Assessment of ozone micro-nano bubble technology for fresh water cooling towers in HVAC systems

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ABSTRACT

In recent years, micro-nano bubbles (MNBs) technologies have drawn great attention due to their wide applications in many fields of science and technology. MNBs feature high internal pressures and rapid mass transfer rates due to the small size and can significantly improve gas dissolution and intensify ozonation in water treatment process. The combination of the MNB technique with ozone could provide an efficient approach for improving water treatment in many fields including heating, ventilation and air-conditioning (HVAC). This research aims to assess the potential and benefits of ozone MNB technology for fresh water cooling towers in HVAC systems. Critical review of the latest international experience and research on ozone MNB technology was conducted to examine the principles and characteristics of MNB for promoting a better understanding. The feasibility and key considerations of applying the technology to fresh water cooling towers in HVAC systems were evaluated to identify the benefits and important issues for further development.

It is found that the major characteristics of MNBs that give rise to the potential benefits include small bubble size, slow rising velocity, decreasing friction drag, high pressure inside the bubble (self-compression effect), large interfacial area, large gas dissolution, dissolution & contraction of MNBs, and negatively charged surface. For the HVAC application, MNB technology has good potential to enhance the ozonation process and effectiveness of cooling water treatment. It is also possible to defoul and clean the heat transfer surface continuously by electrochemically generated NBs, as well as enhance the vaporization potential of the cooling tower. In order to develop an effective ozone MNB system for HVAC application, it is essential to examine the bubble characteristics at functional levels and investigate the corresponding system operating parameters to achieve optimization.

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1. Introduction

Micro-nano bubbles (MNBs) are defined as very fine gas bubbles with diameters on the order of micrometers and nanometers. In recent years, MNBs technologies have drawn great attention due to their wide applications in many fields of science and technology, such as water treatment, biomedical engineering, and nanomaterials [1,2]. MNBs feature high internal pressures and rapid mass transfer rates due to the small size, which can significantly improve gas dissolution and intensify ozonation in water treatment process [3,4]. It is believed that the combination of the MNB technique with ozone could provide an efficient approach for improving water treatment in many fields including heating, ventilation and air-conditioning (HVAC).

This research aims to assess the potential and benefits of ozone MNB technology for fresh water cooling towers in HVAC systems. Critical review of the latest international experience and research on ozone MNB technology is conducted to examine the principles and characteristics of MNB for promoting a better understanding. The feasibility and key considerations of applying the technology to fresh water cooling towers in HVAC systems are evaluated to identify the benefits and important issues for further development.

2. Principles of Micro-nano Bubble Technology

Microbubbles (MBs) and nanobubbles (NBs) are tiny or fine gas bubbles with a respective typical diameter of 10-50 micrometer and < 200 nm. At this small size, these bubbles present different physicochemical and fluid dynamic properties than ordinary bubbles. Figure 1 gives an overview of gas bubble size and their general classification. It is interesting to note that NBs are stable spherical packages of gas within the liquid and this property gives rise to a significant importance for many potential research and applications on MNBs.

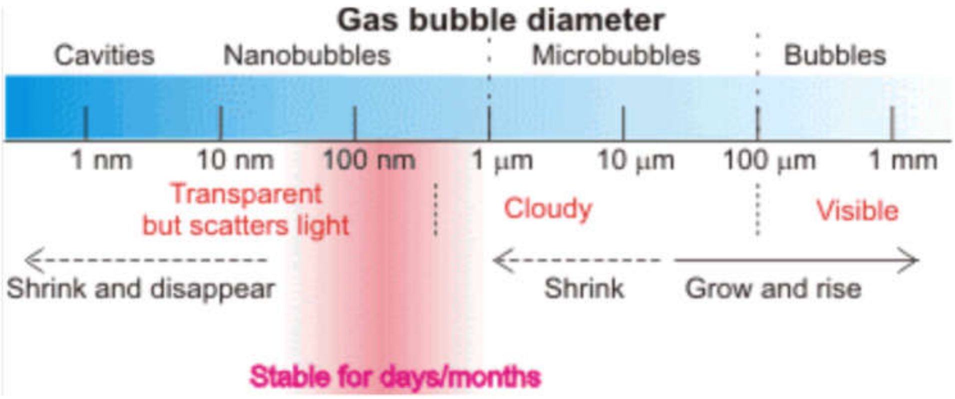

Fig. 1. Overview of gas bubble size (Image source: http://oxydoser.com/)

Since first hypothesizing the existence of NBs in 1994, the empirical study of NB properties and commercialization of NB generators have rapidly evolved [5,6]. At present, the NB research has largely been split between research into surface NBs and research into bulk NBs [7,8].

2.1 Types and Characteristics of Water Bubbles

In general, water bubbles can be categorized into three major types: ordinary or macrobubbles, MBs, and NBs. Figure 2 shows the basic concepts of macro, micro and nanobubbles. Normal macrobubbles rapidly rise and burst at the water surface; MBs and NBs are stable for longer periods of time underwater [9]. MBs tend to gradually decrease in size and subsequently collapse due to long stagnation and dissolution of interior gases into the surrounding water, whereas NBs remains as such for months and do not burst out at once [10].

Bubble formation is considered as a static or quasi-static process. It is followed by the dynamic processes, namely, coalescence and break up of the fine bubbles. In the case of coalescence, fine bubbles combine to form bigger bubbles, whereas the possibility of further breakup favours the formation of ultrafine bubble generation and/or collapse. To understand better the fundamental mechanisms of MNBs, the basic components of a MB is shown in Figure 3. In case of an air-water system, the core is filled with air (gas phase) and the liquid phase is water with surfactants or similar nano-particles capable of adhering to the shell and constituting a part of the MB.

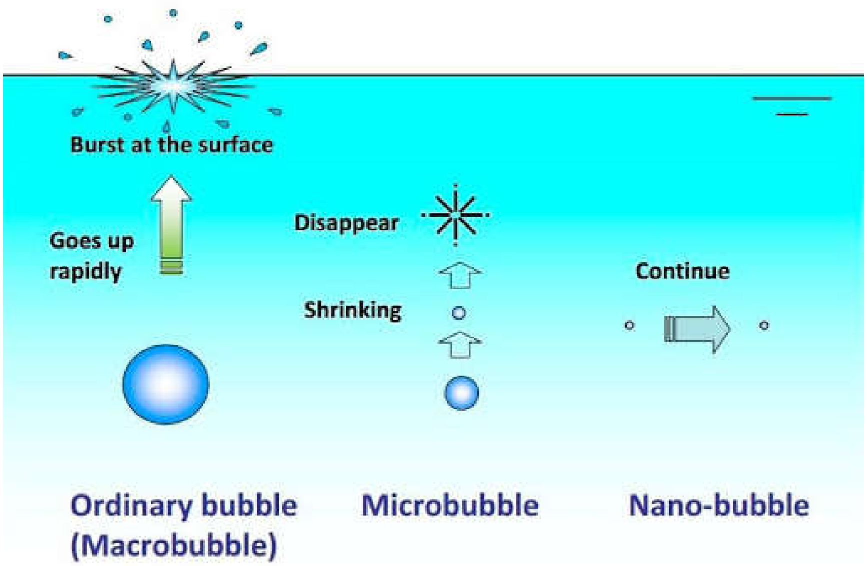

Fig. 2. Basic concepts of macro, micro and nanobubbles [11]

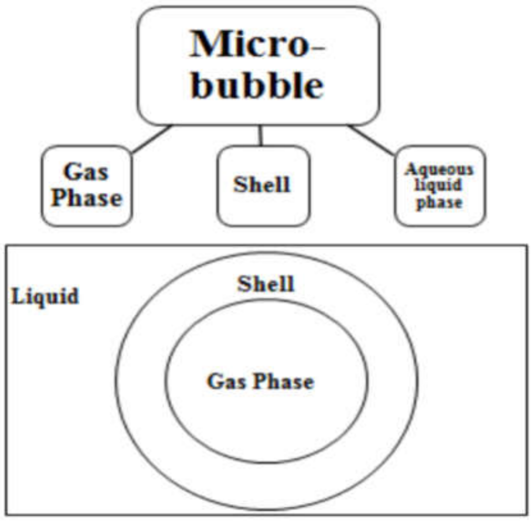

Fig. 3. Basic components of a microbubble [12]

Inside of micro sized fine bubble just before breaking is in the ultra-high heat and ultra-high-temperature state that generate free radicals when they break into nano sized bubbles called ultrafine bubble or NB. Therefore, NBs may be defined as MB residues stabilized by the effect of condensed ionic cloud around the gas-water interface at the final stage of the collapsing process [11]. The external electrostatic pressure created by the charged NB interface, balances the internal Laplace pressure; therefore, no net diffusion of gas occurs at equilibrium and the NBs are stable [13].

2.2 Applications of Micro-nano Bubbles

In the past decade, research on MNBs for water-related applications has significantly increased and MNB is considered a sustainable technology with good future trends for water treatment [14,15], water purification [16,17], environmental pollution control [18,19], groundwater bioremediation [20,21], wastewater treatment [22-24] and minerals engineering [25]. The most commonly known processes applied in water treatment utilizing bubble technology are floatation, aeration, disinfection and advanced oxidation processes. In addition, the application of MNBs has been extended to various fields such as agriculture, medical, industry, aquaculture and domestic use [2,26,27]. Figure 4 shows the recent trends in practical applications of MNB technology.

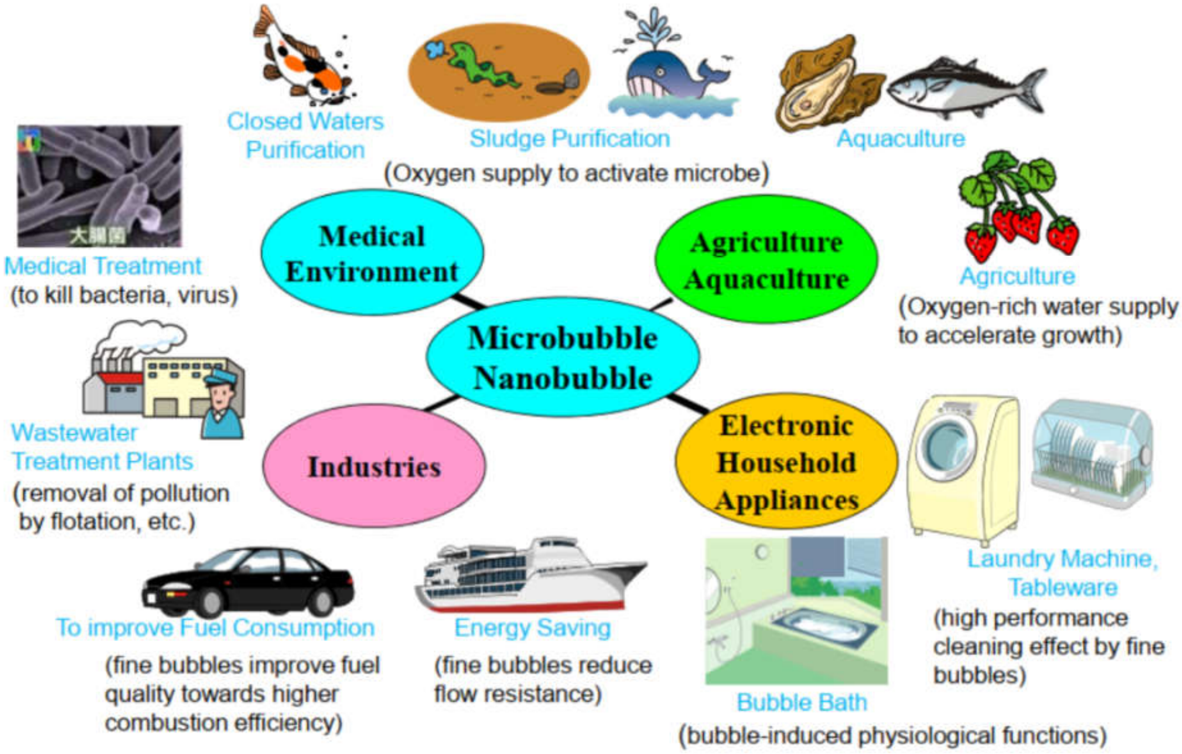

Fig. 4. Recent trends in practical applications of micro-nano bubble technology (Source: Prof. Akimi Serizawa, Kyoto University, Japan)

With its unique properties, MNB technology can be put to a multitude of cleaning uses [11]. Its cleaning power is more effective than regular water, using less water, and less manpower. Also, these bubbles are good for the environment, as pre-determined by the amount of water used or waste generated. It also reduces the need or use for toxic chemicals and other detergents. The cost implication of producing MNBs is far smaller than most businesses would spend on traditional cleaning and water treatment solutions. Therefore, it has a good potential on those applications.

3. Ozone Integrated with Micro-nano Bubbles

Ozone is one of the commonly known and powerful disinfectants for water purification as they attach to the cell walls of bacteria and immobilize them rendering them inactive. The oxidation of any compound could occur via either through the oxidation of compounds via ozone molecule (direct reaction) or the oxidation through the reaction of the compound with the hydroxyl radicals formed from ozone (indirect reaction) [28]. Figure 5 shows the typical water ozonation process and oxidation methods. Since the standard oxidation potential of ozone is lower than the hydroxyl radical (•OH), the indirect oxidation of water pollutants via hydroxyl radical generation is highly reactive and non-selective to almost all kinds of organic pollutants [29,30]. Therefore, the oxidation reaction with the pollutants is better accelerated by the indirect reactions.

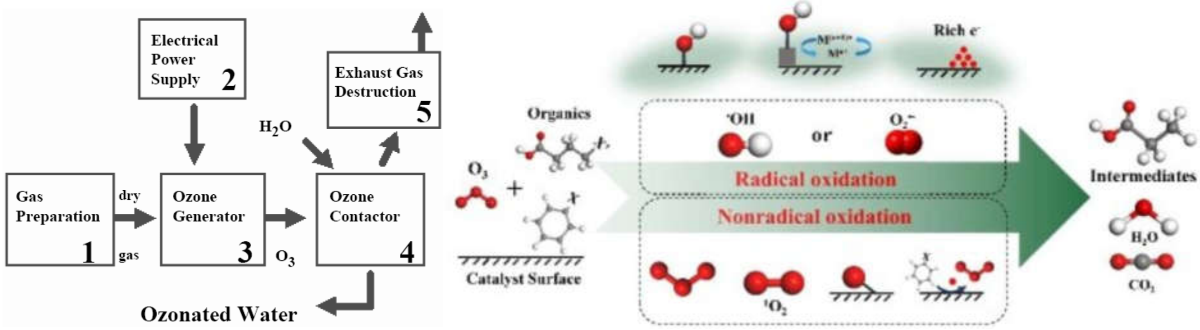

Fig. 5. Typical water ozonation process and oxidation methods

3.1 Enhanced Ozonation with Micro-nano Bubbles

Although ozone is a powerful oxidant that can be used to decompose organics, improve biodegradability and inactivate microorganisms, more widespread implementation of ozone is limited by its low mass transfer efficiency, low saturation solubility, and short half-life. These limitations often lead to lower reaction concentration and underutilization of ozone in water treatment of ozonation [31]. For example, more ozone is often needed for the water treatment in cooling towers and HVAC systems as its performance cannot last for a long period of time [32].

It is found that the ozonation process in water treatment and groundwater remediation can be aided and enhanced economically by using the MNB technology [20,33,34]. As MNBs can present large surface area, rapid mass transfer rates and longevity in water, they can help increase the stability of ozone and greatly improve remediation efficiency, if the system is designed properly. Critical parameters that influence solubility of ozone into water include the mixing characteristics of the gas-liquid contactor, the process of ozone decay inside water along with the bubble density and size.

A promising enhancement for ozonation effects can be achieved by a combination of ozone and MNBs which creates positive synergetic effects on solubility, stability, and mass transfer efficiency that in turn will prolong reactivity of ozone and improve the decomposition rate of the reactive species [35]. Figure 6 shows an example of techniques to intensify ozonation using MNB technology. It is found that the reduction of bubble size will also improve the oxidation of different pollutants by enhancing the formation of hydroxyl radical for advanced oxidation.

3.2 Hydroxyl Radicals and Zeta Potential

Hydroxyl radicals (•OH) are strong oxidants in aqueous solution, reacting rapidly with a wide range of dissolved compounds [36]. When microbubbles of ozone in strongly acidic aqueous solution collapse, the ozone progressively decomposes and large quantities of hydroxyl radicals are generated. In addition, collapsing MBs can be used not only for the progressive decomposition of ozone but also for inducing chemical reactions that lead to the decomposition of organic chemicals.

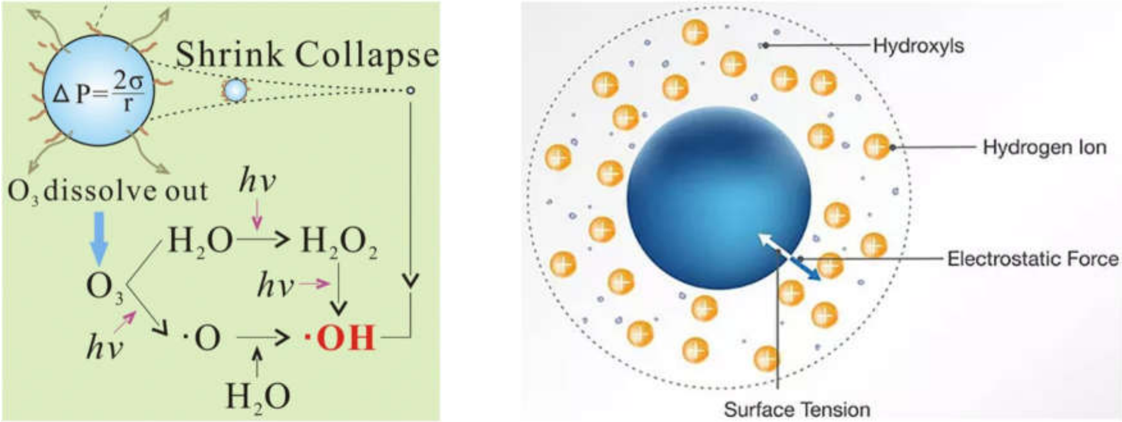

Fig. 6. Intensify ozonation using MNB technology [3]

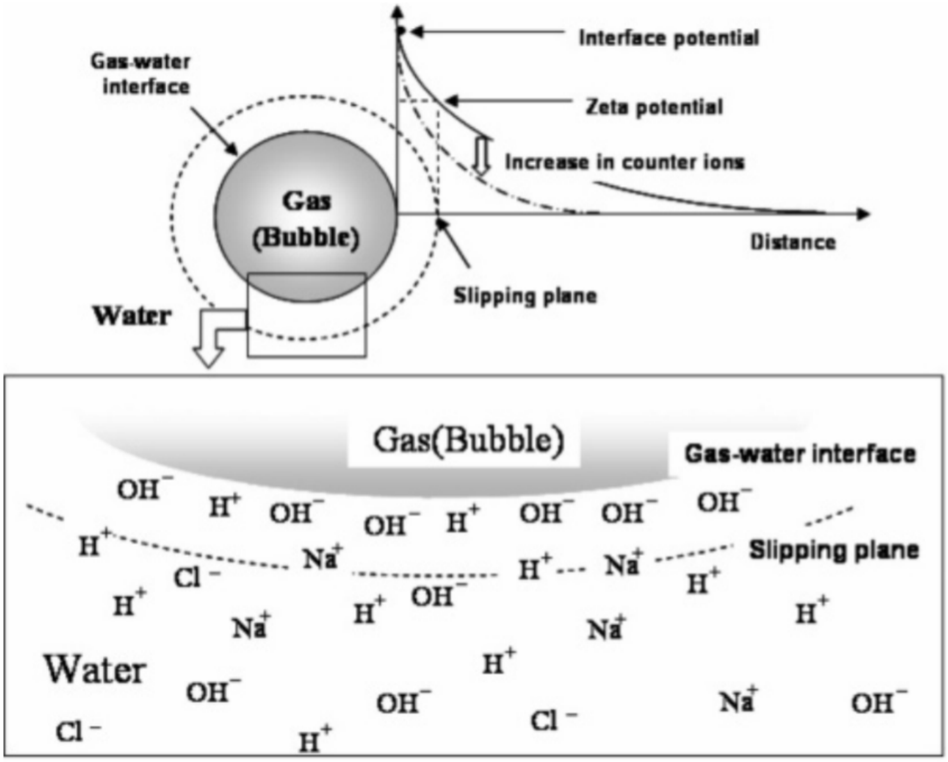

Fig. 7. Distribution of ions at and near the gas-water interface [37]

Zeta potential or surface charge is a physical characteristic used to measure the magnitude of the attraction between particles and bubbles or electrostatic repulsion [38]. It is an important property that determines the longevity of MNBs in a colloidal system. In principle, zeta-potential is defined as the electrical potential at the slipping plane between the bulk liquid and bulk liquid. The electrical properties of gas bubbles are important in determining the interaction of bubbles in coalescence and the way bubbles interact with other materials, such as solid particles and oil droplets, to provide a basis for technical application in many fields.

Research studies has found that the bubbles were negatively charged under a wide range of pH conditions and positively charged under strongly acidic conditions [37]. Figure 7 shows the distribution of ions at and near the gas-water interface in an aqueous solution of NaCl. The electrolyte ions are attracted to the interface charged by H+ and OH- and create the electrical double layer. The zeta potential is determined by the amount of ions and their valency in the slipping plane.

4. Benefits and Key Considerations

MNBs are able to catalyze chemical reactions, inactivate pathogens, mitigate biofouling and enhance the detoxification efficiency, thereby improving the efficiency of chemical and biological treatment of water. When applied to water pretreatment, they can help reduce biological, chemical and physical loads in order to reduce the running costs and increase the treated water quality. In this context, MNBs as a pretreatment means has been shown to be highly beneficial for downsizing the water/wastewater treatment plants and improving the quality of product water [1].

4.1 Characteristics of Micro-nano Bubbles

The major characteristics of MNBs that give rise to the potential benefits are summarized in Table 1. Good understanding of the characteristics can help people identify appropriate applications and design suitable systems and components for effective implementation of the technology. Figure 8 indicates the unique physicochemical characteristics of NBs which are important for improving water treatment processes [6,39].

Table 1. Characteristics of MNBs [2]

1.	Small bubble size
2.	Slow rising velocity
3.	Decreasing friction drag
4.	High pressure inside the bubble (self-compression effect)
5.	Large interfacial area
6.	Large gas dissolution
7.	Dissolution & contraction of MNBs
8.	Negatively charged surface

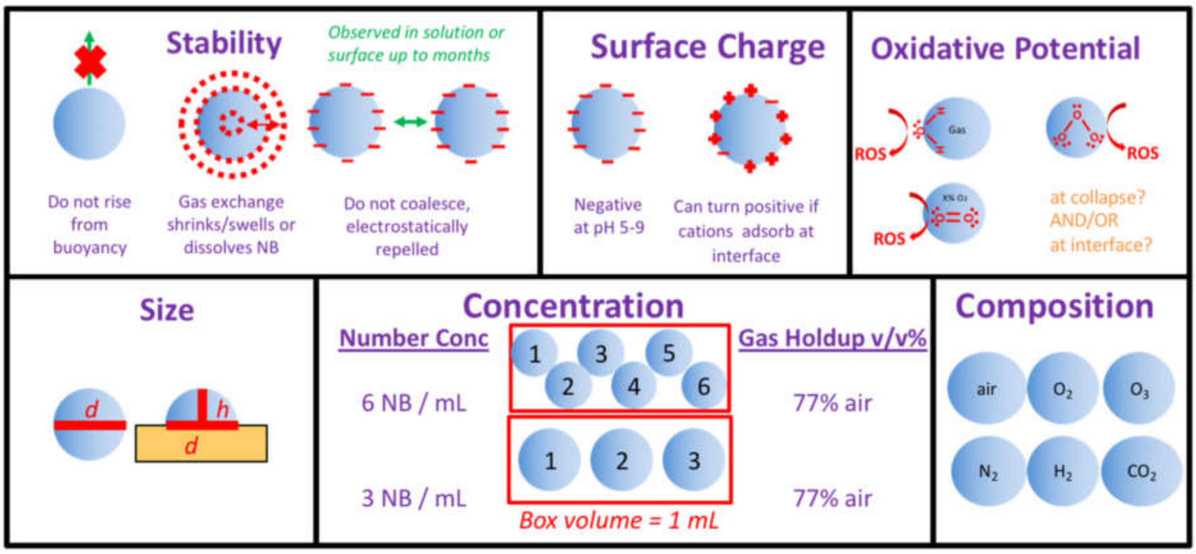

Fig. 8. Unique physicochemical characteristics of NBs [6]

In fact, NBs have more than 400 times the surface area of a typical MB, measured at 40 micrometers in diameter. Their unique property of having large surface area enables an efficient mass transfer process between the liquid and gas phases, which helps to ensure virtually any gas is effectively delivered to water to facilitate chemical reactions. In addition, the neutral buoyancy and negative surface charge of NBs allows them to remain in suspension for months at a time. This occurs even after the solution reaches oxygen saturation. In this capacity, the NBs act as a gas reserve in the solution.

4.2 Potential Benefits

The longevity of NBs in water, together with their high surface area per volume, makes them the most efficient aeration method with high gas (ozone) transfer efficiency and allow operators to significantly reduce operating costs. The main objectives of applying MNB technology are to downsize the facilities, reduce operation time and reduce operation and maintenance cost of water treatment plants, with the aim to decrease the cost of the water treatment process.

The MNBs can generate free radicals during the collapsing process under water and this is a very effective property for surface cleaning in a wide variety of technical fields [11]. For the ozonation process, MNBs can increase the concentration of ozone and hydroxyl radical (•OH) which will help achieve efficient reduction of oxidative chemical oxygen demand (COD) of the treatment process. The bursting energy of MB and improved aeration potential of NB have also a future in membrane defouling by improving surface scouring and reduction of sludge formation in membrane bioreactors [40].

For HVAC applications, it is believed that effective and efficient use of ozone in cooling water treatment provides triple bottom line benefits (economic, social and environmental). Environmental benefits include effluent disposal reduction, water and energy conservation. Social benefits include safety and health impacts. Ozone treated cooling water systems are a technically practical, cost-effective and sensible alternative when compared to conventional cooling water treatment systems. Ozone MNB has excellent water sanitization efficiency so that it can be used to remove broad ranges of bacteria, fungi and virus in a short period of contact time. The MNBs of gases with oxidizing power (e.g. ozone) can be applied to various water treatment processes since the ozone MNB have high solubility and improved disinfection ability due to the generation of •OH radical and/or pressure waves [41]. The use of ozone MNB can reduce or replace the use of chemical detergents or disinfectants and minimize the risk of chemical allergy.

In addition, it is found that NBs can form gas bridges that enhance particle-particle aggregation to aid in particulate or surfactant removal [6,42]. Figure 9 illustrates how NBs on surfaces coalesce and form a "bridge" between particles or between particles and filtration media, thus acting as a chemical-free means of enabling particle removal and separation through settling, filtration, or flotation. If attractive forces are assumed to be uniform between NBs and the adsorbent surface, then hemispherical gas-NB formation on the surface is thermodynamically most favourable because the largest number of gas molecules would interact with the adsorbent surface. Thus, evidence supports the use of NBs to mitigate fouling for a wide variety of surfaces.

Fig. 9. NBs form gas bridges to aid in particulate removal [6]

When properly arranged, NBs can be applied for cleaning and defouling of solid surfaces [1,43]. It has been shown that adsorption of proteins onto various surfaces could be inhibited by NBs, thus preventing the surfaces from fouling [43]. For example, NBs can block adsorption of bovine serum albumin on mica surface [44], while NBs also helps remove organic contaminants from pyrolytic graphite and gold surfaces. Recently, similar defouling effect of NBs was also observed on stainless steel surface [45].

Moreover, NBs has shown great potential in control of bacteria and algae attachment onto solid surfaces. Destabilized and reduced biofilms have been observed after treatment by NBs. The bubble size has been found to affect the membrane fouling in case of tubular and hollow fibre membranes. It was observed that smaller air bubbles were more efficient in reducing fouling. Subsequent burst of the NBs would provide a greater disinfection and cleaning.

4.3 Key Considerations

In order to apply MNB technology effectively and verify the likely benefits, it is important to understand the basic theories and properties of the bubbles. Assessment of parameters influencing the size of MNBs will be helpful too [46]. The relevant physical laws and experimental research findings can be used to assess the behaviour and characteristics of the respective system using the ozone MNB technology. Below are the examples of key considerations for the basic theories and properties. The size of MNBs and the number of bulk NBs in the aqueous solution will determine the effectiveness of the system.

Decrease in size of MBs below the water surface results in high internal pressure inside MBs, which is directly proportional to the bubble's diameter (see Figure 10). The relationship between the interior gas pressure and the bubble diameter is expressed by the Young-Laplace equation (Eq. 2.1) [9]:

$$P_g = P_1 + 2\sigma/r \tag{2.1}$$

where P_g is the gas pressure, P_1 is the liquid pressure, σ is the surface tension, and r is the radius of the bubble.

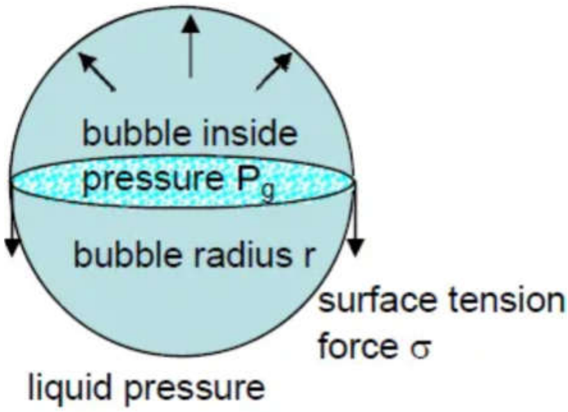

Fig. 10. Bubble size and internal pressure

According to Henry's law, the amount of dissolved gas surrounding a shrinking bubble increases with rising gas pressure. The area surrounding a MB has been shown to change its state in a pressure-temperature (P-T) diagram to favour hydrate nucleation. This is a typical characteristic of MBs.

The bubble size and rise velocity share a direct proportionality which is ascertained by Stokes law of rise velocity as shown below (Eq. 2.2) and illustrated in Figure 11.

$$S = \frac{1}{18}(\rho_l - \rho_g) \times g \times \frac{d^2}{\mu} \tag{2.2}$$

where S is the bubble rise velocity, ρ_l is the density of liquid, ρ_g is the density of the gas, g is the acceleration due to gravity, d is the equivalent bubble diameter and μ is the dynamic viscosity of the liquid.

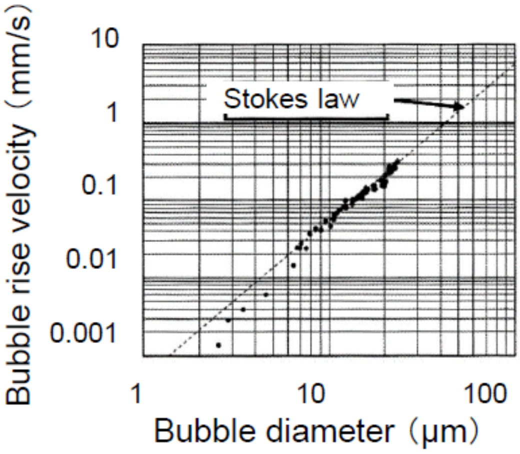

Fig. 11. Bubble rise velocity vs. bubble diameter

Interfacial area of bubbles (A) divided by volume (V) is obtained by the following equation (Eq. 2.3). With decreasing bubble diameter d, A/V increases and contributes to gas dissolution fraction.

$$A/V = 6/d \tag{2.3}$$

Mass transfer rate from gas to liquid, or dissolving rate N (mol/s), is written by the following equation Eq. (2.4) when the gas phase mass transfer resistance is neglected.

$$N = \frac{k_L A1(p-p^*)}{H} \tag{2.4}$$

where k_L is the liquid phase mass transfer coefficient (m/s), $A1$ is the bubble surface area (m^2), p is the partial pressure of dissolved component in bubble (Pa), p^* is the partial pressure of gas phase equilibrium with dissolved component in liquid (Pa) and H is the Henry constant.

5. Application to Fresh Water Cooling Towers in HVAC Systems

Cooling towers have an important role in the HVAC system to dissipate heat generated during the cooling process [47]. As the condenser water circulates through the cooling towers, heat will be discharged into the ambient air resulting in a drop in condenser water temperature. Most of the heat transfer or heat discharge takes place through evaporation. In a cooling tower system the amount of water in the basin will be reduced by drift loss and evaporation loss [32]. To compensate for this loss, make-up water is added to the basin to replace the amount of water due to drift loss and evaporation loss. Blow-down is necessary to avoid the build-up of undesirable materials in the re-circulating water because of evaporation. The amount of the blow-down and make-up in each of cooling water systems is a function of the evaporation loss and cycles of concentration [48].

5.1 Practical Issues of Cooling Towers

Cooling tower evaporation is composed only of water. A high percentage of the materials dissolved in the water remain concentrated in the basin water. Thus, with more water evaporating, dissolved mineral salts are continually becoming more concentrated. Also, appreciable quantities of airborne impurities, such as dust and gases, may enter during operation. During the condensation process soluble minerals are deposited as scale in the condenser tubes and microscopic plant matters tend to deposit as biological film (or biofilm) in the condenser tubes, collectively scales and biological film are known as fouling which gives rise to low heat transfer and high power consumption. Figure 12 shows a schematic diagram of a cooling tower system and Figure 13 gives examples of condenser tubing and fouling effects.

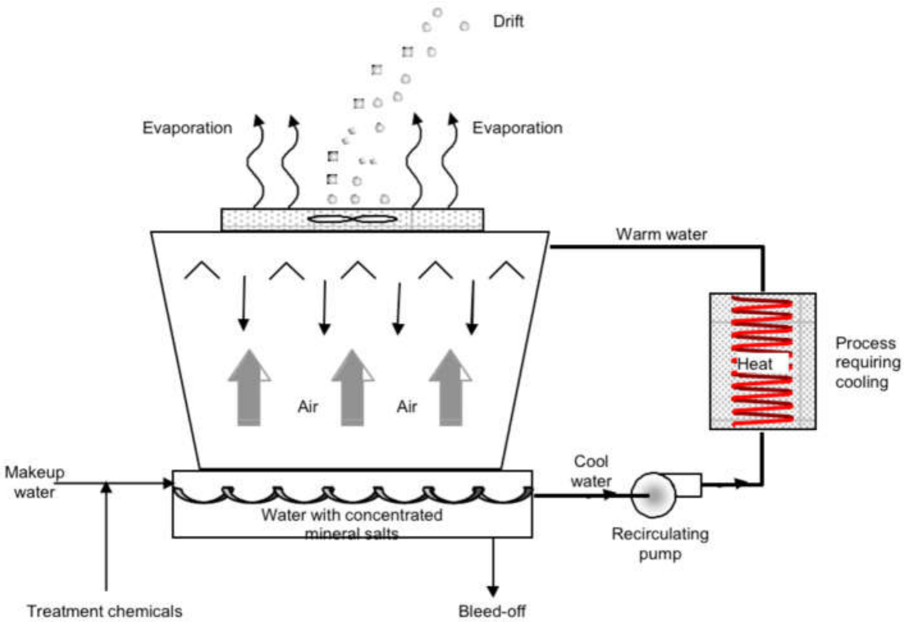

Fig. 12. Schematic diagram of a cooling tower system

The extent and nature of the treatment depends on the chemistry of the available water and on the system design characteristics [49]. On large systems, fixed continuous-feeding chemical treatment systems are frequently installed in which chemicals, including acids for pH control, must be diluted and blended and then pumped into the condenser water system. The common water treatment methods for fresh water cooling towers involve chemical dosing, biocide, corrosion inhibitor, bleed-off arrangement, monitoring and control devices [50].

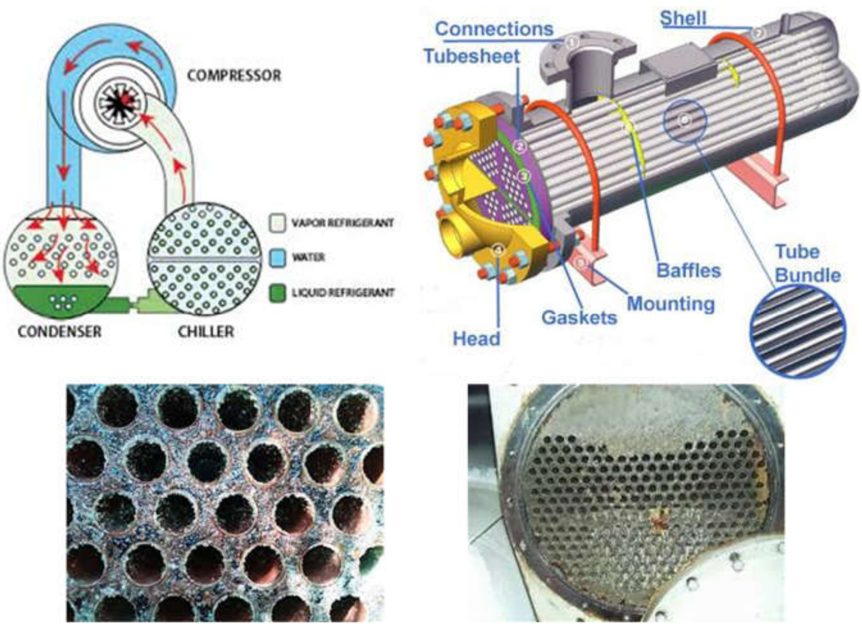

Fig. 13. Condenser tubing and fouling effects (Image source: Source: https://ahrinet.org/contractors?S=134)

Water from the condenser plays an integral role in shifting heat. In order for a cooling tower to work efficiently the quality of the water must be controlled [51]. Without proper water treatment, corrosion and scaling occurs in the pipes and basin which results in poor heat transfer and renders the cooling tower inefficient. Corrosion occurs because of material interaction, chemically or electro-chemically, with the environment. Not only does corrosion escalate in the cooling tower when it comes into contact with untreated water but bacteria in the water encourages the growth of moss. Very often, biofouling from cooling tower water is responsible for poor efficiency and increased corrosion.

5.2 Ozone Application and Limitations

An ozone water treatment system for cooling tower will compress ambient air, then dry and ionize it to produce ozone. When applied in the cooling tower, ozone can affect effectiveness, levels of energy, corrosion on piping and more [52]. Usually, the ozone is added to the circulating water in the cooling tower to inactivate the infectious bacteria, algae and viruses in the tower. In addition, microorganisms tend to accumulate in a biofilm on the sides and on the components of the cooling tower system, thereby impeding heat transfer efficiency, increasing energy consumption and adding to maintenance costs.

Furthermore, ozone acts as a disinfectant for salmonella typhimurium which is a microorganism that can cause scaling or crust. Crust raises the fouling factor value and increases the energy demand of the cooling tower. Ozone, in a cooling tower system, also affects electrical conductivity as well as levels of calcium and alkalinity in the water. Integration of ozone water treatment within the cooling tower decreases the concentration of insoluble components into the circulating water and further reduces the blow-down dramatically.

The heat flow mechanism and thermal resistance in chiller heat exchanger tubes are influenced by scaling and water quality. Scale precipitation can obstruct thermal effectiveness of the heat exchange unit due to its natural high thermal resistance properties. The ozonation process is expected to decrease the potential of scale precipitation thereby improving the thermal performance of cooling tower and chiller condenser. In fact, ozone can be said to affect water quality in the cooling tower system but usually ozone cannot affect the performance for a period longer than 10 days [32]. Also, ozone cannot be stored for long periods of time and thus requires on-site generation which when paired with the relatively higher costs of operating an ozone treatment system is more expensive to operate than other common treatment methods, such as using chlorine [31].

5.3 Advantages of Micro-nano Bubbles

Research findings indicate that ozone MNBs are potentially useful in water treatment applications and can be applied to the cooling water in a cooling tower. For example, hydrodynamic cavitation device for controlling cooling tower water quality has been evaluated and it is found that the performance is good [53]. Nanofluids can be utilized as efficient heat transfer fluids in in condensing and evaporating systems to improve the system's thermal efficiency [54]. By injecting ozone gas into the cooling water in the form of ultrafine bubbles, it is possible to achieve higher levels of dissolved ozone in the water and allow the dissolved ozone to remain present in water for a much longer time.

Moreover, bacterial biofilms are a major operational and health issue in cooling water systems. NBs control biofilm formation through directly acting on microbes and indirectly acting on water quality. NBs could interact and inactivate bacteria that often foul membrane or other surfaces through disruption of cell structure [6]. The vibrational motion of NBs may induce shear forces that disrupt biofilms. Evidence supports the use of NBs to mitigate fouling for a wide variety of surfaces, leading to reduced chemical usage and energy-intensive washing.

In addition, cooling tower water containing NBs enhances the vaporization potential of the liquid by increasing surface area, which in turn improves the efficiency of the cooling tower. Combining ozone with the NBs has the benefit of adding a powerful anti-microbial agent that reduces biofilm from building up, increasing the efficiency of the cooling process.

6. Discussions

Fouling refers to the accumulation of deposits on the heat transfer surface which provide a resistance to the heat transfer, thereby decreasing the heat transfer capacity of the surface [55]. The deposits are usually present in the fluid and adhere to the heat transfer surface causing fouling (see also Figure 13). The accumulation of deposits on the heat transfer surface and pipe wall decreases the area available for fluid flow thereby causing an increase in pressure drop across the surface which results in an increase in pumping power.

Fouling affects the heat transfer surfaces of water-chilling evaporators and water-cooled condensers used in HVAC systems [56]. In principle, fouling factor is defined as the thermal resistance due to the accumulation of contaminants on the water-side of the heat transfer surface. As temperature can be a strong contributor to the rate of fouling, condenser water (say, at temperature 35 to 40 °C) which is much warmer than evaporator water will be affected more. Also cooling towers tend to have more contaminants in the water due to the loss of water from evaporation in the tower.

6.1 Fouling Characteristics and Chiller Performance

Fouling of heat transfer surface and tubes introduces a major uncertainty into the design and operation of cooling water systems [57]. The extent of the fouling problem depends upon the water quality, operating conditions, monitoring system, and maintenance practice. In practice, significant precipitation and particulate fouling may occur for internally enhanced tubes in cooling tower systems [58]. Corrosion and biological fouling may be found in different parts of the water systems. Unfortunately, fouling characteristics cannot be easily determined and generalized for all applications at present [55].

In many buildings and facilities, chillers are the largest energy-using component, and can consume over 50% of the electrical usage during hotter months. As chillers operate, their water-cooled condensers often accumulate deposits via scaling, sedimentation, corrosion, and biological fouling. These deposits build up an insulating layer on the tube walls, impeding heat transfer and affecting the chiller's performance and efficiency. A classical experimental result to indicate the impact of fouling factor on chiller performance and condensing temperature by an empirical linear correlation is given in Figure 14 [59]. As the fouling factor increases, both the condensing temperature and power input will rise due to poor heat dissipation, resulting in lower chiller coefficient of performance (COP). For instance, for a condenser with a design fouling factor of 44 mm^2.K/W, an increment of scale fouling by 50% in the condenser will cause the chiller COP to decline more than 2%.

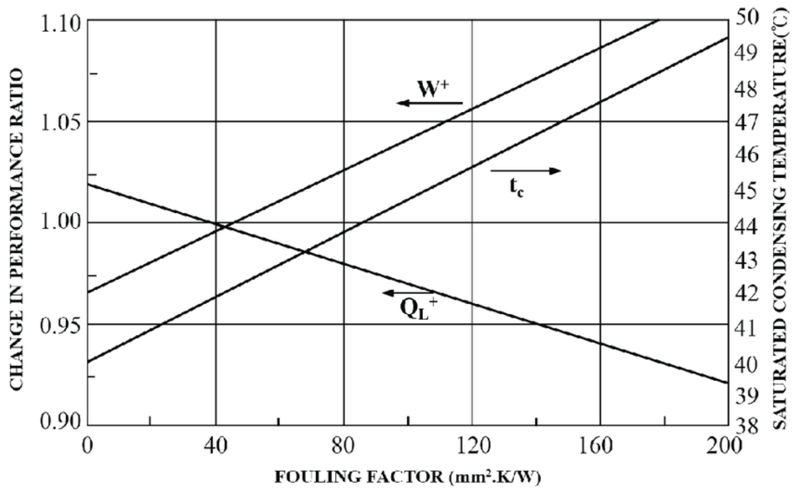

Fig. 14. Impact of condenser fouling factor on chiller performance [59]

The effect of condenser fouling on thermal performance of condensers and cooling tower systems can be evaluated using experiments, numerical analysis or simulation models [60-63]. Effective elimination or control of the four main cooling tower problems; scaling, biological microorganism, corrosion and pH control are objective requirements for a successful cooling water treatment system.

6.2 Energy Impact and Operation Costs

Maintenance and water treatment are the critical aspects that affect the life and energy efficient operation of evaporative cooling tower equipment. Inefficient operation results in poor performance and economic loss; for example, through water loss, equipment damage, poor equipment efficiency and poor heat transfer. Therefore, proper water treatment and regular tube cleaning are recommended for all liquid chillers to reduce power consumption and operating problems.

Proper water treatment improves the performance and energy efficiency of the HVAC systems, extends the life of equipment (by controlling scaling, corrosion and fouling which result in equipment damage) while helping to protect human health and safety. As the condenser and evaporator heat exchangers are critical equipment for HVAC systems, inefficient heat exchanger heat transfer denotes high energy consumption by the compressor and escalation in energy costs. Optimal energy efficiency and equipment efficiency can be evaluated through operational relations and performance between system equipment.

Chiller consumes more energy in order to compensate the loss of heat transfer efficiency caused by scale formation and bio-fouling in the cooling tower and chiller condenser tubes. For example, cumulatively 0.3 mm thickness of scale layer will cause 10% of more energy consumption for the chiller.

7. Conclusions

MNBs have been increasingly used as a highly efficient and environmentally friendly non-chemical gas-liquid phase process in water treatment, water purification, environmental pollution control, groundwater bioremediation, wastewater treatment, aquaculture, agriculture, and water ecosystem restoration. In particular, the application of MNB technology has a significant importance in water treatment because of the ability of the bubbles: long residence time, high mass transfer efficiency, relatively lower rising velocity, high zeta potential at the interface, easily tailored surface charge, free radical generation ability and improved collusion efficiency.

It is found that a combination of ozone and MNBs has positive synergetic effects on solubility, stability, and gas transfer efficiency that in turn will prolong reactivity of ozone and improve the decomposition rate of the reactive species. When applied to fresh water cooling towers in HVAC systems, the ozone MNB technology can provide economic, social and environmental benefits. It is believed that this technology is a technically practical, cost-effective and sensible alternative when compared to conventional cooling water treatment systems using chemicals. In order to develop an effective ozone MNB system and successfully promote its applications, it is essential to examine the bubble characteristics at functional levels and investigate the corresponding system operating parameters to achieve optimization.

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