

Applications of micro–nano bubble technology in environmental pollution control

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Owing to some advantages of high oxidation capacity, high mass-transfer efficiency, high utilisation rate of reagents, simple system for treating pollutants, micro–nanobubble technology (MNBT) has gradually attracted attention and has been successfully applied in environmental pollution control. Currently, its applications in this field are mainly in the aspects of surface water purification, sewage (waste) water treatment, soil and groundwater remediation and sludge treatment which are reviewed. These studies primarily focus on the MNB generation (MNBG) methods, the parameters of pollution treatment and its effect improvement, the coupling techniques of this technology and other advanced oxidation technologies. However, in order to successfully promote its applications to the actual environmental pollution control process, especially the industrial scale, the following efforts are required: covariant response mechanism of water quality – micro–nano aeration parameters – bubble characteristics, further optimisation of synergistic process with other advanced oxidation methods, development of lower energy consumption and more efficient MNBG devices. After discussion and analysis, this work further points out that the purification of exhaust gas such as volatile organic compounds (VOC) and flue gas is one of the research directions worth exploring in the future application of the MNBT.

1. Introduction: Microbubbles (MBs) and nanobubbles (NBs) are tiny bubbles with a respective diameter of 10–50 μm and <200 nm [1]. So, the tiny bubbles between the two in diameter are usually called micro–NBs (MNBs). Researchers have noted that the MNBs have the following six superior properties to the ordinary bubbles.

1.1. Specific surface area of the MNBs is large: It can be calculated that the surface area (S) per unit volume (V) of a bubble is inversely proportional to the bubble radius (r) by the following equations:

$$S = 4\pi r^2 \quad (1)$$

$$V = 4/3\pi r^3 \quad (2)$$

$$S/V = 3/r \quad (3)$$

Thus, for a unit volume, the specific surface area of the MNBs with a radius of 1 μm is 1000 times as much as that of the conventional bubbles with a radius of 1 mm [2].

1.2. Time when the MNBs stay in the water is longer: Normally, the macrobubbles rapidly rise and burst at the water surface, whereas the MBs can exist for a long time under the water surface [3]. Turner [4] first confirmed that the MBs with a radius of 30 μm became stabilised in a body of the water and persisted for prolonged periods of time. Ohgaki *et al.* [5] found that the NBs of nitrogen, methane or argon with a radius of 50 nm have a lifetime of more than two weeks. Additionally, the research results of Takahashi [6] showed that some NBs could even exist in water for months.

1.3. MNBs can be self-pressurised and dissolved in the water: In fact, back in 1998, Bredwell and Worden [7] proposed that large specific surface area and high interior gas pressure of the MNBs conferred to these bubbles' high gas dissolution capability. It is well known that the relationship between the interior gas pressure and the bubble radius is expressed by the Young–Laplace equation

$$P = P_1 + 2\sigma/r \quad (4)$$

where P is the gas pressure; P_1 is the liquid pressure; σ is surface tension; and r is the radius of the bubble [8]. It explains that the pressure inside the bubble increases with the decrease of the bubble diameter. As the MNBs rises under the water, it shrinks to become smaller so as to increase interior gas pressure. According to Henry's law, the amount of dissolved gas surrounding a shrinking bubble increases with rising internal gas pressure. Ultimately, the gas in the MNBs can be dissolved in the water during the process of shrinkage [3] which can make the gas solubility in the water reach a state of oversaturation. Fig. 1 [9] shows the differences in the behaviours among ordinary bubble, MBs and NBs.

1.4. MNBs has high mass-transfer efficiency: The specific surface area of the bubble determines the mass-transfer efficiency of the gas. For the MNBs, the mass-transfer rate of the bubble gas from bubbles to surrounding liquid increases with a decrease in the bubble radius and an increase in the bubble's internal pressure [10]. Therefore, it is believed that the self-pressurised dissolution of the MNBs can enhance the gas–liquid mass transfer so as that this exclusive property allows the MNBs to continue the gas mass-transfer process and maintain an efficient mass-transfer efficiency even when the gas content in the water reaches the condition of oversaturation. For instance, it has been confirmed that the MNBs significantly increase the mass-transfer efficiency of ozone [11] and oxygen [10].

1.5. High zeta potential is formed at the interface of the MNBs: The charged ions around the interface of the MNBs can create an electrical double layer which is illustrated in Fig. 2 [12]. The interface potential of the MNBs, which is a crucial factor to determine the adsorption performance of the bubble interface, represents the potential difference between the electrical double layer on the surface of the bubbles. When the MNBs shrink in the water, the charged ions are rapidly concentrated and enriched at a very narrow bubble interface, showing a significant increase in zeta potential and a very high potential value is generated at the interface before the bubbles burst [9]. Researchers found that the values of zeta potential are negative under a wide range of pH conditions and the absolute values are in the range between 34–45 mV (oxygen), 17–20 mV (air), 29–35 mV (nitrogen), 20–27 mV

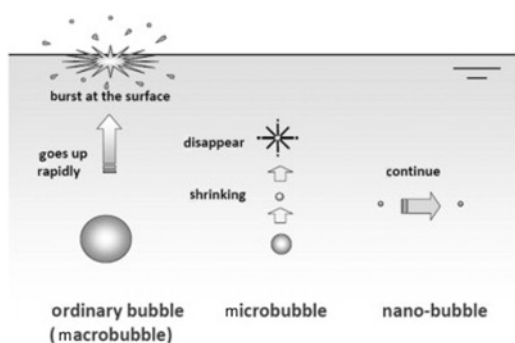


Fig. 1 Schematic diagram showing macro, micro and NBs [9]

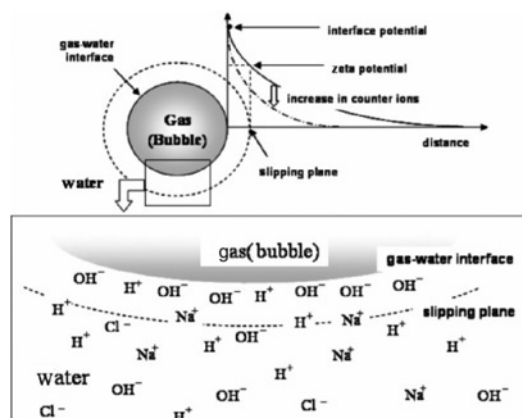


Fig. 2 Distribution of ions at and near the gas-water interface in an aqueous solution of NaCl and creation of the electrical double layer [12]

(carbon dioxide) and 11–22 mV (xenon) [13], but the MNBs are positively charged under strongly acidic conditions [12].

1.6. MNBs can spontaneously generate free radicals: When the MNBs contract and collapse, the disappearance of the gas-liquid interface lead to drastic changes, which can release the energy accumulated by a high concentration of positive and negative ions on the interface so as to generate a mass of hydroxyl radicals [9]. However, the number of free radicals generated is also affected to some extent by the type of gas in the MNBs [14, 15].

1.7. Applications of the MNBs in environmental pollution control have been widely concerned: The six major properties mentioned above make the MNBs show some prominent advantages such as increasing the solubility of the gas in aqueous solution, enriching the active oxygen in the water, enhancing adsorption performance of the bubble and strong oxidation property. Thus, the MNBs have attracted the interest of researchers. Since Takahashi *et al.* [16] conducted the study of bubble formation in dissolved air pressure flotation in 1979 (the average diameter of the bubbles generated is 100–200 μm), for obtainment of higher-quality MNBs, many other researchers have developed a variety of the MNB generation (MNBG) methods such as shear method [17–19], pressurised dissolution method [20], electrolysis method [21, 22], micropipette [23] and ultrasonic cavitation [24]. With the development of these methods, the applications of the MNBs in the field of environmental pollution control have attracted more and more attention from researchers. Simultaneously, with the expansion of its application research, The MNB technology (MNBT) gradually exhibits technical advantages and bright development prospects. At present, the applications of the MNBT in environmental pollution control are mainly in the aspects of

surface water purification, sewage (waste) water treatment, soil and groundwater remediation and sludge treatment, which are reviewed in this Letter.

2. Surface water purification: Surface water has a natural purification process. In addition to the direct oxidation of pollutants [combined with the dissolved oxygen (DO) in the water], the purification process of any natural water body can only be completed with the direct participation of aquatic organisms, which is called biological purification, which is the most important and active process of surface water self-purification. It has been demonstrated that microbes could effectively decompose, transform and mineralise nutrients, organic matter and recalcitrant contaminants in urban rivers [25–27]. DO in the water is a basic condition for the survival and purification of aquatic organisms. The content of DO in the water is one of the main factors influencing the biological purification of the water body and is also the main index to measure the self-purification ability of the water body.

Aeration is one of the most important engineering contents in the water purification. Traditional aeration not only has low efficiency and high energy consumption, but also produces large bubbles, causing surface disturbance and odour gas volatilisation. Owing to the MNBs' characteristics of large specific surface area, long stagnation under the water, self-shrinking pressurised dissolution and radicals' generation during collapse, aeration with the MNBs instead of traditional bubbles can not only form a highly dispersed gas-liquid interface in the water so as to play a good role in the air flotation water purification and oxidation of organic pollutants (including refractory organic pollutants), but also greatly improve the oxygen-increasing efficiency. Studies have shown that the MNBs generated from air and nitrogen could enhance the activities of microorganisms and/or bacteria in both anaerobic and aerobic conditions to accelerate the biodegradation of the pollutants in the water and sediment [1, 28–36], which also evidence that the MNBs can improve the biological purification capacity of the water bodies. As a consequence, it is believed that through aeration with the MNBs, the water purification can be achieved more effectively. Sun *et al.* [37] first used the MNB and submerged resin floating bed composite technology (MNBSR) to restore two black and stinking urban rivers in the South of China. After restoration, the water pollution indices such as DO, ammonia nitrogen ($\text{NH}_4^+\text{-N}$), total phosphorous (TP), chemical oxygen demand, water clarity and the number of faecal coliforms were significantly improved. It has been reported that positively charged MBs could efficiently separate algae from the freshwater, with $\sim 90\%$ of cell number removal and 92% of chlorophyll a reduction [38–40]. Since the MNB aeration technology can more effectively enhance the oxygen mass-transfer effect, the concentration of DO and the oxidation effect than the traditional aeration, it can improve the efficiency and effect of the water purification. However, the research on the application of the MNBT in the surface water purification is just beginning, the mechanism and principle of its action need to be further studied.

3. Sewage (waste) water treatment: Up till now, the applications of the MNBT in the sewage (waste) water treatment have been attracting more attention. Liu *et al.* [41] carried out comparison experiments of coagulation MB flotation and coagulation conventional air bubble flotation for the pretreatment of dyeing wastewater. Results showed that the MBs could reach a higher oxygen transfer rate (the total mass-transfer coefficient of the MBs was 1.1754 min^{-1} and that of conventional air bubbles was of 0.7535 min^{-1}), and under the same conditions the removal efficiencies of COD, colour and oil for the MB flotation increased 30, 110 and 40%, respectively, compared the conventional air bubble flotation. Furthermore, the wastewater biodegradability was increased from 0.290 to 0.363 after coagulation MB flotation and to 0.301 after coagulation conventional air bubble flotation. It follows that

the treatment of wastewater by the MNBs is better than by the conventional bubbles. Besides, gas flotation, aeration, disinfection and advanced oxidation processes combined with the MNBT, which can more effectively realise adsorption and removal of suspended solids [42], intensive decomposition of refractory organic pollutants [39], disinfection [43, 44] and decolourisation [45], are the most commonly known processes.

3.1. Removal of suspended solids: The strong adsorption performance of the MNBs can very effectively remove suspended solids, oil pollutant and fine particulate matter in the sewage (waste) water. To study the effects of the bubble size and bubble concentration which have a major impact on the bubble-floc collisions, Li and Tsuge [19] improved the induced air flotation process with a rotating-flow MB generator combined a centrifugal pump and altered the air induced way of the generator. The results indicated that the smaller MBs were obtained, while the MBs concentration was increased by the improved method and a slight overdose, achieved better removal efficiency and no or less flocculation time performed very well, i.e. the particle removal efficiency of over 95% was achieved by recycling only 10% of treated water. Through laboratory and pilot-scale experiments of the NB flotation technology with coagulation/flocculation process for the enhanced treatment of chemical mechanical polishing (CMP) wastewater, Tsai *et al.* [46] found out that this method increased the wastewater clarification efficiency by 40% as compared with the traditional coagulation/flocculation process, eliminating more than 95% turbidity, total solids and total silica. Thereby, it can be reasonably believed that the CMP wastewater could be treated efficiently at a minimum cost by using this approach. Many reports have shown that the MNBT is a simple, efficient, low-cost and environmentally friendly technology for removing oil pollutants and fine particulate matter from the wastewater [47–55].

3.2. Decomposition of organic pollutants and decolourisation: There is a lot of experimental evidence indicating intensive decomposition ability of the MNBs to various organic pollutants in the wastewater, even high-concentrated organic wastewater such as dimethyl sulphoxide [56], phenol [9, 57], rhodamine B [58], organic constituents of dye wastewater [59, 60], alachlor [61] and p-nitrophenol [62]. To further improve the treatment efficiency of organic pollutant, the synergistic effect of the MNBT and other strong oxidation methods such as ultraviolet (UV), pure oxygen and ozone is favoured by researchers. Liu *et al.* [63] carried out comparison experiments with three kinds of MBs (air, oxygen and ozone) on the coagulation flotation process for coke wastewater. The experiments demonstrated that the absolute zeta potential values of ozone MBs were the highest, which enhanced flotation efficiency and could generate a large number of free radicals which effectively oxidised the pollutants in coke waste. By contrast, either air MB flotation and oxygen MB flotation processes, pyridine removal efficiencies of the ozone MB flotation process were 4.5 and 1.7 times higher and benzene removal efficiency 3.6 and 1.5 times higher. Tasaki *et al.* [64] used UV light (185 and 254 nm) auxiliary to enhance the pure oxygen microair bubble effect on the degradation of methyl orange. The experimental results showed that under the irradiation of UV auxiliary, the speeds of the pure oxygen MBs produce hydroxyl radicals could be increased, the decolourisation rate of methyl orange was accelerated and the total organic carbon removal rate was significantly improved. It is worth mentioning that MNBs ozonation is a more efficient process of high-concentrated organic wastewater treatment. Chu *et al.* [65] achieved gratifying results utilising ozone MBs to treat the high-concentrated textile wastewater. In contrast to traditional ozone bubble, the COD removal efficiency was higher by 20% and the time required for 80% removal of colour was less by 140 min in the MBs system. More studies [66–72] showed that the synergistic effects of the MNBT and ozone/UV could give full play to their

advantages to effectively enhance the decomposition of organics, the biodegradability and the effect of decolourisation.

3.3. Water disinfection: The MNBT has good application prospects in water disinfection. For example, high deactivation efficiency of *Escherichia coli* can be achieved in water disinfection by the MBs generated through cavitation [73–77]. Particularly, the disinfection process combined the MNBT with ozone, which is a highly cost-effective method, can further improve efficiency. In the study of Sumikura *et al.* [78], they found out that in contrast with the traditional ozonation disinfection process, the ozone MBs has the faster disinfection kinetics of *E. coli*, the reactor size required was smaller and less ozone dose was required. Bathing pool assembly having water full of the ozone NBs for rehabilitation has been developed to prevent pathogen growth, to provide a more effective means for cleaning and disinfecting both the bath and the reservoir than the MBs [79].

In addition, some scholars have also used the MNBT to treat other pollutants in wastewater such as As(III) [80], ammonia [81], fluoride [82], residual pesticides [83] etc., the effect of which is also superior to conventional technology.

The MNBT provides an efficient and cost-effective approach for wastewater treatment. There are also relatively many studies on this aspect, in most of which, the main objectives of applying the MNBT are to downsize the facilities, to reduce operation time and reduce operation and maintenance cost of water-treatment plants, with a greater contaminant removal efficiency [84]. These are the bottlenecks that need to be resolved for the applications of the MNBT in the wastewater treatment and necessary for any technologies to be commercialised as well.

4. Soil and groundwater remediation: In situ bioremediation are one of the most common and environmental-friendly methods to remediate soil and groundwater [85–89]. The MNBs can greatly enhance bioremediation by accelerating the oxygen transfer process [2] while this process is capable of adsorbing small impurities so as to remove pollutants through its excellent adsorption capacity. For this reason, the MNBT has an obvious advantage in soil and groundwater remediation which has aroused great interest from scholars in this field. In the early 1990s, Jenkins *et al.* [90] carried out an experiment on in situ aeration remediation for soil contaminated by xylene. They injected the oxygen MBs mixed with *Pseudomonas putida* into the interstitial space of the soil column. The results showed that during the process, the MBs remained in the remediation area for up to 45 min and the utilisation rate of microbial strains on oxygen was up to 71–82%. After treatment, the residual xylene concentration in the soil was lower than the detection limit of the instrument. The study demonstrated that the hydraulic conductivity of the sand was not affected by the MNBs inside the pore water, and the mass-transfer rate of oxygen to the water was found to be 125 times faster than the macro-bubbled water which was 16 times less DO enhancement durability compared with micro-NB water [10]. Moreover, it has been recognized by many other scholars that the applications of the MNBT in in-situ soil and groundwater remediation showed strong technical advantages and application potential [2, 91–94]. What is more gratifying is that the results of a pilot test of this application, conducted in a pharmaceutical facility located in Milan Province with main contamination by total petroleum hydrocarbon (TPH) and Benzene, Toluene, Ethyl benzene, m,p-Xylene and o-Xylene (BTEXS), were great (100% of degradation in 5–6 months) [95]. Moreover, several scholars have successfully applied the ozone MNBs to the remediation of residual trichloroethene and non-aqueous-phase liquid in saturated soils [96–99].

Even today, soil and groundwater pollution are a serious threat and their efficient and simple treatment is still an uphill task for environmental protection. Therefore, more efficient and economic

methods are needed. As a new in situ repair technology with good application prospects, the MNBT is worth further studying.

5. Sludge treatment: Although the applications of the MNBT in the sludge treatment can be traced back to 1985, there are not many relevant reports so far. The research in this field mainly focuses on sludge concentration and sludge dissolution. Zabel [100] used MB flotation technology to concentrate the remaining sludge. The results were encouraging. However, no new related reports have emerged afterwards.

It is well known that sludge digestion is one of the traditional biological techniques for the stabilisation of sewage sludge discharged from the wastewater treatment plants [101, 102]. However, there are still some problems and shortcomings in typical sludge digestion technology such as high-water content, low biodegradability and high energy cost. Since the MNBs can improve the biodegradability and cell disintegration of sewage sludge, some scholars have introduced the MNBT into sludge digestion and pretreatment [103, 104]. According to the relevant reports, in comparison with the process of the same dosage carried by the ordinary bubbles, the MNBT can obviously enhance the utilisation rate of the gas contained in the bubbles, greatly improve sludge solubility, significantly increase the dissolution speed of sludge and reduce the operational costs [101, 105, 106]. These reports also demonstrated that the MNBT can significantly improve aquaculture water quality, which is mainly affected by the aquaculture sludge, to promote the creation of the benign ecological environment of aquaculture. Owing to the above-mentioned advantages of the MNBs, they can enhance the capacity of DO supplementation and microbial activity in aquaculture water to effectively inhibit the production of breeding sludge, even digest the existing sludge.

6. Conclusions and prospects: In summary, the major objectives of the current studies are the methods of the MNBG, the parameters of pollution treatment and its effect improvement, the coupling techniques of this technology and other advanced oxidation technologies and the mechanism of pollutant removal and have achieved the remarkable results. However, in order to successfully promote its applications to the actual environmental pollution control process, especially industrial scale, the following efforts are needed yet: covariant response mechanism of water quality – micro–nano aeration parameters – bubble characteristics, further optimisation of synergistic process with other oxidation methods, development of lower energy consumption and more efficient MNBG devices.

To be sure, according to the current research results, the MNBT can be considered as a technology with less chemical consumption, smaller equipment size, less land area, higher utilisation rate of oxidants such as ozone, less/no production of secondary pollutants and excellent effects of pollution treatment. Consequently, it is reasonable to believe that it is a low-cost, efficient and green technology which exhibits its great advantages in the applications of environmental pollution control. Its applications in the field of environmental pollution control will certainly be further studied. It may be a good idea to expand its pollution control field to the exhaust gas purification. For example, the applications in the treatment of VOCs and flue gas. The absorption method is one of the effective methods to treat VOCs. As mentioned before, the hypothesis is that the high absorption rate of VOCs can be achieved efficiently, if it is injected into the absorbent in the form of the MNBs. The study on the removal of flue gas pollutants using the MNBT combined with the oxidation–absorption technology should be an interesting one and is worth exploring. The fundamental principle of oxidation–absorption technology is that the harmful components in flue gas oxidised by the oxidants and absorbed by the absorbing medium for pollutants elimination. It is one of the promising technologies for flue gas treatment. The six superior features of the MNBs enhance the possibility of NO and SO₂ in

flue gas being oxidised and absorbed so as to improve the removal efficiency. It may even be considered to conduct the research on the non-differentiated and non-selective integrated-removal of multi-pollutants in flue gas using the MNBT.

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8 References

- [1] Agarwal A., Ng W.J., Liu Y.: 'Principle and applications of microbubble and nanobubble technology for water treatment', *Chemosphere*, 2011, **84**, pp. 1175–1180
- [2] Li H.Z., Hu L.M., Xia Z.R.: 'Impact of groundwater salinity on bio-remediation enhanced by micro–nano bubbles', *Materials*, 2013, **6**, pp. 3676–3687
- [3] Shanguan Y.F., Yu S.L., Gong C., *ET AL.*: 'A review of microbubble and its applications in ozonation', *IOP Conf. Ser., Earth Environ. Sci.*, 2018, **128**, p. 012149
- [4] Turner W.: 'Microbubble persistence in fresh water', *J. Acoust. Soc. Am.*, 1961, **33**, (9), p. 1223
- [5] Ohgaki K., Khanh N.Q., Joden Y., *ET AL.*: 'Physicochemical approach to nanobubble solutions', *Chem. Eng. Sci.*, 2010, **65**, pp. 1296–1300
- [6] Takahashi M.: 'Base and technological application of micro-bubble and nano-bubble', *Mater. Integr.*, 2009, **22**, pp. 2–19
- [7] Bredwell M.D., Worden R.M.: 'Mass-transfer properties of microbubbles. 1. Experimental studies', *Biotechnol. Prog.*, 1998, **14**, (1), pp. 31–38
- [8] Takahashi M., Kawamura T., Yamamoto Y., *ET AL.*: 'Effect of shrinking microbubble on gas hydrate formation', *J. Phys. Chem. B*, 2003, **107**, (10), pp. 2171–2173
- [9] Takahashi M., Chiba K., Li P.: 'Free-radical generation from collapsing microbubbles in the absence of a dynamic stimulus', *J. Phys. Chem. B*, 2007, **111**, (6), pp. 1343–1347
- [10] Li H.Z., Hu L.M., Song D.J., *ET AL.*: 'Subsurface transport behavior of micro–nano bubbles and potential applications for groundwater remediation', *Int. J. Environ. Res. Public Health*, 2014, **11**, (1), pp. 473–486
- [11] Hu L.M., Xia Z.R.: 'Application of ozone micro–nano-bubbles to groundwater remediation', *J. Hazard. Mater.*, 2018, **342**, pp. 446–453
- [12] Takahashi M.: 'Z potential of microbubbles in aqueous solutions: electrical properties of the gas–water interface', *J. Phys. Chem. B*, 2005, **109**, pp. 21858–21864
- [13] Ushikubo F.Y., Enari M., Furukawa T., *ET AL.*: 'Zeta-potential of micro- and/or nano-bubbles in water produced by some kinds of gases', *IFAC Proc. Vol.*, 2010, **43**, (26), pp. 283–288
- [14] Li P., Takahashi M., Chiba K.: 'Enhanced free-radical generation by shrinking microbubbles using a copper catalyst', *Chemosphere*, 2009, **77**, (8), pp. 1157–1160
- [15] Takahashi M., Chiba K., Li P.: 'Formation of hydroxyl radicals by collapsing ozone microbubbles under strongly acidic conditions', *J. Phys. Chem. B*, 2007, **111**, (39), pp. 11443–11446
- [16] Takahashi T., Miyahara T., Mochizuki H.: 'Fundamental study of bubble formation in dissolved air pressure flotation', *J. Chem. Eng. Jpn.*, 1979, **12**, (4), pp. 275–280
- [17] Fujikawa S., Zhang R.S., Hayama S., *ET AL.*: 'The control of micro-air-bubble generation by a rotational porous plate', *Int. J. Multiph. Flow*, 2003, **29**, (8), pp. 1221–1236
- [18] Kukizaki M., Goto M.: 'Size control of nanobubbles generated from shirasu-porous-glass (SPG) membranes', *J. Membr. Sci.*, 2006, **281**, (1), pp. 386–396
- [19] Li P., Tsuge H.: 'Water treatment by induced air flotation using microbubbles', *J. Chem. Eng. Jpn.*, 2006, **39**, (8), pp. 896–903
- [20] Edzwald J.: 'Fundamentals of dissolved air flotation', *J. New England Water Works Assoc.*, 2007, **121**, (2), pp. 89–112
- [21] Sakai O., Kimura M., Shirafuji T., *ET AL.*: 'Underwater micro-discharge in arranged microbubbles produced by electrolysis in electrolyte solution using fabric-type electrode', *Appl. Phys. Lett.*, 2008, **93**, pp. 231501–231503

- [22] Xie G.X., Luo J.B., Liu S.H., *ET AL.*: 'Effect of external electric field on liquid film confined within nanogap', *J. Appl. Phys.*, 2008, **103**, (9), pp. 094306–094307
- [23] Najafi A.S., Xu Z.H., Masliyah J.: 'Single micro-bubble generation by pressure pulse technique', *Chem. Eng. Sci.*, 2008, **63**, (7), pp. 1779–1787
- [24] Moussatov A., Granger C., Dubus B.: 'Cone-like bubble formation in ultrasonic cavitation field', *Ultrason. Sonochem.*, 2003, **10**, (4), pp. 191–195
- [25] Beale D.J., Karpe A.V., Ahmed W., *ET AL.*: 'A community multi-omics approach towards the assessment of surface water quality in an urban river system', *Int. J. Environ. Res. Public Health*, 2017, **14**, pp. 303–310
- [26] Chen Y.N., Liu Y., Li Y.P., *ET AL.*: 'Influence of biochar on heavy metals and microbial community during composting of river sediment with agricultural wastes', *Bioresour. Technol.*, 2017, **243**, pp. 347–355
- [27] Pi Y.R., Chen B., Bao M.T., *ET AL.*: 'Microbial degradation of four crude oil by biosurfactant producing strain *Rhodococcus* sp', *Bioresour. Technol.*, 2017, **232**, pp. 263–269
- [28] Ghadimkhani A., Zhang W., Marhaba T.: 'Ceramic membrane defouling (cleaning) by air nanobubbles', *Chemosphere*, 2016, **146**, pp. 379–384
- [29] Yamasaki K., Uda K., Chuhjoh K.: 'Wastewater treatment equipment and method of wastewater treatment'. U.S. Patent, 2009, 11/816880
- [30] Park J.S., Kurata K.: 'Application of microbubbles to hydroponics solution promotes lettuce growth', *Hot Technol.*, 2009, **19**, (1), pp. 212–215
- [31] Ushikubo F.Y., Oshita S., Furukawa T., *ET AL.*: 'A study of water containing micro and nano-bubbles and its possible effect on physiological activity'. Proc. Int. Conf. Agricultural Engineering, Iguassu Falls City, Brazil, 2008
- [32] McGinnis D.F., Little J.C.: 'Predicting diffused-bubble oxygen transfer rate using the discrete-bubble mode', *Water Res.*, 2002, **36**, (18), pp. 4627–4635
- [33] Ohnari H.: 'Wastewater purification in wide water area by use of micro-bubble techniques', *Jpn. J. Multiph. Flow*, 1997, **11**, (3), pp. 263–266
- [34] Ohnari H.: 'Water purification of ocean environment and revival of fisheries cultivation using micro bubble technology'. Proc. 21st Symp. Multiphase Flow, Nagoya, Japan, 2002
- [35] Ago K., Nagasawa K., Takita J., *ET AL.*: 'Development of an aerobic cultivation system by using a microbubble aeration technology', *J. Chem. Eng. Jpn.*, 2005, **38**, (9), pp. 757–762
- [36] Ushikubo F.Y., Furukawa T., Nakagawa R., *ET AL.*: 'Evidence of the existence and the stability of nano-bubbles in water', *Colloids Surf. A, Physicochem. Eng. Aspects*, 2010, **361**, (1–3), pp. 31–37
- [37] Sun Y.M., Wang S.W., Niu J.F.: 'Microbial community evolution of black and stinking rivers during in situ remediation through micro-nano bubble and submerged resin floating bed technology', *Bioresour. Technol.*, 2018, **258**, pp. 187–194
- [38] Teixeira M.R., Sousa V., Rosa M.J.: 'Investigating dissolved air flotation performance with cyanobacterial cells and filaments', *Water Res.*, 2010, **44**, (11), pp. 3337–3344
- [39] Nam S.N., Han M., Bui T.T.: 'Micro-bubble flotation of freshwater algae: a comparative study of differing shapes and sizes', *Sep. Sci. Technol.*, 2015, **50**, (7), pp. 1066–1072
- [40] Bui T.T., Han M.: 'Removal of phormidium sp. by positively charged bubble flotation', *Miner. Eng.*, 2015, **72**, pp. 108–114
- [41] Liu S., Wang Q.H., Ma H.Z., *ET AL.*: 'Effect of micro-bubbles on coagulation flotation process of dyeing wastewater', *Sep. Purif. Technol.*, 2010, **71**, (3), pp. 337–346
- [42] Guet S., Ooms G.: 'Fluid mechanical aspects of the gas-lift technique', *Annu. Rev. Fluid Mech.*, 2006, **38**, pp. 225–249
- [43] Jyoti K.K., Pandit A.B.: 'Water disinfection by acoustic and hydrodynamic cavitation', *Biochem. Eng. J.*, 2001, **7**, (3), pp. 201–212
- [44] Jyoti K.K., Pandit A.B.: 'Hybrid cavitation methods for water disinfection: simultaneous use of chemicals with cavitation', *Ultrason. Sonochem.*, 2003, **10**, (4–5), pp. 255–264
- [45] Quan X.J., Luo D., Wu J., *ET AL.*: 'Ozonation of acid red 18 wastewater using $O_3/Ca(OH)_2$ system in a micro bubble gas-liquid reactor', *J. Environ. Chem. Eng.*, 2017, **5**, (1), pp. 283–291
- [46] Tsai J.C., Kumar M., Chen S.Y., *ET AL.*: 'Nano-bubble flotation technology with coagulation process for the cost-effective treatment of chemical mechanical polishing wastewater', *Sep. Purif. Technol.*, 2007, **58**, (1), pp. 61–67
- [47] Liu J.T., Xu H.X., Li X.B.: 'Cyclonic separation process intensification oil removal based on microbubble flotation', *Int. J. Min. Sci. Technol.*, 2013, **23**, pp. 415–422
- [48] Xu H.X., Liu J.T., Gao L.H., *ET AL.*: 'Study of oil removal kinetics using cyclone-static microbubble flotation column', *Sep. Sci. Technol.*, 2014, **49**, (8), pp. 1170–1177
- [49] Poh P.E., Ong W.Y.J., Lau E.V., *ET AL.*: 'Investigation on micro-bubble flotation and coagulation for the treatment of anaerobically treated palm oil mill effluent (POME)', *J. Environ. Chem. Eng.*, 2014, **2**, (2), pp. 1174–1181
- [50] Li X.B., Xu H.X., Liu J.T., *ET AL.*: 'Cyclonic state micro-bubble flotation column in oil-in-water emulsion separation', *Sep. Purif. Technol.*, 2016, **165**, pp. 101–106
- [51] Calgaroto S., Azevedo A., Rubio J.: 'Separation of amine-insoluble species by flotation with nano and microbubbles', *Miner. Eng.*, 2016, **89**, pp. 24–29
- [52] Filho J.A., Azevedo A., Etchepare R., *ET AL.*: 'Removal of sulfate ions by dissolved air flotation (DAF) following precipitation and flocculation', *Int. J. Miner. Process.*, 2016, **149**, pp. 1–8
- [53] Etchepare R., Azevedo A., Calgaroto S., *ET AL.*: 'Removal of ferric hydroxide by flotation with micro and nanobubbles', *Sep. Purif. Technol.*, 2017, **184**, pp. 347–353
- [54] Etchepare R., Oliveira H., Azevedo A., *ET AL.*: 'Separation of emulsified crude oil in saline water by dissolved air flotation with micro and nanobubbles', *Sep. Purif. Technol.*, 2017, **186**, pp. 326–332
- [55] Lim M.W., Lau E.V., Poh P.E.: 'Micro-macro-bubbles interactions and its application in flotation technology for the recovery of high density oil from contaminated sands', *J. Petroleum Sci. Eng.*, 2018, **161**, pp. 29–37
- [56] Li P., Tsuge H., Itoh K.: 'Oxidation of dimethyl sulfoxide in aqueous solution using microbubbles', *Ind. Eng. Chem. Res.*, 2009, **48**, (17), pp. 8048–8053
- [57] Shin W.T., Mirmiran A., Yiaccoumi S., *ET AL.*: 'Ozonation using microbubbles formed by electric fields', *Sep. Purif. Technol.*, 1999, **15**, (3), pp. 271–282
- [58] Wang X.K., Wang J.G., Guo P.Q., *ET AL.*: 'Chemical effect of swirling jet-induced cavitation: degradation of rhodamine B in aqueous solution', *Ultrason. Sonochem.*, 2008, **15**, pp. 357–363
- [59] Sivakumar M., Pandit A.B.: 'Wastewater treatment: a novel energy efficient hydrodynamic cavitation technique', *Ultrason. Sonochem.*, 2002, **9**, pp. 123–131
- [60] Khuntia S., Majumder S.K., Ghosh P.: 'A pilot plant study of the degradation of brilliant green dye using ozone microbubbles: mechanism and kinetics of reaction', *Environ. Technol.*, 2014, **36**, (3), pp. 336–347
- [61] Wang X.K., Zhang Y.: 'Degradation of alachlor in aqueous solution by using hydrodynamic cavitation', *J. Hazard. Mater.*, 2009, **161**, pp. 202–207
- [62] Kalumuck K.M., Chahine G.L.: 'The use of cavitating jets to oxidize organic compounds in water', *J. Fluids Eng.*, 2000, **122**, (3), pp. 465–470
- [63] Liu S., Wang Q.H., Sun T.C., *ET AL.*: 'The effect of different types of micro-bubbles on the performance of the coagulation flotation process for coke wastewater', *J. Chem. Technol. Biotechnol.*, 2012, **87**, (2), pp. 206–215
- [64] Tasaki T., Wada T., Fujimoto K., *ET AL.*: 'Degradation of methyl orange using short-wavelength UV irradiation with oxygen micro-bubbles', *J. Hazard. Mater.*, 2009, **162**, (2–3), pp. 1103–1110
- [65] Chu L.B., Xing X.H., Yu A.F., *ET AL.*: 'Enhanced treatment of practical textile wastewater by microbubble ozonation', *Process Saf. Environ.*, 2008, **86**, (5), pp. 389–393
- [66] Tasaki T., Wada T., Baba Y., *ET AL.*: 'Degradation of surfactants by an integrated nanobubbles/VUV irradiation technique', *Ind. Eng. Chem. Res.*, 2009, **48**, (9), pp. 4237–4244
- [67] Chu L.B., Xing X.H., Yu A.F., *ET AL.*: 'Enhanced ozonation of simulated dyestuff wastewater by microbubbles', *Chemosphere*, 2007, **68**, pp. 1854–1860
- [68] Yasuda K., Ban N.: 'Wastewater treatment for bioethanol production system using ozone microbubbles', *J. Chem. Eng. Jpn.*, 2012, **45**, (9), pp. 672–677
- [69] Takahashi M., Ishikawa H., Asano T., *ET AL.*: 'Effect of microbubbles on ozonized water for photoresist removal', *J. Phys. Chem. C*, 2012, **116**, (23), pp. 12578–12583
- [70] Zheng T.L., Wang Q.H., Zhang T., *ET AL.*: 'Microbubble enhanced ozonation process for advanced treatment of wastewater produced in acrylic fiber manufacturing industry', *J. Hazard. Mater.*, 2015, **287**, pp. 412–420

- [71] Jabesa A., Ghosh P.: 'Removal of diethyl phthalate from water by ozone microbubbles in a pilot plant', *J. Environ. Manage.*, 2016, **180**, pp. 476–484
- [72] Khuntia S., Majumder S.K., Ghosh P.: 'Catalytic ozonation of dye in a microbubble system: hydroxyl radical contribution and effect of salt', *J. Environ. Chem. Eng.*, 2016, **4**, (2), pp. 2250–2258
- [73] Mezule L., Tsyfansky S., Yakushevich V., *ET AL.*: 'A simple technique for water disinfection with hydrodynamic cavitation: effect on survival of *Escherichia coli*', *Desalination*, 2009, **248**, (1–3), pp. 152–159
- [74] Jyoti K.K., Pandit A.B.: 'Water disinfection by acoustic and hydrodynamic cavitation', *Biochem. Eng. J.*, 2001, **7**, (3), pp. 201–212
- [75] Jyoti K.K., Pandit A.B.: 'Hybrid cavitation methods for water disinfection: simultaneous use of chemicals with cavitation', *Ultrason. Sonochem.*, 2003, **10**, (4–5), pp. 255–264
- [76] Jyoti K.K., Pandit A.B.: 'Ozone and cavitation for water disinfection', *Biochem. Eng. J.*, 2004, **18**, pp. 9–19
- [77] Arrojo S., Benito Y., Tarifa A.M.: 'A parametrical study of disinfection with hydrodynamic cavitation', *Ultrason. Sonochem.*, 2008, **15**, pp. 903–908
- [78] Sumikura M., Hidaka M., Murakami H., *ET AL.*: 'Ozone micro-bubble disinfection method for wastewater reuse system', *Water Sci. Technol.*, 2007, **56**, (5), pp. 53–61
- [79] Chen K.K.: 'Bathing pool assembly with water full of nano-scale ozone bubbles for rehabilitation'. US Patent, 2009, 7488416
- [80] Khuntia S., Majumder S.K., Ghosh P.: 'Oxidation of As(III) to As(V) using ozone microbubbles', *Chemosphere*, 2014, **97**, pp. 120–124
- [81] Khuntia S., Majumder S.K., Ghosh P.: 'Removal of ammonia from water by ozone microbubbles', *Ind. Eng. Chem. Res.*, 2012, **52**, (1), pp. 318–326
- [82] Sharifuzzaman M.D., Yang H.N., Park S.M., *ET AL.*: 'Performance comparison of micro–nano bubble, electro-oxidation and ozone pretreatment in reducing fluoride from industrial wastewater', *Eng. Agric. Environ. Food*, 2017, **10**, (3), pp. 186–190
- [83] Ikeura H., Kobayashi F., Tamaki M.: 'Removal of residual pesticides in vegetables using ozone microbubbles', *J. Hazard. Mater.*, 2011, **186**, (1), pp. 956–959
- [84] Temesgen T., Bui T.T., Han M., *ET AL.*: 'Micro and nanobubble technologies as a new horizon for water-treatment techniques: a review', *Adv. Colloid Interface*, 2017, **246**, pp. 40–51
- [85] Pardieck D.L., Bouwer E.J., Stone A.T.: 'Hydrogen peroxide use to increase oxidant capacity for in situ bioremediation of contaminated soils and aquifers: a review', *J. Contaminant Hydrol.*, 1992, **9**, pp. 221–242
- [86] Farhadian M., Vachelard C., Duchez D., *ET AL.*: 'In situ bioremediation of monoaromatic pollutants in groundwater: a review', *Bioresour. Technol.*, 2008, **99**, pp. 5296–5308
- [87] Stempvoort D.V., Biggar K.: 'Potential for bioremediation of petroleum hydrocarbons in groundwater under cold climate conditions: a review', *Cold Regions Sci. Technol.*, 2008, **53**, (1), pp. 16–41
- [88] Wu W.M., Carley J., Fienen M., *ET AL.*: 'Pilot-scale in situ bioremediation of uranium in a highly contaminated aquifer. 1. Conditioning of a treatment zone', *Environ. Sci. Technol.*, 2006, **40**, (12), pp. 3978–3985
- [89] Wu W.M., Carley J., Gentry T., *ET AL.*: 'Pilot-scale in situ bioremediation of uranium in a highly contaminated aquifer. 2. Reduction of U(VI) and geochemical control of U(VI) bioavailability', *Environ. Sci. Technol.*, 2006, **40**, (12), pp. 3986–3995
- [90] Jenkins K.B., Michelsen D.L., Novak J.T.: 'Application of oxygen micro bubbles for in situ biodegradation of p-xylene-contaminated groundwater in a soil column', *Biotechnol. Prog.*, 1993, **9**, (4), pp. 394–400
- [91] Tsai Y.J., Kuo Y.C., Chen T.C.: 'Groundwater remediation using a novel micro-bubble sparging method', *J. Environ. Eng. Manage.*, 2007, **17**, (2), pp. 151–155
- [92] Choi H.E., Jung J.H., Han Y.R., *ET AL.*: 'A study on the treatment of oil contaminated soils with micro–nano bubbles soil washing system', *J. Environ. Sci. Int.*, 2011, **20**, (10), pp. 1329–1336
- [93] Xia Z.R., Hu L.M.: 'Remediation of organic contaminated industrial sites by ozone micro–nano bubbles'. Conf. Geo-Chicago, Chicago, Illinois, USA, 2016, pp. 371–380
- [94] Li H.Z., Hu L.M., Song D.J., *ET AL.*: 'Characteristics of micro–nano bubbles and potential application in groundwater bioremediation', *Water Environ. Res.*, 2014, **86**, (9), pp. 844–851
- [95] D'anna A., Brutti R., Gigliuto A., *ET AL.*: 'Micro-bubbles oxygen injection in groundwater contaminated by organic biodegradable compounds and metals'. Environmental Forensics: Proc. 2014 INEF Conf., St John's College, Cambridge, UK, 2014, pp. 130–137
- [96] Kerfoot W.B.: 'Microbubble ozone sparging for chlorinated ethene spill remediation', in Henry S.M., Warner S.D. (Eds.): 'Chlorinated solvent and dnapl remediation: innovative strategies for subsurface cleanup, ACS symposium series' (American Chemical Society Washington, D.C., 2003), pp. 86–108
- [97] Kerfoot W.B.: 'Coated ozone micro-bubbles speed groundwater cleanup', *Pollut. Eng.*, 2007, **39**, (4), pp. 26–30
- [98] Scheffer B., Ven E.: 'Experiences of perozone and C-spargers at two former dry cleaner sites in the Netherlands', *Ozone Sci. Eng.*, 2010, **32**, (2), pp. 130–136
- [99] Sung M., Teng C.H., Yang T.H.: 'Dissolution enhancement and mathematical modeling of removal of residual trichloroethene in sands by ozonation during flushing with micro–nano-bubble solution', *J. Contaminant Hydrol.*, 2017, **202**, pp. 1–10
- [100] Zabel T.F.: 'Advantages of dissolved air flotation for water treatment', *J. Am. Water Works Assoc.*, 1985, **77**, (5), pp. 42–46
- [101] Chu L.B., Yan S.T., Xing X.H., *ET AL.*: 'Enhanced sludge solubilization by microbubble ozonation', *Chemosphere*, 2008, **72**, pp. 205–212
- [102] Borowski S., Szopa J.S.: 'Experiences with the dual digestion of municipal sewage sludge', *Bioresour. Technol.*, 2007, **98**, pp. 1199–1207
- [103] Gunten U.V.: 'Ozonation of drinking water: part I. Oxidation kinetics and product formation', *Water Res.*, 2003, **37**, (7), pp. 1443–1467
- [104] Kim D.H., Jeong E., Oh S.E., *ET AL.*: 'Combined (alkaline + ultrasonic) pretreatment effect on sewage sludge disintegration', *Water Res.*, 2010, **44**, (10), pp. 3093–3100
- [105] Okamoto K., Hotta K., Toyama T., *ET AL.*: 'Experiments on purification of ocean sludge by activating microorganisms'. Proc. 21st (2011) Int. Offshore and Polar Engineering Conf. IOPE, Maui, Hawaii, USA, 2011, pp. 895–899
- [106] Wang L., Li Y.J., Xiong Y., *ET AL.*: 'Spectroscopic characterization of dissolved organic matter from sludge solubilization treatment by micro-bubble technology', *Ecol. Eng.*, 2017, **106**, (Part A), pp. 94–100