Review article

Common Issues in Aeration System Choice for Flotation Wastewater Treatment

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Abstract

Keywords

wastewater treatment;

flotation;

system of aeration;

flotator;

parameters of wastewater

Flotation wastewater treatment is widely used in various treatment systems. The choice of aeration system plays a considerable role in the development of highly efficient flotation tanks. The objective of this work is to point out factors that influence the choice of flotator type, and to offer recommendations based on literature review and data analysis. In this paper, the various types of aeration systems used in flotation tanks are considered: mechanical, pneumatic, pneumohydraulic and ejection systems as well as dissolved air flotation and electroflotation systems. Their main advantages and disadvantages are pointed out. The specific features of flotation tank constructions are considered. The factors that influence the choice of aeration system such as the parameters of wastewater (pH, conductivity, temperature), requirements for the quality of treated water, reliability and simplicity of maintenance, capital and operating costs are defined. The peculiarities of various aeration system applications in different conditions are revealed. A comparison of the energy consumption of the considered systems of aeration is presented. In conclusion, practical recommendations for the choice of aeration system depending on various factors are offered.

1. Introduction

The problem of wastewater treatment is an actual problem for almost all branches of the economy including transport, agriculture, oil production, energy, and other sectors. The wastewater produced from the oil, transport and energy industries is mainly contaminated with oil and grease and suspended substances; there can be also some specific contaminating substances, for example heavy metals, depending on the technological process involved. Wastewater produced from the

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agricultural sector is mainly contaminated with organic substances and is characterized by high fat content, high chemical oxygen demand (COD) and high biochemical oxygen demand (BOD). There can be also nutrients, pathogens, detergents and sometimes antibiotics in the water. The release of such effluents without prior treatment has a negative impact on ecosystems and is unacceptable [1].

One of the sustainable development goals (SDGs), set by United Nations (UN) is: “Ensure availability and sustainable management of water and sanitation for all”. More specifically, the UN aims by 2030 to improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halve the proportion of untreated wastewater and substantially increase recycling and safe reuse globally; and by 2030, to expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies [2].

One of the ways to achieve these goals is to develop highly efficient wastewater treatment systems. A wastewater treatment is, as a rule, a multistage process. Flotation is considered to be the main stage in many cases, especially for the treatment of wastewater that contains fats, grease and oil; for example, wastewater from meat processing plants and petrochemical refineries [3]. The process of flotation is based on the effect of wettability: wastewater is aerated with gas bubbles, and particles of hydrophobic contamination become attached to the bubbles and float, forming a froth layer on the surface [4]. Flotation tanks can be classified into different categories, one of which is a system of aeration (or method of gas bubbles formation). The aeration system is the base of the flotation process, and the main target of its development is to produce air-water mixtures with the desired parameters: appropriate bubble size (usually less than 100 μm) and high superficial gas velocity.

The froth flotation process was first developed and used in the mining industry at the beginning of 1900s and gained further widespread application in wastewater treatment industry. The first aeration systems were mechanical and pneumatic air induced systems. Later, electrolytic and vacuum methods were introduced. Vacuum flotation in wastewater treatment systems was first used in the 1920s, and then the technology was developed to include dissolved air flotation (DAF) in the 1960s. At that time, it started to be widely used in the pulp and paper industry, in drinking water production, and in wastewater treatment [3].

Nowadays the most commonly used systems of aeration are dissolved air flotation (DAF), mechanical flotation, pneumatic flotation and electroflotation. There are also methods in which an air-water mixture is formed using ejectors and pneumohydraulic aerators [5]. DAF is considered to be the most commonly used technology for wastewater treatment in various sectors: agricultural, industrial and domestic and municipal [1]. Examples of wastewater treated with DAF are: oil-refinery wastewater [6, 7], diary wastewater [8, 9], textile wastewater [10], and restaurant wastewater [11]. Mechanical flotation is widely used in the oil and gas industry, and in the pulp and paper mills, and diary industries [5]. Electroflotation is used for highly polluted wastewater with hardly removed contaminants such as heavy metals in various industries: textile industry, oil production industry, metal finishing, semiconductor industry and so on [12]. Pneumatic, ejection and pneumohydraulic systems of aeration can be applied in the transport and energy industries. It is also possible to combine various systems of aeration in one flotation tank [13, 14].

Flotation wastewater treatment is carried out in an apparatus called flotation tank (flotator), or in a combined apparatus that involves several consecutive or parallel processes that include a flotation tank as one of them. Examples of combined apparatus are flotation-sedimentation tank (combines the processes of flotation and sedimentation) [15], and electrocoagulation-flotation tank (combines the processes of coagulation and flotation) [16-23]. The use of a combination apparatus allows the reduction of the area occupied by the treatment equipment, capital, and operating costs.

The development of a wastewater treatment system is a complicated task with the target to intensify the treatment process in order to meet regulatory requirements while reducing the cost of the treatment process [24]. As the flotator is often the main device in the system, the choice of its type is quite a common question that arises during the development of a wastewater treatment system. Moreover, its efficiency and reliability depend not only on the chosen type but on other parameters.

The aims of this work are the clarification of the factors that influence the choice of flotator type, and the recommendation of a flotator.

2. Flotation Systems

The initial data for the development of new wastewater treatment system or the modernization of an existing one include characteristics of contamination, requirements for the quality of treated water, and wastewater flow rate (volume of wastewater produced during an hour or a day (24 h)).

The inconsistency of wastewater contamination can cause problems during the development of a treatment system [25]. There is always an economical factor that includes capital and operating costs [24]. These costs depend on the area of treatment, maintenance staff, usage of chemicals and electric power costs. The significance of various factors was analyzed and the following factors that influence flotator type choice were chosen [24-26]:

- parameters of wastewater, requirements for the quality of treated water – which define the required efficiency and appropriate parameters of the aeration system;
- the possibility of preliminary experiments – which allows the acquisition of more precise initial data for the flotator development;
- compactness of equipment – the provided area for the flotation set up defines its configuration, geometrical shape, while the compactness of the equipment also influences the costs;
- reliability and operational complexity – which define the special requirements for the staff during maintenance;
- the capital and operating costs – important economic factors which need to be reduced;
- the reason for adopting a new flotator installation – the factors that have influence on the choice of aeration system, and the configuration of flotation set up.

These factors can contradict each other. Ideally, the best solution is to develop a simple compact reliable and efficient flotator with minimal capital and operating costs. However, this is hard to achieve in practice. These factors along with the recommendations for the choice of flotator are described further after brief characteristics of aeration systems.

2.1 Systems of aeration

Considering the parameters of aeration systems, the efficiency of the flotation process is influenced by bubbles size and superficial gas velocity. The smaller the bubbles are, and the bigger their quantity is, the higher the probability of bubble-particle aggregate is [4, 27]. However, the increase of air flow rate in most cases leads to an increase of bubble size [4]. Further, the most common (widely used) systems of aeration are considered.

2.1.1 Pneumatic

The pneumatic system of aeration or induced air flotation (IAF) is considered to be the simplest one. The air is supplied through the special devices, aerators (see 6 in Figure 1) that have a porous structure. As a result, the air comes out forming bubbles with size of about 0.2 mm and larger. The size of the bubble depends on the construction of the aerator and the air flow rate [28, 29]. However,

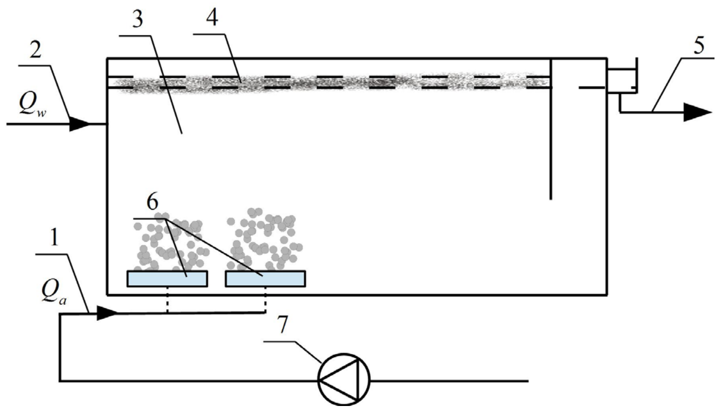

Figure 1. Scheme of a pneumatic flotator
1 – air inlet; 2 – wastewater inlet; 3 – flotation cell; 4 – froth layer; 5 – treated water outlet; 6 – aerators; 7 – compressor

this type of aeration does not always perform efficiently. For example, its efficiency when used in the treatment of oily emulsions was less than 50 %, so a combination of coagulation and flotation was proposed instead by Chawaloesphonsiya *et al*. [30].

2.1.2 Electroflotation

In case of electroflotation, hydrogen bubbles are formed on the cathode and oxygen bubbles are formed on the anode due to the electrolysis of water caused by a direct electric current. The bubble sizes generated are approximately in the range of 40-80 µm, depending on the current density, pH, and conductivity [31-35].

When a sacrificial anode is used, the anode dissolves forming metal hydroxides, and a process of electrocoagulation takes place. Iron and aluminum anodes are the most commonly used [18, 36], however, zinc, copper [37, 38] and dimensionally stable anodes made of coated metals such as titanium [39-41] are also used. The electrodes can be placed in the flotation cell horizontally (as shown in Figure 2) or vertically. A typical electroflotation tank is equipped with additional wires that can be seen on the outside.

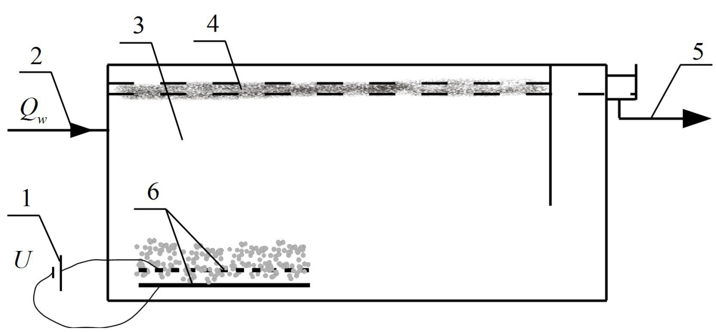

Figure 2. Scheme of an electroflotator
1 – direct current source; 2 – wastewater inlet; 3 – flotation cell; 4 – froth layer; 5 – treated water outlet; 6 – electrodes

2.1.3 Mechanical flotation

In this method, bubbles are generated using an impeller (see 6 in Figure 3) that rotates at high speed and produces a zone of lower pressure where air is induced [4, 29, 42]. The bubble size is about 0.5-1.5 mm. The impeller engine can be seen in the upper part of this apparatus [28, 43-45]. This aeration system is widely applied in flotation tanks used in wastewater treatment systems at oil refineries, natural gas processing plants, and petrochemical and chemical plants [46].

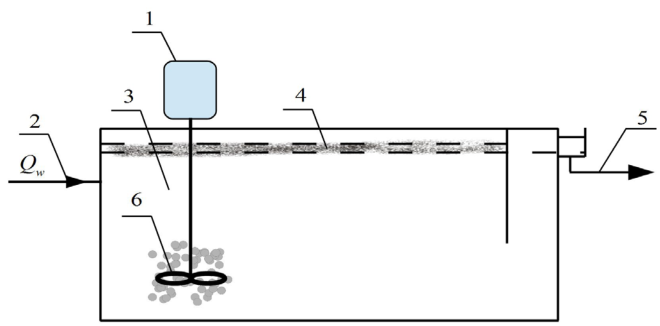

Figure 3. Scheme of a mechanical flotator
1 – engine; 2 – wastewater inlet; 3 – flotation cell; 4 – froth layer; 5 – treated water outlet; 6 – impeller

2.1.4 Ejection flotation

The principles of aeration with the use of ejector (Figure 4) are described. Water goes through the convergent nozzle of the ejector at a high speed (about 15-17 m/s), and a zone of low pressure is formed. Due to this, the air is sucked into the ejector [47]. Thus, there is no need for any additional equipment such as compressors for air supply. According to Serizawa *et al*. [48] and Kawamura *et al*. [49], the average size of bubbles generated by the ejectors of simplest construction is about 1-3 mm and about 250-500 μm under certain operating conditions. This set up does not allow the achievement of high quality of purification.

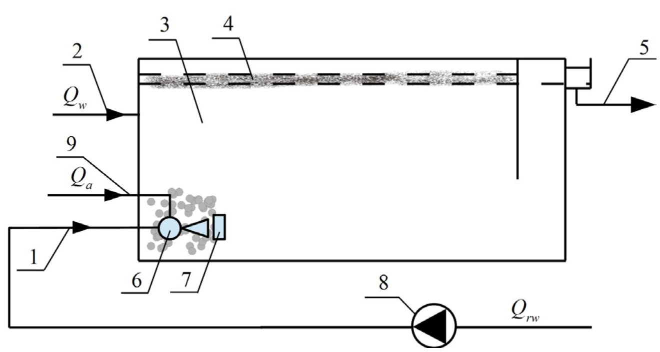

Figure 4. Scheme of an ejection flotator
1 – recycle water inlet; 2 – wastewater inlet; 3 – flotation cell; 4 – froth layer; 5 – treated water outlet; 6 – ejector; 7 – disperser (optional); 8 – pump

Modified constructions of ejectors have been applied in order to increase efficiency. Examples are Venturi ejector [50-52], swirling Venturi ejector [52], and microbubble generators [51, 53-55]. Special disperses used for bubble break up and improve bubble distribution in the flotation chamber that are installed after the ejector include swirling chambers [56], breaker disks [56, 57], and vortex mix devices [58]. The main advantage of a disperser is its universality: it can be used in a newly developed system, or in an existing one for its enhancement.

2.1.5 Dissolved air flotation (DAF)

In DAF devices, air is dissolved in water using a special device called a saturator under the pressure of about 300-600 kPa. As the saturated water is passed through the nozzle (see 6 in Figure 5) in the flotation chamber, sudden depressuration occurs, and the air is released forming microbubbles with sizes of about 10-100 μm [59-61]. The bubble size and gas hold up depend on the temperature [60, 62], spraying devices [63], saturator pressure [60, 62], and water flow velocity [64].

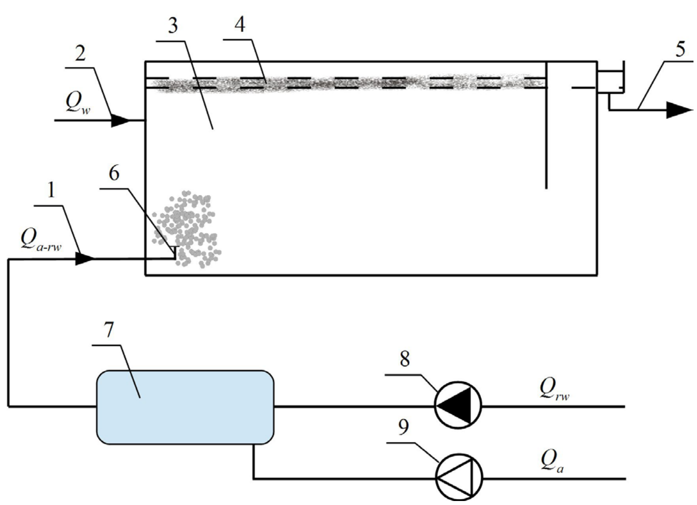

Figure 5. Scheme of a DAF flotator
1 – saturated water inlet; 2 – wastewater inlet; 3 – flotation cell; 4 – froth layer; 5 – treated water outlet; 6 – nozzle; 7 – saturator; 8 – pump; 9 – compressor

2.1.6 Pneumohydraulic flotation

The pneumohydraulic method is realized by the transmission of an air-water mixture through the aerator. Previous works [11, 55, 65-68] showed that the supply of the air before the pump is the most efficient method to generate microbubbles. This aeration method is shown schematically in Figure 6. In this case, air is continuously injected into the low-pressure suction side of the pump (self-priming pump or a special centrifugal multiphase pump like NIKUNI) and then through the aerator. As a result, bubbles of sizes 30-80 μm are generated [55, 67, 68]. The mechanism of bubble formation combines the bubble break up due to the shearing effect caused by the pump impeller and the dissolution of air in water at high operating pressure [67]. According to Hayatdavoudi *et al*. [66], a novel compact flotation unit (CFU) that had been equipped with dissolved gas flotation pump was proposed. It possessed such advantages as a small footprint and shorter residence time.

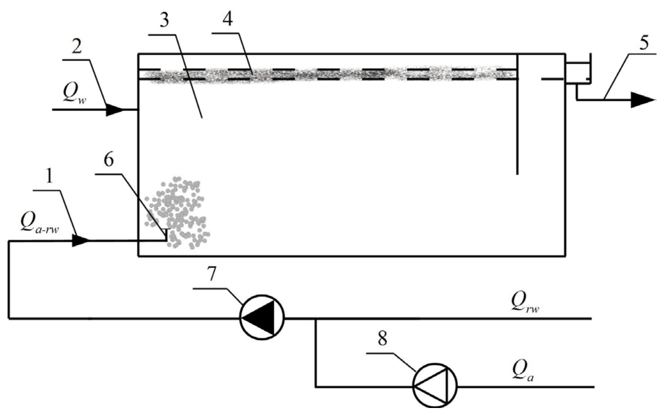

Figure 6. Scheme of pneumohydraulic flotator
1 – air-water mixture inlet; 2 – wastewater inlet; 3 – flotation cell; 4 – froth layer; 5 – treated water outlet; 6 – aerator; 7 – pump; 8 – compressor

2.1.7 Other aeration systems

There are also other methods of bubble generation such as thermoflotation (bubbles are formed in a boiling process), chemical (bubble formation as a result of chemical reactions), and biological (the use of microorganisms) [45]. All these methods are quite specific and are seldom used due to the complicated maintenance and difficulty in control of the operating parameters. For example, special conditions (temperature, nutrition and so on) for microorganisms in biological flotation must be provided. The drawbacks of chemical flotation are connected to uneven air bubble production: when a chemical reaction takes place in a liquid phase, the value of gas saturation firstly increases and then falls with the bubble growth. In the case of using solid chemical substances, the bubbles are produced mainly on their surface [69]. The possible application of chemical and biological flotation can be seen in the field of sewage sludge compaction [24]. Speaking of thermoflotation, its usage requires special operating conditions due to the high temperature of water which also leads to very high energy consumption. However, thermoflotation is used for the separation of biological suspensions and wastewater treatment in the biotechnology industry [70-72].

2.2 Flotation gases

Different gases can be used in different aeration systems (see Table 1); however, atmospheric air is the most commonly used.

Table 1. Flotation gases

№	Flotation Type	Gas
1.	Pneumatic	Air or depends on the source*
2.	Electroflotation	Oxygen and hydrogen
3.	Mechanical	Air
4.	Ejection	Air
5.	Dissolved air flotation	Air or depends on the source*
6.	Pneumohydraulic	Air or depends on the source*

* Different types of gases can be supplied by compressor.

But in some cases, different types of gases such as carbon dioxide [73], ozone [74, 75], and nitrogen [76] are supplied by a compressor. The solubility of gases in water influences the process of DAF. The use of gases with higher solubility can improve the operation of a DAF system: the recycled flow rate can be decreased, and the thicker floats are produced in this case [77]. The solubility values of different gases are presented in Table 2.

Table 2. Solubility of gases (20º C, 760 mm Hg) [61, 77, 78]

№	Type of Gas	Solubility, cm^3 of gas/ cm^3 of water
1.	Oxygen	0.031
2.	Hydrogen	0.018
3.	Nitrogen	0.015
4.	Carbon dioxide	0.88
5.	Atmospheric air	0.02
6.	Ozone	0.368

For example, the use of carbon dioxide can reduce energy consumption in a dissolved carbon flotation aeration system due to the higher solubility of CO_2 in water compared to that of O_2. However, the bubbles generated from CO_2 are bigger (80-300 μm) compared to air bubbles (40-80 μm) and their size increases with increase of pressure in the saturator. On the other hand, the size of air bubbles decreases with an increase in saturator pressure. The typical range of operating pressure for flotation using dissolved CO_2 is about 150-200 kPa, while for dissolved air flotation, it is 400-600 kPa [73].

The use of ozone instead of atmospheric air allows the combination of two methods (flotation and ozonation) in one unit: flotable contamination components can be recovered with bubbles and soluble organic components can be oxidized by an oxidizing agent – ozone [74, 75]. The advantages of such technology are: the decrease of coagulants and flocculants dosage, removal of pathogen compounds, micro-pollutants removal, and the decrease in the amount of excess biological sludge (in cases when dissolved ozone flotation is used for separation of effluent from excess activated sludge) [75]. The combination of two processes in one unit also allows a decrease in the area occupied by the equipment.

Nitrogen is mostly used in mining industry, for example, in molybdenite flotation [79]. According to Hoseinian *et al*. [76], nitrogen was used in ion flotation for Ni(II) removal and the Ni(II) removal rate with the use of nitrogen was the highest when compared to air and oxygen. Speaking about wastewater treatment, it is important to point out that the solubility of nitrogen is about two times lower than that of oxygen, so the presence of nitrogen in the air lowers the air saturation efficiency. In Colic *et al*. [80], continuous venting for nitrogen removal is recommended.

2.3 Factors that influence the choice of flotator type

2.3.1 Parameters of wastewater and requirements for the quality of treated water

The initial data for the choice of wastewater treatment system generally includes the parameters of the wastewater: qualitative and quantitative characteristics of contamination, temperature, pH, conductivity, and water flow rate. These parameters depend on the source of wastewater. The requirements for the quality of treated water are also considered. They depend on the intended method used to treat water, for example, treated water may be destined for a water basin, or another treatment system (municipal canalization), or recycled water supply system [26].

The qualitative and quantitative characteristics of contamination have a big influence on the choice of aeration system. In the most favorable situation, the wastewater has already been produced and the technological processes need not be changed, so the characteristics of contamination are quite stable. In this case, primary experiments are recommended to be carried out. This method can reasonably be used for the modernization of existing equipment, or if the treatment system has not been developed yet. If wastewater is not available for the experiments, it is important to pay attention to the possible expected compounds of contamination. First, experiments can be carried out using synthetic water with similar characteristics to the expected wastewater. It is important to determine whether it is practical to use flotation as one of the treatment stages. Secondly, if the flotation is decided to be used, it is then important to pay attention to some kind of contamination that can potentially change the properties of the water and thus increase or decrease the efficiency of treatment. Moreover, if the treatment systems have already been developed for a similar kind of wastewater (for example similar car washes in one region), it is then reasonable to use the developed flotators.

When water is contaminated with hydrophobic substances with good flotability, such as oil and fat emulsions and the requirements for water quality are not very strict, the application of an aeration system such as pneumatic, mechanical, or ejection flotation system that generates bubbles of size about 250-1000 μm is possible. When the water is contaminated with fine particles, or hydrophobic-hydrophilic substances with low flotability such as coal particles, and the requirements of water quality are high, it is necessary to choose an aeration system that allows the generation of microbubbles with size less than 100 μm. For example, microbubbles with size 30-50 μm allow the recovery of oil drops with size more than 30 μm without chemicals. The addition of coagulants and flocculants allows the recovery of oil drops of size more than 10 μm [81], and also of oil in the emulsified and dissolved state. The most appropriate aeration systems are the DAF, pneumohydraulic and electroflotation systems.

When a wide range of contaminants of different properties including fine particles with low flotability are present in the water, a system of aeration that generates a polymodal distribution [82] with a wide range of bubble sizes can be used. It can be achieved by combining different aeration systems [13, 14], or using special aeration devices [83, 84].

The use of combined aeration systems facilitates the production of a wide range of bubble sizes due to the addition of bubbles less than 100 μm to the conventional bubbles (with size 0.5-2 mm) generated by more simple aeration systems. For example, a hybrid device that combined mechanical Denver-type flotation cell and electroflotation was proposed by Tsave *et al*. [13]. It led to a 10% increase in the recovery efficiency of fine particles. Moreover, the combination of mechanical flotation and microbubble generation by a special air-in-water micro-dispersion generator was proposed by Farrokhpay *et al*. [14].

However, it is possible to produce a wide range of bubble sizes using one aeration system; for example, an ejection system with disperser [85] allows the generation of bubbles that can be divided into several groups by size. At this point, contaminants of high flotability are recovered with large bubbles (250-300 μm), and contaminants of low flotability are recovered with microbubbles (55-100 μm).

It is important to pay attention to the presence of specific contaminants that can influence the durability of materials used in the equipment. In such cases, equipment needs to be made from materials that are resistant to such influences. An example would be the use of oil resistant rubber in aerators. Moreover, high concentrations of suspended solids and oil or fat emulsions in the water can cause aerators and ejection nozzles to clog. A preliminary treatment stage before flotation should be undertaken in such cases. For systems of aeration that require an operating liquid, it is recommended to use recycled treated water.

Surfactants play an important role in the flotation process. They reduce the surface tension that causes the decrease of bubble size [4, 47, 86, 87]. For example, the bubble size distribution generated by mechanical flotation machine that was initially bimodal became unimodal with smaller bubble average size with the addition of a surfactant [82, 87]. So, in the case of surfactants presence in wastewater, simpler and cheaper aeration systems such as ejection and pneumatic can be used. On the other hand, the presence of surfactants reduces the rising velocity of the bubbles which is then a factor that also has to be taken into consideration [88].

The pH has a significant influence on the size of bubbles generated by electroflotation. Hydrogen bubble size commonly conforms to a normal distribution, and the bubbles have minimal size when pH is neutral [89]. The results of experiments carried out in da Cruz *et al*. [31] and Hacha *et al*. [32] show that the Sauter mean diameter of hydrogen bubbles decreases with increase of pH. On the contrary, the Sauter mean diameter of oxygen bubbles increases with increase of pH [31, 32, 89]. With the increase of pH from 8 to 11, the size stays approximately constant [31].

Moreover, pH also influences the properties of some kinds of contamination that affect flotation efficiency. For example, a change of pH influences the solubility of certain organic compounds and their interfacial properties. It affects oil attachment efficiency on gas bubbles [90].

Conductivity also influences the efficiency of electroflotation. Low conductivity values lead to high electric power costs. The addition of NaCl increases the current density, gas hold-up and also inhibits bubble coalescence [34]. However, conductivity values that are too high cause the bubble-particle aggregate detachment process due to very intensive bubble generation. That is why moderate values of conductivity are required. According to Belkacem *et al*. [91], the highest turbidity removal efficiency was achieved with conductivity values in the range of 1.2-2.2 mS/cm.

In Piccioli *et al*. [90], it was noted that salinity affects gas-bubble-oil droplet attachment and oil droplet coalescence: at sufficiently low salinity, the attachment efficiency is reduced. Also, the presence of electrolytes affects bubble size: higher levels of salinity lead to more efficient gas dispersion.

The temperature of treated water is a factor that can strongly influence the operating quality of some aeration systems. The solubility of gases in water decreases with increase of temperature [60, 78], so the application of DAF cannot be efficient at water temperatures higher than 30ºC. The optimal temperature range for DAF is 15-20ºC [45]. In a pneumohydraulic system, operating at high temperature, due to the poor dissolution, the gas is mostly sheared by the impeller and thus bubble generation is not so efficient [90].

On the other hand, for pneumatic (IAF) systems, Al-Maliky [92] showed an enhancement of treatment efficiency of 10-17% with increase of temperature up to 80-84°C. However, the application of rubber aerators in a pneumatic aeration system for the treatment of highly contaminated oily water at the temperatures more than 50°C leads to change in the rubber properties: it loses elasticity and prevents the generation of bubbles of the required sizes [93], and therefore, treatment efficiency is reduced.

2.3.2 Compactness of equipment

The area occupied by the equipment is one of the limiting factors during the development of a treatment system [26]. Flotation system size (or space occupancy) can be commonly described by Hydraulic Loading Rates (HLR). The average values of HLR for different types of flotation tanks according to previous works [44, 94-96] are presented in Table 3, and F_A m/h can be defined by equation:

$$F_A = \frac{Q_{ave}}{A},$$

where Q_{ave} is the mean flow rate, m^3/h, A is the equipment area, m^2 [94, 95].

Table 3. Average values of HLR

№	Flotation System	F_A, m/h
1	Induced gas flotation	2.4-16
2	Dissolved air flotation	5-50
3	Flocculation-flotation unit	140-2000
4	CFU (with pneumohydraulic aeration)	45-90

In previous studies [59, 97], it is pointed out that DAF has the largest footprint compared with other systems of aeration, while the electroflotator is the most compact.

Speaking about such aeration systems as DAF, ejection flotation, pneumohydraulic flotation aeration systems, the necessity of recycled water usage increases the size of the flotator. The recycled water ratio varies but is usually in the range of 10-60% (sometimes up to 100%) [5, 8]. The recycled water ratio depends on the concentration of contaminants, gas solubility (in DAF), and gas hold up. Minimizing the amount of recycle flow in a system can be achieved by increasing bubble quantity and reducing bubble size [60]. It should be noted that in cases when treated water is not highly contaminated, it can be used as operating liquid, which lessens the energy costs and apparatus size. Pneumatic and mechanical flotators do not need operating liquid. However, the higher efficiency of flotation treatment is, the lesser the area can be occupied by equipment in the final treatment stage.

The use of an electroflotator with dissoluble aluminum electrode allows the combination processes of electrocoagulation and electroflotation. The process of sorption of contamination occurs on freshly formed hydroxides that are produced due to the electrode oxidation. Further, bubble-particle aggregates are formed from hydroxides and microbubbles of hydrogen and oxygen generated during electrolysis. In other flotation methods, special coagulants are needed instead of dissoluble electrodes. So, special tanks for producing and storing chemicals and equipment for their dosage are required. The other point is that when treated water contains high concentration of chloride ions, active chlorine species such as free chlorine and chlorine dioxide are formed due to the reaction of oxidation. In this case, disinfection takes place in the same apparatus [98, 99], which makes the treatment system more compact. However, Xu *et al*. [99] point out that co-existence of such chlorine species and organic compounds can lead to the formation of harmful disinfectant by-products such as chloroform, dichloroacetic acid, trichloroacetic acid, some of which are potential carcinogens.

The development of CFU is also a way to decrease the area occupied by the equipment. CFU is a flotation device with an operation principle that is based on the combination of the effect of swirl separation and flotation mechanism. There can also be the combination of different aeration systems, for example, induced gas flotation and dissolved gas flotation and several swirls. The advantages of such systems are high separation efficiency, low retention time and a small reflux ratio, and a small footprint [97, 100].

2.3.3 Reliability and simplicity

Important factors that also influence the choice of aeration system are reliability and simplicity of operation [64]. These are especially important for small organizations and operations that have less qualified staff, for example, car washes. In such cases, the choice of simplicity in construction and maintenance of the aeration system is preferable, and recommended systems include ejection, pneumatic and pneumohydraulic flotators [92, 101]. The efficiency of these flotation treatments is lower in comparison with other flotation types. However, this can be compensated for by the use of filters at the final treatment stage. The filters should also be quite simple in operation. Though filters can require more frequent regeneration, no other devices or processes such as saturators, formation of hydrogen-oxygen mixtures, or rotating vanes, are required. Minimal maintenance and relatively simple control are required.

Ejection flotation tanks are used for oil or fat contaminated wastewater treatment. In the case of more strict requirements for the quality of treated water, a disperser can be used after the ejector. At some points, an ejector may cause restrictions or make the construction more complicated, but the disperser can significantly increase the treatment efficiency. However, there is also the possibility of clogging and scaling of the ejector (especially with highly contaminated wastewater), so special maintenance can be required [59].

Although pneumatic flotation in general is less efficient, it can be applied in systems such as car wash wastewater treatments due to its simplicity and low energy costs [92].

Speaking about pneumohydraulic systems, it is important to point out that the control of the air flow rate is important in order to provide the normal operation of the pump. It is recommended that air flow rate should be no more than 5-7% of water flow rate [65], and for special multiphase centrifugal pumps, the air flow rate should be in the range of 10-20% [80]. According to some researchers [54, 55, 102], the most effective microbubble generation occurs with an air flow rate ratio of 4-5%. Azevedo *et al*. [68] also noted that maintenance of pumps used in a pneumohydraulic system is needed because of the deterioration of pumps due to forced cavitation. In fact, the performance of such pumps after long periods of operation is an issue that has to be studied further.

In mechanical flotation, reliability and durability decrease with the wear and tear of moving mechanical parts, such as the rotating vanes of an impeller [59].

With electroflotation systems, there are also special requirements for maintenance. Firstly, there is the possibility of flammable or explosive gas generation, so the appropriate ventilation is needed [103]. Another problem is electrode passivation [104]. So, special procedures need to be carried out in order to solve this problem such as aggressive ion addition [104-107], polarity reversal using different current types [105, 107-110], ultrasonication [107, 111], mechanical and chemical cleaning of electrodes, hydrodynamic scouring [104], and centrifugal electrodes [107]. Also, in the case of dissoluble aluminum electrodes, there is the necessity of electrode replacement [111]. Besides the highest efficiency among all flotation types, electroflotation also has another advantage, and this is the possibility for it to be used in a batch mode process. Moreover, electroflotation tanks can be used for experimental research.

2.3.4 The capital and operating costs

From the point of view of capital and operating costs, the energy consumption and equipment used for bubble generation are compared.

Operating costs are mainly characterized by energy consumption for the generation of gas bubbles, as the purpose of an aeration system is the generation of microbubbles and the probability of bubble-particle aggregate formation, which depends on the quantity of bubbles and gas hold up (the higher the values, the better).

Capital costs are defined by the cost of the flotation cell and the equipment. In the case of recycled water (operating liquid) usage, a flotation cell has to be enlarged by 20-40%, so the cost increases.

DAF tanks have quite high capital costs. Speaking about the operating costs, about 50% of them can be attributed to air saturators [62]. The energy consumption is about 0.2 $kW \cdot h/m^3$ [6]. The energy consumption of pneumohydraulic and ejection aeration system is lower compared to DAF due to the lower pressure required and the absence of a compressor (for ejection system). However, an operating liquid is commonly used in these three aeration systems, which causes the increase of the apparatus size.

The highest operating costs are associated with the use of electroflotation. These costs are related to energy consumption and electrodes [112]. However, if dissolution of aluminum electrodes efficiently produce coagulation, there are less additional chemicals used, so the costs of the system decrease. In any case, electroflotation is the most efficient process. The energy costs are about 1.4-6 $kW \cdot h/m^3$ [113, 114]. Lower values of energy consumption are obtained for water with good conductivity (containing enough electrolytes). Otherwise, either energy consumption increases due to the higher voltage needed for the proper current density value, or the conductivity has to be increased, for example, by the addition of sodium chloride.

For mechanical flotation, the capital costs are relatively low, however, the operation costs can be quite high due to the wear and tear of impellers [5].

Pneumatic aeration has the lowest operating and capital costs. So, in cases when high gas hold up is needed and large bubbles are acceptable, it is preferable. In the case of highly contaminated water with hardly any recoverable substances and low water flow rate, the use of electroflotation can be reasonable as the absolute costs are relatively low.

2.3.5 The recommendations for new flotator installation

The reasons for the development and installation of a new flotator include:

- modernization of an existing wastewater treatment system due to the change of technological process or due to the increase of water flow rate;
- planned repair/renovation of equipment without change of quality and volume of wastewater;
- the development of new system for new production.

If a treatment system already exists, the existing area may be limited. Furthermore, it is desirable to use the existing equipment as much as possible in order to decrease capital costs. In the case of new production development, it is important to consider all factors.

The general criteria for the choice of aeration system from this review are presented in Table 4. The Table shows the best choice of flotator depending on particular conditions and requirements, and also points out the conditions at which the particular systems of aeration are not efficient.

3. Conclusions

One of the sustainable development goals set by the United Nations deals with the need to have a clean water supply and to solve the problem of water contamination. The development of efficient wastewater treatment system is one way to achieve this goal. As the flotation processes are often one of the main stages of water treatment systems, a lot of attention should be paid to their development. There are different types of flotators: mechanical, pneumatic, pneumohydraulic, ejection, DAF, electroflotator, and others that are less frequently used. It is important to point out that the choice of the best type of flotator is seldom simple and unambiguous, as it is a multi-factor process. For example, even the most efficient type – electroflotation – in some cases (with low conductivity water) can provide lower efficiency than the other types. If the requirements for treated water are not strict, simple pneumatic flotation can be used. When developing flotators, the best option is to carry out the experiments with the real target wastewater. However, new needs for treatment can arise, so there should be an individual approach for any particular case. Special attention during the development of a flotator should be paid to the following factors: parameters of treated wastewater (temperature, conductivity, flotability of contamination), the area available for

Table 4. General criteria for the choice of aeration system

Criteria	**System of Aeration**						**References**
	Mechanical	**Pneumatic**	**Dissolved Air Flotation**	**Electroflotation**	**Pneumohydraulic**	**Ejection**	
Footprint	medium	compact	large	compact	medium	large	[59, 97]
Factors that influence reliability and durability	wear and tear of moving parts, rotating vanes	clogging of aerators	saturater operating at high pressure (400-600 kPa)	passivation of electrodes	air flow rate	clogging, scaling of ejectors and dispersers	[59, 65, 68, 102, 104]
Operation maintenance requirements	simple operation; maintenance of impellers	simple operation; replacement of aerators	maintenance of high pressure saturater	replacement of electrodes; ventilation system is required	air flow rate control; maintenance of the pump	simple operation; maintenance of ejectors	[5, 68, 92, 111]
Operating liquid	not required	not required	required	not required	required	required	[5, 8, 68]
Energy consumption	high	low	high	high	medium	low	[5, 62, 104, 112, 115]
Operating costs	high (high cost of energy consumption; cost for the maintenance and replacement of impellers)	low (low cost of energy consumption, medium cost for the replacement of aerators)	medium (cost of energy consumption)	high (high cost of energy consumption, cost of the electrodes)	medium (cost of energy consumption)	low (low cost of energy consumption)	[5, 62, 68, 92, 104, 111, 112, 115]

Table 4. General criteria for the choice of aeration system (continued)

Criteria	**System of Aeration**						**References**
	Mechanical	**Pneumatic**	**Dissolved Air Flotation**	**Electroflotation**	**Pneumohydraulic**	**Ejection**	
Treatment efficiency, %:	medium	compact	large	compact	medium	large	[59, 97]
TSS	n/a	n/a	75-95	93-99	92	57.3	[7, 113, 114, 116-118]
Oil (oil and grease)	76-93	66-70	80-93	94-99	85	74.5	[7, 112, 118-124]
COD	n/a	47	60-91	80-97	83.6	53.7	[7, 11, 16, 18, 30, 114, 116, 118, 125]
BOD	n/a	n/a	76-80	92-93	n/a	77	[9, 114, 116, 118]
Wastewater parameters:							
Low conductivity	+	+	+	–	+	+	[34, 45, 90-92]
High temperature (t > 30ºC)	+	+ (heat resistant material of aerators)	–	+	+ less efficient	+	[45, 60, 78, 90, 92, 93]

n/a – no data available
\+ - possibility of operation in such conditions
– - inefficient in such conditions

the treatment system, and special requirements for maintenance. But when similar kinds of wastewater are produced in one region (for example, wastewater from similar car washes in one area), a reasonable approach is to use the already developed and existing flotators. The issues considered in this article and proposed recommendations can be used in flotation development and set up. The proper choice of aeration system and development of an efficient–flotator allows the achievement of a range of sustainable development goals, including those of the UN, in a more effective and rapid way.

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