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Experimental Aeration Investigations on Supersaturated Total Dissolved Gas Dissipation

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ABSTRACT

Supersaturation of total dissolved gas (TDG) is mainly produced by high dam discharge, excess oxygen production by plant photosynthesis, and a sharp increase in water temperature, which may directly lead to fish and aquatic organisms suffering from “gas bubble disease” (GBD) or death. Aeration was one of the methods used to solve the dissipation of supersaturated TDG. In this paper, aeration had an obvious promotion effect on the dissipation of supersaturated TDG. For the calculation and analysis of supersaturated TDG dissipation coefficient, the aeration rate was proportional to TDG dissipation coefficient and had a promoting effect on it, while the aeration depth and aeration aperture were inversely proportional to TDG dissipation coefficient and played an inhibitory effect on it. The supersaturated TDG dissipation coefficient was affected by a factor of $K_{TDG,Q} > K_{TDG,D} > K_{TDG,H}$. A quantitative relationship between the supersaturated TDG dissipation coefficient and aeration rate, aeration depth, and aeration aperture was obtained, respectively, as well as important expressions with comprehensive effect factors; their margins of error average within 10%. This research method has an important guiding significance for improving the living environment of fish and other aquatic organisms, alleviating the adverse effects of supersaturated TDG.

INTRODUCTION

In recent decades, hydroelectric power generation had become one of the main new energy sources, which not only saved the exploitation of fossil energy and avoided air pollution but also improved people’s living environments (Cai 2016, Zuo 2005). However, some researchers found that many fish died in the dam watershed (Tan et al. 2006); they believed that when the high dam discharged, the gas was drawn into the water and the strong turbulence in the water cushion pond caused the surface of the water to inhale, the two methods might lead to a large number of air bubbles in the water, resulting in a significant increase in the dissolved gas content (Cheng et al. 2005), this formed supersaturated total dissolved gas (TDG) (Weitkamp et al. 1980, Harvey 1967), which may directly lead to “gas bubble disease” (GBD) and even death of fish and organisms in water (Wu et al. 2021, Yuan et al. 2017). In addition, excess oxygen production in plant photosynthesis and a rapid increase in water temperature might also lead to total dissolved gas supersaturation in water (Agarwal et al. 2001, Boyd et al. 1994). Among them, the dissipation of supersaturated TDG belonged to the dissipation at the interface of the air-water and water, and both dissipation processes were affected by factors such as water turbulence, temperature, bubble size, and concentration variation (Wang et al. 2019).

So far, many researchers have proposed their own mitigation measures for reducing the generation of supersaturated TDG and accelerating its release. They set up deflectors in the spillway, optimized the way of water discharge, and adjusted cascade reservoirs (Monk et al. 2011, Fu et al. 2010, Politano et al. 2012), and Colt et al. (1984) used siphon devices and packed columns to reduce the supersaturated TDG concentration in the culture pond. Feng et al. (2012, 2014, 2017) also found that the design of a water-blocking medium with different arrangement forms, densities, and surface roughness was conducive to the dissipation of supersaturated TDG under the action of the column as a water-blocking medium; this method was also conducive to the release of supersaturated TDG under certain conditions of sand content and turbulent intensity. Huang et al. (2017) added adsorbent substances (activated carbon) into supersaturated water, which significantly promoted the dissipation of supersaturated TDG, and the

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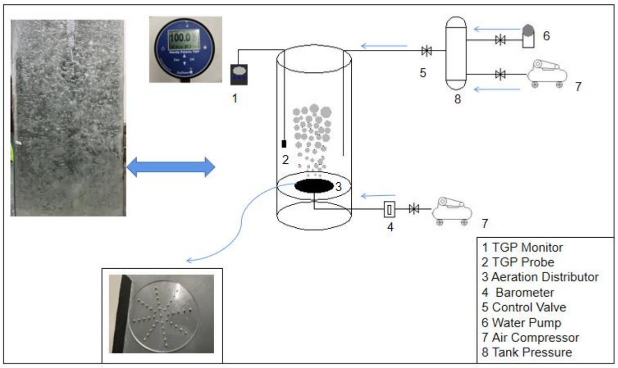

Fig. 1: Experiments and sketches.

effect of substances with a large surface area was more obvious. Du et al. (2017) designed a submersible pump, and different pump numbers, powers, placement methods, and drainage directions were conducive to the dissipation of supersaturated dissolved oxygen. Liu et al. (2015) found that a certain wind speed can promote the dissipation of supersaturated TDG under different wind speeds and fit their relational expressions. Based on the gas-liquid mass transfer theory, Huang et al. (2016) used the aeration method to have a significant effect on the dissipation of dissolved oxygen (DO) and obtained the relationship between its dissipation coefficient (release rate) and aeration conditions. Microporous aeration can increase dissolved oxygen. Cheng et al. (2013) found a relationship between oxygen dissipation and microporous conditions. Li et al. (2007) summarized the theory of the optimal bubble group for microporous aeration and obtained the regular changes of oxygen mass transfer rate, bubble size, and aeration performance.

Under experimental aeration conditions, the effect of aeration on the dissipation of supersaturated TDG and the expression of its dissipation coefficient and aeration conditions (aeration rate, aeration depth, and aeration aperture) were studied to provide new methods and research directions for alleviating the adverse effects of supersaturated TDG.

MATERIALS AND METHODS

Laboratory instrumentations: the supersaturated TDG generation device in Fig. 1 was modified and designed with reference to Li et al. (2010). The experimental device mainly includes an aeration distributor (D = 0.6, 0.9, and 1.2 mm), tank pressure (D = 0.6 m, h = 1.2 m), barometer (Q = 0.5–5.0 $m^3.h^{-1}$), release tank (D = 0.4 m, H = 1.8 m), measuring instrument TGP (0 - 600 %, ± 0.1%), air compressor (90 $L.min^{-1}$).

Experimental steps: During the experiment, the water pump pumped water, the air compressor input gas, which was mixed in the venturi tube, then entered the autoclave together to form supersaturated water, and we put the supersaturated water into a square water tank equipped with an aeration distributor. When the water depth reached the predetermined depth, the set aeration rate was mobilized, and the TGP started to continuously measure the supersaturated TDG concentration in the water and stopped recording when the concentration reached about 100%. Table 1 was the experimental aeration condition. There were 36 groups of experiments.

EXPERIMENTAL RESULTS ANALYSIS AND LINEAR FITTING

Analysis of Experimental Results

Fig. 2 shows the experimental aeration conditions with aeration aperture D = (0.6, 0.9, 1.2) mm, aeration depth H = (0.4, 0.8, 1.2) m, and aeration rate Q = (0.5, 1.0, 1.5, 2.0) $m^3.h^{-1}$. It can be seen from this that the initial concentration of supersaturated TDG is about 140%, which belongs to the supersaturated state, and then gradually reaches the saturated state (Colt 1983). Moreover, under the same aeration depth and aeration aperture, the increase in the aeration rate causes the dissipation time to decrease, but under other same conditions, the increase in aeration depth and aeration aperture leads to an increase in the dissipation time. The reason analysis shows that: (1) the increase in aeration rate enhances the turbulence intensity of the water body, increases the number of bubbles in the water, and also strengthens the mass transfer between the bubble interface and the water surface (Witt et al. 2018, Chanson 2004). (2) The increase of water depth leads to the weakening of the turbulence

Table 1: Experimental aeration conditions.

Aeration depth (H/m)	Aeration aperture (D/mm)	Aeration rate ($Q/m^3•h^{-1}$)
0.4, 0.8, 1.2	0.6, 0.9, 1.2	0.5, 1.0, 1.5, 2.0

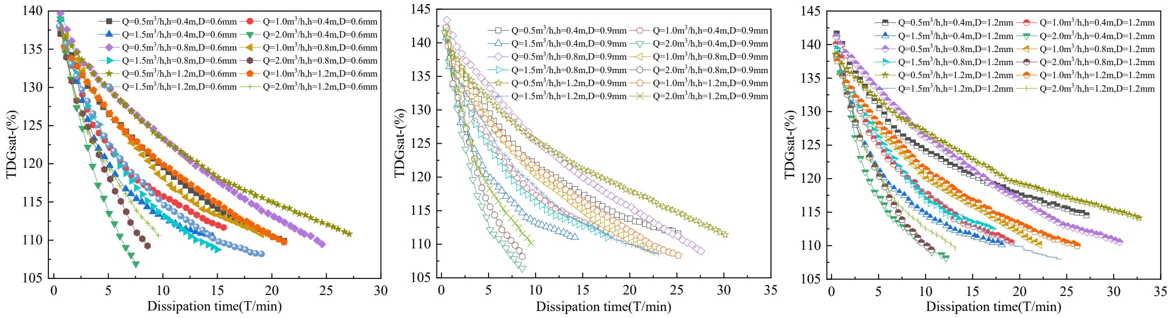

Fig. 2: The dissipation process of supersaturated TDG.

intensity caused by the bubbles in water, and the increase of the aeration aperture causes the bubble diameter to become larger, so that the number of bubbles at the same aeration rate decrease, and the two factors lead to the mass transfer at the bubble interface and water surface mass transfer being weakened (Cao et al. 2019, Huang et al. 2010).

Supersaturated TDG Linear Fitting

To further analyze the effect of aeration on the release of supersaturated TDG, a first-order kinetic equation was introduced to change the saturation of supersaturated TDG with time as equation (1) (U.S. Army Corps of Engineers 2005), with the fitting of results shown in Table 2.

$$\frac{d\left(G-G_{eq}\right)}{dt}=k_{TDG}\left(G-G_{eq}\right) \quad ...(1)$$

Where G is the TDG saturation (%), G_{eq} is the equilibrium saturation of TDG (usually 100%), K_{TDG} is the dissipation

Table 2: Dissipation coefficient k_{TDG}.

Number	Aeration aperture (D/mm)	Aeration depth (H/m)	Aeration rate (Q/m^3•h)	k_{TDG}	R^2
1.	0.6	0.4	0.5	0.063 ± 0.00	0.999
2.	0.6	0.4	1.0	0.073 ± 0.00	0.968
3.	0.6	0.4	1.5	0.092 ± 0.00	0.949
4.	0.6	0.4	2.0	0.245 ± 0.00	0.998
5.	0.6	0.8	0.5	0.056 ± 0.00	0.997
6.	0.6	0.8	1.0	0.067 ± 0.00	0.990
7.	0.6	0.8	1.5	0.102 ± 0.00	0.993
8.	0.6	0.8	2.0	0.172 ± 0.00	0.996
9.	0.6	1.2	0.5	0.046 ± 0.00	0.998
10.	0.6	1.2	1.0	0.062 ± 0.00	0.998
11.	0.6	1.2	1.5	0.083 ± 0.00	0.990
12.	0.6	1.2	2.0	0.136 ± 0.00	0.993
13.	0.9	0.4	0.5	0.050 ± 0.00	0.987
14.	0.9	0.4	1.0	0.067 ± 0.00	0.977
15.	0.9	0.4	1.5	0.088 ± 0.00	0.951
16.	0.9	0.4	2.0	0.226 ± 0.00	0.995
17.	0.9	0.8	0.5	0.054 ± 0.00	0.997
18.	0.9	0.8	1.0	0.067 ± 0.00	0.998
19.	0.9	0.8	1.5	0.072 ± 0.00	0.969
20.	0.9	0.8	2.0	0.198 ± 0.00	0.997
21.	0.9	1.2	0.5	0.039± 0.00	0.996
22.	0.9	1.2	1.0	0.060 ± 0.00	0.996
23.	0.9	1.2	1.5	0.067 ± 0.00	0.991
24.	0.9	1.2	2.0	0.151 ± 0.00	0.990

Number	Aeration aperture (D/mm)	Aeration depth (H/m)	Aeration rate (Q/m^3•h)	k_{TDG}	R^2
25.	1.2	0.4	0.5	0.036 ± 0.00	0.970
26.	1.2	0.4	1.0	0.069 ± 0.00	0.985
27.	1.2	0.4	1.5	0.071 ± 0.00	0.946
28.	1.2	0.4	2.0	0.133± 0.00	0.968
29.	1.2	0.8	0.5	0.047 ± 0.00	0.999
30.	1.2	0.8	1.0	0.057 ± 0.00	0.997
31.	1.2	0.8	1.5	0.070 ± 0.00	0.976
32.	1.2	0.8	2.0	0.141 ± 0.00	0.999
33.	1.2	1.2	0.5	0.030 ± 0.00	0.992
34.	1.2	1.2	1.0	0.051 ± 0.00	0.997
35.	1.2	1.2	1.5	0.064± 0.00	0.994
36.	1.2	1.2	2.0	0.107 ± 0.00	0.983

coefficient (release rate) (h^{-1}), and T is the dissipation time(h).

It can be seen from Table 2 that the error values of the supersaturated TDG dissipation coefficient are relatively small, and the average correlation coefficient exceeds 0.99, which has certain practical significance. Among them, when the aeration rate increases from 0.5 m^3.h^{-1} to 2.0 m^3.h^{-1}, the average increment of the supersaturated TDG dissipation coefficient is 245.62%; when the aeration depth increases from 0.4 m to 1.2 m, the average reduction of the supersaturated TDG dissipation coefficient is 24.74%; and when the aeration aperture increases from 0.6 mm to 1.2 mm, the average reduction of the supersaturated TDG dissipation coefficient is 31.75%, which shows that effect on the supersaturated TDG is $K_{TDG,Q}$> $K_{TDG,D}$> $K_{TDG,H}$. Therefore, it is shown that the aeration rate can promote the release of supersaturated TDG, while the aeration depth and aeration aperture inhibit its dissipation.

Relationship Between $K_{TDG,Q}$ and Aeration Rate

According to the relevant research results of the effect of aeration on the re-oxygenation dissipation coefficient, the relationship between the re-oxygenation dissipation coefficient and aeration did not increase linearly (Mavinic et al. 1974, Cheng et al. 2013). The aeration rate is the first important factor, the reason analysis shows that the increasing

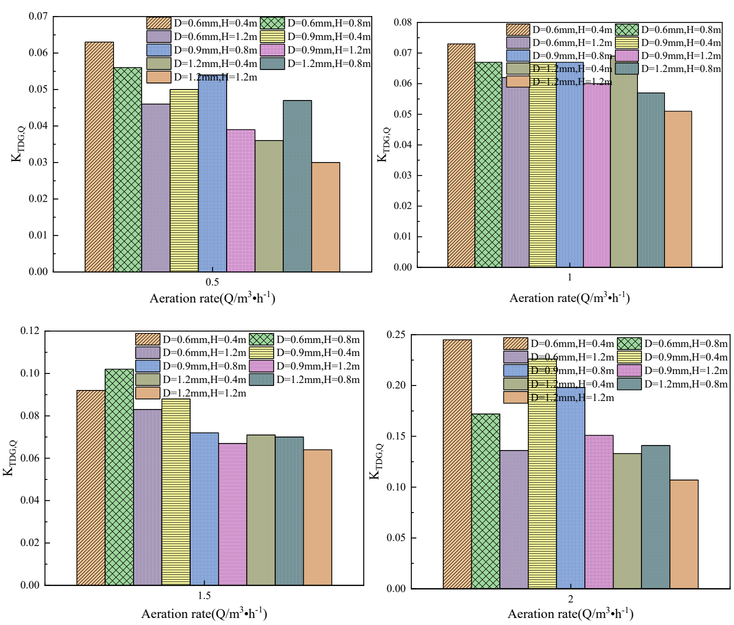

Fig. 3: Relationship between aeration rate and dissipation coefficient.

water depth leads to the weakening of the turbulent intensity of the water induced by bubbles, thus weakening the mass transfer effect of TDG at the water-air interface (Cheng et al. 2005, Huang et al. 2010). The aeration rate and dissipation coefficient are brought into the ORIGIN software to obtain Fig. 3 and the multivariate nonlinear regression analysis of SPSS to obtain the proportional relationship between the two as equation (2).

$$K_{TDG,Q} = 0.153(\frac{Q}{2.0})^{1.296} \quad ...(2)$$

where $K_{TDG,Q}$ is the dissipation coefficient (release rate) (h^{-1}), Q is the aeration rate (m^3/h).

Relationship Between $K_{TDG,D}$ and Aeration Aperture

Aeration aperture is the second important factor, the reason analysis shows that the increasing aeration aperture decreases the density of the bubble group in the water tank, which weakens the turbulence intensity of the water and the transfer effect of the gas-liquid interface (Cheng et al. 2014, 2015). The aeration aperture and dissipation coefficient are brought into the ORIGIN software to obtain Fig. 4, and the inverse relationship between the two is obtained in the multivariate nonlinear regression analysis of SPSS as equation (3).

$$K_{TDG,D} = 0.102(\frac{0.6}{D})^{0.395} \quad ...(3)$$

where $K_{TDG,D}$ is the dissipation coefficient (release rate) (h^{-1}), D is the aeration aperture(mm).

Relationship Between $K_{TDG,H}$ and Aeration Depth

Aeration depth is the third important factor; the reason for this is that the analysis shows that the increasing water depth leads to the weakening of the turbulent intensity of the water induced by bubbles, thus weakening the mass transfer effect of TDG at the water-air interface (Cheng et al. 2005, Huang et al. 2010). The aeration depth and dissipation coefficient are brought into the ORIGIN software to obtain Fig. 5 and the inverse relationship between the two is obtained in the multivariate nonlinear regression analysis of SPSS as equation (4).

$$K_{TDG,H} = 0.103(\frac{0.4}{H})^{0.249} \quad ...(4)$$

where $K_{TDG,H}$ is the dissipation coefficient (release rate) (h^{-1}), H is the aeration depth (m).

Relationship Between K_{TDG} and Q, D and H

In the process of an aeration experiment, the supersaturated

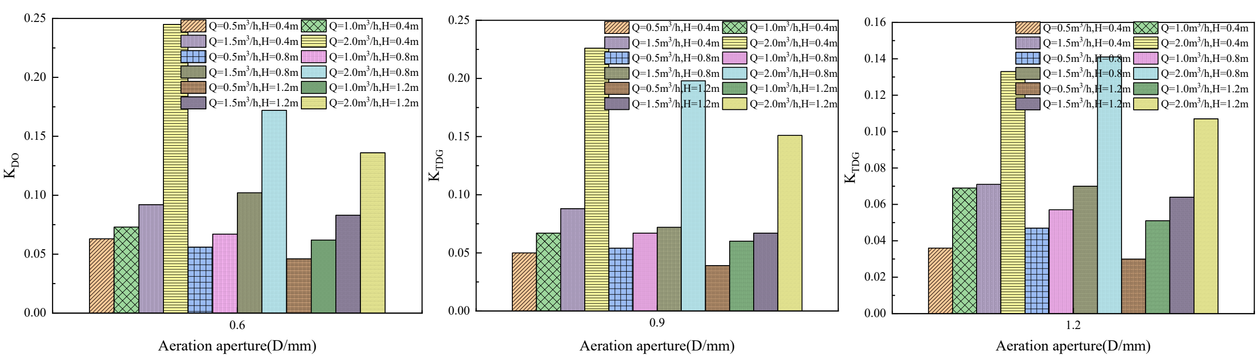

Fig. 4: Relationship between aeration aperture and dissipation coefficient.

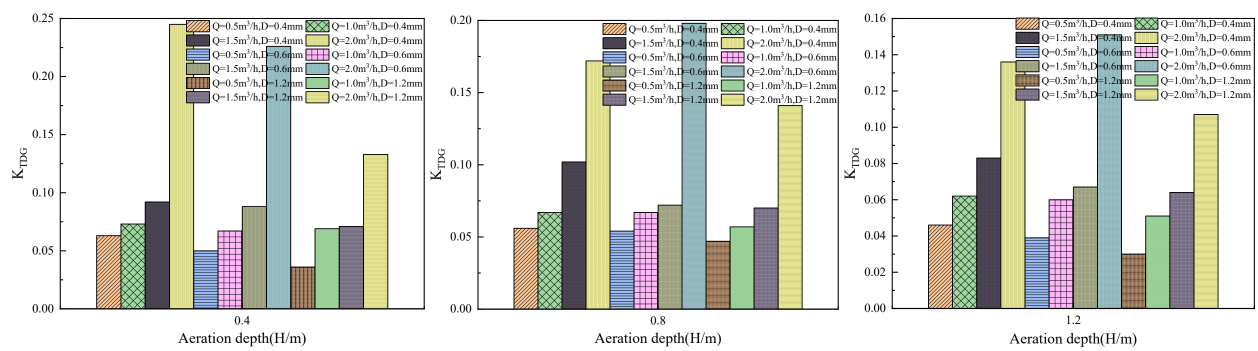

Fig. 5: Relationship between aeration depth and dissipation coefficient.

Table 3: Ranges of dissipation coefficients in the quantitative relationship.

Q_0	D_0	H_0	α	β_1	β_2	β_3
2.0	0.6	0.4	0.211	1.322	0.420	0.294

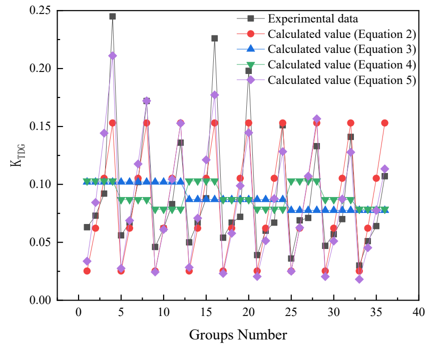

Fig. 6: Error between experimental data and calculated value

TDG release coefficient is mainly affected by the aeration rate, aeration aperture, and aeration depth. According to the specific tank size and experimental data, all the experimental values are brought into the multivariate nonlinear regression analysis of SPSS, and the quantitative relationship between TDG dissipation coefficient and initial value is shown in Table 3, and their relationship is obtained as equation (5).

$$K_{TDG} = \alpha\left(\frac{Q}{Q_0}\right)^{\beta_1}\left(\frac{D_0}{D}\right)^{\beta_2}\left(\frac{H_0}{H}\right)^{\beta_3} \rightarrow K_{TDG} = (0.211)\left(\frac{Q}{2.0}\right)^{1.322}\left(\frac{0.6}{D}\right)^{0.420}\left(\frac{0.4}{H}\right)^{0.294} \quad ...(5)$$

where K_{TDG} is the dissipation coefficient (release rate) (h^{-1}), Q is the aeration rate ($m^3.h^{-1}$), D is the aeration aperture (mm), H is the aeration aperture (m).

Errors Between Experimental Date and Calculated Values

Drawing on the former error analysis method (Cheng et al. 2015), the root mean square error (6) and the absolute average error (7) were used for error analysis to judge the availability of the equation. The error is obtained as shown in Fig. 6.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(a_i - b_i)^2}{n}} \quad ...(6)$$

$$AME = \frac{\sum_{i=1}^{n}|a_i - b_i|}{n} \quad ...(7)$$

For equation 2, the error of RMSE is 2.99% and AME is 2.25%, the error of RMSE is 5.12% and AME is 3.91% for equation 3, the error of RMSE is 5.12% and AME is 4.04% for equation 4 and the error of RMSE is 2.40% and AME is 1.97% for equation 5. Their errors are all within 10%. This shows that the quantitative relationship between the supersaturated TDG release coefficient and aeration rate, aeration aperture and aeration depth can reflect the effect of aeration on the release of supersaturated TDG, and has strong applicability in practical environmental application engineering.

DISCUSSION

(1) TDG dissipation is related to many factors, such as bubble area, turbulence intensity of the water body, temperature, and so on. Due to limited experimental conditions, the influence of these factors on TDG dissipation needs to be further studied in the next step.

(2) At present, aeration plays an obvious role in promoting the TDG dissipation process, and the influence relationship between aeration rate, aeration depth, and aeration aperture on release coefficient is preliminarily obtained as equation (5). However, the application of this equation requires further systematic experimental research and theoretical analysis, summarizes the evolution law of TDG dissipation, and establishes a more generally applicable quantitative relationship between the dissipation process and the aeration conditions.

(3) A natural water body is affected by water velocity, seasonal hydrological conditions, and complex geological structures. If the actual supersaturated TDG river basin is aerated, this will be disturbed by unknown problems. Aeration in local river basins may effectively mitigate the harm of supersaturated TDG.

CONCLUSION

Under aeration conditions, aeration can promote the dissipation of supersaturated TDG. The aeration rate is proportional to the dissipation coefficient of supersaturated TDG and promotes its release, while the aeration depth and aeration aperture are related to the dissipation coefficient of supersaturated TDG in an inversely proportional relationship and inhibit its dissipation, as well as affect the size of the dissipation coefficient of supersaturated TDG as $K_{TDG,Q} > K_{TDG,D} > K_{TDG,H}$. A quantitative relationship between the supersaturated TDG dissipation coefficient and the aeration rate, aeration aperture, and aeration depth, respectively, is obtained: $K_{TDG,Q} = 0.153(\frac{Q}{2.0})^{1.296}$, $K_{TDG,D} = 0.102(\frac{0.6}{D})^{0.395}$, $K_{TDG,H} = 0.103(\frac{0.4}{H})^{0.249}$ and the important expressions of the comprehensive effect factors: $K_{TDG} = (0.211)(\frac{Q}{2.0})^{1.322}(\frac{0.6}{D})^{0.420}(\frac{0.4}{H})^{0.294}$. Their errors are all within 10%.

Aeration is one of the important methods to mitigate the adverse effects of supersaturated TDG, and it has important guiding significance for exploring and mitigating the harm of supersaturated TDG.

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