Experimental Investigations on the Wall-attached Bubble Growth Process in Water With Supersaturated Total Dissolved Gas

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Experimental investigations on the wall-attached bubble growth process in water with supersaturated total dissolved gas

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Abstract: Due to dam discharge, waterfalls, sudden increases in water temperature and oxygen production by photosynthesis, the total dissolved gas (TDG) in water is often supersaturated, which may have serious effects on aquatic ecology. When the atmospheric pressure is lower than the TDG pressure in water, the supersaturated dissolved gas in water will slowly release into air. Wall-attached bubbles were formed during the TDG release process. The generation and departure of wall-attached bubbles influence the release process of TDG in water. To simulate the growth period of the wall-attached bubbles under different pressures, a decompression experimental device was designed to record the supersaturated TDG release process. Based on experimental data and mathematical calculations, the quantitative relationship

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between the bubble growth rate and environmental pressure was obtained. The supersaturated TDG dissipation rate increases monotonically with increasing relative vacuum degree. Based on the wall-attached bubble growth rate calculation method applied in this paper, a formula of the supersaturated TDG adsorption flux based on wall-attached bubbles was proposed, and a prediction method of the TDG release coefficient was established. The simulation results show that with increasing relative vacuum degree, the TDG coefficient increases correspondingly, and the adsorption mechanism of vegetation surface area can be obviously promoted under lower environmental pressure. This study provides an important theoretical basis for the accurate calculation of the TDG release process and provides a scientific basis for the accurate prediction of the spatial and temporal distribution of supersaturated TDG under different environmental conditions.

Keywords: Total dissolved gas; Supersaturation; Wall-attached bubble; Pressure; Release coefficient

1. Introduction

In the natural environment, dam discharge, waterfall, sudden rise of water temperature and oxygen production by photosynthesis may lead to total dissolved gas (TDG) supersaturation in water. Due to the pressure difference between water and atmosphere, supersaturated TDG in water will slowly release to air. Supersaturation TDG exists for a long time in water, which may lead to fish bubble disease or even death and cause serious adverse effects on aquatic ecology (Weitkamp, 2000; Li et al.,

2009).-The release rate of TDG supersaturation is directly related to the extent of the TDG level in water and the TDG pressure difference between water and air (Lu, 2019). For example, the environment under low atmospheric pressure in the plateau may promote the release process because of the large difference in the pressure inside and outside the TDG supersaturated water.

In practical engineering applications, there are many solid walls in rivers, such as vegetation and suspended solids, which can easily adsorb bubble nuclei. The rougher the wall is, the larger the area it provides, and the release process of supersaturated TDG is accelerated (Ou et al., 2016). Feng et al. (2012) reported that the release coefficient of TDG is positively correlated with the sediment concentration in supersaturated sediment-laden water. Niu observed that the release rate of supersaturated TDG increased with an increasing amount of activated carbon in water (Niu et al., 2015). The process of the gas phase fraction separating out from water can be the form of bubbles, and the characteristic parameters affecting the bubble shape play a key role in the study of mass transfer. Yuan proposed a supersaturated TDG dissipation model to describe the function of vegetation wall adsorption of TDG, and the equation for the adsorption flux of supersaturated TDG over a unit time was achieved from a macroscopic perspective (Yuan, 2018). Based on experiments focusing on the adsorption effect of solid walls, the quantitative relationship between the adsorption coefficient and contact angle of solid surfaces was obtained (Yuan, 2020). Li experimented on a superheated superhydrophobic surface to study the formation and escape of single bubbles on the vessel wall, revised Zuber's prediction equation of the bubble escape diameter and

frequency (Zuber, 1963), and obtained the relationship between gas-liquid interface surface tension, liquid density, and equilibrium bubble diameter (Li et al., 2016). Grinin considered that the factors affecting bubble growth include temperature, pressure and dissolved gas concentration in gas-liquid mixture systems (Grinin et al., 2009).

Previous studies have shown that solid walls in water can effectively promote the release of supersaturated TDG. To clarify the quantitative relationship between pressure and bubble growth rate on solid walls, a decompression experiment was designed in this paper to investigate the influence of solid wall media on TDG release under different decompression conditions.

2. Experimental study on the effect of pressure on bubble growth

2.1 Measurement instruments and method

The experiment was conducted in the State Key Laboratory of Hydraulics and Mountain River Development and Protection (Sichuan University). The experimental device includes rectangular Plexiglas sheet (PMMA) tanks with dimensions of 220 mm*160 mm*210 mm. The air pressure in the water tank was adjusted by a 180 W vacuum pump and a pressure gauge. The water depth in the tank was kept at 120 mm, and the back of the water tank was arranged against a black background to ensure clear wall-attached bubble images during the experiment. The light source is an LED lamp with a uniform distribution to the left of the water tank, and the camera is fixed in front of the water tank. A sketch of the experimental device is shown in Fig. 1.

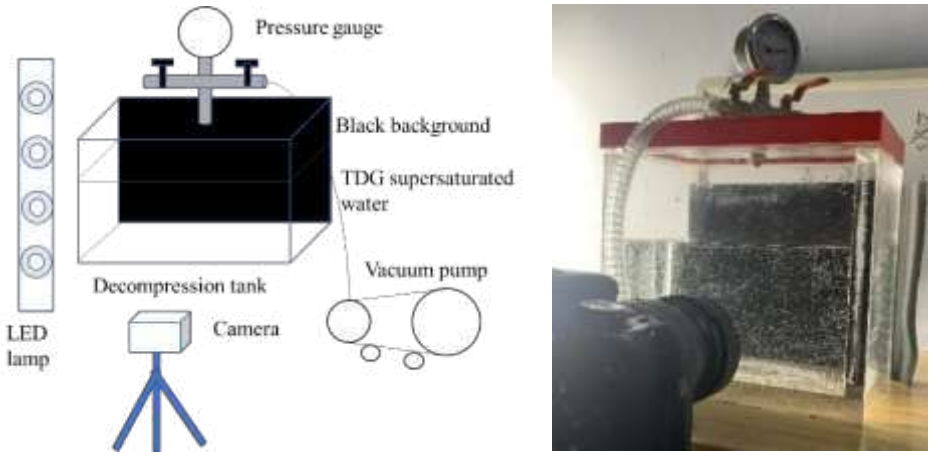


Fig. 1 Sketch of the experimental device

In this experiment, wall-attached bubbles in TDG supersaturated water were observed under vacuum. Bubbles generated in TDG supersaturated water can be adsorbed on the wall and continue to grow. When the size of bubbles reached a certain volume, the bubbles escaped from the wall. According to the observation of the experiment, the growth rate of bubbles can be significantly improved under the condition of reduced pressure.

TDG supersaturated water was provided by the supersaturated TDG generation system, which was developed by Sichuan University, China (Li et al., 2010). The pressure in the experimental water tank was adjusted to a constant vacuum degree, and the temperature was kept at 20 centigrade during the whole experimental process. A digital camera was used to record the precipitation, growth and escape process of wall-attached bubbles. The photographic equipment consisted of a Canon 600D digital camera with 17-85 lenses (Taiwan, China), a polarizer and XPRO. The TDG saturation is measured with a total dissolved gas pressure (TGP) detector composed of Pentair Point Four TGP portable trackers (California, U.S.), the TGP measuring range is 0–200%, and the accuracy is 2%. The TDG concentration in the experimental water tank

was analyzed by membrane injection mass spectrometry (MIMS 2000). The concentration of TDG dissolved in water can be converted into TDG saturation according to actual needs.

2.2 Experimental conditions

Five pressure conditions were set in the experiment: 0 kPa, 20.265 kPa, 40.53 kPa, 60.795 kPa and 81.06 kPa. To express the pressure condition clearly, the relative vacuum degree Φ is introduced as Eq. (1). The pressure conditions in this experiment represent the pressure conditions with relative vacuum degrees of 0, 0.2, 0.4, 0.6 and 0.8. For each group of pressure conditions, six TDG initial saturation conditions were set as 110%, 120%, 130%, 140%, 150% and 160%. The TDG concentration can be calculated according to the measured value of TDG saturation and the solubility of air in water.

The relative vacuum degree $\emptyset$ is introduced as follows:

$$\emptyset = P/P_{\mathrm{B}} \tag{1}$$

where $\emptyset$ is the relative vacuum degree (RVD), P is the vacuum degree, and P_{B} denotes the standard atmospheric pressure.

The variation in the TDG solubility at different relative vacuum degrees was expressed as:

$$C_{\emptyset}^{*} = C_{\emptyset=0}^{*}(1 - \emptyset) \tag{2}$$

where $C_{\emptyset=0}^{*}$ represents the TDG solubility at 1 atm ($mg \cdot L^{-1}$) and $C_{\emptyset}^{*}$ represents the equilibrium TDG concentration at the relative vacuum degree $\emptyset$ ($mg \cdot L^{-1}$).

115 The conversion of TDG saturation to TDG concentration is shown in the following.

$$C = C^{*}G \tag{3}$$

116 where C is the TDG concentration ($mg \cdot L^{-1}$), C^{*} is the equilibrium TDG
117 concentration ($mg \cdot L^{-1}$), and G is the saturation of TDG (%).

118 Table 1 shows the pressure conditions, and Table 2 shows the TDG initial
119 saturation conditions at a temperature of 20 ° C. There were 30 combined working
120 conditions. The water temperature in the experimental tanks was controlled at 20 °C
121 during the whole experimental process.

122 Table 1. The experimental case of different pressure conditions

Pressure group number	Pressure (kPa)	Vacuum degree (kPa)	Relative vacuum degree ∅
1	101.325	0	0
2	81.06	20.265	0.2
3	60.795	40.53	0.4
4	40.53	60.795	0.6
5	20.265	81.06	0.8

123

124 Table 2. The experimental case of different initial TDG level

TDG group number	Initial TDG supersaturation level (%)	TDG concentration C_0 (mg/L)
a	110	26.35
b	120	28.74
c	130	31.14
d	140	33.53
e	150	35.93
f	160	38.33

2.3 Experimental results of TDG concentration

USACE (2000) proposed that the dissipation process of supersaturated TDG involves a first-order kinetic reaction. The first-order kinetic reaction is shown as follows.

$$\frac{d(C_t - C^*)}{dt} = -k_{\mathrm{T}}(C_0 - C^*) \quad (4)$$

where t represents the dissipation time (min), C_t represents the TDG solubility of t, (mg·L^{-1}); C_0 represents the initial TDG solubility, (mg·L^{-1}); C^* represents the equilibrium TDG concentration, (mg · L^{-1}); and k_{T} represents the dissipation coefficient of supersaturated TDG, (min^{-1}).

The TDG saturation level at the initial and end times was measured for each case. The dissipation coefficients under different experimental cases were estimated according to the first-order kinetic equation. Fig. 2 shows that the dissipation coefficients under different pressure conditions were linearly enhanced with increasing relative vacuum degree.

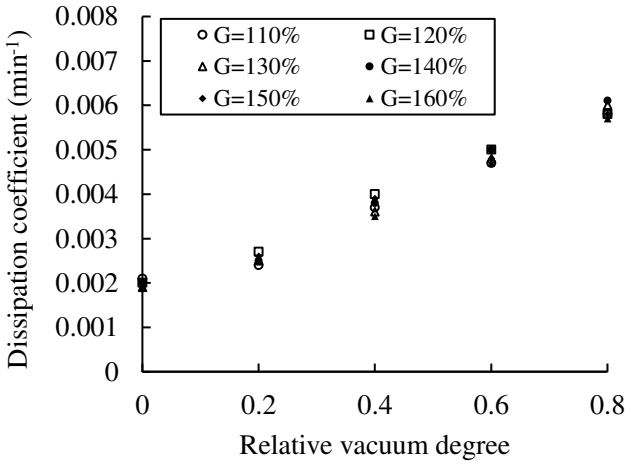


Fig. 2 Relationship between the TDG release coefficient and relative vacuum degree

141 According to the experimental results under various conditions, the relationship
142 between the dissipation coefficient and the relative vacuum degree by the fitting method
143 is obtained as follows:

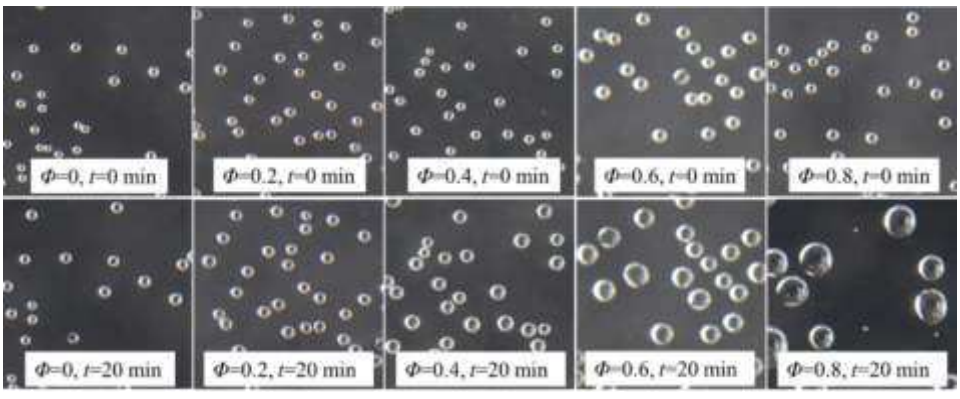
$$k_{\mathrm{T},\emptyset} = k_{\mathrm{T},\emptyset=0} e^{1.3987\emptyset} \quad (5)$$

144 where $k_{\mathrm{T},\emptyset}$ represents the dissipation coefficient under relative vacuum degree $\emptyset$
145 (min^{-1}) and $k_{\mathrm{T},\emptyset=0}$ represents the dissipation coefficient under relative vacuum degree
146 0 (min^{-1}).

147 The coefficient of determination, R^2, is 0.978.

148 2.4 Image source of wall-attached bubbles

149 The wall-attached bubble images under different pressure cases were taken for
150 each group of experiments. Taking the group with an initial concentration of TDG of
151 160% as an example, the wall-attached bubble images at different pressure cases were
152 recorded by the camera, as shown in Fig. 3. It was clear that the relative vacuum degree
153 has an obvious promotional effect on the wall-attached bubble growth rate.



154

155 Fig. 3 Bubble images of different pressure cases

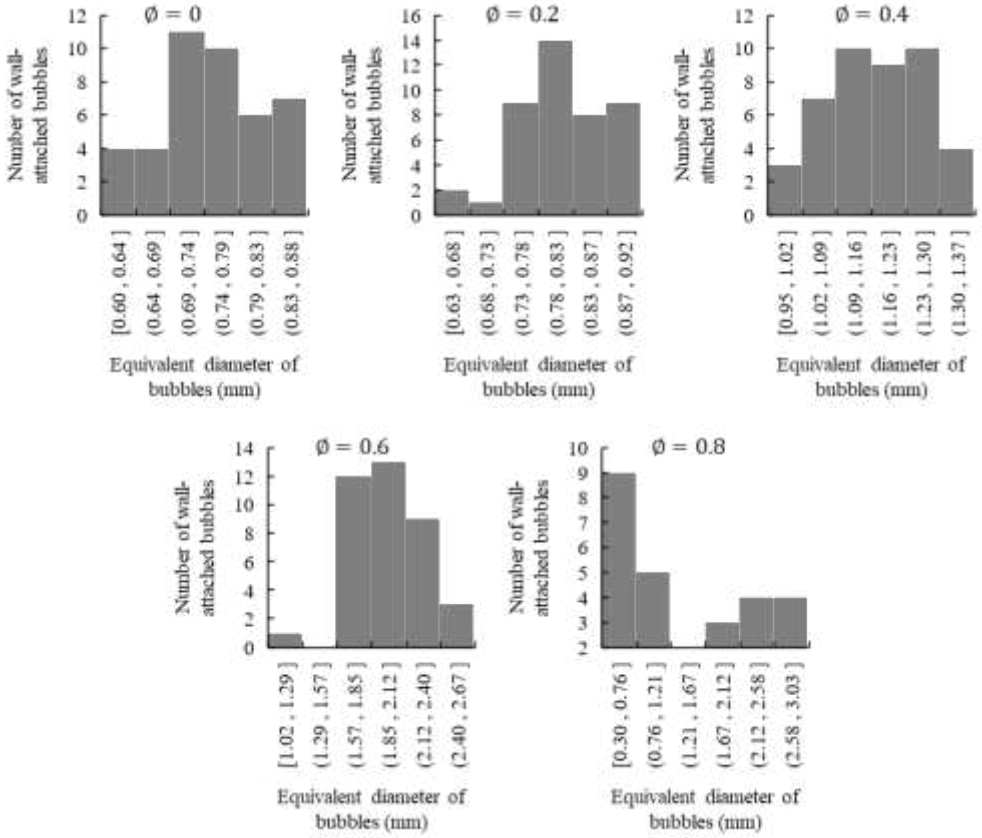
156 By using the image processing method, the wall-attached bubbles in each image
157 were numbered in MATLAB (Lin, 2021). Otsu proposed by Gonzalez (2010) was used

158 to process the image binarization. The equivalent diameter of bubbles was calculated
159 as follows:

$$D = \sqrt{\frac{4a_{\mathrm{B}}}{\pi}} \tag{6}$$

160 where D represents the equivalent diameter of bubbles (mm) and a_{B} represents
161 the projected bubble area (mm^2).

162 The statistics of the bubbles' equivalent diameter distribution under different
163 pressure conditions are shown in Fig. 4.



164

165 Fig. 4 Statistics of bubbles' equivalent diameter distribution

166 According to the statistics of the equivalent diameter of wall-attached bubbles in
167 Fig. 4, the equivalent diameter of wall-attached bubbles exhibits a single peak
168 distribution when the value of the vacuum degree is below 0.4 and presents a double

peak distribution when the value of the vacuum degree is above 0.4.

3. Analysis of the TDG release process based on wall-attached bubbles

3.1 The role of wall-attached bubbles in the supersaturated TDG release coefficient

Based on a previous study on the wall adsorption effect on the TDG release process, the calculation method of the supersaturated TDG coefficient based on wall-attached bubbles can be used to predict the TDG release process. The dissipation process of supersaturated TDG in water consists of three parts (Yuan 2018). However, in static water, there are almost no free bubbles in water, so the TDG dissipation process can be simplified into two parts: air-water mass transfer and wall adsorption, as shown in Fig. 5.

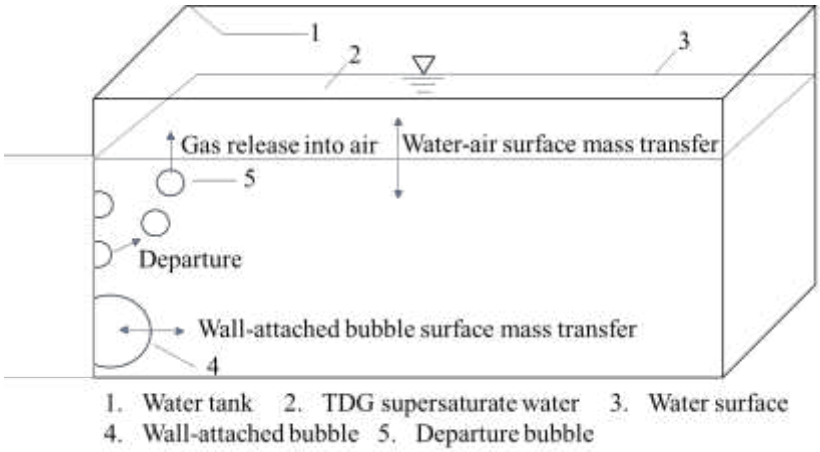


Fig. 5 Sketch of the TDG mass transfer

The amount of supersaturated TDG released in static water can be expressed as:

$$F_G = F_s + F_w \tag{7}$$

where F_G represents the release rate of supersaturated TDG, (mg·L^{-1}min^{-1}); F_s represents the release rate of supersaturated TDG from air-water mass transfer, (mg·L^{-}

184 ^{1}min^{-1}); and F_{w} represents the release rate of supersaturated TDG from wall adsorption,

185 (mg·L^{-1}min^{-1}).

186 (1) The release rate of supersaturated TDG from air-water mass transfer is:

$$F_{\mathrm{G}} = k_{\mathrm{T}}(C - C_{\emptyset}^{*}) \tag{8}$$

187 where k_{T} represents the TDG release coefficient (min^{-1}); C represents the

188 concentration of supersaturated TDG (mg·L^{-1}); and $C_{\emptyset}^{*}$ represents the equilibrium

189 concentration of supersaturated TDG (mg·L^{-1}).

190 (2) The release rate of supersaturated TDG from wall adsorption:

$$F_{\mathrm{s}} = K_{\mathrm{s}} a_{\mathrm{s}}(C - C_{\emptyset}^{*}) \tag{9}$$

191 where K_{s} represents the mass transfer coefficient of the air-water interface

192 (m·min^{-1}) and a_{s} represents the specific surface area of supersaturated water (m^{-1}).

193 The quantitative relationship between the mass transfer coefficient of the air-water

194 interface and the surface turbulent kinetic energy was proposed by Li (2000):

$$K_{\mathrm{s}} = 0.085 T_{\mathrm{s}}^{1/2} + 0.0014 \tag{10}$$

195 where T_{s} represents the surface turbulent kinetic energy (m^{2}·s^{-2}).

196 (3) The formula for calculating the adsorption rate of TDG by solid walls in

197 supersaturated water is as follows:

$$F_{\mathrm{w}} = \frac{dM_{\mathrm{w}}}{dt} a_{\mathrm{d}} \tag{11}$$

198 where a_{d} represents the specific solid wall area of supersaturated water (m^{-1}).

199 M_{w} represents the TDG adsorption flux, (mg·m^{-2}), which can be expressed as the sum

200 of the amount of TDG contained in the wall-attached bubbles and the amount of TDG

201 released from the escaped bubbles.

The release process of supersaturated TDG in static water includes mass transfer at the water-air interface, internal release of TDG in water and mass transfer at the wall-attached bubble interface. The formula of TDG adsorption flux can be expressed as follows:

$$M_{\mathrm{w}} = M_{\mathrm{B}} + M_{\mathrm{d}} \tag{12}$$

where M_{B} represents the amount of TDG contained in the wall-attached bubbles (mg·m^{-2}) and M_{d} represents the amount of TDG released from the escaped bubbles (mg·m^{-2}).

The amount of TDG contained in the wall-attached bubbles M_{B} was defined as the wall-attached bubble adsorption flux, and the calculation formula is as follows:

$$M_{\mathrm{B}} = \rho_{\mathrm{B}} V_{\mathrm{B}} N \times 10^{-2} \tag{13}$$

where ρ_{B} represents the air density in wall-attached bubbles, (mg·L^{-1}); V_{B} represents the wall-attached bubble volume, (mm^3); and N represents the wall-attached bubble number density, (cell·cm^{-2}).

The amount of TDG released from the escaped bubbles M_{d} was defined as the bubble escapable adsorption flux, and the calculation formula is as follows:

$$M_{\mathrm{d}} = \rho_{\mathrm{B}} V_{\mathrm{d}} N \times 10^{-2} \tag{14}$$

where V_{d} represents the wall-attached bubble departure volume, (mm^3); N represents the wall-attached bubble number density, (cell·cm^{-2}), which changes with the TDG concentration in water.

The TDG release coefficient under the influence of a solid wall was simplified as follows:

$$k_{\mathrm{T}} = \frac{\frac{dM_{\mathrm{w}}}{dt} a_{\mathrm{d}} + (C - C^{*}) K_{\mathrm{s}} a_{\mathrm{s}}}{(C - C^{*})} \tag{15}$$

Where k_{T} represents the TDG dissipation coefficient, ($\mathrm{min^{-1}}$); M_{w} represents the TDG adsorption flux, ($\mathrm{mg \cdot m^{-2}}$); t represents time, (min); a_{d} represents the specific solid wall area of supersaturated water ($\mathrm{m^{-1}}$); C represents the concentration of supersaturated TDG ($\mathrm{mg \cdot L^{-1}}$); $C_{\emptyset}^{*}$ represents the equilibrium concentration of supersaturated TDG ($\mathrm{mg \cdot L^{-1}}$); K_{s} represents the mass transfer coefficient of the air-water interface ($\mathrm{m \cdot min^{-1}}$) and a_{s} represents the specific surface area of supersaturated water ($\mathrm{m^{-1}}$).

3.2 Analysis of the growth rate of the wall-attached bubble

Due to the release process of supersaturated TDG in water, the wall-attached bubble diameter increases gradually. The mass transfer process of TDG on the surface of wall-attached bubbles is shown in Fig. 6.

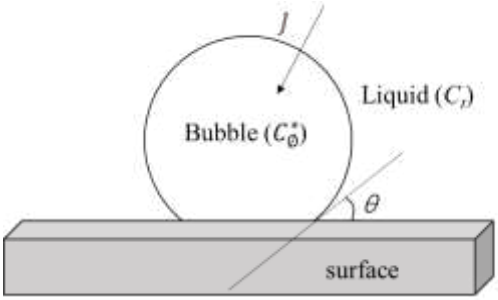


Fig. 6 Mass transfer process of TDG on the surface of wall-attached bubbles

The air mass transfer flux from the liquid to bubbles can be expressed as follows:

$$J = K_{\mathrm{B}}(C_t - C_{\emptyset}^{*}) \tag{16}$$

where J represents the air mass transfer flux from the liquid to bubbles ($\mathrm{mg \cdot mm^{-2} \cdot min^{-1}}$); K_{B} represents the mass transfer coefficient at the bubble surface ($\mathrm{mm \cdot min^{-1}}$);

237 C_t represents the TDG concentration (mg·L^{-1}); and $C_{\emptyset}^{*}$ represents the equilibrium
238 TDG concentration under relative vacuum degree $\emptyset$ (mg·L^{-1}).

239 By substituting Eq. (4) into Eq. (8), the mass transfer flux of supersaturated TDG
240 on the bubble surface can be expressed as:

$$J = K_{\mathrm{B}}\left[\left(C_{t=0} - C_{\emptyset}^{*}\right)e^{-k_T t}\right] \tag{17}$$

241 According to mass conservation, the relationship between the TDG dissipation
242 process and wall-attached bubble volume growth rate can be expressed as:

$$\frac{dV_B}{dt} = \frac{K_{\mathrm{B}}A_{\mathrm{B}}}{\rho_{\mathrm{B}}}\left[\left(C_{t=0} - C_{\emptyset}^{*}\right)e^{-k_{\mathrm{T}} t}\right] \tag{18}$$

243 where V_{B} represents the wall-attached bubble volume, (mm^3); A_{B} represents the
244 wall-attached bubble surface area, (mm^2); and $\rho_B$represents the air density in wall-
245 attached bubbles, (mg·L^{-1}).

246 By applying the bindery condition that $V_{\mathrm{B}_{t=0}} = 0$, the differential Eq. (10) can be
247 solved as:

$$V_{\mathrm{B}} = \frac{K_{\mathrm{B}}A_{\mathrm{B}}\left(C_{t=0} - C_{\emptyset}^{*}\right)}{\rho_{\mathrm{B}}k_{\mathrm{T}}}\left(1 - e^{-k_{\mathrm{T}} t}\right) \tag{19}$$

248 Due to the contact angle between water, gas and solids, the shape of wall-attached
249 bubbles is not a complete sphere (Adamson, 1990). The volume of the wall-attached
250 bubbles was calculated accurately from the images accounting for the contact angle
251 effect, as described by Lin (2021). Thereafter, the mass transfer coefficient at bubble
252 surface K_{B} in Eq. (11) under different relative vacuum degrees $\emptyset$ can be calculated.
253 The relationship between K_{B} and $\emptyset$ is shown in Fig. 7.

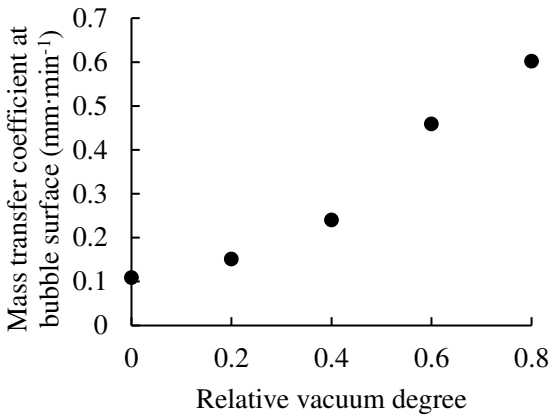


Fig. 7 Relationship of the bubble surface mass transfer coefficient and the relative vacuum degree

According to the experimental results under various conditions, the quantitative relationship between K_{B} and $\emptyset$ by the fitting method was obtained as follows:

$$K_{\mathrm{B},\emptyset} = K_{\mathrm{B},\emptyset=0} e^{2.1755\emptyset} \tag{20}$$

where $K_{\mathrm{B},\emptyset}$ represents the mass transfer coefficient at the bubble surface under a relative vacuum degree of $\emptyset$ (mm·min^{-1}) and $K_{\mathrm{B},0}$ represents the mass transfer coefficient at the bubble surface under a relative vacuum degree of 0 (mm·min^{-1}).

The coefficient of determination, R^2, is 0.985.

3.3 Analysis of the number density of wall-attached bubbles

The number density (cell·cm^{-2}) of wall-attached bubbles for each experimental case can be obtained by program calculation in MATLAB, and the statistical results are shown in Fig. 8.

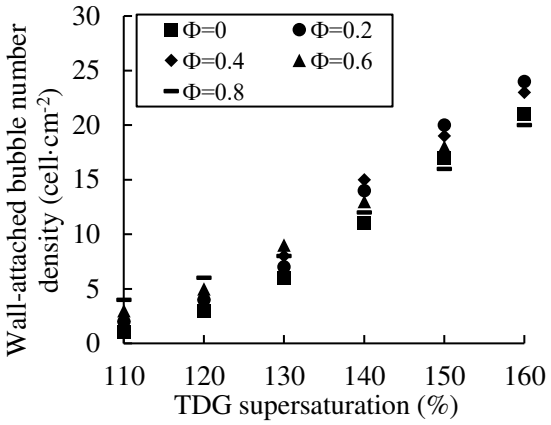


Fig. 8 Statistics of the wall-attached bubble number density

According to the experimental results, the supersaturation level of TDG is the key factor that influences the wall-attached bubble number density. The quantitative relationship of the wall-attached bubble number density increasing with TDG supersaturation by the fitting method is obtained as follows:

$$N = 0.017(G - 100)^{1.74} \tag{21}$$

where N represents the wall-attached bubble number density (cell $\cdot$ cm^{-2}). G represents the supersaturation of TDG, (%).

The coefficient of determination, R^2, is 0.997.

3.4 Analysis of wall-attached bubble departure in static water

According to observations during experiments, wall-attached bubbles depart from the wall to the water surface when they grow to a certain diameter (Chen, 2015). According to the statistical results regarding the relative vacuum degree of 0.8 in the experiment, the departure diameter of wall-attached bubbles ranged from 1.5 mm to 2.3 mm, and the average bubble departure diameter in static TDG supersaturated water was 1.94 mm. The statistical results were consistent with Brennen's (Brennen, 1995)

conclusion that all bubble nuclei would grow to the same maximum radius.

The volume of the departure bubbles comprises the important part of the release of TDG in water. The departure time of wall-attached bubbles was defined as X, which represents the retention time from the formation to the departure. According to the quantitative relationship between the TDG dissipation process and the wall-attached bubble volume growth rate, the value of X can be calculated as follows.

$$X = -\frac{1}{k_{\mathrm{T}}}\exp\left(1 - \frac{V_{\mathrm{d}}\rho_{\mathrm{B}}k_{\mathrm{T}}}{K_{\mathrm{B}}A_{\mathrm{B}}\left(C_0 - C_{\emptyset}^{*}\right)}\right) \tag{22}$$

where V_{d} represents the wall-attached bubble volume of departure time (mm^3) and A_{B} represents the wall-attached bubble surface area (mm^2).

The departure frequency of wall-attached bubbles was defined as follows:

$$f = \frac{N}{X} \tag{23}$$

where f represents the departure frequency of wall-attached bubbles, ($min^{-1}\cdot cm^{-2}$) and N represents the wall-attached bubble number density, ($cell\cdot cm^{-2}$).

The supersaturated TDG decay process can be described by a first-order kinetic equation (USACE, 2000). The departure frequency of wall-attached bubbles can be simulated as shown in Fig. 9. In the simulation results, the departure frequency of wall-attached bubbles decreased obviously with decreasing TDG concentration.

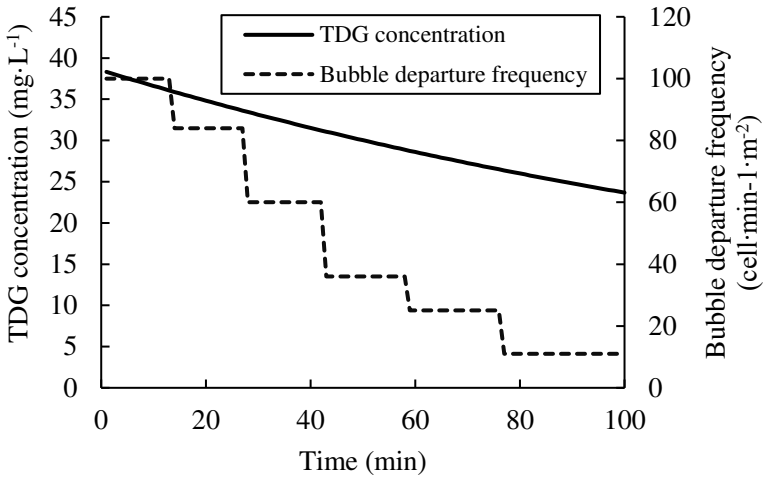


Fig. 9 Simulation result of the wall-attached bubbles' departure frequency

296 3.5 Calculation of the adsorption flux through the wall-attached bubbles

297 Under environmental conditions of a relative vacuum degree $\emptyset = 0$, the bubble
298 growth rate was slow, and it was difficult for wall-attached bubbles to escape. By
299 considering the TDG release process, the TDG adsorption flux under this condition can
300 be simulated, as shown in Fig. 10. With decreasing TDG concentration, the growth rate
301 of wall-attached bubbles gradually slowed down, and the wall adsorption rate of
302 supersaturated TDG decreased over time.

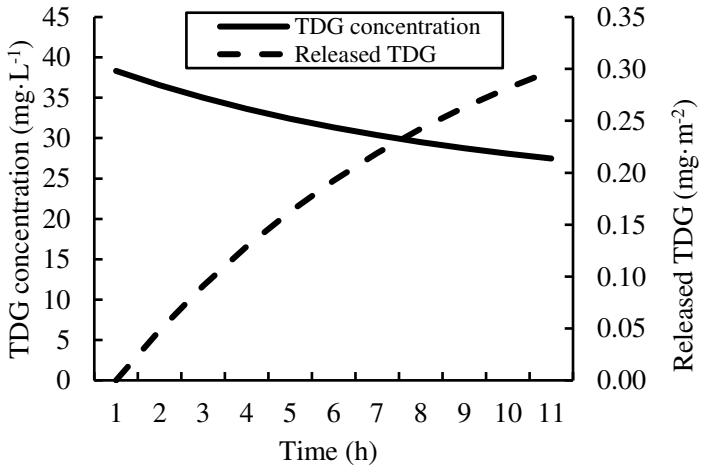


Fig. 10 The simulation of TDG adsorption flux ($\emptyset = 0$)

303 The growth period was defined to describe the time of a group of wall-attached
304 bubbles from appearance to departure. In the following simulations, the statistical value
305 of a group of wall-attached bubbles' average departure time was used to represent the
306 value of the growth period. At a high value of the relative vacuum degree ($\emptyset = 0.8$),
307 due to the promotion effect of pressure on the bubble growth rate, the growth period of
308 wall-attached bubbles was significantly shortened. Considering the influence of bubble
309 growth and escape on supersaturated TDG release, the total amount of TDG adsorption
310 flux under this condition can be simulated, as shown in Fig. 11.

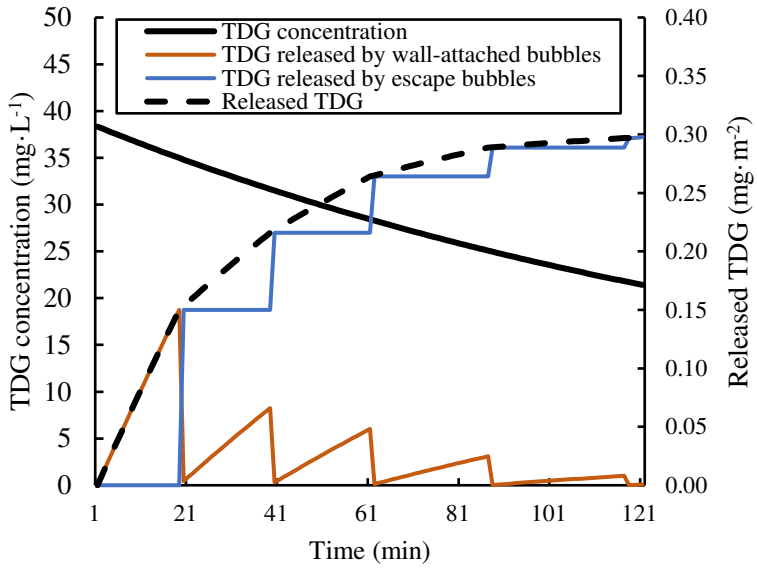


Fig. 11 Simulation of the supersaturated TDG adsorption flux ($\emptyset = 0.8$)

311 **4. Discussion**

312 In practical engineering applications, there are many solid walls in lakes and rivers,
313 such as vegetation and suspended solids, which easily adsorb bubbles and promote

wall-attached bubble growth. To discuss the effect of solid wall adsorption on the TDG release coefficient, a prediction of the TDG release coefficient accounting for the wall adsorption effect was proposed. The simulation is based on a water tank that has different amounts of plants, and the air pressure over the water tank depends on the local altitude. The volume of water was assumed to be 1 m^3, and the initial supersaturated TDG was assumed to be 150% for the modeling calculation. The diagram of the simulated water tank is shown in Fig. 12.

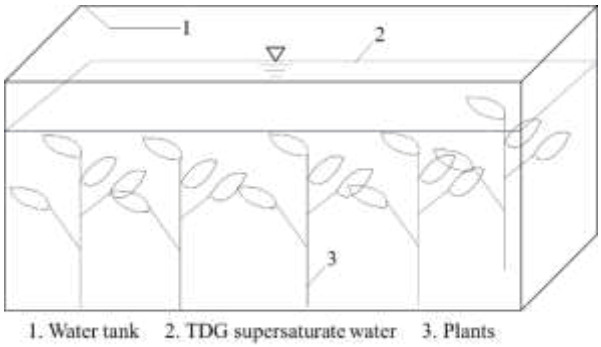


Fig. 12 The simulated water tank

The simulation cases of the pressure condition are shown in Table. 3.

Table. 3 The simulation cases of pressure condition

Pressure group number	Pressure (kPa)	Vacuum degree (kPa)	Relative vacuum degree ∅
1*	101.33	0	0
2*	91.20	10.13	0.1
3*	81.07	20.26	0.2
4*	70.93	30.40	0.3
5*	60.80	40.53	0.4

As the calculation result of Eq. (10), the mass transfer coefficient of the air-water interface in the case of static water was 0.0014 min^{-1}. According to the leaf surface

contact angle of the vegetation in natural water, a contact angle of 90° was chosen for simulation. The departure diameter of wall-attached bubbles can be calculated as 3.01 mm (Lin, 2021). The initial TDG release coefficient in the case of different pressures was calculated according to Eq. (5), and the simulated TDG release time was 120 min. The TDG release coefficients under different vegetation superficial areas and different pressure conditions were calculated, as shown in Fig. 13.

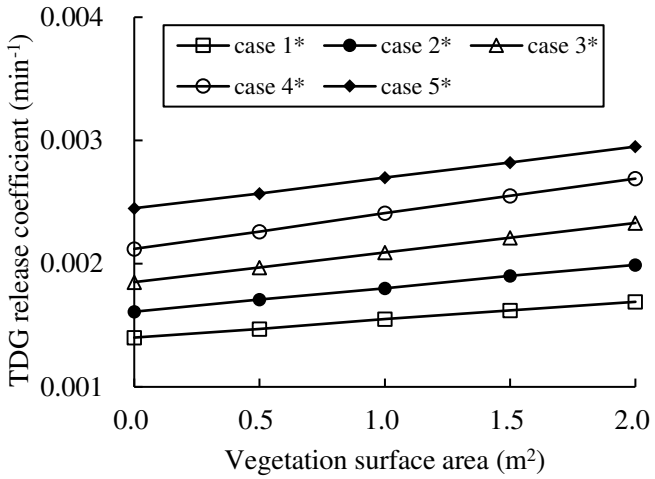


Fig. 13 Calculation results of the TDG release coefficient

The results show that both pressure and vegetation surface area can promote the release process of supersaturated TDG. Under lower pressure, the effect of vegetation surface area on the TDG release coefficient is more obvious.

5. Conclusions

An experimental water tank with controllable pressure was designed in this paper to study the release process of supersaturated TDG under different environmental pressures. The quantitative relationship between the relative vacuum and the TDG adsorption flux on the wall was obtained. Based on the experimental research

conclusions, the effects of the vegetation surface area and pressure on the TDG release process were simulated. The simulation results show that with increasing relative vacuum degree, the TDG coefficient increases correspondingly, and the adsorption mechanism of vegetation surface area can be obviously promoted under lower environmental pressure.

The analysis of the wall-attached bubble growth rate in this paper provides a statistical basis for the study of the supersaturated TDG release process under different environmental pressures and different solid wall areas. The calculation model of the supersaturated TDG release coefficient established in this paper provides an important theoretical basis for accurately evaluating the effect of environmental pressure on the supersaturated TDG release process. This paper also provides a technical path to explore the measures of using wall media to promote the supersaturated TDG release process in practical engineering applications.

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Notation

The following symbols are used in this paper:

a_B=projected bubble area (mm^2)
a_d=specific solid wall area of supersaturated water (m^{-1})
a_s=specific surface area of supersaturated water (m^{-1})
A_B=wall-attached bubble surface area (mm^2)

C^*=equilibrium TDG concentration ($mg \cdot L^{-1}$)

C=TDG concentration ($mg \cdot L^{-1}$)

D=equivalent diameter of bubbles (mm)

D_d=wall-attached bubble's departure volume (mm^3)

f=departure frequency of wall-attached bubbles ($min^{-1} \cdot cm^{-2}$)

F_G=release rate of supersaturated TDG ($mg \cdot L^{-1} min^{-1}$)

F_s=release rate of supersaturated TDG from air-water mass transfer ($mg \cdot L^{-1} min^{-1}$)

F_w=release rate of supersaturated TDG from wall adsorption ($mg \cdot L^{-1} min^{-1}$)

G=saturation of TDG (%)

J=air mass transfer flux from the liquid to bubbles ($mg \cdot mm^{-2} \cdot min^{-1}$)

k_T=TDG dissipation coefficient (min^{-1})

K_B=mass transfer coefficient at bubble surface ($mm \cdot min^{-1}$)

K_s=mass transfer coefficient of air-water interface ($m \cdot min^{-1}$)

M_w=TDG adsorption flux ($mg \cdot m^{-2}$)

M_B=wall-attached bubble adsorption flux ($mg \cdot m^{-2}$)

M_d=departure bubble adsorption flux ($mg \cdot m^{-2}$)

N=wall-attached bubble number density ($cell \cdot cm^{-2}$)

P=pressure (kPa)

P_B=standard atmospheric pressure (kPa)

t=time (min)

Ts=surface turbulent kinetic energy ($m^2 \cdot s^{-2}$)

V_B=wall-attached bubble volume, (mm^3)

V_g=departure bubble volume (mm^3)

X=bubble retention time from the formation to the departure (min)

Φ=relative vacuum degree

ρ_B=air density in wall-attached bubbles ($mg \cdot L^{-1}$)

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