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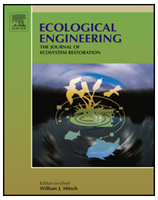

Relationship investigation between the dissipation process of supersaturated total dissolved gas and wind effect

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ABSTRACT

The elevated supersaturation of total dissolved gas (TDG) downstream of high-dam spills may lead to gas bubble disease or mortality in fish. Wind velocity is an important factor in accelerating the dissipation process of TDG. The accurate simulation and assessment of the dissipation process of supersaturated TDG are hampered by the scarcity of a quantitative description of the wind effect on the TDG dissipation process. The wind-driven experiments in this paper quantified the dissipation coefficients of supersaturated TDG under different wind velocities. A dimensionless ratio number, r, which represents the ratio between the dissipation coefficient with wind, K_w, and the coefficient without wind, K_0, was introduced. A formula was developed to quantify the relationship between the dimensionless ratio number r and the wind velocity. The quantitative relationship was applied in a three-dimensional simulation to investigate the transportation and dissipation process of TDG in the wind-driven flow. The eddies generated by the wind-driven flow, which greatly contributed to the dissipation of TDG, and the spatial and temporal evolution of supersaturated TDG were obtained and were in good accordance with the measured data. The investigation provides a quantitative basis for the accurate prediction of the dissipation process of supersaturated TDG at different wind velocities.

1. Introduction

Hydropower is a kind of renewable energy sources, but it may cause many negative impacts on river ecosystem, such as habitat fragmentation, ecological degradation et al. (Cai et al., 2011; Yang et al., 2015). In past decades, much more extensive attention has been paid to supersaturated total dissolved gas (TDG) problems caused by high dam discharge, which may cause fish to suffer from gas bubble trauma and even die (Weitkamp and Katz, 1980; Weitkamp et al., 2003). Therefore, accelerate simulation and quantitative assessment of the dissipation process of supersaturated TDG is a critical step in the exploration of mitigation measures. The dissipation process of supersaturated TDG has been studied for many years. Roesner and Norton (1971) first proposed a physical-based model of TDG transportation in a stilling basin. They also found that the variation of the TDG level was controlled by the mass transfer coefficient and the residence time of the bubbles in the stilling basin. Picktt et al. (2004) proposed a longitudinal model to predict the TDG dissipation process along the river far from the spillway by combining field observations with the first-order kinetics theory. Orlins and Gulliver (2000) predicted the TDG concentration within 300 m downstream of a dam by developing a two-dimensional, laterally averaged model with convection, and turbulent diffusion through bubbles and the free surface were incorporated into the mass transport. Politano and Carrica (2003); Politano et al. (2007, 2009, 2012) simulated the TDG transport process with a two--phase flow model, and used a bubble density transport equation to predict the bubble size. However, the mass transfer across the air-water interface was neglected. Fu et al. (2010) used an unsteady three-dimensional, two-phase model to simulate TDG transport 3 km downstream. In this model, the source term in the TDG transport equation was expressed as the mass transfer through both the bubble-liquid interface and the air-water surface. A bulk dissipation coefficient was suitable to represent the overall effects of the processes integrated over the river cross-section. Depending on the river velocity, the water depth and the molecular diffusion, the U.S Army Corps of Engineers (USACE, 2005) proposed a predictive formula for the dissipation coefficient by combining field observations from the Columbia River with first-order kinetics. In this regard, Feng et al. (2014) proposed a formula, involving the effects of water depth, friction velocity, hydraulic radius and Froude number, for estimating the dissipation coeffi-

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cient of supersaturated TDG. In addition to these studies, many previous studies have focused on how the TDG dissipation process from supersaturation to saturation is associated with various conditions, such as water depth, turbulence characteristics, the Reynolds number, sediment concentration and water temperature (Jiang et al., 2008; Qu, 2011; Feng, 2013; Shen et al., 2014). However, no research has reported on the quantitative effects of wind velocity regarding the supersaturated TDG dissipation process.

As previously mentioned, most studies of the supersaturated TDG dissipation process are confined to watercourse conditions. The effect of wind is ignored in these models. However, in some slow-flowing water, such as reservoirs or lakes, wind may be an important factor that significantly affects the mass transfer process in the field. There are several formulations used to calculate the gas-liquid transfer rate, such as Gualtieri et al. (2002) developed a dimensionless equation for the mass-transfer rate, based on dimensional analysis. However, the most common ones are the two film theory (Whitman, 1923) and the surface renewal theory (Higbie, 1935; Danckwerts, 1953). O'Connor (1983) determined the relationship between the mass transfer coefficient and the wind velocity based on the theory of the liquid film and surface renewal concepts. Oxygen mass transfer coefficient enhancement due to wind speed at the air-wind interface was also proposed. This function considered the Schmidt number (*Sc*), the Reynolds number (*Re*), and the Weber number (*We*). Wanninkhof (1992) proposed a general formulation for the oxygen mass transfer coefficient as a function of mass transfer due to physical absorption and mass transfer enhancement due to the wind speed. Chu and Jirka (2003) determined the relationship of the transfer velocity, the reaeration coefficient and the wind shear velocity through experiments. According to Banks (1975) and Wanninkhof (1992), wind speed is also a parameter describing the transfer mechanism in static water. Most of these studies focused on the unsaturated dissolved oxygen transfer effect rather than supersaturated TDG. However, Li et al. (2013) proposed that the dissipation process is different between dissolved oxygen and TDG. Therefore, it is necessary to conduct research on the quantitative relationship between the dissipation process of supersaturated TDG and wind velocity.

Research on the numerical simulation of wind-driven flow began early. Ralph et al. (1976) presented three large, primary, numerical models of large-scale, wind-driven circulation in lakes: the layered models, the Ekman-type models, and the other three-dimensional models. Müsteyde and Roger (2004) developed a three-dimensional wind-driven flow model using the unsteady Reynolds-Averaged Navier-Stokes equations, in which the non-hydrostatic pressure distribution was included. Mohammad and Saeed-Reza (2010) described a low time consumption numerical modeling technique to solve a wind-induced flow problem in a basin with deep water surrounded by shallow water parts using coupled two- and three-dimensional flow solvers.

These previous studies show that the effect of wind on supersaturated TDG dissipation has not been quantitatively investigated. The current paper provides insight into the effects of wind velocity on the TDG supersaturation dissipation process based on experimental results and a numerical simulation.

2. Experiments description

2.1. Experimental devices

The experiments were conducted at the State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, China (SKLH). The experimental devices included a wind-generation system and a Plexiglas experimental water tank. The wind-generation system consisted of an air blower and a wind duct; the wind duct included a gradually enlarged section with a length of 0.8 m and a straight section with a length of 2.2 m. The dimensions of the water tank were 0.7 m × 0.6 m × 0.6 m. To keep the water temperature constant during the experiments, the experimental water tank was immerged in a cylindrical water-bath tank. The experimental devices are shown in Fig. 1.

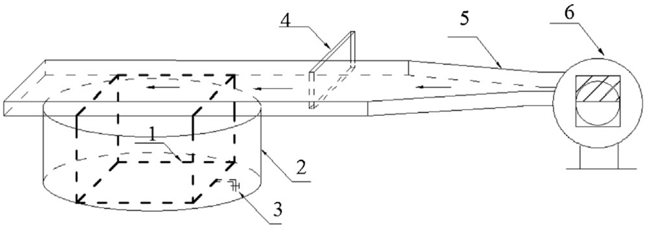

Fig. 1. Sketch of the experimental devices.

2.2. Experimental procedure and measuring method

At the beginning of the experiments, supersaturated water was generated by a TDG generation device (Li et al., 2012) and was added to the water tank, the water depth was 0.59 m. Wind was generated by the air blower. The wind velocity and distribution near the water surface were adjusted by controlling the height of the plastic flap inside the wind duct and the valve of the air blower. The water temperature inside the experimental water tank was maintained at 20 °C using a water bath.

Wind velocities were monitored by a hot-wire anemometer (TES-1341, Tes Electrical Electronic Corp., Taiwan). The measuring range of the wind velocity is 0–30 m/s, with an accuracy of 1%. Two measuring points for wind velocity were set at 0.1 m and 0.3 m from the side wall of the water duct. The average value of the two measured points, $W_{0.1}$ and $W_{0.3}$, was adopted to represent the experimental wind velocity for each case. All probes were kept 5 cm from the water surface.

The TDG saturation level was measured using a total dissolved gas pressure (TGP) detector by a PT4 Tracker sensor (Point Four Systems, Inc., Canada). The measuring range of the TDG is 0–200% of saturation, with an accuracy of 1%. Two measuring points for TDG were set near the water surface and the bottom of the tank, respectively.

The temperature was monitored by a temperature sensor (L93-22, Hangzhou Loggertech Co. Ltd, China). The measuring range of temperature is −40 to 100 °C, with an accuracy of 0.2 °C.

Experimental cases were designed with different wind velocities, as listed in Table 1.

2.3. Experimental results and analyses

During the experiments, the water became turbulent due to the wind action. There were waves induced on the free surface of water when the wind was large. The wind-driven circulation appears owing to the influence of the tank boundary. The dissipation process of supersaturated TDG, indicated by the average value of the two measuring points, for each specific wind velocity case is shown in Fig. 2.

The dissipation process of TDG follows the first-order kinetics theory, as shown by Eq. (1) (University of Washington, 2000). Using the curve fitting method, the dissipation coefficient of the supersaturated TDG in each experimental case was obtained and is summarized in Table 1. All correlation coefficients (R^2) are larger