Mecánica Computacional Vol. XXIV
A. Larreteguy (Editor)
Buenos Aires, Argentina, Noviembre 2005

PREDICTION OF TOTAL DISSOLVED GAS DOWNSTREAM OF SPILLWAYS USING A MULTIDIMENSIONAL TWO-PHASE FLOW MODEL

Marcela Politano, Pablo Carrica and Larry Weber

IIHR - Hydroscience & Engineering
The University of Iowa,
300 South Riverside Dr., Iowa City, IA 52242, USA
e-mail: marcela-politano@uiowa.edu

Key words: Total dissolved gas, Air dissolution, Gas bubble disease, Two-phase flow, Bubbles, Dams.

Abstract. *Elevated supersaturation of total dissolved gas concentration in water (TDG), which may cause gas bubble disease in fish, constitutes an important negative environmental effect of dams. Spillway discharges at hydropower dams are the main source for TDG supersaturation in the Columbia and Snake basins in the Northwest USA.*

The most important source for the TDG is the gas transferred from the bubbles, therefore a proper model for TDG prediction must account for the two-phase flow generated in the stilling basin. Most of the numerical studies on TDG downstream of spillways found in the literature are based on experimental correlations for the gas volume fraction. A better approach involves the use of a multiphase flow model that rely less on empirical information. In this work, an algebraic slip mixture model that accounts for the drag and turbulent dispersion forces and employs the modified $k-\varepsilon$ *model for the turbulence is used to calculate the gas volume fraction and velocity of the bubbles. A bubble number density transport equation is implemented to predict the bubble size, which can change due to bubble/liquid mass transfer and pressure. The TDG is calculated with a two-phase transport equation whose source is the bubble/liquid mass transfer which is a function of the gas volume fraction and bubble size.*

The equations of the proposed model were implemented into the commercial code FLUENT using the available multiphase flow algorithm based on the finite-volume method. The multidimensional fields of TDG, gas volume fraction, bubble sizes and velocities of the bubbles are presented and discussed. Quantitative agreements between the numerical results and field data for the TDG in the stilling basin of Wanapum Dam on the Columbia River are obtained.

1 INTRODUCTION

High total dissolved gas (TDG) concentrations may cause gas bubble disease (GBD) in fish. The effects of GBD include hemorrhages, tissue necrosis, emphysema and circulatory emboli[1,2].

Spillway discharges at hydropower dams are the main source of TDG in the rivers of the Pacific Northwest. During the spring runoff season, hydropower operators are forced to spill large volumes of water, causing the TDG levels to increase, frequently above the 110 % limit imposed by the EPA[3]. Other spill releases may occur due to maintenance, lack of energy market or voluntary spill aimed at passage of juvenile salmonids.

The flow downstream of a spillway is a complex two-phase flow. The main source of TDG is the gas transferred from bubbles to the water. These bubbles could be entrained along the spillway face (pre-entrainment) or when the liquid jet impacts the tail water pool (entrainment). At high pressures the bubbles transfer air to the water increasing the TDG and supersaturating the water of atmospheric gases[4]. When the water with high TDG concentration reaches shallower locations the dissolved gas is released from the water, if interfacial area is available from existing bubbles or through the interface. Fish swimming through areas of high pressure and elevated TDG levels will experience a similar release of TDG and bubble formation if they later swim to areas of reduced ambient pressure, and hence, suffer GBD. To reduce the level of TDG supersaturation several dams were retrofitted with spillway deflectors that prevent bubbles from reaching too deep in the stilling basin[5].

Several studies had been conducted in the past to predict TDG downstream of a spillway; most of them based on experimental test programs[5,6]. This approach had been reasonably effective, however can be expensive and time-consuming requiring qualitative laboratory model testing and subsequent field prototype testing. Earlier analytical work used a material control volume approach to calculate the downstream concentration for the Columbia River dams[7,8] and at four Bureau of Reclamation spillways[7]. This approach cannot be used to calculate a multidimensional TDG distribution and, thus, the model is unable to predict the most dangerous regions for the fish and cannot be used to evaluate spillway designs to reduce the supersaturation. In a later work, the 2D TDG field downstream of a spillway was calculated using the hydrodynamic data of a physical model and an exponential function for the gas volume fraction[6].

Numerical models to predict the TDG distribution and hydrodynamics downstream of spillways have been developed at IIHR[9], including the first two-phase mechanistic models on the literature[10,11]. The liquid field was predicted through the solution of the RANS equations assuming no influence of the bubble field on the liquid field (one-way coupling), which is a reasonable hypothesis for low gas volume fraction as found downstream of spillways. In the earlier work a monodisperse flow (single-size bubbles) and a exponential function for the gas volume fraction was used[9]. In a later research, the gas volume fraction and velocity of the bubbles were predicted using a two-fluid model with a $k-w$ model for the liquid turbulence[10]. The velocity of the bubbles was calculated with a single law considering a gravity dominated flow and neglecting other interfacial forces different than the drag force.

The mass transfer from the bubbles to the liquid, function of the velocity and size of the bubbles, was calculated using validated correlations. In this effort, one variable bubble size (monodisperse flow), which may change due to local bubble/water mass transfer and pressure, was used. The bubble size was determined by means of a bubble number density transport equation considering that the breakup and coalescence of the bubbles are negligible. Due to the lack of experimental data for the bubble size and gas volume fraction in the inlet (entrainment), sensitivity analyses were performed. More recently, a polydisperse model was developed and implemented to take into account the different bubble sizes usually found in the flow downstream of spillways[11]. A Boltzmann transport equation is used to obtain the bubble size distribution. This size distribution is in turn used to predict the dissolution rate of the bubbles. The bubble sizes were discretized in groups with variable mass. The dynamic pressure and the turbulent dispersion terms were incorporated into the two-fluid model. The mean radius, the standard deviation of the inlet distribution, and the overall gas volume fraction were the experimental parameters of the model. As the method uses only mechanistic models and the two-phase flow is predicted, considerable fewer assumptions and empirical parameters are necessary than in previous models. The applicability of the numerical model is general as long as the air entrainment and entrapment sources can be estimated. In these researches, simulations were performed on a 2D domain and the results of the model were compared with the TDG field data on Wanapum dam.

In this work a two-phase flow model was implemented into the commercial code FLUENT 6.1.22 to calculate the multidimensional TDG field downstream of spillways. The mixture model is used to predict the gas volume fraction and velocities of the bubbles for a monodisperse flow. A transport equation for the bubble number density is used in conjunction with the void fraction equation to calculate the bubble size at each point and time. 3D numerical results of TDG, gas volume fraction and bubble sizes are presented and discussed. The TDG downstream of spillways was compared with available field data on Wanapum dam.

2 MATHEMATICAL MODEL

The TDG transport equation, considering the volume occupied by the bubbles, is:

$$\frac{\partial\left(C\,\alpha_l\right)}{\partial\hat{t}}+\nabla\cdot\left(C\,\alpha_l\,\vec{u}_l-\Gamma_l\,\alpha_l\,\nabla C\right)=S_g \tag{1}$$

where $\vec{u}_l$ is the velocity, C is the air concentration in the liquid phase (TDG) and α_l is the liquid volume fraction. The subscripts l and g denote liquid and gas, respectively. $\Gamma_l=\Gamma^m+\Gamma^t$ is the diffusion coefficient, where the superscripts m and t denote molecular and turbulent, respectively. The source term S_g is the air mass transferred from the bubbles to the liquid which can be modeled as:

$$S_g = N_g\, a_g\, k_{\mathrm{lg}} \left(\frac{P + 2\sigma}{H} - C \right) \tag{2}$$

where N_g is the bubble number density and $a_g = 4\pi R_g^2$ is the bubble interfacial area with R_g the radius of the bubble. H is the Henry's constant, P is the pressure and k_{lg} is the mass transfer coefficient which can be modeled as[12]:

$$k_{\mathrm{lg}} = \frac{\Gamma^m}{R_g \sqrt{\pi}} \left\{ 1 - \frac{2}{3} \frac{1}{\left(1 + 0.09\, Re_g^{\;2/3}\right)^{3/4}} \right\} Pe_g^{\;1/2} \tag{3}$$

where Re_g and Pe_g are the gas Reynolds and Peclet numbers based on the bubble radius and the gas/liquid relative velocity.

To solve Eq. (1) is necessary to know the liquid volume fraction and the bubble size at each point and time. For this purpose, a mixture model is used together with a transport equation for the bubble number density. The continuity equation for the mixture gas/liquid is[13]:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot \left(\rho_m\, \vec{u}_m \right) = 0 \tag{4}$$

where $\vec{u}_m = \dfrac{\sum_{k=l,g} \alpha_k\, \rho_k\, \vec{u}_k}{\rho_m}$ is the mass-averaged velocity with $\rho_m = \sum_{k=l,g} \rho_k\, \alpha_k$ the mixture density. The gas density can be calculated assuming ideal gas. The momentum equation for the mixture is[12]:

$$\frac{\partial \left(\rho_m\, \vec{u}_m \right)}{\partial t} + \nabla \cdot \left(\rho_m\, \vec{u}_m\, \vec{u}_m \right) = -\nabla P + \nabla . \left[\mu_m \left(\nabla \vec{u}_m + \nabla \vec{u}_m^{\,T} \right) \right] + \rho_m\, \vec{g} + \nabla . \left(\sum_{k=l,g} \alpha_k\, \rho_k\, \vec{u}_{dr,k}\, \vec{u}_{dr,k} \right) \tag{5}$$

where $\mu_m = \sum_{k=l,g} \alpha_k\, \mu_k$ is the mixture velocity and the drift velocity is $\vec{u}_{dr,k} = \vec{u}_k - \vec{u}_m$. The continuity equation for the gas phase is[14]:

$$\frac{\partial \rho_g\, \alpha_g}{\partial t} + \nabla \cdot \left[\rho_g\, \alpha_g\, \vec{u}_g \right] = -S_g \tag{6}$$

Due to small density and viscosity in the gas phase, the inertia, gravity force and the viscous shear stresses are much smaller than the pressure and other interfacial forces, and thus usually neglected in the gas momentum equation[15,16]. In addition, assuming that the pressure at the interface is the same as the pressure in the liquid phase, the gas momentum equation reduces to[17]:

$$0 = -\alpha_g \nabla \left(P + \frac{2}{3} k \right) + \vec{M}_g \tag{7}$$

where $\vec{M}_g$ is the interfacial force between bubbles of group-*g* and the liquid. In this particular application, most interfacial forces, such as lift and virtual mass, are negligible, leading to $\vec{M}_g = \vec{M}_g^D + \vec{M}_g^{TD}$, where $\vec{M}_g^D$ is the drag force and $\vec{M}_g^{TD}$ is the turbulent dispersion for bubbles of group-*g*. The drag force can be modeled as[18]:

$$\vec{M}_g^D = -\frac{3}{8} \alpha_g \frac{C_g^D}{R_g} \vec{u}_{rg} \left| \vec{u}_{rg} \right| \tag{8}$$

where $C_g^D = \dfrac{24}{\mathrm{Re}_g}\left(1 + 0.1\mathrm{Re}_g^{0.75}\right)$ is the drag coefficient. The turbulent dispersion term is modeled as[19]:

$$\vec{M}_g^{TD} = -\frac{3}{8} \frac{C_g^D \left| \vec{u}_{rg} \right|}{R_g} \frac{\nu^t}{Sc} \nabla \alpha_g \tag{9}$$

where the turbulent viscosity can be written as $\nu^t = C_\mu \dfrac{k^2}{\varepsilon}$ with $C_\mu = 0.09$ and the bubble Schmidt number is $Sc \approx 1$. Combining Eqs. (7), (8) and (9) an algebraic relation for the gas/liquid relative velocity is obtained.

The transport equation for the bubble number density, assuming negligible breakup and coalescence, is[17]:

$$\frac{\partial N_g}{\partial t} + \nabla \cdot \left(N_g \, \vec{u}_g \right) = 0 \tag{10}$$

3 NUMERICAL METHOD

The equations of the model were implemented into the commercial flow simulation code FLUENT 6.1.22 (Fluent Inc., USA). The TDG concentration and bubble number density equations (Eqs. (1) and (10)) were implemented using User Defined Scalar (UDS) transport equations. The source term S_g (Eqs. (2) and (3)), material properties as diffusivity and gas density, and the relative gas/liquid velocity (Eqs. (7) to (9)) were programmed through User Defined Functions (UDF).

4 NUMERICAL SIMULATIONS

The two-phase model is used to study the field of TDG concentration downstream of the Wanapum Dam on the Columbia River. The dam has a 235 *m* long spillway with twelve gates (see Fig. 1). Water discharge takes place in the powerhouse exits and in the 12 spillways.

The grid has 1765482 hexahedral cells. Tables 1 and 2 summarize the conditions used for the numerical simulations[20]. The inlet gas volume fractions used were between $\alpha = 0.05$ and $\alpha = 0.02$, and the bubble diameter between $D_b = 1mm$ and $D_b = 2mm$, according to values referenced in the bibliography[21,22]. The water surface elevation in the forebay is 550.57 *feet* and in the unit 10 of the powerhouse 495.09 *feet*.

Spillway Gate	1	2	3	4	5	6	7	8	9	10	11	12	Total
Flowrate (kcfs)	4.2	6.0	6.1	6.3	6.0	6.1	6.1	6.1	5.9	6.0	6.0	8.7	73.9

Table 1: Flowrate in the spillway gates

Powerhouse Gate	1	2	3	4	5	6	7	8	9	10	Total
Flowrate (kcfs)	15.3	15.2	15.8	15.4	17.7	17.3	0	15.2	15.9	0	127.8

Table 2: Flowrate in the powerhouse

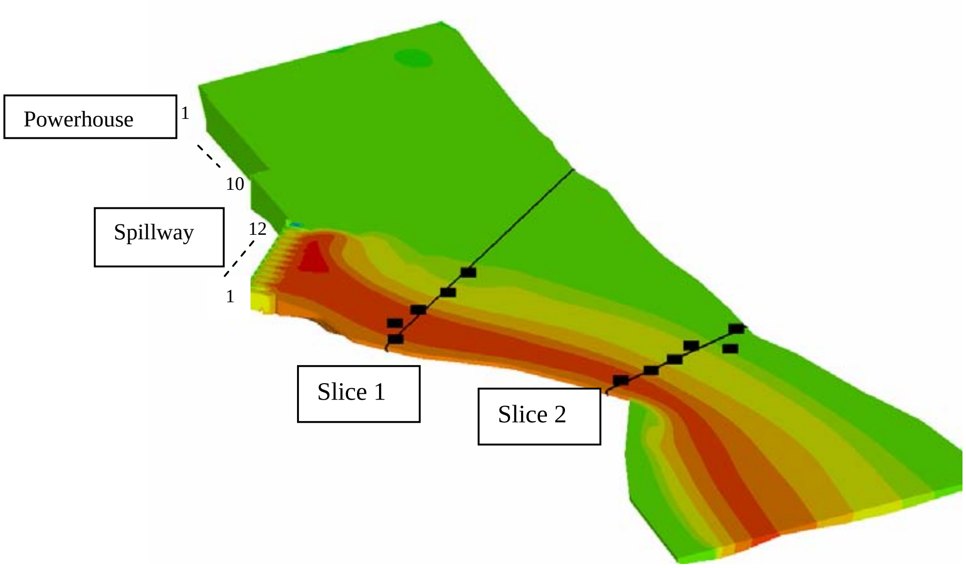

Figure 1: Measurement stations in Wanapum Dam and slices used for comparison with experimental data.

4.1 Boundary conditions

Inlet: The inlet velocity at the spillways is calculated assuming uniform profiles considering the water depth, the inflow rate and the spillway slope. The turbulent kinetic energy, gas volume fraction and TDG concentration used as Dirichlet conditions are listed in table 1. A turbulent dissipation rate of approximately $\nu^t \sim 5\ m^2/s$ was used[6].

Free surface: The mass transfer between the free surface and the atmosphere is neglected[6]. A slip condition for the liquid phase and free flow for the gas phase were used. These boundary conditions were programmed through UDF's into FLUENT 6.1.22.

No slip boundary conditions in all the impermeable walls and free flow for the liquid and gas phases in the exit were used.

5 NUMERICAL RESULTS

Figure 1 shows Wanapum Dam, the measurements stations and the slices selected to study the 3D effects on the TDG profiles and to compare the results of the model against the experimental data.

In Fig. 2 streamlines at the free-surface are shown for an inlet bubble diameter $D_b = 1.8\,mm$ and $\alpha = 0.05$. Note that the liquid entrainment from the powerhouse decreases the TDG levels in the gates near the powerhouse.

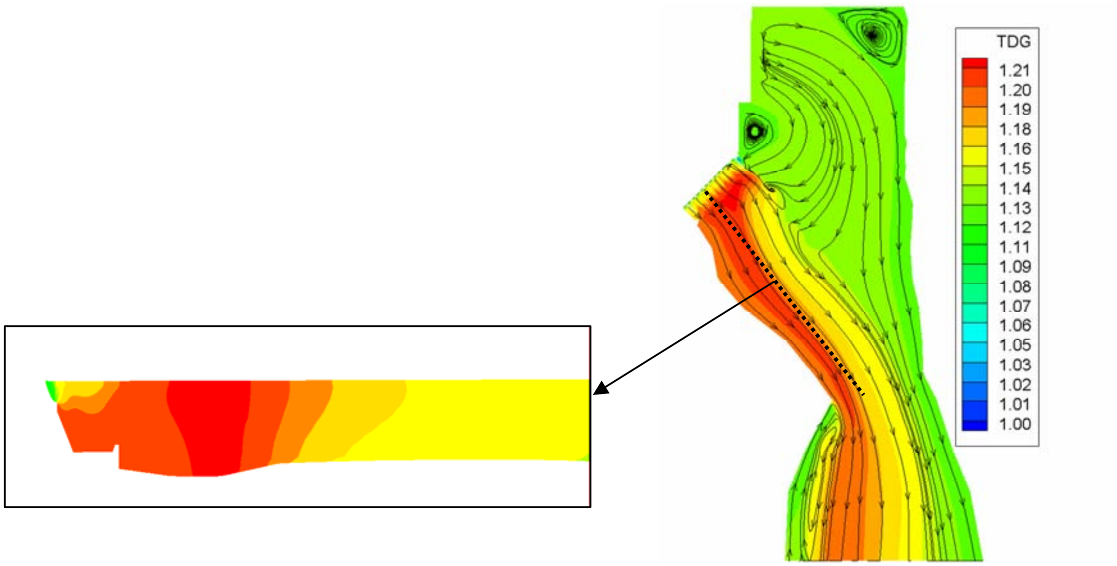

Figure 2: TDG distribution and streamlines at the free-surface downstream of the spillway

As the bubbles are transported downstream in the stilling basin, the bubble size decreases due to air dissolution into the liquid and increase in density due to higher pressure, see Fig. 3. Bubbles that can reach a region with low pressure and high air concentration in the water can regain mass and reduce the TDG. Most of the bubbles will be leaving the free-surface near the inlet due to the effect of the deflector installed in the spillway. Some bubbles reach deep into the water pool before they are transported back to the free-surface by the mean flow. In addition, bubbles rise due to the buoyancy force.

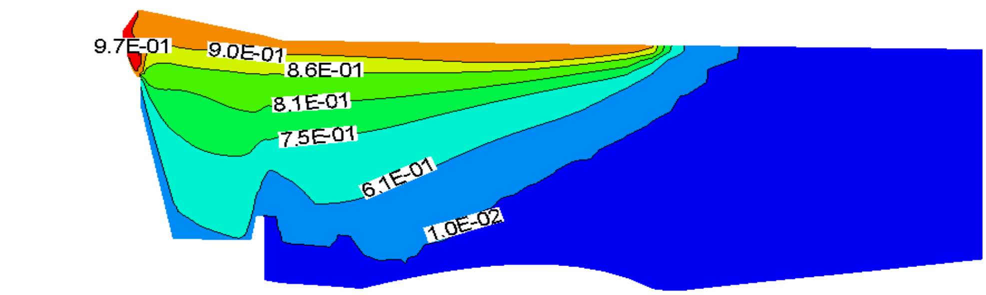

Figure 3: Bubble radius (*mm*) at slice 2 and $D_b = 2\ mm$

Figures 4 and 5 show the depth averaged TDG as a function of the distance from the river bank at slices 1 and 2. The TDG concentration is smaller for larger bubbles. Big bubbles have higher terminal velocities and reach the free-surface faster and closer to the spillway, before they transfer mass. Also, for the same gas volume fraction, bigger bubbles have smaller interfacial area concentration and transfer less air to the liquid. In addition, the internal pressure is also smaller since the radius of curvature is bigger.

Notice in Fig. 4 that the experimental TDG data shows a peak at about 125 m from the river bank, and then decreases rapidly. The numerical model fails to properly predict this behavior. It is believed that entrainment of fresh water coming from the powerhouse below the spillway flow is responsible for this phenomenon. This entrainment cannot be captured with our rigid lid model. The physics leading to this behavior are not very well understood and are a matter of current research.

6 CONCLUSIONS

A three dimensional numerical study was conducted to predict the TDG concentration downstream of spillways. A two-phase flow model was developed within the framework of FLUENT to calculate the gas volume fraction and velocity of the bubbles. A transport equation for the TDG was solved considering the dissolution/absorption of air. In this work we assume one variable bubble size, which may change due to local bubble/water mass transfer and pressure. The simultaneous solution of a bubble number density equation allows the prediction of the bubble size at each point and time.

The predictions of the model were compared against experimental field data under two operational conditions. It was found that the model was able to capture the main features of the flow. However, considerable discrepancy was found on the diffusion observed experimentally and on the model, this last predicting much sharper concentration gradients than those observed experimentally. In addition, the CFD model fails to predict the attraction of powerhouse water by the spillway. The lack of free surface mass transfer and a possible underestimation of the diffusivities are two of the possible causes for the observed inconsistencies. Other possible causes were discussed and will be subject to future work.

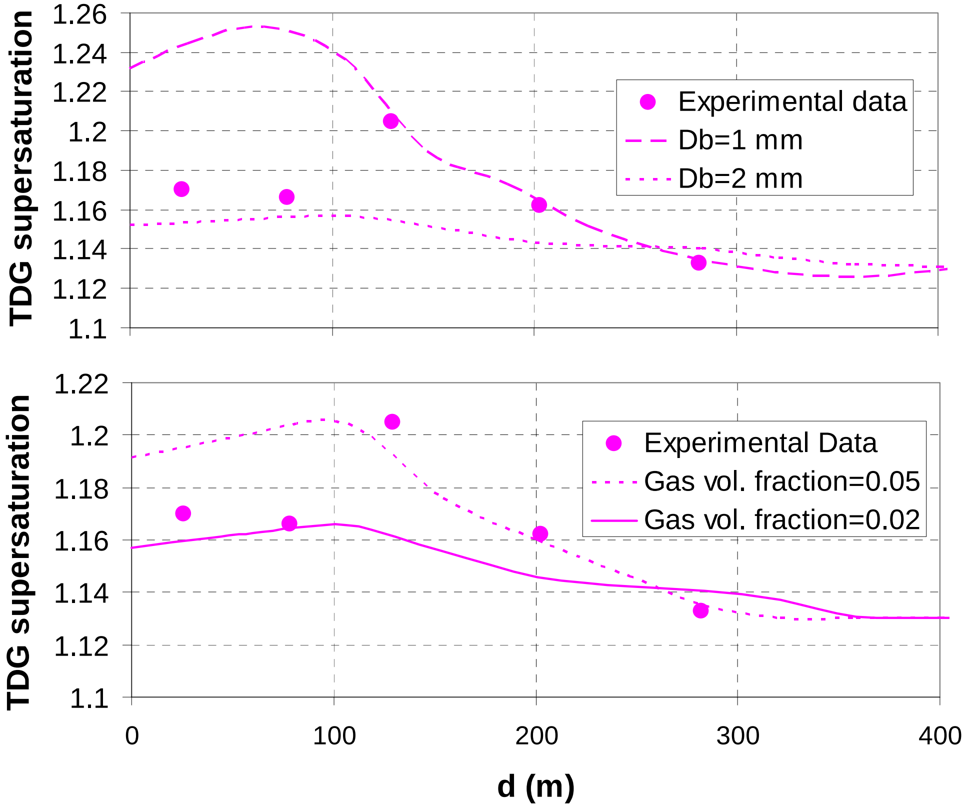

Figure 4: TDG as a function of the distance to the river bank at slice 1. Solid lines: simulations results. Symbols: experimental data. a) $\alpha = 0.05$ b) $D_b = 1.8\,mm$

7 AKNOWLEDGMENTS

This work was partially supported by National Computational Science Alliance under grant DEB030004N. The computations were ran the IBM P690.

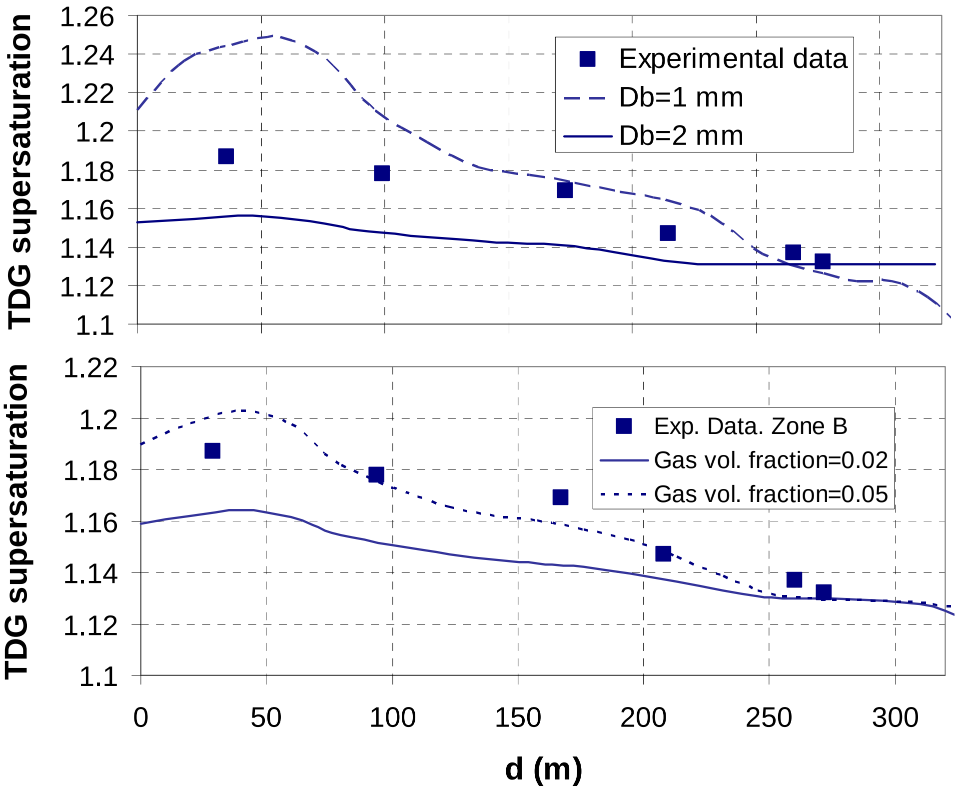

Figure 5: TDG as a function of the distance to the river bank for $D_b = 1.8\,mm$ at slice 2. Solid lines: simulations results. Symbols: experimental data. a) $\alpha = 0.05$ b) $D_b = 1.8\,mm$

8 REFERENCES

[1] A.V. Nebeker, D.G. Stevens and R.K. Stroud, “Effects of Air-Supersaturated Water on Adult Sockeye Salmon (Oncorhychus Nerka)”, *J. of Fisheries Res. Board of Canada*, **33**, 2629-2633 (1976).

[2] D.E. Weitkamp and M. Katz, “A Review of Dissolved Gas Supersaturation Literature”, *Trans. Am. Fisheries Soc.*, **109**, 659-702, (1980).

[3] P.J. Pickett and M. Herold, “Total Maximum Daily Load for Lower Snake River Total Dissolved Gas”, Pub 03-03-020, Washington State Dept. of Ecology, (2003).

[4] T. Brattberg and H. Chanson, “Air Entrainment and Air Bubble Dispersion at two-dimensional Plunging Water Jet.” *Chem. Eng. Sc.*, **53**(24), 4113-4127, (1998).

[5] C. Mannheim and L.J. Weber, “Unique Approach for Physical Model Studies of Nitrogen Gas Supersaturation.” *Cong. Int. Hyd. Res., IAHR*, 518-523, (1997).

[6] J.J. Orlins and J.S. Gulliver, “Dissolved Gas Supersaturation Downstream of a Spillway II: Computational Model.” *J. Hyd. Res.*, **38**(2),151-159, (2000).

[7] L.A. Roesner and W.R. Norton, “A Nitrogen Gas (N_2) Model for the Lower Columbia River”. Rep. 1-350. *Water Resources Engineers*, Inc., Walnut Creek. Calif. (1971).

[8] D.A. Geldert and J.S. Gulliver, “Modeling Dissolved Gas Supersaturation Below Spillway Plunge Pools.” *J. Hyd. Eng.,* **124**(5), 513-521, (1998).

[9] L.J. Weber, H. Huang, Y. Lai and A. McCoy, “Modeling Total Dissolved Gas Production and Transport Downstream of spillways: three-dimensional Development and Applications”, *Int. J. of River Basin Management,* **2**, 3, 157-167, (2004).

[10] M. Politano, P.M. Carrica, C. Turan and L. Weber, “Prediction of the Total Dissolved Gas downstream of spillways using a two-phase flow model”, *World Water & Environmental Resources Congress,* ASCE, Utah, (2004).

[11] M. Politano, P. M. Carrica, C. Turan and L.Weber, “A multidimensional two-phase flow model for the total dissolved gas downstream of spillways”, *J. Hyd. Res.In press.*

[12] F. Takemura and A. Yabe, “Gas Dissolution Process of Spherical Rising Gas Bubbles.” *Chem. Eng. Sc.,* **53**(15), 2691-2699, (1998).

[13] G. B. Wallis, *One Dimensional Two-Phase Flow,* Mc Graw-Hill Book Company, (1969).

[14] D.A Drew. and R.T. Lahey Jr, “Application of General Constitutive Principles to the Derivation of Multidimensional two-phase Flow Equation.” *Int. J. Multiphase Flow,* **5**, 243-264, (1979).

[15] S. Antal, R.Jr. Lahey and J. Flaherty, “Analysis of Phase Distribution in Fully Developed Laminar Bubbly two-phase Flow”, *Int. J. Multiphase Flow*, **17**, 635-652, (1991).

[16] M.A. Lopez de Bertodano, R.T. Jr. Lahey and O.C. Jones, “Phase Distribution in Bubbly Two-phase Flow in Vertical Ducts”, *Int. J. Multiphase Flow*, **20**, 805-818, (1994).

[17] P.M. Carrica, D. Drew, F. Bonetto & R.T. Lahey Jr., “A Polydisperse Model for Bubbly Two−Phase Flow Around a Surface Ship.” *Int. J. Multiphase Flow,* **25**, 257-305, (1999).

[18] M. Ishii and N. Zuber, “Drag Coefficient and Relative Velocity in Bubbly, Droplet or Particulate Flows.” *AIChE J*., **25**. 843-855, (1979).

[19] P. M. Carrica, F. Bonetto, D. Drew and R. T. Jr. Lahey, “The Interaction of Background Ocean Air Bubbles with a Surface Ship”, *Int. J. Num. Methods in Fluids,* **28**, 571-600, (1998).

[20] V.D. Caroll and Lemons, “Preliminary Wanapum Phase III Total Dissolved Gas Spillway Performance Test, July 14-16, 1999”, CEERD-ES-P, Public Utility District No. 2 of Grant County, (2000).

[21] A. Bin, “Gas Entrainment by Plunging Liquid Jet.” *Chem. Eng. Sc.,* **48**(21), 3585-3630, (1993).

[22] H. Chanson, Air Bubble Entrainment in Free-Surface Turbulent Shear Flows, Ac. Press, California, (1997)