INCREASING THE EFFICIENCY OF WASTEWATER TREATMENT AT DAIRY INDUSTRY ENTERPRISES USING CAVITATION EQUIPMENT

O. Obodovych[1], B. Tselen[1], G. Ivanitsky[1, 2], L. Sablii[2],
L. Hozhenko [1], A. Nedbailo [1], N. Radchenko[1]

[1] Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine, Ukraine,
ittf_tds@ukr.net

[2] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Ukraine,
larisasabliy@ukr.net

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The article considers the problems of neutralization concentrated milky whey wastewater. The actuality of the research caused by the difficulty of utilization of acidic milky whey wastewater due to its unstable composition, high acidity and significant microbial pollution, which resulted in a high biological oxygen demand. In addition, the high chemical oxygen demand, which reflects a significant organic load and creates a problem for treatment technologies and ecological danger. The authors analyzed traditional and innovative treatment technologies with an accent on the advantages and disadvantages of each. Based on the analyzed data, it has proposed to use hydrodynamic cavitation as an auxiliary intensifying method in the technologies of neutralization concentrated milky whey wastewater. To realize it, the authors proposed a specially designed device of rotary-pulsation type. In order to determine the feasibility of the proposed solution, it is formulated by the tasks of evaluating the change in the microbiological indicator, chemical oxygen demand and biological oxygen demand under different treatment regimes. Also, determine the pattern of changes in temperature and dissolved oxygen concentration over the treatment time. According to the research results, the microbiological indicator of mesophilic aerobic and facultative anaerobic microorganisms showed the most significant decrease from at 3600 rpm within 10 minutes of treatment. At the same time, the neutralization of coliform bacteria has achieved after 2 minutes of treatment. The biological oxygen demand value showed a maximum reduction of 30 % at 3600 rpm during a 20-minute treatment cycle. The chemical oxygen demand value for the same time showed a similar pattern of decrease by 40 % at a linear temperature rise. In other words, the treatment in the proposed type of rotor-pulsation apparatus can be considerate as auxiliary equipment in the technologies of neutralization of concentrated milky whey wastewater. Recirculation treatment for 20 minutes at 3600 rpm is consider as optimal.

Keywords: *biological oxygen demand, chemical oxygen demand, hydrodynamic cavitation, microbiological indicator, rotor-pulsation apparatus, wastewater of acidic milky whey*

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1. Introduction

The dairy industry is one of the key sectors of the food industry. At the same time, it is the most material- and energy-intensive industry, which is associated (Kaur et al., 2021; Demire et al., 2005; Stasinakis et al., 2022; Sablii, 2013; Ete, 2024; Givlyud, 2014) with the generation of a significant amount of high- and low-concentrated wastewater. Their insufficient treatment causes a significant environmental load. Particularly acute is the problem of utilization of acid milky whey, which is considered one of the main by - products of cheese production, greek yogurt, casein, etc.) (Erickson, 217; Dinkci, 2021; Sablii, 2013). Its volume is actually equal to the amount of milk processed at the dairy. According to the International Dairy Federation, about 50 % of milky whey ends up in the sewer system as wastewater. In Ukraine, according to the authors (Ivanitsky et al., 2022; Kosheleva, 2020; Givlyud, 2014), most of the whey is poured into the sewer along with wastewater. The difficulty of ensuring treatment is associated (Sablii, 2013; Slavov, 2017; Kushwaha et al., 2011) with the instability of the wastewater composition and its acidity. (pH 3.6…5.1). Since high acidity creates a microbial load, which determines the high level of biological oxygen demand (BOD). In addition, such wastewater has a high chemical oxygen demand (COD), indicating its high organic load. Thus, according to some sources (Kushwaha et al., 2011; Dinkci, 2021; Sablii, 2013; Kosheleva, 2020; Gyvljud, et al., 2015; Semenova et al., 2019), COD can reach 10000…50000 mg O_2 / L, and BOD about 4970…26400 mg O_2 / L, which makes wastewater the particularly problematic effluent for treatment technologies and dangerous in terms of ecology. Therefore, before the wastewater enters the sewage system, enterprises carry out their preliminary neutralization by mixing acidic and alkaline wastewater. However, this requires appropriate volumes of wastewater and requires a large production area due to the need to store it in special tanks. It complicated by the need for mandatory mixing with averaging in the reactor and secondary sedimentation. At the same time, this does not protect against accidental discharges of aggressive wastewater into the sewage system. Therefore, in order to prevent emergency discharges and decrease the BOC and COD in dairy wastewater to the standard, it recommended using a combination of different treatment methods depending on the type and concentration of the pollutant.

Utilization technologies are traditionally the first to carry out mechanical treatment to remove suspended solids. It is realized by settling, filtering and, most often, (Kovalchuk, 2021) using pressure flotation. Then, depending on the concentration of the pollutant and the capabilities of the enterprise, various combinations are used: chemical, physico-chemical or biological treatment. The use of chemical treatment allows reducing the organic load (COD, BOD) in dairy wastewater, neutralizing the increased acidity, and removing suspended solids by oxidation and neutralization. It mainly implemented in coagulation / flocculation technologies by adding coagulants (metal salts) and flocculants (polymers) to destabilize colloidal particles (proteins, fats) and form flakes. Chemical neutralization technologies use alkaline reagents to increase the pH of wastewater, neutralize lactic acid and partially precipitate salts. Technologies for chemical oxidation of milky whey wastewater involve the use of strong oxidants, including hydrogen peroxide, Fenton's reagent, ozone, which allow lactose and proteins to decompose in the wastewater to CO_2 i H_2O. In addition to the above approaches, enterprises use electrochemical treatment. The principle of operation of such equipment based on the use of electrodes to generate coagulants (Fe^{3+}, Al^{3}) and oxidants (O_2, $OH\cdot$) in wastewater. As a reagent, considered electrodes with Fe or Al (Yonar, et al., 2018; Kushwaha, et al., 2010; Şengil, et al., 2006) to be the most effective. In case of phosphates and nitrogen, chemical sediment also occurs. Despite the rather high efficiency of the reagent method, it does not allow for the complete eliminate of lactose and resistant organic compounds, which limits the reduction of COD and BOD to the regulatory values. In addition, it remains highly costly and accompanied by the generation of significant amounts of sediment and by-products that require additional utilization. Therefore, the combination of the chemical method with various physical processes (filtration, sedimentation, etc.) is still consider (Yonar, et al., 2018) to be a priority and more effective today. For example, chemical destabilization of colloids (proteins, fats) by coagulants followed by physical deposition using flocculants or chemical formation of coagulants (Fe^{3+}, Al^{3+}) on electrodes with physical deposition of contaminants (electrocoagulation). It is known that the effective effect on the pH and composition of the wastewater of the physical separation of ions (Ca^{2+}) through membranes under the influence of current with chemical influence (electrodialysis). It is also effective to use filtration through a porous layer (marble, limestone, ash, slag) with chemical neutralization of acidity. A well-known combination of adsorption of organic compounds on sorbent with chemical interaction, which involves the binding of acid. In this case, activated carbon or various modified sorbents are most often used. In different countries, according to different data (Sablii, 2013; Myronchuk, 2019; Ibañez, 2023; Yonar, 2018; Pillath 2023; Buchanan et al., 2023) preference are given to coagulation-flocculation technologies, membrane filtration or (Bortoluzzi, et al., 2017) integrated systems that include the sequential use of microfiltration plus nanofiltration and reverse osmosis. Other sources cite data (Kosheleva, 2020; Sakalova, et al., 2024; Gyvljud, et al., 2015) on the priority of using sorption and (Sablii, 2013) reagent flotation. Baromembrane equipment and the passage of wastewater through ion exchange resins with chemical ion exchange are also considered (Mironchuk, et al., 2019; Zmievskyi et al., 2013; Al-Tayawi, N.; et al., 2013) quite effective, although they are more expensive. According to (Kosheleva, 2020; Sablii, 2013), sorption and reagent flotation technologies are considered the most popular in Ukraine. However, the use of the last ones has limitations associated with the formation of a significant amount of sediment and its required neutralization. Extraction technologies are less popular, although effective, as they remove up to 90 % of lactic acid in one cycle, decreasing COD to 70 % in just a few hours. However, the use of organic solvents poses a risk to the environment and requires neutralization.

In view of the authors (Sablii, 2013; Tkachenko, et al., 2012; Bazrafshana, et al., 2016) effective today and promising in the future is the use of biological purification technologies. Currently, it mainly uses in aero tanks, biofilters, bioreactors, and methane digesters. According to other sources (Gavala, et al., 1999; Ramasamy, et al., 2004), preference give to the use of methane fermentation plants, UASB reactors with an upward flow of anaerobic sludge (anaerobic digestion of milky whey). However, the implementation of the process requires time, large areas, and energy consumption due to the need to supply air to maintain aerobic conditions. In addition, there is need to neutralize the biomass of activated sludge and the inability to reach wastewater indicators to the level recommended by standards. Therefore, it considers more effective to use a combination with other methods.

The analysis of the latest data shows that the increase in regulatory requirements for wastewater treatment requires the use of deeper treatment involving not only traditional technologies but also hybrid innovative approaches. For this purpose, more high-cost technologies are increasingly involved, which are an alternative to traditional. These include photocatalytic oxidation using TiO_2 photocatalysts under the influence of ultraviolet light, plasma-chemical oxidation using low-temperature plasma, which allows for 99 % mineralization of organic substances due to the plasma's reactivity. However, these studies are currently at the stage of pilot devices which testing in the laboratories. Also, under active research are electromagnetic treatment with high-frequency pulses and bio electrochemical purification systems. For disinfection, UV-lamps and various cavitation devices are consider to be among the most effective, in particular, treatment with ultrasound, hydrodynamic cavitation, magnetic action, ultraviolet light, high frequency current, gamma rays. According to (Zheng, et al., 2022; Vitenko, et al., 2006; Veretelnyk, et al., 2014; Sukhatskyi, et al., 2020; Gyvljud, et al., 2015) acoustic and hydrodynamic cavitation is the most promising among them. At the same time, other numerous studies (Zheng, et al., 2022; Tselen, et al., 2022; Vitenko, 2009) have shown that hydrodynamic cavitation should be considered as a more significant alternative to acoustic cavitation both in terms of productivity and energy saving. According to Fedotkin I., Nemchishin A., Komarov A., Vitenko T., Sun H. and (Zheng, et al., 2022; Chaudhuri, et al., 2024; Gashin, et al., 2010), it has been proven that hydrodynamic cavitation causes a disinfection effect in the treatment of various liquid systems. Therefore, the method is successfully used as an auxiliary equipment for the treatment of industrial wastewater in the pharmaceutical, chemical, oil refining and food industries (Zheng, et al., 2022; Falyk et al., 2017). Its undoubted advantage is ecological, high efficiency with a relatively with short processing duration. Today, the process is realized mainly in special cavitation devices (orifice plate, venturi tube, rotor reactor), hydrodynamic injectors. At the same time, it is important to choose the optimal process modes, the design and the ability to scale.

The peculiarity of cavitation mechanism lies in creating a local pressure drop below saturated vapor pressure that causes the formation of cavitation bubbles in the liquid. When they are compressed, a quick collapse occurs. As a result, there is an instantly increase temperature (up to 2000 K) and pressure (up to 400 MPa) in localized areas of the liquid (Ivanitsky, et al., 2022; Tselen, et al., 2023). This process is characterized (Song, et al., 2022) by the release of a large amount of energy, which contributes to the oxidation of organic compounds and the decomposition of complex molecules such as lactose, proteins, and fats, which are the main components of dairy wastewater. Numerous studies have shown (Prazeres, et al., 2013; Aftanaziv, et al., 2020; Thanekar, et al., 2018) that the prospect of using this method is in combination with other traditional or innovative methods, for example, combination with reagent treatment using hydrogen peroxide, Fenton's reagent, ozone, etc. or combination with membrane technologies. It is known that exposure to hydrodynamic cavitation not only destroys organic molecules, but also improves their bioavailability for further treatment by biological methods such as anaerobic digestion or biological treatment.

Thus, the analyzed data prove the effectiveness of combining hydrodynamic cavitation with traditional and innovative methods, and especially their prospects for improving the technologies of dairy industry wastewater treatment. In particular, to reduce energy costs, improve treatment efficiency, and increase processing productivity by scaling up to industrial needs.

Having analyzed the experience of previous research and disadvantages of existing equipment, the authors proposed the use of a rotor-pulsation apparatus (RPA) of a specially designed unit of the rotor-stator-rotor type with a gap of 100 μm to improve the efficiency of milky whey wastewater treatment with the prospect of integration into existing technologies.

In order to determine the effectiveness of the proposed design of the RPA, as well as to find the optimal modes of the process, we formulated a number of tasks:

- Investigation of the effect of changing the treatment time and speed of rotation (from 1800 to 3600 rpm) on the dynamics of microbiological parameters, BOD and COD of treated samples;

- Investigation of the effect of changes in processing time and the number of rotations on the dynamics of temperature and dissolved oxygen concentration in the samples under study.

The solution of these problems will provide an intense and simultaneously uniform hydrodynamic effect on the treated milk whey, neutralizing its negative impact, eliminating the problem of low productivity of cavitation devices with the prospect of combining with other treatment methods.

2. Materials and methods

The material for the study was samples of concentrated wastewater from acidic milky whey with a pH of 4.3. The total number of microorganisms was $1 \cdot 10^5$ CFU/ml where lactic acid bacteria prevailed (*Lactococcus, Lactobacillus*) and coliforms bacteria in quantity 10^1 CFU/ml. The initial BOD is 20000 mg O_2/ L, COD 35000 mg O_2/ L.

Experimental studies carried out on a laboratory stand (Fig. 1), which included a storage recirculation tank 1 and RPA 2 for hydrodynamic treatment.

Fig. 1. *Experimental stand:*
1 - storage tank; 2 - RPA

During the experiment, the model fluid fed from the recirculation storage tank 1 to the RPA 2 for hydrodynamic treatment. The minimum recirculation time was 2 minutes, the maximum – 30 minutes with sampling at regular intervals. For the first series of the experiment, the rotation speed was 1800 rpm, and for the second – 3600 rpm. The temperature of the researched samples before treatment was 20 °C. After each experiment was completed, liquid samples were collected to following determination of COD, BOD, microbiological indicators, and dissolved oxygen concentration. During each experiment, temperature changes in the treated samples were measured. COD studied in accordance with KND 211.1.4.021-95, which is based on dichromate oxidation with heating and titration of excess oxidant with adaptation to the high organic load of wastewater. The BOD is determined in accordance with KND 211.1.4.024-95. The analysis of microbiological parameters carried out according to DSTU 7357:2013. The concentration of dissolved oxygen measured on an oximeter EZODO PDO-408. The measurements were carried out according to the standard methodology without contact of the samples with air. The data set analyzed in Microsoft Excel software.

3. Results and discussion

The research results have shown that the developed design of the RPA and the processing parameters allow reducing the number of mesophilic aerobic and facultative microorganisms (MAFAM) in research samples (Table 1). It was found that the effect of 10 minutes treatment reduces the indicator from $1{\cdot}10^5$ to 10 CFU in 1 g at 3600 rpm and to $1{\cdot}10^2$ CFU in 1 g at 1800 rpm. The observed dynamics were explained by the synergistic the influence of localized thermal effect, shear stresses, turbulent flows, and oxidation caused by the formation of free radicals. Thus, the factor of thermal influence is the sensitivity of mesophilic bacteria to temperature jumps (up to 2000 K), which are created because of the collapse of bubbles in local areas of the treated fluid. This leads to inactivation of enzymes and impaired metabolism. At the same time, the resulting collapse of bubbles splits water molecules and organic compounds, forming reactive oxygen species such as hydroxyl radicals (OH•). In conditions of high acidity, their activity increases. The formed radicals destroy lipid membranes, proteins of microorganisms, causing irreversible changes. The intense shear stresses and turbulent flows created in the RPA cause instantaneous breaking of lactic acid bacteria cells, which are the basis of MAFAM. It is known that these bacteria do not have resistant spores and have rather weak membranes, which explains their inactivation (Table 1)

Table 1. *Number of mesophilic aerobic and facultative microorganisms MAFAM, (CFU in 1 g) in the treated samples*

Time, min	RPA speed of rotation	
	1800 rpm	3600 rpm
0	$1{\cdot}10^5$	$1{\cdot}10^5$
1	$5.3{\cdot}10^4$	$5{\cdot}10^4$
2	$5{\cdot}10^3$	$1{\cdot}10^3$
4	$2{,}5{\cdot}10^3$	$5{\cdot}10^2$
6	$1.3{\cdot}10^3$	$2.4{\cdot}10^2$
8	$6.2{\cdot}10^2$	$1{\cdot}10^2$
10	$1{\cdot}10^2$	10
12	50	8
14	30	6
16	20	4

Analysis of the number of coliform bacteria showed their absence after 2 minutes of treatment. It can be assumed that within the first few minutes of treatment, the destruction of the outer membrane and the thin cell wall occurs, causing the lysis of coliform cells. Membranes are damaging by radical oxidation (OH•), and local heating contributes to the denaturation of cellular components.

Also analyzed the influence of cavitation effects on the BOD (Figure 2) and established that for the developed design of the RPA and the selected operating parameters, the most intense decrease occurs to 20 minutes of treatment. At the same time, in the first 1-2 minutes, the BOD even slightly increases, which can be explain by the release of organic compounds (cytoplasm, enzymes, and metabolites) due to cell destruction. These substances create biodegradable material and temporarily increase the BOD slightly until other microorganisms begin to decompose it.

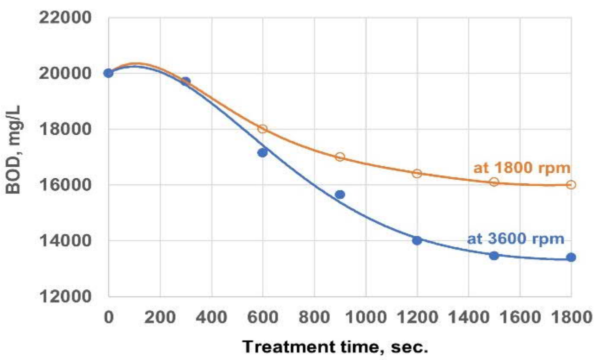

Fig. 2. *Change BOD depending on the treatment time and number of rotations of the RPA*

During the next 20 minutes of treatment, the most intensive decrease occurred, namely by 30 % at 3600 rpm and by 18 % at 1800 rpm. The inactivation of microorganisms, oxidation of lactose, which has a major impact on BOD, and lactic acid by free radicals, and mechanical degradation of proteins explain it. Continuing treatment up to the 30th minute showed stabilization of the parameters and a slight further decrease of 2 % at 1800 rpm and 3 % at 3600 rpm.

Also defined the pattern of changes the COD (Figure 3). The most intense COD reduction observed within 20 minutes of treatment at 3600 rpm to 40 % and another 2 % within the next 10 minutes. Reducing the rotation speed to 1800 rpm made it possible to reduce COD by 29 % in 20 minutes of processing and by 3 % in the next 10 minutes. We explain this pattern by the generation of radicals (OH·) and mechanical influence, which oxidize the main components of wastewater: lactose, lactic acid and, to a lesser extent, proteins, fats and other organic acids. The intensity of oxidation is explained by the simple structure of lactose and lactic acid, as well as the high concentration of radicals (OH•) in an acidic environment.

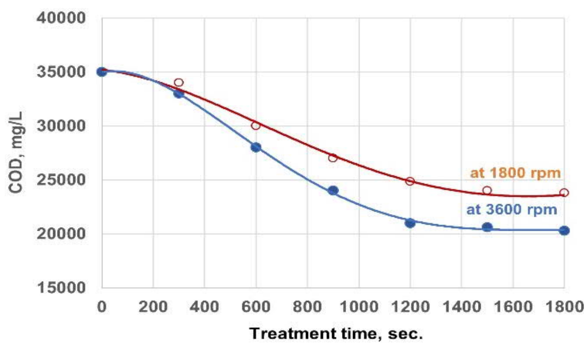

Fig. 3. *Change COD depending on the treatment time and number of rotations of the RPA*

Since one of the main parameters for assessing the effectiveness of cavitation treatment (Zheng, et al., 2022) is temperature, we determined its dynamics during experiment (Figure 4) and the depending with the dynamics of COD and BOD reduction. We observed that the most intense decrease in COD and BOD occurred before reaching 40 ºC at 3600 rpm and up to 30 ºC at 1800 rpm for 20 minutes of treatment. Thereafter, the temperature continued to increase linearly to 54 ºC at 3600 rpm and to 38 ºC at 1800 rpm, however, COD and BOD values, stabilized. The observed dynamics are explained by the fact that an increase the temperature leads to changes in the physicochemical mechanisms of cavitation. The main factors include an increase in saturated vapor pressure, which hinders bubble formation, a decrease in collapse intensity, and a reduction in OH· radical generation, thereby slowing down the oxidation of lactose and lactic acid.

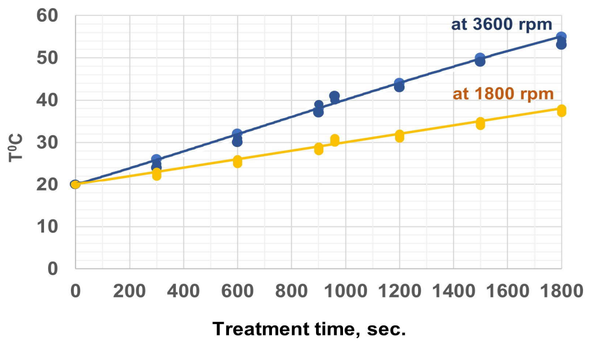

Fig. 4. *Temperature dependence on treatment time*

Figure 5 shows the dependence of the change in the concentration of dissolved oxygen in research samples during treatment and shows that its concentration influences the stability of wastewater. In particular, low oxygen concentration promotes anaerobic fermentation, increasing acidity (pH drops below 4) while its high concentration maintains a neutral pH.

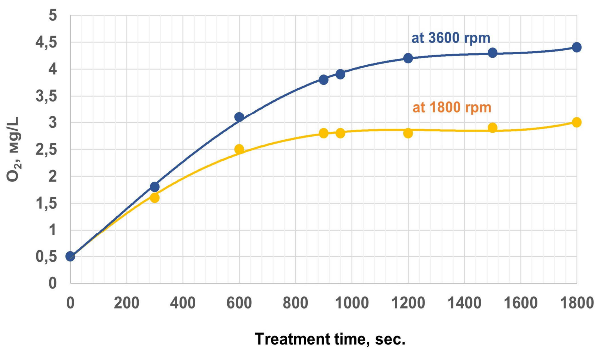

Fig. 5. *Changing the concentration of dissolved oxygen depending on the time of treatment*

In this case, the low concentration of dissolved oxygen before cavitation treatment (0.5 mg/L) associated with high microbial activity and BOD. The results after treatment showed an increase of up to 3.0 mg/L within 30 minutes of treatment at 1800 rpm and up to 4.4 mg/L at 3600 rpm. This pattern can be explained by the inactivation of bacteria and the oxidation of organic compounds. The mechanism is that the treatment of cavitation inactivates bacteria, reducing the consumption of oxygen, which allows accumulating dissolved oxygen. On the other side, the formed OH· radicals to oxidize lactose and lactic acid to CO_2 and H_2O, reducing COD, which also partially reduces the need for oxygen and contributes to its accumulation.

3. Results and discussion

The possibility of using the developed RPA design for treatment the wastewater of acid milky whey is studied. Evaluation carried out according to microbiological indicators, BOD and COD under different treatment regimes. As a result of the research, it was found that the microbiological indicator MAFAM decreased most significantly from $1 \cdot 10^5$ CFU in 1 g to 10 CFU in 1 g at 3600 rpm and to $1 \cdot 10^2$ CFU in 1 g at 1800 rpm within 10 minutes of treatment. At the same time, the neutralization of coliform bacteria was achieved after 2 minutes of treatment.

It has been found that the pattern of decrease in BOD and COD indicators observed regardless of the treatment modes. The most significant decrease in BOD achieved during the 20-minute treatment cycle by 30 % at 3600 rpm. The COD value for the same time showed a 40 % decrease. Continuing the treatment up to 30 minutes showed stabilization these parameters.

Experimentally obtained linear temperature rise from 20 °C to 54 °C within

30 minutes at 3600 rpm and up to 38 ℃ at 1800 rpm.

The concentration of dissolved oxygen increased from 0.5 mg/L to 3.0 mg/L at 1800 rpm and to 4.4 mg/L at 3600 rpm over the same period.

The obtained dependences of COD and BOD reduction under conditions of increasing temperature showed the most intensive reduction up to 40 ℃ at 3600 rpm and up to 30 ℃ at 1800 rpm during 20 minutes of treatment.

In other words, cavitation treatment is most effective during 20 minutes of treatment and the optimal recirculation mode is 20 minutes at 3600 rpm. The results obtained with the proposed equipment can be further use to improve the efficiency of neutralization of concentrated milky whey wastewater.

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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ОЧИЩЕННЯ СТОКІВ НА ПІДПРИЄМСТВАХ МОЛОЧНОЇ ПРОМИСЛОВОСТІ З ЗАСТОСУВАННЯМ КАВІТАЦІЙНОГО ОБЛАДНАННЯ

Ободович О.М.[1], *Целень Б.Я.*[1], *Іваницький Г.К.*[1, 2], *Саблій Л.А.*[2],

Гоженко Л.П.[1], *Недбайло А.Є.*[1], *Радченко Н.Л.*[1]

[1] Інститут технічної теплофізики НАН України, Україна, ittf_tds@ukr.net

[2] Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Україна

В статті розглянуто проблему нейтралізації концентрованих стоків молочної сироватки. Актуальність досліджень зумовлена складністю процесу утилізації стоків кислої сироватки через нестабільність їх складу, високу кислотність, мікробне навантаження, яке визначає високий рівень біологічного споживання кисню. До цього додається високий показник хімічного споживання кисню, котрий відображає значне органічне навантаження створюючи цим проблему для очисних технологій і екологічну небезпеку. Авторами проаналізовано традиційні та інноваційні технології очищення з акцентом на недоліках і перевагах кожного. Запропоновано використання гідродинамічної кавітації, як допоміжного інтенсифікуючого методу в технологіях нейтралізації концентрованих стоків молочної сироватки і спеціально розроблену конструкцію роторно-пульсаційного апарату для його реалізації. З метою визначення доцільності пропонованого рішення сформульовано завданням оцінити зміну показників хімічного споживання кисню, біологічного споживання кисню та мікробіологічного показника при різних режимах обробки та визначити закономірність зміни температури, концентрації розчиненого кисню від часу обробки. За результатами досліджень визначено, що найбільш суттєво мікробіологічний показник мезофільних аеробних і факультативно анаеробних мікроорганізмів знизився протягом 10 хвилин обробки при 3600 об/хв. Разом з цим, знешкодження коліформних бактерій досягнуто вже через 2 хвилини обробки. Показники біологічного споживання кисню і хімічного споживання кисню найбільш інтенсивно знижувались протягом 20 хвилинного циклу обробки відповідно на 30 % та на 40 % при лінійному зростанні температури. Таким чином, обробку в роторно-пульсаційному апараті пропонованого типу можна розглядати, як допоміжну стадію в технологіях нейтралізації концентрованих стоків молочної сироватки. Для цього оптимальною слід вважати обробку в режимі рециркуляції протягом 20 хв при 3600 об/хв.

Ключові слова: *біологічне споживання кисню, хімічне споживання кисню, гідродинамічна кавітація, мікробіологічний індикатор, роторно-пульсаційний апарат, стічні води кислої молочної сироватки*