Biological treatment of brewery wastewater in a sequencing batch reactor

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Abstract. Today, beer is probably the most common and popular low-alcohol beverage in the world and the range of beer products is enormous. And while raw materials and technologies used in beer production may seem similar, their specific character affects both final products and associated contamination in terms of the beer composition and concentration. Together with natural raw materials, beer producers use flavoring additives and preservative agents. A wide range of different detergents while washing the technological equipment and containers and while indoor cleaning is used. These processes cause changes in the quality of brewery wastewater and lead to the formation of new components. These components immensely complicate brewery wastewater purification.

1. Introduction
Wastewater from various food processing plants creates a complex physical and chemical system. It retains not only water-soluble particles, but also particles of various degrees of dispersion. The main consumers of fresh water include agriculture, industry and energy, as well as the municipal infrastructure. The ratio of water used by them, respectively, is (%) 70:20:10.

Enterprises of fermentation industry produce a great amount of wastewater [1]. At the moment, researchers pay much attention to water treatment for the brewing industry and the beverage industry. At the same time, brewery and beverage wastewater treatment is studied not sufficiently enough and remains and area with a great potential for optimization. The quality and composition of brewery wastewater vary widely. They depend on used raw materials and technology, as well as on the place of wastewater formation.

2. Research Basis
Beer is a drink produced during alcoholic fermentation using grainy sugars with the addition of hop flowers (or their substitutes) and prepared water. Figure 1 shows a typical brewing technological process (Fig. 1).
Figure 1. Brewing technological process: 1 – centrifuge; 2 – yeast generation.

The process of making any beer begins with the preparation of raw materials. As a rule, most breweries receive ready-made raw materials. They enter the receiving building, which houses the equipment for receiving and transporting grains to the production building. From the bunker, the auger feeds the grains to the belt-type bucket elevator. When feeding the grains, it is mandatory to pass a protective electromagnetic device to remove accidentally trapped metal inclusions that could get into the finished product or damage the process equipment. Next, the malt (grains of cereals) goes to the polishing and crushing machine, after which the malt is mashed (during the process of mixing crushed malt with water). Crushed malt and unmalted grains are then mixed with water, heated and matured at a certain temperature. This mixture is called mash, is loaded into the digester together with water. In the process of mashing, the mash is saccharified. At the end of the process, it contains two phases: liquid (known as beer wort) and solid (beer pellets). To separate the phases, the mash is sent for filtration. At the initial stage the first beer wort is extracted. Then, after washing, the second wort is extracted. Both of them enter the wort boiler, where water and other prescription components are added in the required proportions. After brewing, the wort enters the separators. Here, the beer wort is clarified by depositing a suspension of hop pellets. The wort is cooled and then goes to fermentation. At the end of the fermentation process, the wort is sent for filtration to diatomaceous or kieselguhr filters. The finished beer is sent for bottling.

All production sites and production stages are sources of wastewater pollution. Wastewater is formed during washing and soaking of raw materials and its germination, during washing of equipment, digesters, fermentation vats, during discharge of diatomaceous earth, from the separation of hops and wort. Wastewater is also formed during the process of filling and cooling of wort and beer, as well as during other technological processes. As a rule, production is divided into three sections: brewing, cooling and bottling. The most polluted wastewater is generated during grain preparation, spent hops discharge and brewing yeast washing. Let us consider the concentrations of the dirtiest wastewater, which is formed during barley washing and soaking and yeast washing. It concentrations are as follows: pH=6.0-7.0, suspended substances – 100-400 mg/l, BOD\text{full} – 400-1000
mg/l, COD – 600-1200 mg/l [2, 3]. However, the actual data collected by the authors' at several brewing industry enterprises has averaged values. These values are significantly higher than those described in other research works (see Table 1). Different brewing technologies and various types of used raw materials cause uneven composition of wastewater. In case of emergency product discharges, COD may exceed 11 000 mg/l.

Table 1. Actual data on wastewater pollution in breweries.

| Parameter                  | "Gorodtsovskoe beer", village. Gorodtsovka, Samara region, Russia | "First Brewery", Almaty, Kazakhstan | "Shymkent-beer", Shymkent, Kazakhstan |
|----------------------------|------------------------------------------------------------------|-------------------------------------|-------------------------------------|
| COD, mgO/l                 | 5150                                                             | 4893                                | 3456                                |
| BOD<sub>full</sub>, mgO/l  | 3020                                                             | 3527                                | 1988                                |
| Suspended materials, mg/l  | 1768                                                             | 1592                                | 566                                 |
| Phosphates, mg/l           | 56.9                                                             | 43                                  | 11                                  |
| Nitrogen ammonium, mg/l    | 16.6                                                             | 19                                  | 28                                  |
| BOD/COD                    | 0.59                                                             | 0.72                                | 0.58                                |
| BOD/nitrogen               | 181.93                                                           | 185.63                              | 71                                  |
| BOD/phosphorus             | 162.8                                                            | 251.93                              | 553.76                              |

The table demonstrates that the ratio of BOD<sub>full</sub> to COD in the wastewater received for treatment fluctuates within the range of 0.5-0.75. These figures show that there is a large amount of easily oxidized organic substances in the wastewater decomposed by biochemical oxidation. However, it can be seen that the requirement for the C:N:P ratio of 100:5:1 for the optimal flow of biological purification processes is not met, which indicates the need for the introduction of nitrogen and phosphorus.

3. Research process and methodology

At the moment, all existing purification methods are used for brewery wastewater, that is mechanical, physico-chemical, biological and disinfection methods. Methods of biological treatment are being intensively developed. Biological methods make it possible not only to purify wastewater, but also to obtain a by-product in the form of a sewage sludge containing organic substances. This product can be used as a source of heat and electricity while producing biogas in methane tanks. Besides, fermented silt can be used as fertilizer or livestock feed, since it does not contain metals, unlike municipal sewage sludge. At the same time, it should be emphasized that if one does not receive energy, i.e., does not ferment this by-product, the excess silt will rot, which will make it difficult to use it. The use of sewage sludge and excess activated sludge is now a popular trend in most developed countries, it is a potential raw material, not just some useless waste.

The main criterion for choosing a particular treatment method is its sufficiently high resistance to fluctuations in the concentration of organic substances coming from wastewater, along with possibly low capital and operating costs.

The SBR (Sequencing Batch Reactor) reactor is now known as one of such wastewater treatment methods. A sequencing batch reactor is a periodic process of biological purification carried out in a single reactor under unstable conditions. Ideal sedimentation conditions during the corresponding phase and the level of automation are additional advantages of this technology. Sequencing batch reactors are resistant to fluctuations in the production wastewater flow rate caused by fluctuations in the feed water flow rate for various technological processes, as well as to changes in pollutants concentrations.
SBR-technology is a biological wastewater treatment process that functionally resembles a classic process based on activated sludge. Depending on the scale of operation, a SBR-system, alongside with its varieties and hybrids, can include one or more tanks with five main operating modes each. These modes are infilling, reaction, sedimentation, decantation, pending. There are many SBR configurations developed in the world, but they all operate on the same principle. A sequencing batch reactor consists of one or more tanks. In a system with multiple tanks, one tank operates in the deposition and decantation mode, while the second one operates in the infilling and aeration mode. In traditional wastewater treatment plants, the treatment processes take place in separate designated areas of the facilities [6]. In SBR reactors, the process, being periodic, makes it possible to adjust the duration of each phase to the necessary parameters to meet the different needs of wastewater treatment. The main phases that alternately occur in SBR reactors are infilling, mechanical mixing, aeration, sedimentation, and decantation. The cycle phases are adjusted depending on the initial parameters and required characteristics of the treated wastewater.

The order and implementation of certain phases may vary depending on the tasks set. For example, M.V. Kevbrina (JSC "Mosvodokanal"), in the course of her experiment, carried out the supply of wastewater by an ascending flow through the lower part of the reactor. At this stage, phosphates were released into the solution under anaerobic conditions, and the liquid phase with oxygen and nitrates was replaced with the initial water without oxygen [7]. Thus, special conditions were created for the operation of structures in the anaerobic mode, in contrast to the pure mixing phase, when the operation of structures is provided only in the anoxic mode.

Industrial wastewater treatment is a serious environmental problem for enterprises. The volume of wastewater generated during a typical brewing process usually varies from 4 to 7 liters per 1 liter of beer produced. Most breweries discharge their wastewater to municipal wastewater treatment plants [4]. In order to ensure that the discharged wastewater meets the standards of municipal drainage networks, some large enterprises have already built local treatment facilities.

Aerobic technologies are well suited for the treatment of wastewater from fermentation plants. SBR reactors have become increasingly popular since Torrijos and Moletta used them in 1997 for the treatment of fermentation wastewater and achieved a COD treatment efficiency of 95% and nitrogen and phosphorus – 50% and 88%, respectively [5].

For the SBR process design, it is necessary to determine the duration of each phase and the total cycle duration, as well as the hydraulic retention time in the bioreactor.

The SBR calculation methodology includes the following steps. First, we determine the specific rates of oxidation of organic substances, nitrification and denitrification, and the corresponding values of these processes duration. The duration of denitrification, \( t_{\text{den},h} \), is calculated by the following formula:

\[
t_{\text{den}} = \frac{N_{\text{total in}} - N_{\text{total out}} - N_{\text{incr}}}{\rho_{\text{den}}(1-s)}
\]

where \( N_{\text{total in}} \) is the total nitrogen at the reactor inlet, mg/l; \( N_{\text{total out}} \) – total nitrogen at the reactor outlet, mg/l; \( N_{\text{incr}} \), mg/l – nitrogen consumption for the increase in activated sludge, mg/l; \( \rho_{\text{den}} \) – specific denitrification rate, mg N/(g*h).

Then we calculate the BOD value at the end of the anoxic phase:

\[
BOD_{\text{den,out}} = BOD_{\text{in}} - \Delta BOD_{\text{anaer}} - \Delta BOD_{\text{den}}
\]

where \( BOD_{\text{den,out}} \) is BOD after denitrification, mg/l; \( BOD_{\text{in}} \) and \( BOD_{\text{den}} \) at the inlet, mg/l; \( \Delta BOD_{\text{den}} \) is BOD consumption for denitrification, mg/l

The duration of the aerobic stage is defined as the greater value as compared to the time required for nitrification and oxidation of organic substances. In this case, the following formulae can be used:
\[ T_{nitr} = \frac{N_{NH4in} + N_{org,in} - N_{NH4out} - N_{incr}}{\rho_{nitr} \alpha(1-s)} \]  

(3)

where \( N_{NH4in} \) and \( N_{org,in} \) are ammonium and organic nitrogen concentrations at the reactor inlet, mg/l; \( N_{NH4out} \) is ammonium nitrogen concentration at the reactor outlet, mg/l; \( N_{incr} \), mg/l – nitrogen consumption for the increase in activated sludge, mg/l; \( \rho_{nitr} \) – specific nitrification rate, mg N/(g*h).

The estimated duration of organic substances oxidation (nitrification stage) will be (hours):

\[ T_{BOD} = \frac{BOD_{den, out} - BOD_{out}}{\rho_{BOD} \alpha(1-s)} \]  

(4)

where \( \rho_{BOD} \) is the specific rate of organic substances oxidation in the aerobic phase, mg BOD/(g*h).

The time of the settling stage, \( t_{set} \), h, is determined considering the sludge sedimentation rate:

\[ t_{set} = \frac{H_{set}}{V_{sed}} \]  

(5)

where \( N_{set} \) is the height of the treated water layer in the reactor, m; \( V_{sed} \) is the activated sludge sedimentation rate, m/h.

The total time of wastewater treatment during one cycle, \( t_{tr} \), h:

\[ t_{tr} = t_{infil} + t_{den} + t_{aerob} + t_{sed} + t_{decan} \]  

(6)

where \( t_{infil} \) is the duration of the infilling phase, h; \( t_{den} \) is the duration of denitrification, h; \( t_{aerob} \) is the obtained maximum value for aerobic processes (nitrification and oxidation of organic substances), h; \( t_{sed} \) is the duration of the sedimentation phase, h; \( t_{decan} \) is duration of the decantation phase.

4. Conclusion

The main trends in the treatment of fermentation industry wastewater today are:

- The phase-out of aeration tanks-displacers, which are gradually replaced by sequencing batch reactors that allow stable treatment of wastewater with considerable changes in their composition.
- The use of technologies that allow creating low-waste and non-waste production.

The researchers made the following conclusions:

1. Brewery wastewater is a complex system characterized by high levels of BOD, COD, and low nitrogen and phosphorus content.
2. The ratio of BOD$_{full}$ to COD in the wastewater received for treatment fluctuates within the range of 0.5-0.75, which makes biological treatment of wastewater from breweries possible.
3. Sharp fluctuations in the concentration and volume of wastewater supplied for treatment give SBR an advantage over traditional facilities due to the stability of SBR to fluctuations in water discharge.
4. The duration of the active phases in the SBR cycle can be determined by the specific rates of biochemical processes.

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