A Review of Mass Transfer Model of Supersaturation Total Dissolved Gas Downstream at High Dam

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Abstract: The total dissolved gas (TDG) supersaturation observed in a spillway that flows downstream various hydraulic structures has long been recognized as having a negative environmental effect on fish and aquatic organisms. This paper focuses on learning the mass transfer of supersaturation total dissolved gas downstream and the rule of mass transfer between air-water interfaces. Besides, the three main coefficients of mass transfer are concluded: the surface mass transfer coefficient, the bubble interface mass transfer coefficient, and the dissipation coefficient and relevant transport process model. These can provide a foundation to analyze the supersaturation of high dam in near future.

1. Introduction

According to the thirteenth Five-Year Plan for Hydropower Development released by National Energy Administration, it’s about 500 billion yuan to make a hydropower investment in China. At present, the important energy that meets one-fifth Chinese electricity demand is hydropower. With the development and construction of high dams, the downstream aquatic ecological environment can have severe crisis. It should be noted that specific fishes may suffer from gas bubble trauma (GBT) within 105%-110%. Moreover, fish will die quickly in a short time when the TDG saturation exceeds 130% [1]. There have been large-scale fish deaths caused by TDG supersaturation in the downstream of the Chinese Three Gorges dam and Xiluodu dam, as well as USA, Canada and other countries. As a result, the U.S. Environmental Protection Agency (USEPA) proposed the limit of TDG saturation is 110% based on laboratory experiments [2]. The limit of TDG saturation by far is not clearly in China, at the same time, there are many high dam projects in the southwestern China, where it’s the upper reach of the Yangtze River and the rare fish habitat. However, when the high dam with high head, large flow rate and strong aeration is discharged, a large number of bubbles will be generated at the plunge pool surface, and flow to some depth of the downstream, it’s the supersaturation phenomenon that the static pressure is continuously increasing due to the dissolved aeration [3].

There are two main ways to alleviate the problem of supersaturation influence TDG in high dams:

1. Reducing the generation of supersaturation TDG near dam area;
2. Accelerating the release of supersaturation TDG on downstream.

Supersaturation TDG flows into the river then not immediately precipitation and be transported quite far away in the downstream, which shows that a typical two-phase flow caused by strong turbulence. So the supersaturation downstream problem and the mass transfer process are closely related. This paper focuses on learning the mass transfer of supersaturation total dissolved gas downstream and the rule of mass transfer between air-water interfaces, then summing the mass transfer law and proposing measures to ease the supersaturated problem.
2. Research of mass transfer model of Supersaturation TDG

2.1 Mass transfer coefficient of supersaturation TDG during the generation

The mass transfer generation process of TDG supersaturation can be divided into two parts [4]:

(1) The water flow meets the air completely when it passes through the dam, and the gas constantly enters the water through the atmosphere liquid film;

(2) The water flow collides with the downstream water body, it can make abundant air drawn into the water body, then increase air content in the water body.

Generally, the mass transfer in the plunge is mainly through bubbles, while the surface mass transfer is the major part after the plunge pool [5].

2.1.1 Mass transfer rate coefficient across the air-water interface

Lamont carried out the laboratory for the water aeration properties in turbulent pipelines, and calculated the mass transfer coefficient by the small eddy model, it can express as [6]:

$$K_{L,s} = \beta_1 S_c^{-1/2} \left( \frac{v \epsilon}{\nu} \right)^{1/4}$$

(1)

where $S_c$ is Schmitt number and equal to $\nu / \Delta m$; $\epsilon$ is the rate of energy dissipate.

However, the rate of energy dissipate $\epsilon$ and turbulent energy $k$ are microscopic scalars, so it’s difficult to calculate. O’Connor chose a specific variable. He held the view that wind could drive the mass transfer, which can be written as [7]:

$$K_{L,s} = -0.0045 \nu_c^3 + 0.1535 \nu_u^2 + 0.6885$$

(2)

where $\nu_u$ is characteristic wind speed.

Chinese scholars also put forward mass transfer formula applying to the dams in China. Cheng [8-9] proposed the relationship of turbulence and mass transfer coefficient based on turbulence re-aeration theory and Fick’s law.

$$K_{L,s} = 0.002436 \nu^{-5/3} k^{4/3}$$

(3)

where $k$ is turbulent energy, $\nu$ is flow rate.

Later, many scholars concluded different formulas for surface mass transfer coefficient based on varied experiments [10-12]. However, the downstream water depth increases to some value, the surface mass transfer accounts for a very small part of the whole part [13]. Geldert [14] observed two different dams and summed the calculation of surface mass transfer rate is applicable to shallow water, which can generate greatly fluctuation and aeration. So depth is larger, the surface mass transfer can be neglected.

2.1.2 Air bubble-water interface transfer coefficient

The main theories for calculating the mass transfer coefficient are: two-film theory, Percolation theory, and surface renewal theory. However, most calculations are not consistent with the measured data, so the mass transfer coefficients are calculated by semi-empirical formulas.

Levich [15] proposed the expression of gas-liquid mass transfer flux for single bubble, but it’s not effective to calculate single bubble due to the large amount of aeration in high dams. Azbel [16] assumed that the bubbles in the turbulent flow were uniformly distributed, and chose the characteristic velocity and length of bubble groups in the eddy field for calculation. Geldert [14] combined with the preceding literatures, proposed the air bubble-water interface transfer coefficient $K_{L,B}$:

$$K_{L,B} = \beta_1 D_{m} \left( \frac{1-\phi}{1-\phi^{4/3}} \right)^{1/4} \frac{S_c^{1/2}}{Re^2}$$

(4)

where $Re$ is Reynolds number, $D_m$ is diffusivity of a gas in a liquid, $\phi$ is the gas void ratio, $h$ is depth, $S_c$ is Schmitt number.
Weber [17] proposed that the mass transfer coefficient is a function of aeration based on the research of proceeding literatures[14-16], can be expressed as:

\[ K_{L,a} = \frac{\beta}{h} \frac{D_m}{h} \left(1 - \frac{\phi}{\phi^{5/3}}\right)^{0.5} \frac{Re^{0.66} Sc^{0.5} \phi^{2/3}}{1 + 0.25 \phi^{5/3}} \]  

(5)

where Re is Reynolds number, \( D_m \) is diffusivity of a gas in a liquid, \( \phi \) is the gas void ratio, \( h \) is depth, \( Sc \) is Schmitt number.

Takemura [18] carried out characteristic analysis of bubble groups including bubble size and bubble rising speed, and obtained the expression of Sherwood number in the condition that the Reynold number was less than 100 and the Peclet number was greater than 1.

\[ \frac{Sh}{Pe^{1/2}} = \frac{2}{\sqrt{\pi}} \left[ 1 - \frac{2}{3} \left(1 + 0.09 Re^{2/3}\right)^{3/4} \right] \]  

(6)

where Re is Reynolds number, \( Pe \) is Peclet number, \( Sh \) is Sherwood number.

Combing with Sherwood number and mass transfer coefficient: \( Sh = \frac{k_\tau \delta}{D_m} \), Cheng [8] proposed the mass transfer coefficient can also be written as:

\[ K_{L,b} = \frac{D_m}{R \sqrt{\pi}} \left[ 1 - \frac{2}{3} \left(1 + 0.09 Re^{2/3}\right)^{3/4} \right] Pe^{1/2} \]  

(7)

where Re is Reynolds number, \( D_m \) is diffusivity of a gas in a liquid, \( Pe \) is Peclet number, \( R \) is air bubble diameter.

2.2 Study on the dissipation coefficient and relevant transport model

The proceeding literature are limited to study on the plunge pool area [19], however, the supersaturation TDG could last until downstream, where the surface mass transfer is dominant during releasing process. Therefore, it is also important to study the TDG release process.

Pickett [20] proposed a prediction model for the longitudinal TDG release process farther downstream. This model considered the influence of flow rate and water depth, and assumed that the TDG release process followed the first-order kinetic equation, and thought that the molecular diffusion was a key parameter in the release process.

The US Army Corps of Engineers [21] proposed that the TDG downstream release process followed a first-order dynamic equation, which can be written as:

\[ \frac{d(G - G_0)}{dt} = k_\tau \left(G_0 - G_{eq}\right) \]  

(8)

where \( G \) is the percent saturation of TDG at time \( t \), \( G_{eq} \) is the equilibrium percent saturation of TDG and is assumed to be 100%, and \( k_\tau \) is the dissipation coefficient.

Feng [22] corrected above release coefficient, considered that the western of China mountainous rivers, flow velocity, turbulence effect is obvious, so it’s necessary to consider the turbulence besides the diffusion effect. So the coefficient can be expressed as:

\[ k_\tau = 3600 \frac{k_\tau v}{H} \]  

(9)

where \( H \) is depth, \( k_\tau \) is the dissipation coefficient, \( v \) is flow rate.

Fu [23-24] took the downstream Chinese sturgeons of Gezhouba dam as the research object, and
simulated the TDG transport process at 3000 meters downstream by two-phase model. The source term of the formula is the bubble interface mass transfer and surface, and the bubble velocity and the turbulent kinetic energy are the influencing factors of the surface mass transfer coefficient. Feng [25] obtained that the release coefficient of supersaturation TDG is related to flow velocity, water depth and turbulence, and the solid wall will also have an effect, so the expression can be written as:

\[ k_T = 3600\phi \frac{u^* H^m}{R^2} Fr^n \]  

where \((H/R)\) is the correction factor due to the influence of the wall, \(H\) is the depth of water, and \(m, n\) and \(\phi\) are dimensionless constants that can be fitted from field and experimental results.

3. Conclusion
Overall, with the completion and operation of large-scale hydroelectric project, the supersaturation TDG problem is extremely urgent, which often shows that high saturation TDG, the slow releasing process, notably accumulated effects, but the current research is far from demand. Most researchers started with the supersaturated phenomenon. This paper analyzed the supersaturated generation and releasing mechanism, which revealed the bubbles and interfacial mass transfer effect of supersaturated TDG generation process, thus, it has a further research and summary, which can provide a solution for the environment problem at high dams in near future.

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