








## Influence of diffuser design on selected operating variables for wastewater flotation systems: a review

M. R. Mukandi <sup>a</sup>, M. Basitere  <sup>b</sup>, B. I. Okeleye <sup>c</sup>, B. S. Chidi <sup>c</sup>, S. K. O. Ntwampe <sup>d,\*</sup> and A. Thole <sup>a</sup>

<sup>a</sup> Bioresource Engineering Research Group (BioERG), Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Cape Peninsula University of Technology, P.O. Box 1906, Bellville 7535, South Africa

<sup>b</sup> Academic Support Programme for Engineering (ASPECT) & Water Research Group, Department of Civil Engineering, University of Cape Town, Rondebosch, Cape Town 7700, South Africa

<sup>c</sup> Bioresource Engineering Research Group (BioERG), Faculty of Applied Science, Cape Peninsula University of Technology, P.O. Box 652, Cape Town 8000, South Africa

<sup>d</sup> Centre of Excellence in Carbon Based Fuels, School of Chemical and Mineral Engineering, North West University, Private Bag X1290, Potchefstroom 2520, South Africa

\*Corresponding author. E-mail: karabo.ntwampe@nwu.ac.za

 MRM, 0000-0002-3169-4223; MB, 0000-0002-1258-5443; BIO, 0000-0002-9970-1178; BSC, 0000-0001-8497-7596; SKON, 0000-0001-7516-6249; AT, 0000-0002-8938-9264

### ABSTRACT

Air diffusers or spargers have been used in separation processes that include conventional wastewater treatment. Over the years, there have been advancements in diffuser design in terms of shape, pore size, orientation and materials of construction as a way of mitigating challenges such as fouling, clogging, energy consumption and poor system efficiency. Some of the available air diffusers are inadequate to solve most of these challenges due to reduced quality and increased quantity of wastewater being treated. Additionally, there is a paucity of information regarding air diffuser design and their effect on operational parameters in wastewater treatment. This review seeks to address the advancement in diffuser design and also the effects of design factors including parameters of air diffusers with a focus of their use in a column flotation system for wastewater treatment.

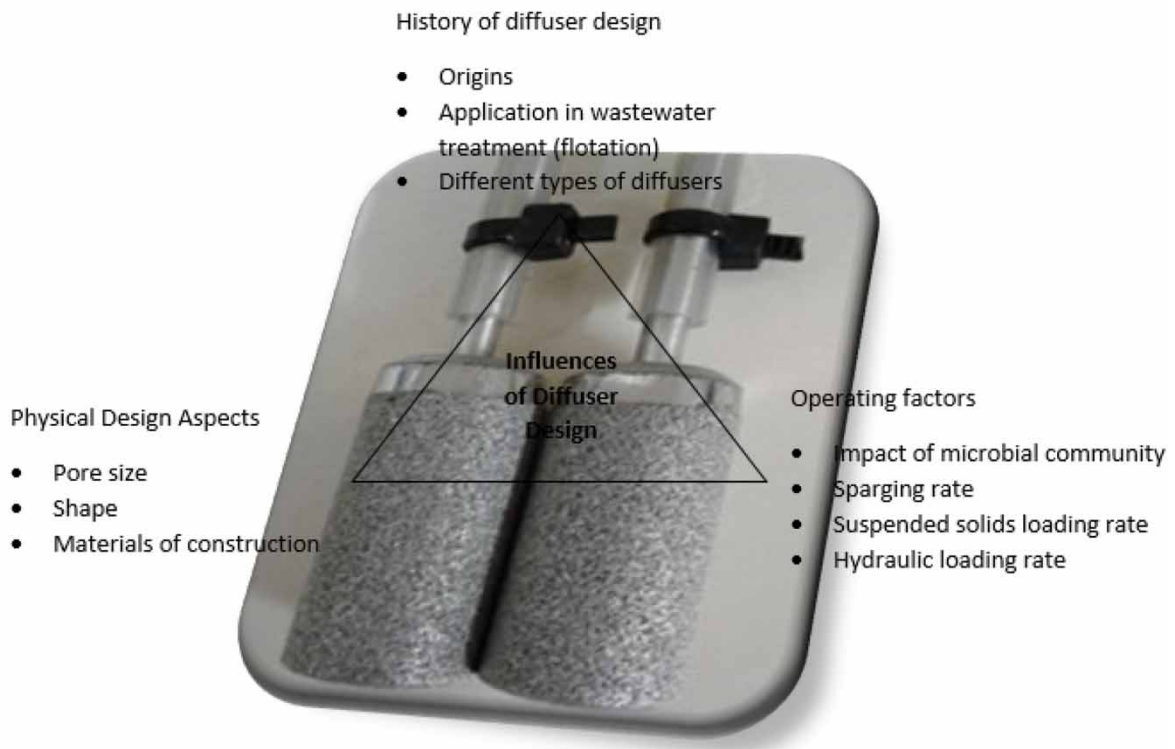
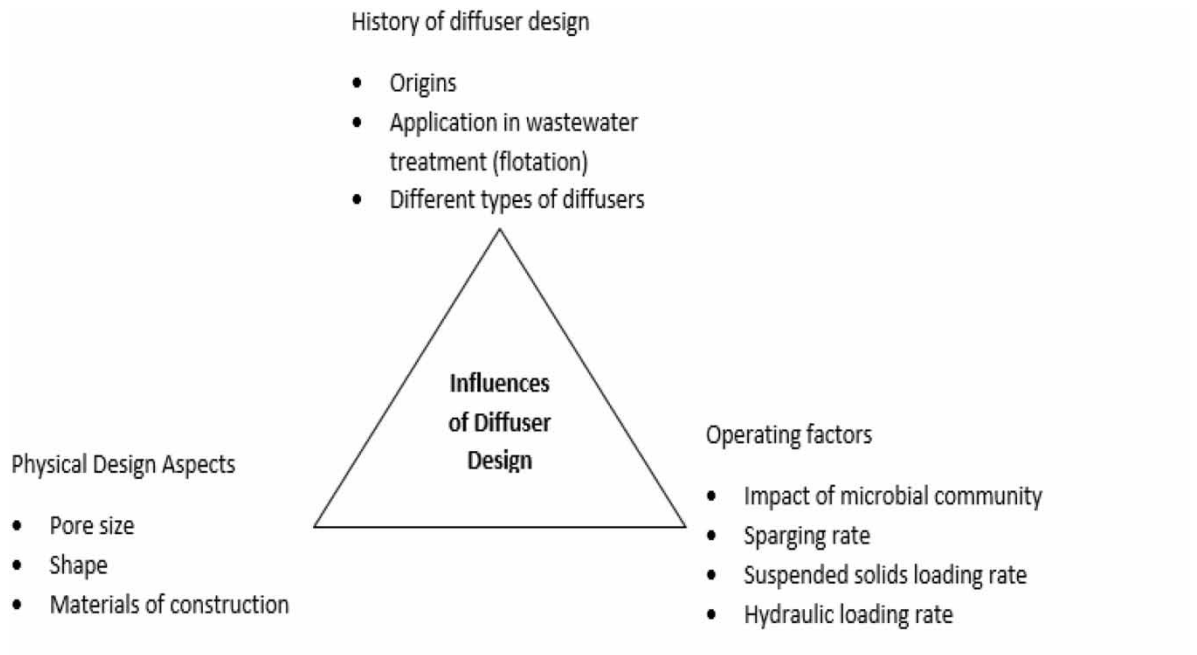
**Key words:** aeration, air diffuser, column flotation, sparger design, wastewater treatment

### HIGHLIGHTS

- Applications of 3D printed air diffusers in a column flotation system.
- The effect of the diffuser design on operational parameters.
- Reducing the rate of fouling and improving the quality of treated water.
- Diffuser designs with oxidative air generating properties for wastewater treatment.
- Advancement in diffuser design for flotation system used for wastewater treatment.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

GRAPHICAL ABSTRACT



SCOPE OF THE REVIEW

The article reviews the influence of diffuser design on flotation operational parameters. This was achieved by focusing on the advancement in diffuser design for flotation systems used for wastewater treatment, physical aspects considered when designing diffusers and operating factors affecting diffuser design.

The review paper starts by introducing the origins of diffusers and their application in wastewater treatment including flotation systems. This is followed by a brief discussion about flotation and the different types of flotation with a column flotation under a dispersed air flotation system being deemed a potential cheaper wastewater pre-treatment method. An insight into column flotation with different methods of bubble generation is provided which then leads to the discussion of different types of air diffusers. This is then followed by an in-depth discussion of diffuser design aspects, which include diffuser shape, pore size and materials of construction. Also, operational factors that affect diffuser design are discussed. Finally, the paper is concluded with overall remarks which gives a summary of the key findings and suggestions that must be explored in future research.

## HISTORICAL PERSPECTIVE OF DIFFUSER DESIGN AND APPLICATIONS

The use of gas or air as a carrier or buoyant medium in separation processes was discovered more than a century ago (Boyle 2003). Initially, it was due to chemical reactions in a liquid medium, which were later harnessed into pneumatical mixing; that is, the direct introduction of air through diffusion by submerged pipes and porous media (Rohlich 1954). The aeration of wastewater began as early as 1882 in England using perforated pipes and tubes. A perforated metal plate diffuser was patented as early as 1904 (Martin 1927). There are different processes in wastewater treatment where bubbles play a role, which include coagulation, flocculation, flotation, oxidation and aerobic biological wastewater treatment (Atkinson *et al.* 2019). However, the addition of chemical agents has improved processes such as coagulation and flocculation. In most cases, for biological treatment methods, aeration is used to meet the dissolved oxygen demand of microorganisms mainly in activated sludge (AS) processes, whereas in other treatment methods, such as flotation, it is used to separate suspended particles from wastewater (Behnisch *et al.* 2018).

At the beginning of the 1900s, air flotation technology use and early development were for froth flotation systems whereby milled mineral ore mixed with water was agitated together with air and aggregate in foam at the top of the water while the gangue settled at the bottom of the flotation vessel. Other bubble generation processes, such as electrolytic and vacuum flotation, were also invented around the same period (Chow 2007). A vacuum air flotation was also used around the 1920s as a water clarification system, with more research being conducted in the 1960s on this technology (Edzwald 2010). Dissolved air flotation (DAF) development in Scandinavia was conducted in the 1960s and has since been well established for use in the pulp and paper industry, drinking water production and wastewater treatment (Crossley & Valade 2006). In Southern Africa during the 1960s, flotation was mainly applied in the mineral industry with little application in municipal or industrial wastewater treatment (Offringa 1995). Although most of the flotation types and cells were designed and developed for various applications including column flotation, some were patented in the first two decades of the 20th century. Column flotation was invented late around 1919 with most research and its extensive introduction in large-scale operations being in the mid-1960s (Rubinstein 1995). These developments might have been achieved as a result of advancement in bubble generation technology or aeration techniques.

In wastewater treatment, perforated pipes were the first to be used for aeration and the first accepted means of aeration diffusers were horizontal porous plates. The theory that small bubbles result in sufficient dissolved oxygen mass transfer led to the use of porous plate diffusers. Moreover, this resulted in the replacement of perforated pipes that produced big bubbles with porous diffusers that improved aeration. The fabrication of porous plates was an advancement and a part of the early development of diffusers whereby porous ceramic diffusers were used due to their ease of operation (Roe 1945; Boyle & Redmon 1983). Overall, air diffusers come in different shapes, designs and materials of construction, ranging from porous wood, perforated metal pipes, to ceramic plates with the latter being deemed the most efficient especially for industrial applications prior to 1945 (Roe 1945). As an attempt to advance diffuser usage, new shapes emerged, which included plates, domes and recently discs. Meanwhile, early investigations used diffusers ranging from basswood plates, perforated iron pipes and even air jets. There is ample evidence that their design influences process operability and efficiency. Most research conducted was based on air permeability, which is a measure of how easily air passes through a liquid (Ernest 1994; Boyle 2003). The reason for improvements of diffusers was to increase their efficiency, and to have simplified servicing, which is cleaning and ease of parts disassembly (Roe 1945). However, to improve diffusers, their designs need to be understood as they exist in different forms or types and such designs can be influenced by the quality characteristics of the liquid in which they operate.

This review seeks to discuss and consolidate information on air diffusers, although other air releasing devices are mentioned and discussed for differentiation purposes. Furthermore, the elucidation of column flotation operations under dispersed air flotation bubble generation method and influences in wastewater treatment diffuser design are also highlighted. This is a neglected area in wastewater technology practice and development.

## FLOTATION IN WASTEWATER TREATMENT

Flotation is made understandable by the Archimedes principle, which is also known as the buoyancy principle whereby the flotation process utilizes microbubbles to form and lift flocs or particles in a fluid to the top for skimming (Gopalratnam *et al.* 1988). The bubble rise rate can be described by the Stokes' principles and for better flotability, the particles are supposed to be hydrophobic as this determines the contact angle of the particles with the wastewater (Gopalratnam *et al.* 1988; Oliveira *et al.* 2010).

Flotation originated from the mineral industry and has gained widespread application in the fresh water and wastewater industry (Ndikubwimana *et al.* 2016). It is a well-known that separation technology with the potential of being applied in wastewater pre-treatment from various industries is a must. Industrial wastewater requires pre-treatment before disposal or reuse to reduce the high level of contaminants including suspended solids (Peleka *et al.* 2018). Flotation in wastewater has been used for the removal of fibre, solids, macromolecule ions and other materials (Rubio *et al.* 2002). Its main advantage over settling techniques is such that high separation kinetics as well as the ability to separate particles that have a low density that cannot be removed through settling can be achieved (Amaral Filjo *et al.* 2016). This also makes it a very useful process for the pre-treatment of industrial wastewater containing fats, grease and oil (FOG), such as those from meat processing plants and petrochemical refineries (Bennett & Shammam 2010). Other advantages include shorter flotation periods even under high solids loading rates (Tian *et al.* 2018).

Flotation is classified based on the microbubble generation technique and is divided into three classes covering DAFs, which is based on Henry's law, a broad range of Dispersed Air Flotation systems (DiAFs), and electrolysis, which sometimes falls under DiAFs (Lu *et al.* 2016; Kyzas & Matis 2018). The DAF depends on the solubility of air in water and is operated such that the water is air saturated at high pressures, albeit with the air being introduced into the tank at atmospheric pressure (Deliyanni *et al.* 2017). Whereas, in electrolysis, bubbles are generated through the electrolysis of the carrier to create the microbubbles. In DiAFs, microbubbles are generated by compressing air directly as it passes through porous material including diffusion discs or by the use of an impeller or hydraulic injectors to get air into the water (Lu *et al.* 2016). In larger agitated cells, the air is introduced through the bottom of the agitator while bubbles are formed as a result of the impeller shearing effect (Deliyanni *et al.* 2017), whereas air diffusers or spargers are used in smaller cells including column flotation. This then results in different flotations under DiAFs based on the equipment used; that is, jet flotation, impeller air flotation, disc/sparger air flotation and pump suction pipe air flotation (Lu *et al.* 2016).

Rubio *et al.* (2002) and Kundu & Mishra (2018) discussed various types of flotation systems and different bubble generation techniques and processes that show variations in bubble generation technology (see Table 1). Many researchers have modified the currently existing flotation processes whereas others have even given the flotation processes different names according to the notable features of the processes. However, designers must determine whether the same classification remains, if the method for bubble generation produces a bubble size out of known specifications.

Flotation is affected by different factors, which include bubble distribution and velocity, including shape, size, specific gravity and surface charge of the suspended solids (Matis 1995). The efficiency of a flotation process is affected by the type of wastewater to be treated, the nature of the contaminants present in the wastewater, the design of the flotation system and its operational parameters (Temesgen *et al.* 2017). Overall, the control of bubble generation to obtain an optimum size range during the flotation process is of paramount importance as it enhances process efficiency (Seeger *et al.* 2019). Bubble size produced in a column flotation can range between 50 and 1,000  $\mu\text{m}$ , while DAF produces smaller bubbles between 30 and 100  $\mu\text{m}$ , which in turn leads to higher removal/separation efficiencies (de Sena *et al.* 2008), especially when treating wastewater with minute particles that require fine bubbles for particle separation. However, DAF has several disadvantages that include high consumption of power, the requirement for a separate flotation tank, and higher service cost, which leads to higher operational costs, and the mechanical complexity of the system due to the use of a saturator and compressor (Li & Tsuge 2006; Painmanakul *et al.* 2010; Tao *et al.* 2019). Equally, electro-flotation is characterized by good

**Table 1** | Different types of flotation and bubble generation methods (Rubio *et al.* 2002; Kundu & Mishra 2018)

Name of the flotation system	Method of bubble generation	Range of bubble size (nm)
Electro flotation	Uses electric field in between electrodes	~20
Dispersed/induced air flotation	Uses mechanical agitation or air injection system	700–1,500
Dissolved air flotation	Dissolve air in water	30–100
Nozzle flotation	Use a gas aspiration nozzle that draws air into recycled water that is discharged in the flotation tank	400–800
Column flotation	Use of many bubble generation techniques that include sparging through porous media, static or mechanical shear contacting and jetting	100–1,500
Centrifugal flotation	Generates bubbles through air suctioning by static mixers/nozzles	100–1,000
Jet flotation	Entraps air into the liquid by a vacuum effect	100–600
Cavitation air flotation	Bubbles formed as a result of the rotation of the cavitation aerator (impeller)	30–70

bubble controllability but it is power intensive and has low treated wastewater throughput; hence, it is not suitable for small-scale applications (Lu *et al.* 2016; Tao *et al.* 2019). Thus, the development of a system that is easy to operate and cheaper is necessary. Therefore, DiAFs can be an attractive alternative as they have a lower capital investment and lower operational costs (Gu & Chiang 1999).

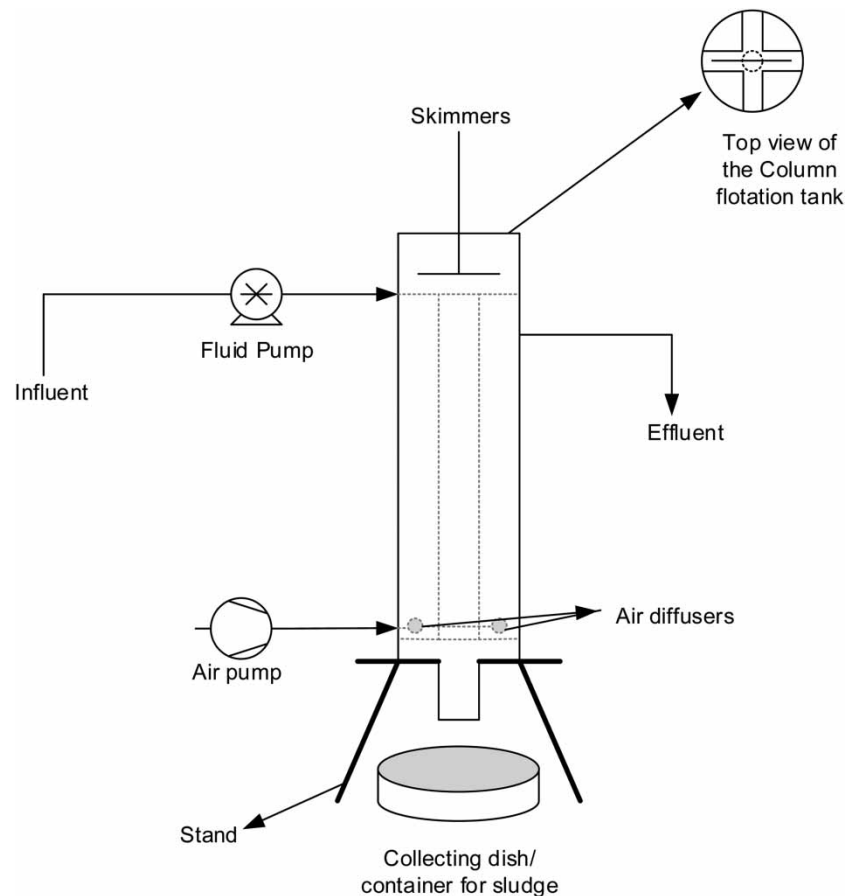
#### COLUMN FLOTATION SYSTEM AS A PREFERRED PRE-TREATMENT METHOD FOR WASTEWATER

Flotation is used mainly where sedimentation is not applicable due to the nature and presence of dispersed solids, and their settling rates, and thus becomes an efficient and economical process to apply (Ahmadi & Mostafapour 2017). For wastewater pre-treatment, the removal of particulate matter, macromolecules, microplastics and fibres results in reduced chemical oxygen demand (COD) and biological oxygen demand (BOD) of the pre-treated wastewater (Ives & Bernhardt 1995). To achieve high treated wastewater quality, treatment technologies that are economical, durable and robust are a necessity as the influent varies in terms of quality and quantity from different industries (Frank *et al.* 2017).

A flotation method combined with a coagulation/flocculation system has been deemed to be an effective pre-treatment method for industrial wastewater (Liu *et al.* 2010). Challenges of a flotation system include the usage of a high dosage of flocculants and breakage of flocs by big bubbles (Ndikubwimana *et al.* 2016). However, the use of synthetic flocculants in flotation processes continues to be criticized due to their toxicity potential during application as their residue ends up in the treated water. Hence, the development of alternative flocculants that are biodegradable to reduce these toxicity concerns and perhaps acceptance or application on an industrial scale in suspended solids separation processes (Silva *et al.* 2019). The usage of a bioflocculant was investigated extensively by Dlangamandla *et al.* (2018) and Mukandi (2017), whereby bioflocculants were used instead of chemical flocculants.

Column flotation is a relatively simple physical separation process whereby microbubbles attach with particles and rise to the top where they are subsequently removed (Shukla *et al.* 2010). Flotation columns are classified based on various reasons that include the column number, bubble generator location, relative motion of solids-wastewater to be separated and whether there is a packed bed or not (Cheng *et al.* 2016a). Column flotation came about as a way of mitigating problems that arise when using conventional mechanical cells such as several cleaning stages required, maintenance requirements and high size to capacity ratio (Al-Thyabat *et al.* 2011). It has been used in various industries that include oil recovery, mineral beneficiation, paper de-inking, food industry and wastewater treatment. Column flotation is still not well understood despite all the advancement in process knowledge over time; hence, scaling up is still a major concern. However, there are three approaches that are employed for column flotation scale-up and these are based on maintaining a constant recovery, column area and column volume (Vashisth *et al.* 2011) through usage of a bench-scale system. Bench-scale testing is an important characterisation tool that is a cheap, simple and quick way of obtaining key information. Figure 1 shows a typical column flotation bench-scale setup for wastewater treatment (Mukandi 2017). The use of such a system (through bench scale testing) would give a better understanding of any new design and its feasibility.





**Figure 1** | Schematic illustration of the column flotation system, bench-scale set-up.

Advantages of a column flotation over others include lower operating costs due to the absence of movable parts, less energy consumption due to the absence of a compressor or rotating parts (agitators), and lower floor space requirements due to its vertical construction, as compared to conventional flotation systems (Rubinstein 1995; Chaiarekij *et al.* 2000), and reasonable flexibility for automatic controls (Wang *et al.* 2019). Due to the recurring expansion of flotation technology application in varying industries, the use of flotation columns has pioneered the development and improvement of sparger systems (Finch 1995). Lu *et al.* (2016) studied the influence of a flotation device for the pre-treatment of oilfield wastewater. They discovered that the use of a bubbling device which was a microporous metallic disc simplified the bubble generation process, thus laying a foundation for microbubble flotation application. Overall, it was found that the device, which included a flotation column, was more reliable, yielding 90% removal efficiency, and was easy to assemble.

Microbubbles for a column flotation under DiAFs are produced by the use of a sparger or mechanical mixer (Tao *et al.* 2019). It is a prerequisite for the system to have sufficient production of microbubbles for high flotation efficiency and to also generate bubble volume concentration that is stable (Haarhoff 2008). Air bubbles must be small to maximize the gas/liquid/particle interfacial area as this can lead to improved particle removal even when flocculants are not used (Offringa 1995). Large bubbles do not easily attach to the particles whereas minutely smaller bubbles lead to breakage of formed flocs. In addressing these challenges, the costs related to bubble generation and breakage of flocs needs critical considerations (Féris *et al.* 2001). Consequently, the average bubble size of 100 microns is preferred (Gopalratnam *et al.* 1988); hence, flotation systems that use this bubble size are capable of removing many pollutants that are found in wastewater (Dupre *et al.* 1998). Moreover, the bubble size in a flotation column is dependent on the generation method and device used, which are the key research points of a flotation column (Zhekun *et al.* 2010). Bubbles generated in column flotation are usually produced through two main types of spargers; that is, internal porous spargers (filter cloth sparger and perforated rubbers) and external generators such as turbo air spargers (Cheng *et al.* 2016a).

Optimization of flotation system operating process variables must focus on sparging rate, solid loading rate, hydraulic loading rate, air-solid ratio (Gopalratnam *et al.* 1988) and the addition of suitable flocculants. In this case, bioflocculants are suitable to impart environmental benignity (Mukandi 2017). There are various other factors apart from process operating variables that are considered when designing a flotation system, which include the type and quality of wastewater, the extent of the contamination, the level of treatment required and the type of diffusers to be used (Dassey & Theegala 2011). Most existing studies are vague in terms of disclosing the geometry or properties of air releasing devices used in flotation systems. Although the investigations focus on improving the bubble properties in a flotation system, the type of diffusers or nozzles used are rarely mentioned. Mostly rudimentary mentions of diffusers or nozzles design properties are used. This creates a gap that needs to be researched for the treatment of a particular type of wastewater using a specified type of diffuser with well-defined design properties.

## DIFFERENT TYPES OF AIR DIFFUSERS

Bubbles are obtained through usage or application of air releasing devices and are generated when the pressure is suddenly changed in the aperture points of the devices. These devices produce bubbles in various ways and come in different forms with the most commonly used being porous air diffusers/spargers, nozzles, gate, fixed orifices and needle valves, amongst others (Zabel 1985). Porous air diffusers generate bubbles by breaking up air through liquid displacement. This is achieved through the injection of air under pressure below the liquid surface. Nozzles are used to release air bubbles through the discharge of air-saturated water (Nadayil *et al.* 2015). The bubbles are formed as a result of a pressure drop on the narrowing of the nozzle whereas a flow constrictor increases the flow velocity, thus inducing bubble nucleation (Etchepare *et al.* 2017). In nozzle flow constriction, bubbles formed travel through the tank at pressures greater than atmospheric pressures but the differences with nozzles is mainly their configuration (Rodrigues & Rubio 2003). For needle valves and other orifices, air-saturated water is passed through constricted areas and clouds of bubbles are formed downstream of the constriction into the wastewater (Rubio *et al.* 2016; Azevedo *et al.* 2018) while on the other hand, injectors provide a jet of saturated water (Nadayil *et al.* 2015).

Some of the nozzles or valves are adjustable, whereas others are fixed (Haarhoff & Van vuuren 1995), with others such as needle valves being adjustable and having a self-cleaning ability. A large number of different nozzles and diffusers were patented between 1970 and 1980 and are continuously being improved under their initial or first patent registration (Rykaart & Haarhoff 1995). Table 2 enlists some of the air releasing devices that were patented, and they offer numerous advantages in comparison to others.

Diffusers that can be removed and serviced are more advantageous than those that are fixed as they can be easily removed without dewatering the tanks or stopping the aeration process (Roe 1945). Diffuser designs determine bubble size, distribution and rise velocity, with diffuser functionality being dependent on pore diameter, number and orientation in the device. Inadequate diffuser designs, for a particular process, result in challenges such as (i) weeping (slow discharge of air bubbles), which may cause undesirable or longer residence time, and result in poor performance of the system, (ii) blockage of pores or clogging, especially when there is a high concentration of solid particulate matter in the wastewater, (iii) fouling and scaling by biofilms, which result in increased dynamic wet pressure (DWP), which lead to bigger bubbles, culminating in a negative effect on the air supply which will require more energy to pump, (iv) dead zones due to non-uniform sparging or redundant placement of diffusers, and (v) high cost of operation due to high energy consumption (Kulkarni & Joshi 2011; Odize *et al.* 2017), and coalesce issues (Rodrigues & Rubio 2003). However, their application can be improved by addressing known challenges; hence, the need to improve existing diffuser designs.

## DIFFUSER DESIGN: AN ENGINEERING APPROACH

In diffuser design, it is important to consider internal hydraulic parameters that include: (1) uniform discharge of air along the diffuser to ensure sufficient distribution of bubbles to minimize operational challenges; (2) use of simple geometries to minimize manufacturing and operational costs; (3) cater for no or low flow of air to prevent particle deposition including backflow to alleviate frequent out of place cleaning and maintenance challenges; and (4) to minimize effects of the unsteady-state performance of compressors supplying the pressurized air (Bleninger *et al.* 2005). Moreover, various factors determine the performance of air diffusers which include

**Table 2** | Examples of patented air releasing devices and their notable attributes

Patent specification number	Name of air release device/description	Notable properties/attributes	References
US2294973A	Fluid treatment diffuser element	Strong, efficient, simple and easy to manufacture as a way of withstanding shocks and avoiding bottom coalesces that result in big bubbles	Ford (1942)
US2639131A	Diffuser for gases	Facilitates cleaning of the air supply orifice thus no need for removal; hence, saving labour and time	Procter (1953)
US2815943A	Diffuser tube	The tube inflates quickly thus removing any lodged solid matter and rapidly deflate to avoid clogging when air is supplied or cut off respectively. Cheap and ease of manufacturing	Lamb (1957)
US4338192A	Clarifier bubble generation and distribution nozzle	For the production of bubbles with a diameter less than 100 micrometres	Krasnoff & Luthi (1982)
US4477341A	Injector apparatus having a constriction in a following adjoining mixing pipe	High airflow rate with economical/reasonable energy consumption	Schweiss & Dorflinger (1984)
US4842777A	Pressurized mixing injector	Inject high airflow rate, Strong and normal aeration which in turn minimize clogging problems	Lamort (1989)
US4981623A	Diffuser for aeration basin	Improved diaphragm diffuser that will keep the membrane in place to prevent rupture or dislodging	Ryan (1991)
US5139663A	Discharge valve for dissolved air flotation	Nozzle assembly that is improved and capable of self-cleaning, and a Nozzle assembly that can have its flow rates changed from a remote location	Maples (1992)
US5154351A	Dispersion water nozzle	Reduction of pressure in dispersion water flow, and To produce bubbles of about 100 micrometres with sufficient distribution of air	Takko (1992)
US6367783B1	Fine bubble diffusers	A diffuser that cannot easily be clogged by organic matter, and that prevents backflow into the diffuser air supply source	Raftis (2002)
US9138752B2	Dissolved gas flotation pressure reduction nozzle	Increased turbulences that favours microbubble production, uniform bubble size, corrosion resistant material used, and simple manufacturing and installation of the nozzles	Amato <i>et al.</i> (2015)
US9808810B2	Nozzle for dissolved air flotation system	To produce microbubbles even at low pressures, To produce uniform sized microbubbles with extended existence time in fluid, nozzles that are easy to manufacture and have a simple structure	Park <i>et al.</i> (2017)

the depth at which they are placed in the wastewater, and thus the external pressure that the diffuser will experience (Cheng *et al.* 2016b).

Additionally, DWP which is defined as the head loss across a diffuser being operated under submerged conditions, is an important parameter to consider when designing air diffusers. It increases with time due to fouling and is material dependent, thus different materials have different DWP. This is attributed to different material properties, with the pressure factor indicating the performance of the diffuser (Rosso & Stenstrom 2006). The DWP ratio of old to new diffusers must be quantifiable to assess the diffuser deterioration over time, although this is dependent on foulant (wastewater) characteristics and cleaning frequency. It is, however, also influenced by process operational conditions. Furthermore, pore geometry has an influence on DWP with round pores being rigid and acting as a control opening that can withstand high pressure, whereas membrane pores/slits can expand when the pressure increases. However, a low DWP does not guarantee the best performance as there is a minimum pressure required for the proper distribution of the air (Rosso *et al.* 2012). Such analysis is scantily reported and there is minimal guidelines or information available for the design of diffusers in published literature.



## DIFFUSER, BUBBLE FORMATION AND DYNAMICS: EFFICACY IN FLOTATION SYSTEMS

For flotation, the air is introduced into the tank in the form of bubbles. Bubbles exist in different forms; that is, as nanobubbles with a diameter of less than 0.2 microns, while microbubbles have a diameter of 10–100 microns and lastly, macro bubbles that have a diameter of greater than 100 microns, which tend to rise faster than the rest. Moreover, microbubbles are of interest in water and wastewater treatment as nanobubbles take longer to rise to the top while macro bubbles are inefficient due to their high rising velocity (Sadatomi *et al.* 2005; Basso *et al.* 2018). They have adsorbent properties as they can adsorb and agglomerate particulate matter due to their bigger surface area and their negative charge (Lee *et al.* 2019), which neutralizes repulsion forces between suspended matter. When bubbles and suspended particles are similar in size, maximum collision efficiency is achieved (Han 2002). Compared to bigger bubbles, microbubbles have an increased interfacial area and thus more interaction area, which improves bubble-particle collision, hence increasing flotation efficiency. In column flotation, the collision probability is higher due to large aerated volumes of the column and long passage that bubbles and particles travel along the height (Rubinstein 1995). Overall, bubble size measurements are conducted using laser-based methods and by image analysis techniques (Zhang *et al.* 2015).

Bubble size is influenced by diffuser design and affects bubble particle collision, and thus attachment of suspended solids including the rise velocity, which affects the efficiency of the system (Edzwald 2010). The size is governed by a sparging rate, pore size and also the wastewater parameter-volumetric quality and mixing velocity (Basso *et al.* 2018). Most researchers have focused their work on micro and nanobubbles in a bid to improve the efficiency of flotation systems. They do this by investigating bubble generation methods, characterization of bubbles and their categories as well as the development of bubble measurement methods (Temesgen *et al.* 2017). Moreover, bubble hydrodynamics have been extensively researched to assess bubble size influences on fluid dynamic behaviour using Computational Fluid Dynamics (CFD) (Chen *et al.* 2016), bubble surface modifications by surfactants (Henderson *et al.* 2008) and pressure effects on bubble size (Han *et al.* 2002). However, most researchers just mention that they used nozzles, needle valves or diffusers without sharing much-needed information about the air releasing devices and design features. Much less attention has also been paid to the type, design or configuration of air releasing devices that are being used to date, thus making it difficult to compare results from researchers using different applications.

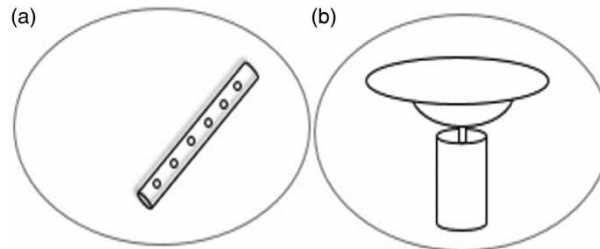
Bubble generation is affected by (1) operating conditions, which include air flow rate and the sparging rate that is influenced by the operational pressure, (2) structural design that includes pore size (or diameter), pore geometrical configuration (e.g. contact angle), the device's materials of construction and submergence attributes and (3) physical properties, which include the quality characteristics of the water as it comes into contact with the diffusers (Xiao *et al.* 2019). Microbubbles have been known to be suitable for flotation systems and are generated mainly through three ways; that is (a) dissolving air in a liquid and subsequently releasing it through air releasing devices that lead to nucleation of small bubbles, (b) cavitation induction through the usage of power ultrasound and (c) air delivered under low pressure forming bubbles with the aid of additional features such as mechanical vibrations, flow focussing and pneumatic fluid oscillation. Dissolving air in wastewater is widely or commonly used and the latter has the lowest energy consumption amongst the three (Zimmerman *et al.* 2008; Zimmerman *et al.* 2009). Bubble formation through cavitation, by forming nuclei first followed by growth as the bubble rises through wastewater, is desirable. However, in bubble growth, coalescence is a major challenge that affects flotation systems (Edzwald 2010).

Generation of bubbles through the saturation of water with air has limitations that include the high pressure needed for injecting the saturated liquid, the mixing of air and the recycling of gas/liquid, which can lead to equipment damage or contamination due to the nature of contaminants present in the water being treated (Ahmed *et al.* 2018). These disadvantages might be overcome by using diffusers without a recycle stream provided they generate the required bubble size for the particular or specified process.

## EFFECT OF DIFFUSER SHAPE

There are many different shapes of air diffusers that have evolved and emerged in accordance with different industry needs. These include domes, which are usually mounted at the bottom of a tank, panels that usually covers the flotation tank floor, flexible membranes that come in many shapes- from tubes, discs to flat surfaces, and flat stripes that usually covers the floor of a flotation tank as well (Ovezea 2009).

The shape of the diffusers can influence the air-water contact volume of rising air/microbubbles such that the greater the contact volume, the higher the flotation efficiency (Roe 1945), which can also affect the formation of flocs. In an attempt to optimise flotation systems, Féris *et al.* (2000) investigated the use of two types of diffusers, traditional, which were longitudinal (Figure 2(a)), and newly developed mushroom type diffusers (Figure 2(b)). The results showed that with the use of surfactants (sodium oleate), the mushroom type had high removal efficiency as compared to the former, thus showing that the shape of diffusers has an effect on the formation and breakage of flocs under turbulent conditions (Féris *et al.* 2000).



**Figure 2** | Illustration of (a) longitudinal and (b) mushroom type diffuser (Féris *et al.* 2000).

Hence, diffuser shape also influences the aeration efficiency, which in turn affects the overall system efficiency. Cheng *et al.* (2016b) investigated the effect of different microporous diffuser shapes – I, C, S and disc shape, on aeration performance and discovered that the I shape had optimal aeration whereas the disc shape had the poorest performance amongst the shapes investigated. Hence, understanding the design of air diffusers for improved flotation efficiency and low energy consumption by maximizing the design shape need not be understated as there is minimal information available on the design of diffuser shape and the shape influences on performance.

### INFLUENCE OF APERTURE/PORE SIZE ON DIFFUSER FUNCTIONALITY

Fixed orifice nozzles and manual needle valves tend to limit the recycle flow to a small range under different operating pressures. With fixed nozzles, the recycling system must be designed to two or three operating points by having each orifice with its pressure inlet that can be controlled by varying pressure control valves. The orifices should be able to be switched on and off with minimized backflow when not in operation (Crossley & Valade 2006). Diffuser pores can be varied in size to affect energy consumption. Coarse bubble diffusers have higher energy consumption as compared to fine pore diffusers, which are considered to be energy efficient (Noble *et al.* 2016). Furthermore, pore size determines bubble size, which in turn affects the type of bubbles formed, with bigger bubbles having lower efficiency while smaller bubbles are determined to have a higher process efficiency (Rosso *et al.* 2008). Moreover, blockage of pores results in increased pressure on diffusers and reduced air supply channels, which is counteracted by increased airflow resulting in high energy cost with the consequential effect being the deformation of pore structure as well as breakage of diffusers. This can however be countered by the use of a diverse pore structure and suitable materials of construction such as blended material containing additives for enhancement of chemical and mechanical properties (Eusebi & Battistoni 2014).

Microbubble generation has its own challenges as most would expect that the smaller the pore size of diffusers, the smaller the bubble size would be; however, this is not the case, as other factors such as the wetting force exerted by the liquid surrounding the diffuser surface acts as an anchor and as a result the bubbles keep growing unless the force is disrupted. This can affect the bubble size apart from the air releasing device aperture size (Zimmerman *et al.* 2009). The other challenge is the spacing between adjacent bubbles or pores in the diffusers, which lead to coalescence of bubbles or channelling (Zimmerman *et al.* 2008). Behnisch *et al.* (2018) investigated different designs of fine aperture pore membrane diffusers, focusing mainly on the slit length and density to improve the aeration system treating water. Diffusers with a dense slit pattern and smaller length were recommended for saline water, whereas in tap water a dense slit resulted in bigger bubbles due to coalescence. This observation showed that diffuser design affects the wastewater being treated and this is also dependent on the contaminants present in the wastewater (Behnisch *et al.* 2018).

Bubble size generation by air diffusers cannot only be varied by use of different types of diffusers but also by other means that include the application of surface tension reducing chemicals, use of alternative pressurised air

generation techniques and diffusers made of different materials of construction (Kyzas & Matis 2018); hence, it is important to improve the design and functionality of air diffusers as a way of mitigating a variety of challenges as mentioned above.

## MATERIALS OF CONSTRUCTION USED IN DIFFUSER MANUFACTURING

Materials of construction used early in the century were bonded silica sands but sometimes could be mixed material such as sand-cement plates. To improve aeration, early investigators focussed on the development and generation of fine bubbles. The materials of construction that they based their investigation on included porous volcanic rock (pumice), firebrick, sandstone, and mixtures of glass and sand. However, many of the mentioned materials were dense thus leading to increased pressure head loss and reduced efficiency (Boyle 2003).

Nowadays, air diffusers are mainly made from ceramics, porous plastics and perforated membranes. Ceramic diffusers are made from a combination of silica, alumina and aluminium silicates. The media consist of sized material particles that are mixed with bonding materials and are moulded into various shapes at a high temperature. This results in an interconnected network of passages whereby the air flows through the diffuser. Porous plastics for diffusers are made from propylene, polytetrafluoroethylene and polyethylene for the rigid diffusers while high density polyethylene and rubber are used for non-rigid diffusers. They are fabricated in such a way that they all have a network of channels through which air travels. Similarly, perforated membranes are made from elastomers and these are normally referred to as flexible diffusers (Shammas 2007). Other materials can be used but the above mentioned are considered to be cost-effective and can be produced in different sizes and specifications. However, they are prone to chemical degradation and biological fouling (Nadayil *et al.* 2015). Several factors determine or contribute to fouling, which include the suitable properties of the materials of construction of diffusers, the nature of the contaminants or the type of wastewater and operating conditions (Odize *et al.* 2017). The air diffusers are currently being coated using different coating materials that include poly-urethanes and silicones that serve as antimicrobials, which however degrade with time (Garrido-Baserba *et al.* 2016); hence, finding materials that minimize biofilms attachment is a necessity.

The physical and chemical characteristics of construction materials used for the production of diffusers each influence the workability of apertures in air diffusers, and thus bubble formation (Eusebi & Battistoni 2014). One of the challenges of bubble generation in relation to the material of construction is that the liquid surrounding the pore on the diffuser surface acts as an anchor, which aids the wetting force in the attachment of the growing bubble to the surface of the diffuser. The bubble will continually grow unless the anchoring force is disrupted or the buoyant force exceeds the anchoring force (Zimmerman *et al.* 2008; Zimmerman *et al.* 2009). Additionally, the mechanical properties of diffuser materials are characterized by parameters such as Young's modulus of elasticity and hardness, which affect the deformation of pore shape. This is used to predict breakage of diffusers and this is further affected by the presence of additive and corrosive pollutants in the water being treated as they affect the material's stiffness and strength over time (Eusebi *et al.* 2017), thus making it important to select a suitable combination of materials of construction for a particular type of application.

Recently, Lee *et al.* (2019) investigated bubble generation at different entry and exit angles. Notably, the nozzles were synthesized using 3D printing specifically using acrylonitrile butadiene styrene (ABS) resin with an aluminium cover casing. Interestingly, can 3D printing be used to print air diffusers which are strong, durable, made with material that affects biofilm formation thus reducing biofilm attachment and formation while having properties to effectively design aperture sites for desired bubble size? These are pertinent questions that must be addressed in future diffuser designs. Thus, this is another niche area for future research.

## OPERATING FACTORS AFFECTING DIFFUSER DESIGN

### Impact on microbial community removal and attachment

Constituents of wastewater pose dangers to both humans and the ecosystem. A greater number of organisms in wastewater are pathogens and viruses that can disrupt nature and make humans sick (Nadayil *et al.* 2015). Edzwald (2010) indicated that an effective flotation system can remove microorganisms such as *Giardia* cysts. Similarly, Andreoli & Sabogal-Paz (2017) investigated the removal of *Giardia spp* and *Cryptosporidium spp* using a combination of flotation and filtration systems. They discovered a higher removal of cysts and oocysts from the wastewater with the flotation system compared to the filtration method. Santos & Daniels (2017) previously used a bench-scale DAF to remove *Giardia* cysts from wastewater but this was an ineffective method as it

was dependent on flocculant supplementation. However, whether diffusers aid in the removal of microorganisms due to their materials of construction possessing antimicrobial properties still needs some further investigations.

Diffuser surfaces are a unique environment for biofilm formation due to the provision of an adherence surface, sufficient oxygen supply from the incoming air and adequate nutrients from the wastewater being treated. Additionally, operating process variables play a role in the formation of biofilms on diffusers. This includes levels of dissolved oxygen, the concentration of ions in the wastewater to be treated as well as the soluble substrate availability, which collectively promote biofilm growth (Garrido-Baserba *et al.* 2018). Consequently, sparger systems' attributes can favour fouling, which can be grouped into three categories that are biological, organic and inorganic fouling with biofouling or the development of biofilm on diffusers being of great concern (Meng *et al.* 2009). Organic matter can also contribute to the deposition of biopolymers (Odize *et al.* 2017) and inorganics can lead to the deposition of different cationic and anionic precipitates of chemical or biological nature, which could further exacerbate the fouling challenges (Wang *et al.* 2008). Additionally, biofouling is a result of deposition of small particles onto the diffusers leading to the formation of a cake layer, which is composed of particles built-up, thereby leading to flow resistance, thus loss of bubble generation efficiency (Harun & Zimmerman 2019). This leads to an increase of back pressure on the air pump or compressor (Rosso & Shaw 2015), resulting in decreased aeration efficiency. DWP increases with increasing time in operation (Zhao *et al.* 2004). This also results in an increase in bubble size as a result of material property alteration, and also leads to increased energy costs (Garrido-Baserba *et al.* 2016). Fouling can either be reversible or irreversible. Reversible fouling is as a result of loosely bound materials, which can be easily removed by physical cleaning processes, whereas irreversible fouling is a more complicated phenomenon and can cause clogging, which requires chemical cleaning for its removal (Odize *et al.* 2017).

Researchers have tried to chemically clean diffusers such that they are less vulnerable to fouling. However, challenges arise since diffusers are porous hence a continuous supply of cleaning chemicals is a challenge. Moreover, by using some coatings on the diffuser material of construction as having been used previously, some of these coatings are not resistant to cleaning chemicals, have poor durability and easily leach (Hamza *et al.* 1997). Zhao *et al.* (2004) investigated the effect of free energy of diffusers surfaces to minimize microbial adhesion. They used a nickel polytetrafluoroethylene (PTFE) coating and achieved a reduced microbial adhesion of 68–94%. To mitigate these challenges, routine cleaning-in-place of diffusers must be implemented. However, diffuser maintenance can delay or take operator's time, thus increasing downtime (Boyle & Redmon 1983); hence, innovative diffusers that require very minimal maintenance are needed. During disinfection, operations using oxidative micro and nanobubbles is deemed effective when compared to normal air bubbles produced through a porous material (Sung *et al.* 2017), as diffusers can be designed in such a way that they produce oxidative bubbles that will affect the microbial community in the wastewater while carrying out their normal flotation process. However, future research needs to investigate if additives such as silver nano-particles that can be incorporated during diffuser production reduce the microbial load in wastewater being treated due to their antimicrobial properties.

### Sparging rate influences

Sparging rate is important in the production of suitable microbubbles. It determines the bubble size, which influences residence time in the form of throughput rates of treated wastewater and rising bubble velocity with bigger bubbles having lesser residence time, and thus less bubble particle collision times than smaller bubbles, which leads to inefficiencies (Edzwald *et al.* 1992). Gas flow rate determines the air bubble quantity that goes into a flotation system, whilst affecting the bubble size and the flow pattern in column flotation; hence, an averaged flow rate is advised (Liu *et al.* 1999).

Also, the pressure loss of a system determines the energy consumption, especially for diffusive aeration. This is usually an indicator of clogging and fouling that further causes increased back pressure on the diffusers, thus indicating reductions in the performance of the system. The pressure loss can be estimated using Equation (1) (Krampe 2011);

$$\Delta P = P_T - P_D - P_P \quad (1)$$

Where

- $\Delta P$  = Diffuser pressure loss
- $P_T$  = Pressure of the total air supply
- $P_D$  = Hydrostatic pressure resultant from injection depth
- $P_P$  = Pressure loss of valves and/or pipes

Hence, when designing diffusers, properties that reduce chances of clogging and fouling thus minimising pressure loss and the need for increased gas flow rate should be considered.

### Suspended solids loading rate influences

The suspended solid loading rate is an important factor in flotation system operation as it determines the quantity and concentration of suspended solids (flocs) to be removed. For example, suspended solids being fed into the tank per minute (Al-Sabagh *et al.* 2015) can affect the performance of the flotation system, which in turn affects the air-solid ratio, which can be estimated by Equation (2).

$$\frac{A}{S} = \frac{1.3S_a(fP - 1)}{X} \quad (2)$$

where:

$\frac{A}{S}$  = air-solid ratio (Kg air/Kg suspended solids in the feed),

$S_a$  = air solubility (mL/L),

$P$  = operating pressure (Kg/cm<sup>2</sup> or Pa)

$f$  = pressurisation system efficiency at pressure 0.8 and

$X$  = influent solids concentration (mg/L).

A/S ratio is the measure of the released quantity of air per solid mass available in a flotation cell. Air-solid ratio affects the collision frequency and buoyancy velocity of particle-bubble formations, including the suspended solids removal rates, which influences the overall performance of a flotation system. Various A/S ratios have been used in different applications (see Table 3).

**Table 3** | Examples of the required A/S ratios used in different applications

A/S ratios	Applications	References
0.05–0.22 kg air/kg solids	Iron hydroxide precipitation	Féris <i>et al.</i> (2001)
0.027–0.066 kg air/kg solids	Wastewater treatment (milk industry)	dos Santos Pereira <i>et al.</i> (2018)
0.015 kg air/kg solids	Textile effluent treatment	Pioltime & Reali (2011)
0.54–0.078 kg air/kg solids	Poultry slaughterhouse wastewater treatment	de Nardi <i>et al.</i> (2008)

Removal efficiencies will be negatively affected if less than the required amount of air is supplied whereas energy will be wasted if too much air is supplied; hence, an optimum supply should be employed thus making the A/S ratio an important parameter to be considered when designing air diffusers and flotation systems (Othman *et al.* 2021). Flotation systems have no tool that satisfactorily expresses it due to system complexity and many unknowns (Tai & Doo 1997; El-Gohary *et al.* 2010); therefore, designing of diffusers that distributes sufficient air is a necessity especially with the increased quantity and reduced quality of wastewater needing treatment.

### Hydraulic loading rate

Flotation systems are limited by operating costs, complex operating process variables, maintenance and optimisation. However, diffuser design has led to technological developments, which in turn resulted in increased hydraulic loading rate (HLR). HLR of up to 30 mh<sup>-1</sup> for high rate flotation systems have been reported (Edzwald 2010; Azevedo *et al.* 2017). However, with such design improvements over the years, it is important to take into account improvements in relation to the rising velocity of bubbles when designing the diffusers to avoid bubble floc aggregate disintegration (Maeng *et al.* 2017).



### Overall remarks on diffuser design and its use in a column flotation

This review allowed for identification of the gaps within diffuser design literature in relation to their physical design aspect and how operational parameters affect it. Importantly, at some instances, questions have been raised and suggestions have been mentioned. However, there is minimal information on the design of air diffusers as most research is focused on hydrodynamic properties rather than the air releasing device's properties and configurations including design. The review of diffuser design has highlighted that:

- Significant progress has been made to improve the efficiency of the diffusers; that is, new shapes have been introduced and materials used for construction has been varied including being mixed, but the diffusers are still inadequate to meet the process efficiency for particular purposes due to increased quantity and reduced quality of wastewater to be treated; hence, the need for improvement need not be understated.
- The challenges associated with air diffusers and their applications are known, and these include fouling, clogging, poor system efficiency and breaking, amongst others, thus reflecting the need to improve their design.
- The importance of understanding the effect of the diffuser design on operational parameters and the factors that are considered important when designing diffusers; that is, cost, durability and robustness using appropriate materials of construction.
- Process variables (sparging rate, suspended solid loading rate and hydraulic loading rate) should be taken into account when designing diffusers as they have an effect on the efficiency of the diffusers.
- Addition of additives to the diffusers can give them extra properties such as antimicrobial activities while carrying out their normal aeration/sparging processes.

Therefore, future work can:

- Explore whether the application of new technology such as 3D printing of air diffusers for use in a column flotation system can provide for suitable bubble size production that can lead to reduced energy consumption and a simplified system.
- Design air diffusers that have oxidative air generating properties, which might affect the microbial community present in the wastewater being treated, thus reducing the rate of fouling and improving the quality of treated water in terms of reduced microbial load while carrying out the normal flotation process.

### ACKNOWLEDGEMENTS

The authors would like to thank the CPUT Vice Chancellor Achiever's Award, National Research Foundation Thuthuka Funding, cost centre R017 and the University Research Fund (URF RK16) for their financial contribution to this work.

### DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

### REFERENCES

- Ahmadi, S. & Mostafapour, F. K. 2017 Survey of efficiency of dissolved air flotation in removal *penicillin G* potassium from aqueous solutions. *Br. J. Pharm. Med. Res.* **15**(3), 1–11.
- Ahmed, A. K. A., Sun, C., Hua, L., Zhang, Z., Zhang, Y., Zhang, W. & Marhaba, T. 2018 Generation of nanobubbles by ceramic membrane filters: the dependence of bubble size and zeta potential on surface coating, pore size and injected gas pressure. *Chemosphere.* **203**, 327–335.
- Al-sabagh, A. M., Sharaky, A. M., Noor El-din, M. R. & Hussein, K. M. 2015 Destabilization of gas condensate oil-water emulsion by dissolved air flotation using new Non Ionic Surfactants. *Tenside Surfact. Det.* **52**, 88–98.
- Al-Thyabat, S., Yoon, R. H. & Shin, D. 2011 Floatability of fine phosphate in a batch column flotation cell. *Mining, Metall. Explor.* **28**(2), 110–116.
- Amaral Filho, J., Azevedo, A., Etchepare, R. & Rubio, J. 2016 Removal of sulfate ions by dissolved air flotation (DAF) following precipitation and flocculation. *Int. J. Miner. Process.* **149**, 1–8.
- Amato, T., Brown, D. M., Ferguson, J. P. & Valentine, N. 2015 inventors; Doosan Enpure Ltd, assignee. *Dissolved gas flotation pressure reduction nozzle.* United States patent US 9,138,752.
- Andreoli, F. C. & Sabogal-Paz, L. P. 2017 Coagulation, flocculation, dissolved air flotation and filtration in the removal of *Giardia spp.* and *Cryptosporidium spp.* from water supply. *Environ. Technol.* **40**(5), 654–663.
- Atkinson, A. J., Apul, O. G., Schneider, O., Garcia-Segura, S. & Westerhoff, P. 2019 Nanobubble technologies offer opportunities to improve water treatment. *Acc. Chem. Res.* **52**(5), 1196–1205.

- Azevedo, A., Etchepare, R. & Rubio, J. 2017 Raw water clarification by flotation with microbubbles and nanobubbles generated with a multiphase pump. *Wat. Sci. Technol.* **75**, 2342–2349.
- Azevedo, A., Oliveira, H. A. & Rubio, J. 2018 Treatment and water reuse of lead-zinc sulphide ore mill wastewaters by high rate dissolved air flotation. *Miner. Eng.* **127**, 114–121.
- Basso, A., Hamad, F. A. & Ganesan, P. 2018 Effects of the geometrical configuration of air–water mixer on the size and distribution of microbubbles in aeration systems. *Asia-Pac J. Chem. Eng.* **13**(6), e2259.
- Behnisch, J., Ganzauge, A., Sander, S., Herrling, M. P. & Wagner, M. 2018 Improving aeration systems in saline water: measurement of local bubble size and volumetric mass transfer coefficient of conventional membrane diffusers. *Wat. Sci. Technol.* **78**(4), 860–867.
- Bennett, G. F. & Shammass, N. K. 2010 Separation of Oil from Wastewater by Air Flotation. In: *Flotation Technology*. (Wang, L. K., Shammass, N. K., Selke, W. A. & Auleribanch, D. B., eds). Humana Press, Totowa, NJ, pp. 85–119.
- Bleninger, T. O., Perez, L. M., Milli, H. U. & Jirka, G. H. 2005 Internal hydraulic design of a long diffuser in shallow water: Buenos Aires sewage disposal in Rio de la Plata estuary. In: *Proceedings of XXXI IAHR Congress*, 11–16 September, Seoul, Korea.
- Boyle, W. C. 2003 A brief history of aeration of wastewater. In: *Environmental and Water Resources History Sessions at ASCE Civil Engineering Conference and Exposition 2002*, 3–7 November, Washington, DC.
- Boyle, W. C. & Redmon, D. T. 1983 Biological fouling of fine bubble diffusers: state-of-art. *J. Environ. Eng.* **109**(5), 991–1005.
- Chaiarekij, S., Dhingra, H. & Ramarao, B. V. 2000 Deinking of recycled pulps using column flotation: energy and environmental benefits. *Resour. Conserv. Recycl.* **28**(3/4), 219–226.
- Chen, A., Wang, Z. & Yang, J. 2016 Influence of bubble size on the fluid dynamic behavior of a DAF tank: a 3D numerical investigation. *Colloids Surf, A Physicochem. Eng. Asp.* **495**, 200–207.
- Cheng, G., Shi, C. L., Liu, J. T. & Yan, X. K. 2016a Bubble-distribution measurement in a flotation column. *Int. J. Coal Prep. Util.* **36**(5), 241–250.
- Cheng, X., Xie, Y., Zheng, H., Yang, Q., Zhu, D. & Xie, J. 2016b Effect of the different shapes of air diffuser on oxygen mass transfer coefficients in microporous aeration systems. *Procedia Eng.* **154**, 1079–1086.
- Chow, L. 2007 *Performance Study on Dissolved air Flotation (DAF) Unit and Process Performance Improvement Study in the Physicochemical Treatment of Wastewater*. Master of Engineering Universiti Teknologi, Malaysia.
- Crossley, I. A. & Valade, M. T. 2006 A review of the technological developments of dissolved air flotation. *J. Water Supply Res. T.* **55**(7/8), 479–491.
- Dassey, A. & Theegala, C. 2011 Optimizing the air dissolution parameters in an unpacked dissolved air flotation system. *Water.* **4**(1), 1–11.
- Deliyanni, E. A., Kyzas, G. Z. & Matis, K. A. 2017 Various flotation techniques for metal ions removal. *J. Mol. Liq.* **225**, 260–264.
- de Nardi, I. R., Fuzi, T. P. & Del Nery, V. 2008 Performance evaluation and operating strategies of dissolved-air flotation system treating poultry slaughterhouse wastewater. *Resour. Conserv. Recycl.* **52**, 533–544.
- de Sena, R. F., Moreira, R. F. & José, H. J. 2008 Comparison of coagulants and coagulation aids for treatment of meat processing wastewater by column flotation. *Bioresour. Technol.* **99**(17), 8221–8225.
- Dlangamandla, C., Ntwampe, S. K. O. & Basitere, M. 2018 A bioflocculant-supported dissolved air flotation system for the removal of suspended solids, lipids and protein matter from poultry slaughterhouse wastewater. *Wat. Sci. Technol.* **78**, 452–458.
- dos Santos Pereira, M., Borges, A. C., Heleno, F. F., Squillace, L. F. A. & Faroni, L. R. D. A. 2018 Treatment of synthetic milk industry wastewater using batch dissolved air flotation. *J. Clean. Prod.* **189**, 729–737.
- Dupre, V., Ponasse, M., Aurelle, Y. & Secq, A. 1998 Bubble formation by water release in nozzles – I. Mechanisms. *Water Res.* **32**(8), 2491–2497.
- Edzwald, J. K., Walsh, J. P., Kaminski, G. S. & Dunn, H. J. 1992 Flocculation and air requirements for dissolved air flotation. *J. Am. Water Works Ass.* **84**, 92–100.
- Edzwald, J. K. 2010 Dissolved air flotation and me. *Water Res.* **44**(7), 2077–2106.
- El-Gohary, F., Tawfik, A. & Mahmoud, U. 2010 Comparative study between chemical coagulation/precipitation (C/P) versus coagulation/dissolved air flotation (C/DAF) for pre-treatment of personal care products (PCPs) wastewater. *Desalination* **252**, 106–112.
- Ernest, L. 1994 *Case History Report on Milwaukee Ceramic Plate Aeration Facilities*.
- Etchepare, R., Azevedo, A., Calgaroto, S. & Rubio, J. 2017 Removal of ferric hydroxide by flotation with micro and nanobubbles. *Sep. Purif. Technol.* **184**, 347–353.
- Eusebi, A. L. & Battistoni, P. 2014 Behaviour of air diffusers and oxygen transfer efficiencies in the biological treatment of matrices at high alkalinity concentrations: experimental and full scale application. *Chem. Eng. J.* **255**, 274–281.
- Eusebi, A. L., Bellezze, T., Chiappini, G., Sasso, M. & Battistoni, P. 2017 Influence of aeration cycles on mechanical characteristics of elastomeric diffusers in biological intermittent processes: accelerated tests in real environment. *Water Res.* **117**, 143–156.
- Féris, L. A., Gallina, S. C. W., Rodrigues, R. T. & Rubio, J. 2000 Optimizing dissolved air flotation design system. *Braz. J. Chem. Eng.* **17**(4/7), 549–556.
- Féris, L. A., Gallina, C. W., Rodrigues, R. T. & Rubio, J. 2001 Optimizing dissolved air flotation design and saturation. *Wat. Sci. Technol.* **43**(8), 145–157.

- Finch, J. A. 1995 Column flotation: a selected review – part IV: novel flotation devices. *Miner. Eng.* **8**(6), 587–602.
- Ford, C. E. 1942 inventor; NAT CARBON CO Inc, assignee. *Fluid treatment diffuser element*. United States patent US 2,294,973.
- Frank, V. B., Regnery, J., Chan, K. E., Ramey, D. F., Spear, J. R. & Cath, T. Y. 2017 Co-treatment of residential and oil and gas production wastewater with a hybrid sequencing batch reactor-membrane bioreactor process. *J. Water Process Eng.* **17**, 82–94.
- Garrido-Baserba, M., Asvathanagul, P., McCarthy, G. W., Gocke, T. E., Olson, B. H., Park, H. D., Al-Omari, A., Murthy, S., Bott, C. B., Wett, B., Smeraldi, J. D., Shaw, A. & Rosso, D. 2016 Linking biofilm growth to fouling and aeration performance of fine-pore diffuser in activated sludge. *Water Res.* **90**, 317–328.
- Garrido-Baserba, M., Asvathanagul, P., Park, H. D., Kim, T. S., Baquero-Rodriguez, G. A., Olson, B. H. & Rosso, D. 2018 Impact of fouling on the decline of aeration efficiency under different operational conditions at WRRFs. *Sci. Total Environ.* **639**, 248–257.
- Gopalratnam, V. C., Bennett, G. F. & Peters, R. W. 1988 The simultaneous removal of oil and heavy metals from industrial wastewater by joint precipitation and air flotation. *Environ. Prog.* **7**(2), 84–92.
- Gu, X. & Chiang, S. H. 1999 A novel flotation column for oily water cleanup. *Sep. Purif. Technol.* **16**(3), 193–203.
- Haarhoff, J. & van Vuuren, L. R. J. 1995 Design parameters for dissolved air flotation in South Africa. *Wat. Sci. Technol.* **31**(3/4), 203–212.
- Haarhoff, J. 2008 Dissolved air flotation: progress and prospects for drinking water treatment. *J. Water Supply Res. T.* **57**(8), 555–567.
- Hamza, A., Pham, V. A., Matsuura, T. & Santerre, J. P. 1997 Development of membranes with low surface energy to reduce the fouling in ultrafiltration applications. *J. Membrane Sci.* **131**, 217–227.
- Han, M. Y. 2002 Modeling of DAF: the effect of particle and bubble characteristics. *J. Water Supply Res. T.* **51**(1), 27–34.
- Han, M., Park, Y., Lee, J. & Shim, J. 2002 Effect of pressure on bubble size in dissolved air flotation. *Wat. Sci. Tech-W. Sup.* **2**(5/6), 41–46.
- Harun, M. H. C. & Zimmerman, W. B. 2019 Membrane defouling using microbubbles generated by fluidic oscillation. *Water Supply* **19**(1), 97–106.
- Henderson, R. K., Parsons, S. A. & Jefferson, B. 2008 Surfactants as bubble surface modifiers in the flotation of algae: dissolved air flotation that utilizes a chemically modified bubble surface. *Environ. Sci. Technol.* **42**(13), 4883–4888.
- Ives, K. J. & Bernhardt, H. J. 1995 *Flotation Processes in Water Treatment and Sludge Treatment*. Pergamon Press, Oxford, UK.
- Krampe, J. 2011 Assessment of diffuser pressure loss on WWTPs in Baden-Württemberg. *Wat. Sci. Technol.* **63**, 3027–3033.
- Krasnoff, E. L. & Luthi, O. 1982 inventors; Ingersoll-Rand Co, assignee. *Clarifier bubble generation and distribution nozzle*. United States patent US 4,338,192.
- Kulkarni, A. V. & Joshi, J. B. 2011 Design and selection of sparger for bubble column reactor. Part I: performance of different spargers. *Chem. Eng. Res. Des.* **89**(10), 1972–1985.
- Kundu, P. & Mishra, I. M. 2018 Treatment and reclamation of hydrocarbon-bearing oily wastewater as a hazardous pollutant by different processes and technologies: a state-of-the-art review. *Rev. Chem. Eng.* **35**, 73–108.
- Kyzas, G. Z. & Matis, K. A. 2018 Flotation in water and wastewater treatment. *Processes* **6**(8), 116–131.
- Lamb, M. A. 1957 inventor; Chicago Pump Co, assignee. *Diffuser tube*. United States patent US 2,815,943.
- Lamort, J. P. 1989 inventor; Feldmühle AG, Lamort Fils E, M SA, assignee. *Pressurized mixing injector*. United States patent US 4,842,777.
- Lee, C. H., Choi, H., Jerng, D. W., Kim, D. E., Wongwises, S. & Ahn, H. S. 2019 Experimental investigation of microbubble generation in the venturi nozzle. *Int. J. Heat Mass Transf.* **136**, 1127–1138.
- Li, P. & Tsuge, H. 2006 Water treatment by induced air flotation using microbubbles. *J. Chem. Eng. Jpn.* **39**(8), 896–903.
- Liu, J. C., Chen, Y. M. & Ju, Y. H. 1999 Separation of algal cells from water by column flotation. *Sep. Sci. Technol.* **34**(11), 2259–2272.
- Liu, S., Wang, Q., Ma, H., Huang, P., Li, J. & Kikuchi, T. 2010 Effect of micro-bubbles on coagulation flotation process of dyeing wastewater. *Sep. Purif. Technol.* **71**(3), 337–346.
- Lu, Y., Zhang, F., Zhang, Y., Hu, K. & Wang, S. 2016 Research of oily wastewater treatment by micro-bubble flotation experimental device. In: *2016 International Field Exploration and Development Conference (IFEDC)*, 11–12 August, Beijing.
- Maeng, M. S., Kim, H. S., Lee, K. S. & Dockko, S. 2017 Effect of DAF configuration on the removal of phosphorus and organic matter by a pilot plant treating combined sewer overflows. *Int. Biodeter. Biodegr.* **124**, 17–25.
- Maples, W. A. 1992 inventor; Microlift Systems Inc, assignee. *Discharge valve for dissolved air flotation*. United States patent US 5,139,663.
- Martin, A. 1927 *The Activated Sludge Process*. Macdonald & Evans, London.
- Matis, K. 1995 *Flotation Science and Engineering*. M. Dekker, New York.
- Meng, F., Chae, S. R., Drews, A., Kraume, M., Shin, H. S. & Yang, F. 2009 Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material. *Water Res.* **43**(6), 1489–1512.
- Mukandi, M. 2017 *Modelling of A Bioflocculant Supported Dissolved air Flotation System for Fats oil and Grease Laden Wastewater Pretreatment*. Master's thesis, Cape Peninsula University of Technology, Cape Town, South Africa.
- Nadayil, J., Mohan, D., Dileep, K., Rose, M. & Parambi, R. R. 2015 A study on effect of aeration on domestic wastewater. *Int. J. Interdiscip. Res. Innov.* **3**(2), 10–15.

- Ndikubwimana, T., Chang, J., Xiao, Z., Shao, W., Zeng, X., Ng, I. S. & Lu, Y. 2016 Flotation: a promising microalgae harvesting and dewatering technology for biofuels production. *Biotechnol. J.* **11**(3), 315–326.
- Noble, P. A., Park, H. D., Olson, B. H., Asvapathanagul, P., Hunter, M. C., Garrido-Baserba, M., Lee, S. H. & Rosso, D. 2016 A survey of biofilms on wastewater aeration diffusers suggests bacterial community composition and function vary by substrate type and time. *Appl. Microbiol. Biotechnol.* **100**(14), 6361–6373.
- Odize, V. O., Novak, J., De Clippeleir, H., Al-Omari, A., Smeraldi, J. D., Murthy, S. & Rosso, D. 2017 Reverse flexing as a physical/mechanical treatment to mitigate fouling of fine bubble diffusers. *Wat. Sci. Technol.* **76**(7), 1595–1602.
- Offringa, G. 1995 Dissolved air flotation in Southern Africa. *Wat. Sci. Technol.* **31**(3/4), 159–172.
- Oliveira, C., Rodrigues, R. T. & Rubio, J. 2010 A new technique for characterizing aerated flocs in a flocculation–microbubble flotation system. *Int. J. Miner. Process.* **96**(1/4), 36–44.
- Othman, M. H. D., Tai, Z. S., Usman, J., Ismail, N. J., Rahman, M. A. & Jaafar, J. 2021 Oily Wastewater Treatment. In: *Water Pollution and Remediation: Organic Pollutants*. (Inamuddin, Ashamed, M. I. & Lichtfouse, E., eds). Springer, Cham, pp. 353–385.
- Ovezea, A. 2009 Saving energy: using fine bubble diffusers. *Filtr. Separat.* **46**(1), 24–27.
- Painmanakul, P., Sastaravet, P., Lersjintanakarn, S. & Khaodhiar, S. 2010 Effect of bubble hydrodynamic and chemical dosage on treatment of oily wastewater by Induced Air Flotation (IAF) process. *Chem. Eng. Re.S Des.* **88**(5/6), 693–702.
- Park, S. W., Park, Y. H., You, S. J. & Park, B. S. 2017 inventors; Doosan Heavy Industries, Construction Co Ltd, assignee. *Nozzle for dissolved air flotation system*. United States patent US 9,808,810.
- Peleka, E. N., Gallios, G. P. & Matis, K. A. 2018 A perspective on flotation: a review. *J. Chem. Technol. Biotechnol.* **93**(3), 615–623.
- Pioltine, A. & Reali, M. A. P. 2011 Use of a multiphase pump as a generating unit of air microbubbles in a flotation system applied to the pretreatment of textile effluent. *Sanitary and Environmental Engineering* **16**(2), 167–174.
- Procter, C. E. (1953) inventor; Activated Sludge Ltd, assignee. *Diffuser for gases*. United States patent US 2,639,131.
- Raftis, S. G. (2002) inventor; Red Valve Co Inc, assignee. *Fine bubble diffuser*. United States patent US 6,367,783.
- Rodrigues, R. T. & Rubio, J. 2003 New basis for measuring the size distribution of bubbles. *Miner. Eng.* **16**(8), 757–765.
- Roe, F. C. 1945 Porous tube air diffusers. *Sewage Works J.* **17**(5), 878–888.
- Rohlich, G. A. 1954 Application of air flotation to refinery waste waters. *J. Ind. Eng. Chem.* **46**(2), 304–308.
- Rosso, D. & Stenstrom, M. K. 2006 Economic implications of fine pore diffuser aging. *Water Environ. Res.* **78**(8), 810–815.
- Rosso, D. & Shaw, A. R. 2015 *Framework for Energy Neutral Treatment for the 21st Century Through Energy Efficient Aeration*. IWA Publishing, London, UK.
- Rosso, D., Libra, J. A., Wiehe, W. & Stenstrom, M. K. 2008 Membrane properties change in fine-pore aeration diffusers: full-scale variations of transfer efficiency and headloss. *Water Res.* **42**, 2640–2648.
- Rosso, D., Jiang, L. M., Pitt, P., Hocking, C. S., Stenstrom, M. K., Murthy, S., Hayden, D. M., Zhong, J., Coller, D. H., Kim, A. Y. & Xu, H. 2012 Methodology for in situ column testing to improve accuracy during design and specification of aeration systems. *J. Environ. Eng.* **139**(4), 530–537.
- Rubinstein, J. B. 1995 *Column Flotation: Processes Designs and Practice*. Gordon and Breach Science Publishers, Basel, Switzerland.
- Rubio, J., Souza, M. L. & Smith, R. W. 2002 Overview of flotation as a wastewater treatment technique. *Miner. Eng.* **15**(3), 139–155.
- Rubio, J., Azevedo, A. & Etchepare, R. 2016 Nanobubbles: their role in dissolved air flotation. In: *The 7th International Conference on Flotation for Water and Wastewater Systems, Flotation 2016*, 26–30 September, Toulouse, France. IWA Publishing, London, UK.
- Ryan, R. J. 1991 inventor; Aquatec Inc, assignee. *Diffuser for aeration basin*. United States patent US 4,981,623.
- Rykaart, E. M. & Haarhoff, J. 1995 Behaviour of air injection nozzles in dissolved air flotation. *Wat. Sci. Technol.* **31**(3/4), 25–35.
- Sadatomi, M., Kawahara, A., Kano, K. & Ohtomo, A. 2005 Performance of a new micro-bubble generator with a spherical body in a flowing water tube. *Exp. Therm. Fluid Sci.* **29**(5), 615–623.
- Santos, P. R. & Daniels, L. A. 2017 Dissolved air flotation as a potential treatment process to remove *Giardia* cysts from anaerobically treated sewage. *Environ. Technol.* **38**(19), 2392–2399.
- Schweiss, P. & Dorflinger, H. D. 1984 inventors; Voith JM GmbH, assignee. *Injector apparatus having a constriction in a following adjoining mixing pipe*. United States patent US 4,477,341.
- Seger, M. A., Oliveira, C. & Rodrigues, R. T. 2019 Development of a laboratory-scale flotation column with inlet bubble size measurement. *Miner. Eng.* **142**, 105936.
- Shammas, N. K. 2007 Fine pore aeration of water and wastewater. In: *Advanced Physicochemical Treatment Technologies*. (Wang, K. L., Hung, Y. & Shammas, N. K., eds). Humana Press, Totowa, NJ, pp. 391–448.
- Shukla, S. C., Kundu, G. & Mukherjee, D. 2010 Study of gas holdup and pressure characteristics in a column flotation cell using coal. *Miner. Eng.* **23**(8), 636–642.
- Silva, E. J., Silva, I. A., Brasileiro, P. P., Correa, P. F., Almeida, D. G., Rufino, R. D., Luna, J. M., Santos, V. A. & Sarubbo, L. A. 2019 Treatment of oily effluent using a low-cost biosurfactant in a flotation system. *Biodegradation.* **30**(4), 335–350.
- Sung, M., Teng, C. H. & Yang, T. H. 2017 Dissolution enhancement and mathematical modeling of removal of residual trichloroethene in sands by ozonation during flushing with micro-nano-bubble solution. *J. Contam.* **202**, 1–10.



- Tai, H. C. & Doo, Y. K. 1997 Significance of pressure and recirculation in sludge thickening by dissolved air flotation. *Wat. Sci. Technol.* **36**(12), 223–230.
- Takko, P. 1992 inventor; *Dispersion water nozzle*. United States patent US 5,154,351.
- Tao, X., Liu, Y., Jiang, H. & Chen, R. 2019 Microbubble generation with shear flow on large-area membrane for fine particle flotation. *Chem. Eng. Process.* **145**, 107671.
- Temesgen, T., Bui, T. T., Han, M., Kim, T. I. & Park, H. 2017 Micro and nanobubble technologies as a new horizon for water-treatment techniques: a review. *Adv. Colloid Interface Sci.* **246**, 40–51.
- Tian, Z., Wang, C. & Ji, M. 2018 Full-scale dissolved air flotation (DAF) equipment for emergency treatment of eutrophic water. *Wat. Sci. Technol.* **77**(7), 1802–1809.
- Vashisth, S., Bennington, C. P., Grace, J. R. & Kerekes, R. J. 2011 Column flotation deinking: state-of-the-art and opportunities. *Resour. Conserv. Recycl.* **55**(12), 1154–1177.
- Wang, Z., Wu, Z., Yin, X. & Tian, L. 2008 Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: membrane foulant and gel layer characterization. *J. Membrane Sci.* **325**, 238–244.
- Wang, J., Park, H., Ng, C. Y. & Wang, L. 2019 Use of oscillatory air supply for improving the throughput and carrying capacity of column flotation. *Powder Technol.* **353**, 41–47.
- Xiao, H., Geng, S., Chen, A., Yang, C., Gao, F., He, T. & Huang, Q. 2019 Bubble formation in continuous liquid phase under industrial jetting conditions. *Chem. Eng. Sci.* **200**, 214–224.
- Zabel, T. 1985 The advantages of dissolved-air flotation for water treatment. *J. Am. Water Works Ass.* **77**(5), 42–46.
- Zhang, W. H., Zhang, J., Zhao, B. & Zhu, P. 2015 Microbubble size distribution measurement in a DAF system. *Ind. Eng. Chem. Res.* **54**(18), 5179–5183.
- Zhao, Q., Wang, S. & Müller-Steinhagen, H. 2004 Tailored surface free energy of membrane diffusers to minimize microbial adhesion. *Appl. Surf. Sci.* **230**(1/4), 371–378.
- Zhekun, L., Min, L. & Yuanli, Q. 2010 Study on microbubble generators for treatment of wastewaters. In: *5th International Conference on Responsive Manufacturing – Green Manufacturing (ICRM 2010)*, 11–13 January, Ningbo, China.
- Zimmerman, W., Tesar, V., Butler, S. & Bandulasena, H. 2008 Microbubble generation. *Recent Pat. Eng.* **2**(1), 1–8.
- Zimmerman, W. B., Hewakandamby, B. N., Tesar, V., Bandulasena, H. H. & Omotowa, O. A. 2009 On the design and simulation of an airlift loop bioreactor with microbubble generation by fluidic oscillation. *Food Bioprod. Process.* **87**(3), 215–227.

First received 14 November 2020; accepted in revised form 23 June 2021. Available online 6 July 2021