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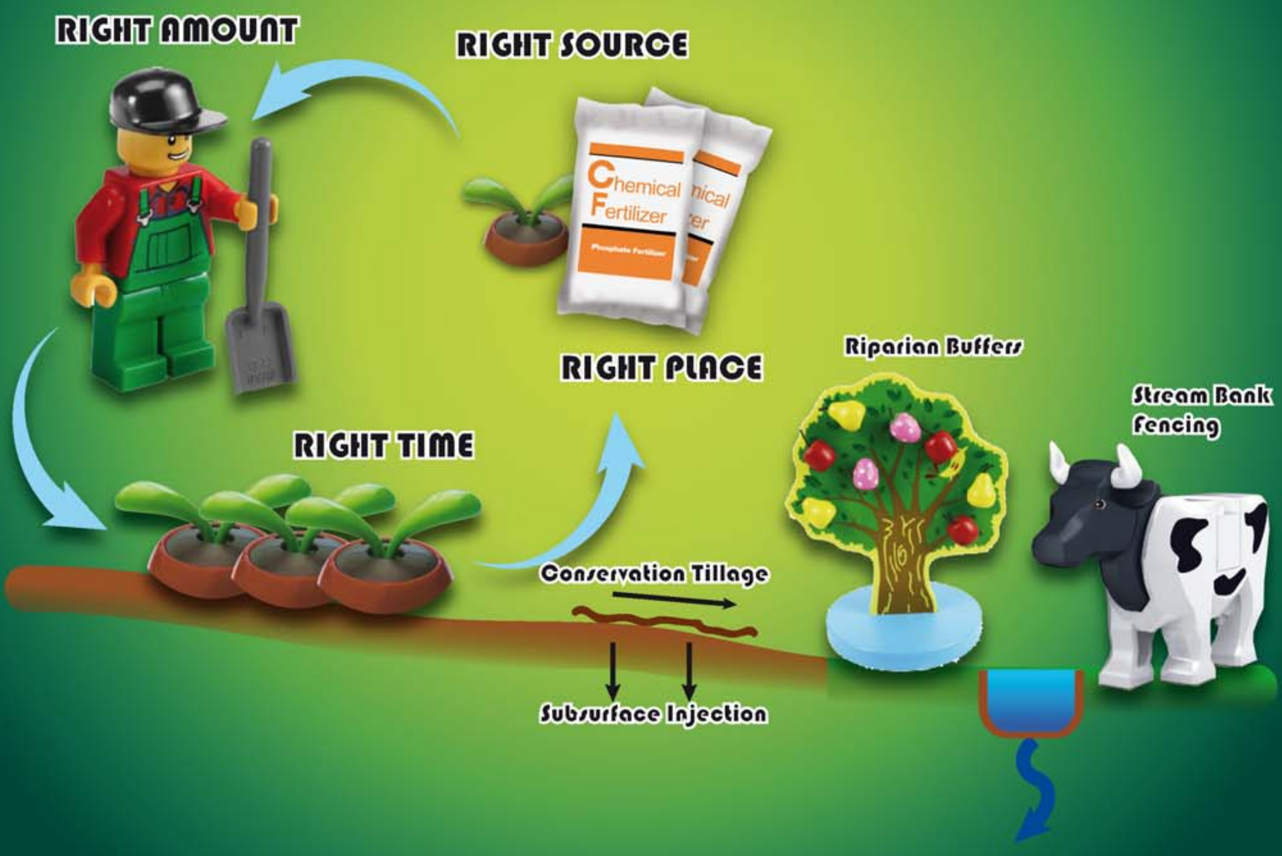

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Experimental study on the impact of temperature on the dissipation process of supersaturated total dissolved gas

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ABSTRACT

Water temperature not only affects the solubility of gas in water but can also be an important factor in the dissipation process of supersaturated total dissolved gas (TDG). The quantitative relationship between the dissipation process and temperature has not been previously described. This relationship affects the accurate evaluation of the dissipation process and the subsequent biological effects. This article experimentally investigates the impact of temperature on supersaturated TDG dissipation in static and turbulent conditions. The results show that the supersaturated TDG dissipation coefficient increases with the temperature and turbulence intensity. The quantitative relationship was verified by straight flume experiments. This study enhances our understanding of the dissipation of supersaturated TDG. Furthermore, it provides a scientific foundation for the accurate prediction of the dissipation process of supersaturated TDG in the downstream area and the negative impacts of high dam projects on aquatic ecosystems.

Introduction

High dam discharge can lead to total dissolved gas (TDG) supersaturation downstream of the dam and may cause fish to suffer from gas bubble trauma and even death (Weitkamp and Katz, 1980; Weitkamp et al., 2003). Many previous studies have focused on how the TDG dissipation process from supersaturation to saturation is associated with conditions such as water depth, turbulence characteristics, Reynolds number and sediment concentration (Jiang et al., 2008a; Qu, 2011; Feng, 2013; Li et al., 2013). However, there are few studies on the quantitative effects of the water temperature on the supersaturated TDG dissipation process. The construction of a hydropower project can change the water temperature in natural rivers and can consequently affect the generation and dissipation processes of supersaturated TDG. In recent years, many studies have been conducted to understand the water temperature structure in reservoirs and downstream river reaches (Lei et al., 2008; Lindim et al., 2011; Deng et al., 2011; Lee et al., 2013), which may contribute to a more comprehensive study on the development of the relationship between TDG and temperature.

Harvey (1967) observed a Canadian lake and found that the increased water temperature due to solar radiation could result in TDG supersaturation. Roesner and Norton (1971) considered the effects of temperature on the molecular diffusion coefficient and presented a physical model of TDG generation downstream of a dam. Demont and Miller (1972) reported that the total dissolved gas pressure over the atmospheric pressure was up to 400 mm Hg when warm wastewater was discharged from a factory to the ambient water. Bouck (1984) observed that the TDG pressure in water is different in different seasons. Krise and Smith (1993) and Mesa and Warren (1997) created supersaturated TDG water by mixing hot and cold water artificially. Jiang et al. (2008b) carried out field observations in the Minjiang River downstream of the Zipingpu Dam and showed that the water temperature affects TDG supersaturation. Feng et al. (2010) improved the dissipation model of supersaturated TDG according to observations in many rivers and laboratory experiments. Wang et al. (2010) concluded

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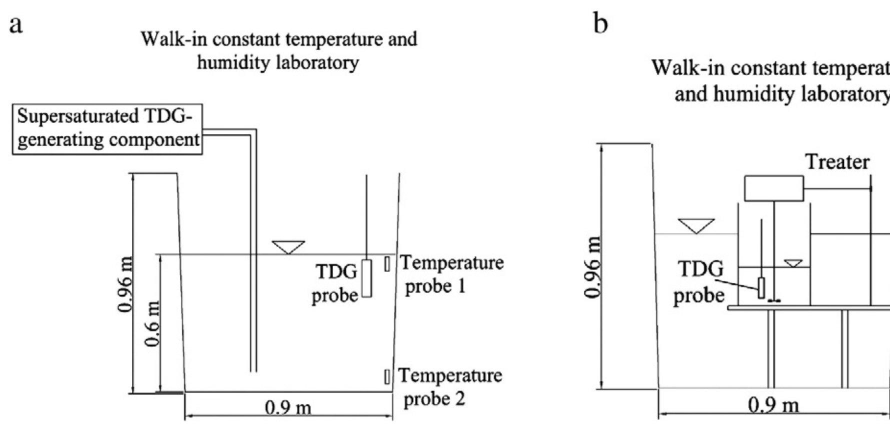

Fig. 1 – Sketch of the experimental apparatus in static water (a) and in stir-induced turbulent water (b). TDG: total dissolved gas.

that the TDG saturation in a river increases with rising temperature and that changes in supersaturated TDG lag behind changes in temperature.

Most of the prior research regarding mass transfer has primarily focused on the reaeration process of dissolved oxygen (DO). Bennett and Rathbun (1972) obtained a relationship between the reaeration coefficient and temperature. Zou et al. (2010) concluded that the oxygen mass transfer coefficient increases with increasing temperature.

Li et al. (2013) indicate that the dissipation process is quantitatively different from the reaeration process, and TDG behavior is quantitatively different from dissolved oxygen (DO). Therefore, it is necessary to carry out research on the quantitative relationship between TDG and temperature.

The present article will provide insight into the effects of temperature on the TDG supersaturation dissipation process based on the experimental results. The experiments were conducted in two types of conditions: static and turbulent. By the use of professional equipment, the TDG dissipation rate at different temperatures in each turbulent case was monitored, and the dissipation coefficients were obtained by data fitting. The results were verified by flume experiment.

1. Dissipation experiments

1.1. *Experiments in static water*

Experiments were conducted in a walk-in constant temperature and humidity laboratory. The experimental device includes a component that generates supersaturated TDG (Li et al., 2012) and a cylindrical water tank (900 mm in diameter and 960 mm in height). The experimental device is shown in Fig. 1a.

At the beginning of the experiment, supersaturated water with a specific temperature was generated with the TDG generation component and drained into the tank. The ambient air temperature was controlled at the specified temperatures for each case. The change in the supersaturated TDG saturation *versus* time was monitored using a PT4 Tracker sensor (Point Four Systems, Inc., Canada). The monitoring results showed that the maximum fluctuation amplitude of the water temperature was 0.7°C/day, and that the humidity was maintained at 45% relative humidity (RH).

The supersaturated TDG dissipation process under different temperatures is shown in Fig. 2. The supersaturated TDG dissipated very slowly in the static condition. The lower the temperature was, the slower the dissipation process was. Using first-order kinetics to fit the dissipation process (US EPA, 2009), the dissipation coefficient of the supersaturated TDG in each temperature case was obtained and is summarized in Table 1. As shown in Table 1 all of the correlation coefficients (R^2) were greater than 0.87, indicating the goodness of fit of the process with the first-order kinetic equation. The relationships between the dissipation coefficients and the corresponding temperatures in Table 1 are depicted in Fig. 3.

Table 1 and Fig. 2 show that the TDG dissipation coefficient in static water increased from 0.0065 to 0.0254 hr^{-1} when the

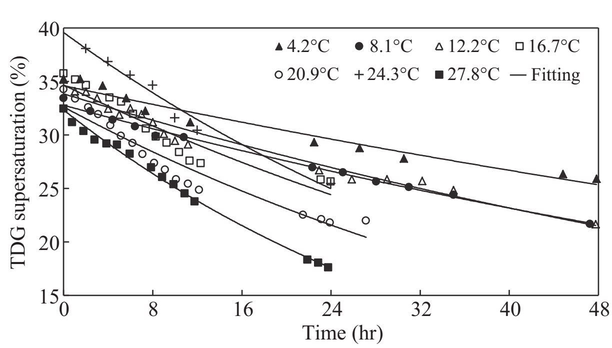

Fig. 2 – TDG dissipation processes and fitting curves at different monitored water temperatures in the static condition.

Table 1 – Dissipation coefficients of supersaturated TDG (total dissolved gas) in static water.

Case number	Temperature* (°C)	Dissipation coefficient (K, hr^{-1})	Correlation coefficient (R^2)
1	4.2	0.0065	0.9638
2	8.1	0.0087	0.9362
3	12.2	0.0095	0.8948
4	16.7	0.0146	0.8775
5	20.9	0.0188	0.9249
6	24.3	0.0192	0.9789
7	27.8	0.0254	0.9962

* Average water temperature monitored in each case.

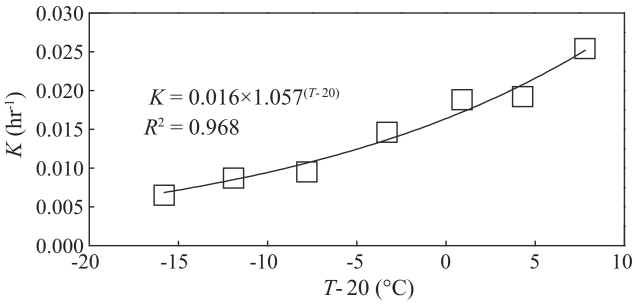

Fig. 3 – TDG dissipation coefficient (*K*) *versus* temperature in the static condition.

temperature increased from 4.2 to 27.8°C. The mass transfer process of the gas–liquid interface is dominated by the gas molecular diffusion coefficient in static water, and this process is closely associated with the temperature (Ma et al., 1996). As the temperature increases, the kinetic energy of molecules increases, resulting in an increased diffusion rate and a dissipation process of supersaturated TDG.

A prior study showed that the relationship between the reaeration coefficient (K_{DO}) and temperature (T, °C) follows an exponential function (Bennett and Rathbun, 1972):

$$K_{DO} = K_{DO(20)} \times 1.024^{(T-20)}. \quad (1)$$

According to the form of Eq. (1), a similar exponential function is assumed for the dissipation coefficient:

$$K = K_{20}\theta^{(T-20)} \quad (2)$$

where, K (hr^{-1}) represents the dissipation coefficient at temperature T, K_{20} (hr^{-1}) is the dissipation coefficient at 20°C, and θ denotes the temperature coefficient. Based on the experimental results in Table 1, a multiple regression for Eq. (2) was conducted, and K_{20} (0.016 hr^{-1}) and θ (1.057) were obtained, as shown in Fig. 3.

Table 2 – Dissipation coefficients of supersaturated TDG in turbulent conditions.

Mixing speed (r/min)	K_{20} (hr^{-1})	θ	R^2
750	2.088	1.066	0.984
900	2.803	1.057	0.979
1000	3.423	1.066	0.994
1200	4.342	1.057	0.980
1250	4.944	1.061	0.994
1500	9.525	1.061	0.993

1.2. *Experiments in stir-induced turbulent water*

Experiments were conducted in the walk-in constant temperature and humidity laboratory. The experimental device includes the supersaturated TDG-generating component (Li et al., 2012), an experimental water tank with a 0.28 m inside diameter, and an electrical stirrer (the rotational speed can be adjusted from 0 to 1500 r/min). The experimental water container was immersed in a larger water tank for a constant temperature bath. The experimental device is shown in Fig. 1b.

First, supersaturated water with a specific temperature was generated with the supersaturated TDG-generating component and drained into the tank. The stirrer was then started at a fixed speed. The change in the supersaturated TDG saturation *versus* time was monitored using a PT4 Tracker sensor. For each temperature case, the following six different revolution speeds were tested: 750, 900, 1000, 1200, 1250, and 1500 r/min.

Supersaturated TDG was released more quickly in turbulent water than that in static water. The measured time evolution of supersaturated TDG is shown in Fig. 4. The first-order kinetic fitting method was employed for each process. The experimental results show that the dissipation process of supersaturated TDG accelerates as the temperature and turbulence intensity increase.

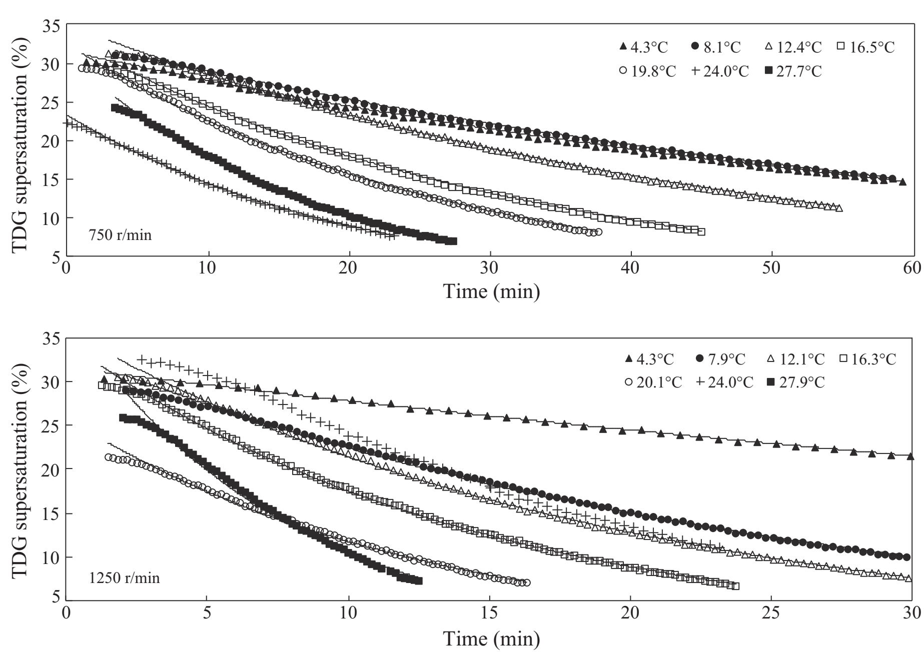

Fig. 4 – TDG dissipation processes and fitting curves at different monitored water temperatures in turbulent conditions.

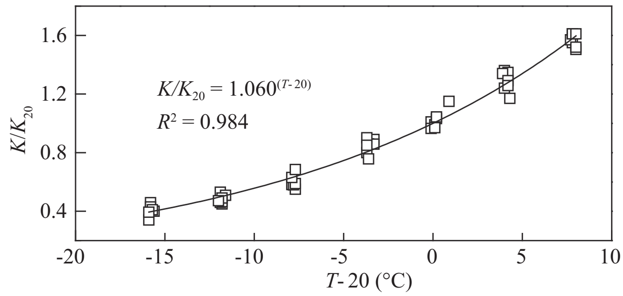

Fig. 5 – Relationship between K/K_{20} and temperature.

On the basis of Eq. (2), the same analysis procedure as in the static experiment was adopted for each turbulent condition and the results are shown in Table 2. K_{20} (hr^{-1}), increases obviously with the increasing turbulence intensity, whereas the temperature coefficients θ, which indicate the temperature effects for different conditions, are very close and vary from 1.057 to 1.066. This result implies that one constant value for the temperature coefficient may be found.

2. Relationship analysis between the dissipation coefficient and temperature

The universal relationship between the dissipation coefficient and temperature can be determined through a comprehensive analysis of the experimental results both in static and turbulent water.

By dimensional analysis, Eq. (2) can be rewritten as follows:

$$K/K_{20} = \theta^{(T-20)}. \tag{3}$$

According to the results of the dissipation coefficients both in static and turbulent conditions, the regression between K/K_{20} and water temperature is illustrated in Fig. 5. The value of parameter θ is 1.060. Thus, the expression for the dissipation coefficient as a function of temperature can be written as follows:

$$K = K_{20} \times 1.060^{(T-20)}. \tag{4}$$

In 90% of experimental cases, the curve fitting error from the experimental data was less than 10%, whereas that of the other cases was within 15%. This result affirmed that the relationship between the supersaturated TDG dissipation coefficient and water temperature is reasonable.

3. Verification of the relationship in a straight flume

Liu (2013) conducted an experimental study on supersaturated TDG dissipation in a straight flume at different temperatures (Table 3). Liu found that the dissipation coefficient in a straight flume at 20°C (K_{20}) in the experimental flume was 3.7 hr^{-1}. By introducing the dissipation coefficient K_{20} of the flume 3.7 hr^{-1}, into Eq. (4), the theoretical dissipation coefficient at various experimental temperatures can be computed, as listed in Table 3. The relative errors between the calculated and measured results ranged from −5.9% to 9.5%. The result shows that the relationship between the dissipation coefficient and the water temperature has good applicability.

4. Conclusions

This article carried out an experimental study on the impact of temperature on supersaturated TDG dissipation in static and turbulent conditions. The experimental results show that the supersaturated TDG dissipation coefficient increases with the temperature and turbulence intensity. According to the experimental results, the quantitative relationship between the dissipation coefficient of supersaturated TDG and water temperature was developed and verified with straight flume experiments. The description of this relationship can provide an important scientific basis for the prediction of the dissipation process of supersaturated TDG at different water temperatures.

Acknowledgments

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Table 3 – Comparison between the calculated and measured dissipation coefficients in the flume.

Case number *	Temperature (°C) *	Discharge flow (L/sec) *	$K_{measured}$ (hr^{-1}) *	$K_{calculated}$ (hr^{-1}) *	Relative error (%)
1	15.4	0.452	2.67	2.83	−5.9
2	15.8	0.440	2.92	2.89	1.2
3	20.4	0.419	3.54	3.78	−6.8
4	20.3	0.437	3.67	3.76	−2.5
5	23.1	0.466	4.93	4.46	9.5
6	24.1	0.442	5.00	4.72	5.5
7	26.8	0.439	5.34	5.53	−3.5
8	27.9	0.462	5.69	5.94	−4.3

* Data were cited from the literature of Liu (2013).

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