Fig. 8. Mean values of contaminant indicators in wastewater introduced into the hybrid reactor.

Table 4
Mean values of contaminant indicators in wastewater introduced into the hybrid reactor, mg dm^{-3}

Variant of the *H* nozzle location in the reactor	BOD_5	COD	NH_4	PO_4	TSS
H34	198.6 ± 35.92	417.4 ± 63.76	54.2 ± 8.87	12.5 ± 3.26	528 ± 139
H84	146.7 ± 51.11	498.5 ± 104.5	62.2 ± 11.72	12.9 ± 3.92	440 ± 205

using the analysis of variance (Table 7). The efficiency of contaminant removal in both stages was compared to determine whether hydraulic conditions affected the wastewater treatment. Analysis of variance using Tukey's post-hoc test (HSD test) was applied. A significance level of $\alpha = 0.05$ was used.

It was found that effects of the removal of organic contaminants from wastewater in two stages of the study significantly differ, while the efficiency of the removal of ammonia nitrogen was independent of the applied design.

The amount of energy required to treat and transport the wastewater was calculated using the average degree of BOD_5 reduction for both stages of the study (Table 8). For the H34W20 design, the energy required to treat 1 kg of BOD_5 load amounted to 33.2 kWh, while the energy required to transport the load was 3.27 kWh m^{-3}. In the case of the H84W20 design, the values were higher at 55.6 kWh kg^{-1} of BOD_5 and 2.22 kWh m^{-3} (due to the higher operating volume of the reactor). For the H84W20 design the energy consumption related to the wastewater treatment was nearly 40% higher than for the H34W20 design; in the case of the wastewater transport this ratio is reversed, with the H84W20 design consuming approximately 32% less energy than the alternative (for the above reason). Nevertheless it is necessary to remember that the rotameter significantly limited the airflow (by approx. 30%). That is why under technical conditions the degree of contaminant reduction may increase while individual energy consumption may decrease.

3.3. Hydraulic conditions

Charts (Figs. 10 and 11) presenting the velocity of the reactor content circulation in M1 and M2 profiles (Fig. 3) were created based on the previously described study results concerning the reactor's hydraulics [33]. The circulation velocity in the BCR section is the dominant velocity for both reactor designs. Its value depends on the measurement location; circulation velocity ranges from 3.05 to 3.42 cm s^{-1} for the H34W20 model compared to 2.02–2.99 cm s^{-1} for the H84W20 model (Figs. 10 and 11). It reaches its maximum values in the case of the H34W20 design.

The average velocity distributions for both reactor zones (BCR and ALR) are more uniform in the case of the H84W20 design.

In the H34W20 model the average mixture circulation intensity is higher in the BCR zone (Fig. 12).

Table 5
Indicators determining the susceptibility of introduced wastewater to biological treatment

Period	COD/BOD_5	COD/NH_4	BOD_5/NH_4
H34W20 design	2.1	7.7	3.7
H84W20 design	3.4	8.0	2.4

Table 7
Analysis of variance for treatment efficiency

Tests	BOD_5	COD	NH_4
Stage T_1 H34W20 Stage T_2 H84W20	YES	YES	NO

"Yes" – statistically significant impact; "No" – statistically insignificant impact.

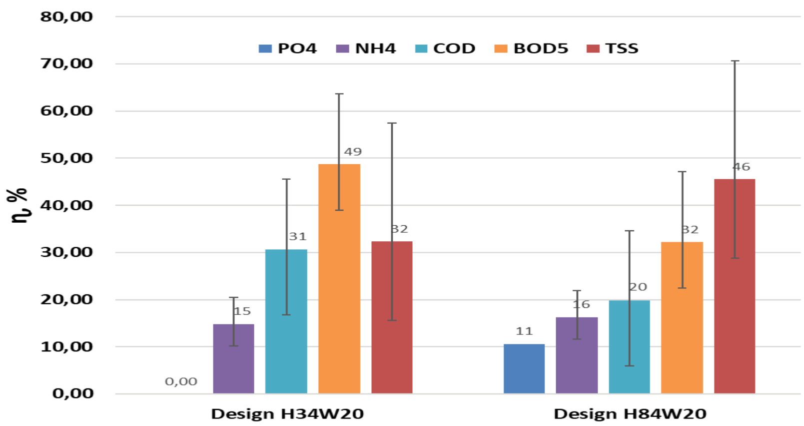

Fig. 9. Degree of contaminant reduction in the analyzed designs of the hybrid reactor.

Table 6
Average parameters of biomass in the barbotage reactor

Variant of the *H* nozzle location in the reactor	Total suspended solids (mg dm^{-3})	Mineral suspended solids (mg dm^{-3})	Organic suspended solids (mg dm^{-3})	Sludge volume index (cm^3 g^{-1})	Sedimentation test (cm^3 dm^{-3})
H34	8,248.7	2,108.6	6,140.1	68.5	70–950
H84	12,137.7	2,595.6	9,542.1	47.5	150–950

Table 8
Working conditions of HBR reactors and costs

Stage	Q_p ($m^3 h^{-1}$)	Q_s (dm^3)	HRT – hydraulic retention time (d)	Aeration time	Nozzle location (cm)	Moving bed filling W (%)	Calculated reactor loads with organic compounds (BOD_5 $g_{d.o.m.}^{-1}$)	Energy consumption (wastewater treatment) (kWh $kg_{BOD_5}^{-1}$)	Energy consumption (transport) (kWh m^{-3})
T_1	5	24 × 27.5	1	Continuous aeration	34	20	0.032 (lightly loaded)	33.2	3.27
T_2		24 × 40.6		Continuous aeration	84		0.015 (lightly loaded)	55.6	2.22

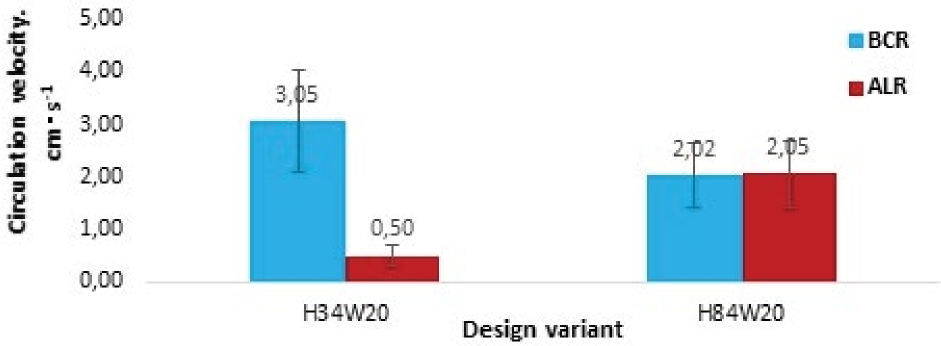

Fig. 10. Hybrid reactor mixture circulation velocity in the M1 profile.

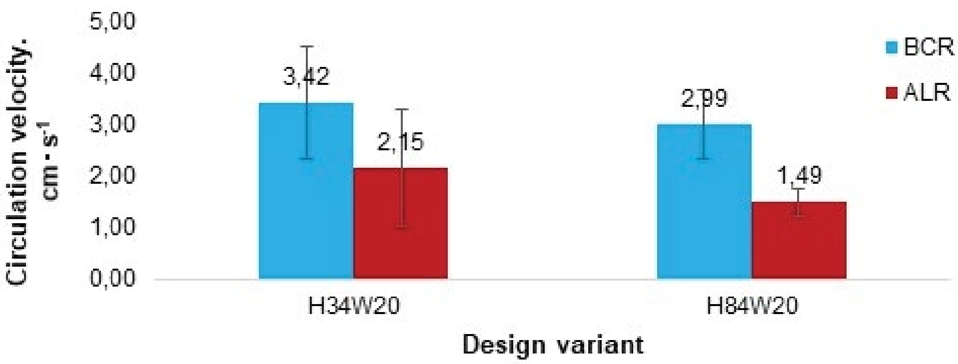

Fig. 11. Hybrid reactor mixture circulation velocity in the M2 profile.

4. Discussion

The article presents a study of the effects of hydraulic and oxygen conditions on the contaminant removal efficiency of two hybrid reactors. During the semi-industrial scale study the hybrid barbotage reactors were operated as pretreated wastewater treatment units. The distribution of dissolved oxygen concentrations in the reactor depended on the design and the P level of measurement. Maximum oxygen concentration values occurred in the BCR part in the case of both hybrid reactors at P = 0 cm. Oxygen concentrations were slightly higher in the H34W20 model compared to H84W20. As the nozzle is submerged deeper (3) the gas holdup in the BCR portion of the reactor increases which translates into increased dissolved oxygen concentrations in the wastewater. Oxygen concentrations in the ALR part were near zero in the case of both designs (H34W20 and H84W20). There was a very high instantaneous oxygen consumption in both designs studied.

The values of the redox potential in wastewater were analogous. The values were significantly higher in the case of the H34W20 design which indicates better oxygen conditions in the reactor.

The average values of contaminant indicators (COD, BOD_5, and PO_4) in raw wastewater corresponded to the values of mechanically pretreated wastewater. The COD/

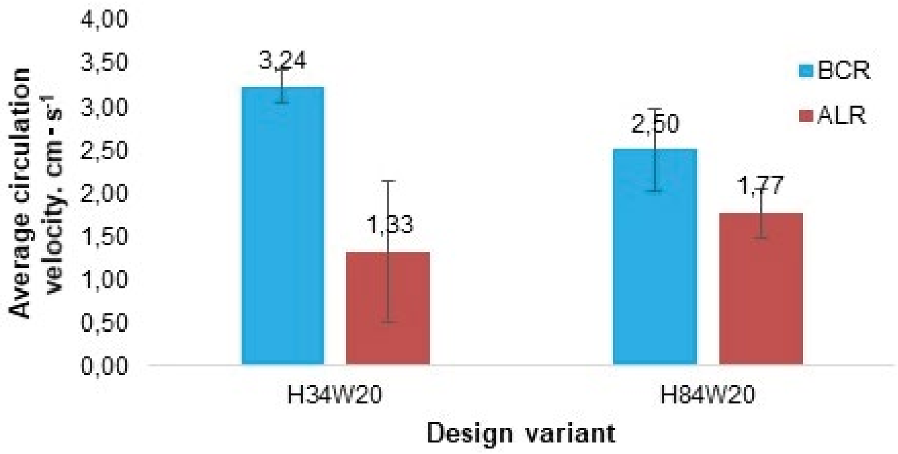

Fig. 12. Average mixture circulation velocity in the studied reactor.

BOD_5 (2.1–3.4) and BOD_5/NH_4 (2.4–3.7) values in the intake wastewater fed into the reactor were characteristic of hard-to-decompose substrates and a low proportion of nitrifying bacteria in the total biomass of the activated sludge for municipal, biodegradable wastewater is accepted $COD/BOD_5 < 2.2$ and $BOD_5N_{tot} > 4.0$ [35]. The wastewater fed into the reactor was dominated by easily soluble and hard-to-decompose fractions. The reactor operated at a low load. The COD and BOD_5 reduction rate in the reactor was nearly 40% higher in the case of the H34W20 model compared to H84W20. Low oxygen concentrations resulted in limited nitrogen reduction in the reactors. Statistical analysis has shown that the effects of the removal of organic contaminants from wastewater in two stages of the study significantly differ while the efficiency of the removal of ammonia nitrogen was independent of the applied design.

Analysis of the mixture velocity distribution in the reactor's BCR and ALR zones indicated that in the case of the H34W20 model the wastewater-biomass mixture circulated significantly better in the BCR section than in the ALR section. The average mixture circulation velocities in both zones (BCR and ALR) are similar in the case of the H84W20 model. As the nozzle is submerged deeper, the circulation velocity in the BCR zone increases which is confirmed by the studies of other authors [21].

Based on the testing performed it was determined that hydraulic conditions related to the placement of the aeration nozzle affect wastewater treatment efficiency in the hybrid reactor. The position of the nozzle affects the intensity of wastewater (mixing) circulation in the reactor as well as the gas holdup time in its BCR zone. This is confirmed by recent studies [33]. The gas holdup ratio for the H34W20 model was significantly higher compared to H84W20. The difference in the reactor's BCR zone was 46% while in the ALR zone it was 31%. Additionally the large air bubbles delivered by the nozzle effectively mix both the wastewater and the moving bed in the BCR zone. The moving bed used in this study tended to float as a thick layer on the reactor's surface, which may have resulted in an increased amount of active biomass in this zone. Gas mixing and holdup enabled improved contaminant removal efficiency in the case of the H34W20 design.

On the basis of the research and analysis it was suggested that the effluent flowing into the reactor should be free of easily falling suspended solids because at the concentration of the total suspension above 600 mg L^{-1}, the viscosity of the liquid changes significantly, so the hydraulic losses (resistance) change, which affects the head of the reactor and its effective aeration capacity.

In addition, it was found that increasing the spigot from 34 to 84 cm in the HBR reactor significantly affects the hydraulics of the reactor's operation. It reduces the possibility of liquid lifting (by approx. 60%) and the reactor's expenditure, but increases its aeration capacity.

It was also suggested, that filling the HBR with a moving bed should not exceed 30% of the working volume of the reactor; larger quantity of moving bed worsens the mixing conditions in the reactor.

5. Conclusions

Based on the technological and hydraulic testing of the hybrid barbotage reactor it was determined that:

- Device is suitable for transporting and treating small quantities of pretreated wastewater. For example, wastewater from small-diameter sewers.
- Changing the position of the hybrid reactor's wastewater circulation and aeration nozzle affects the hydraulic conditions within (mixture circulation velocity in both the BCR and ALR zones).
- If the nozzle is submerged deeper, the removal efficiency of contaminants designated as COD and BOD_5 is nearly 40% better than in the case of the H84W20 model.
- Circulation (mixing) velocity and oxygen conditions (gas holdup) in hybrid barbotage reactors affect the organic contaminant removal efficiency in wastewater.

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