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Discussion

Verification and Validation of a Computational Fluid Dynamics (CFD) Model for Air Entrainment at Spillway Aerators

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The Authors presented the outputs of some numerical modelling of spillway aerator conducted using a commercial package. A spillway aeration device is located on the spillway bottom and sometimes on the sidewalls. It is designed to deflect high velocity flow away from the chute surface (and walls) to introduce artificially air into the flow and protect the spillway invert from cavitation erosion (Fig. 1). The main flow regions are: (a) the approach flow region which characterises the initial nappe flow conditions, (b) the transition region which coincides with the length of the deflector, (c) the aeration region, (d) the impact point region and (e) the downstream flow region (Fig. 1) (Chanson 1989a,b, Kramer et al. 2006). A key feature of the flow above and downstream of an aerator is the strong mixing of air and water yielding a complicated high-velocity air-water flow. Herein it is argued that the validation and certification of the commercial CFD package were ill-performed and that the physical modelling technique based upon a proper dimensional analysis remains the basic design tool.

The authors use the Algebraic Slip Mixture (ASM) model available with the Fluent™ software. The software User's Guide states clearly that "typical applications include sedimentation, cyclone separators, particle-laden flows with low loading, and bubbly flows where the gas volume fraction remains low". Did the authors check that their case study involves "low gas volume fraction"? Numerically, several comments must be added. The authors never specified the initial and boundary conditions, nor discussed the sensitivity of their numerical results to these parameters. The authors chose the standard k-ε turbulence model on the basis of a CPU time argument. It is well known that this turbulence model is the poorest for near-wall turbulence, and the RNG model is far better for no extra CPU time calculation. The v^2-f model is also known to be the most appropriate model and is available with the software. The authors stated that the numerical results are very similar whatever the turbulence model: where are the comparisons? What did "very similar" mean in terms of verification and validation? Which quantities were evaluated to select the right turbulence model? In this paper, no turbulence validation was proposed, although turbulence plays a major role in this type of spillway flow! No velocity profiles, turbulence intensities nor turbulent coherent structures behaviour were shown, although crucial for a proper validation. The authors did not estimate the compatibility between the turbulence model and the ASM model: the turbulence model was used within the framework of the Reynolds-Averaged approach, which meant that the set of equations were averaged. This introduced additional terms in the governing equations; thus some turbulence model was needed in order to achieve "closure". Was the set of equations used for the mixture averaged? What about the additional terms appearing due to the averaging?

The validation of a numerical model must be based upon some independent data sets that were not used during the verification and calibration of the model. Several researchers discussed the intricacy of the validation process Mehta (1998), Roache (1998) and Rizzi and Vos (1998) and more recently Sagaut et al. (2008a,2008b). In a complex air-water flow such as the flow above a spillway aeration device, the model outputs must be compared with the detailed air-water flow properties including the distributions of void fraction, velocities and bubble sizes. The literature on air-water flows at spillway aerators includes a number of detailed air-water flow experimental data sets, most of which being open access (Low 1986, Rutschmann et al. 1986, Chanson 1988, Toombes 2002, Kramer 2004, also Chanson 1989a,1989b, Kramer et al. 2006, Toombes and Chanson 2007). The authors' study was solely limited to a single parameter: the air flow rate supplied by the air ducts, and it ignored a very large chunk of experimental literature. This is a trifle and the absence of basic "experimental data means no validation" (Roache 2009). The authors' approach lacks credibility because it does not present an accurate representation of the reality flow physics from the perspective of its intended use (Mehta 1998). The air demand is a crude parameter that gives no indication on whether the spillway flow and the air flow in the ducts are properly modelled nor physically sound as recommended by the American Institute of Aeronautics and Astronautics (Rizzi and Vos 1998, Roache 1998).

A key challenge is the uncertainty which exists in all physical systems. This is true, for example, of spillway aerator flows in which some effect of the intrusive phase-detection probes on the flow field always exists. The experimental data are subjected to an intrisic uncertainty, caused by a combination of technological limitations and accuracy of the post-processing tools. The same applies to the numerical data, which are subjected to modelling, numerical and round-off errors, and whose optimal values of various parameters of interest may be biased (Sagaut et al. 2008a). Therefore, an uncertainty analysis must be carried out for both physical and numerical data. Despite this simple recommendation, most CFD analyses including the present one fail to address the problem, possibly because only a few mathematical techniques are presently mastered by the CFD community to analyse the results of the sensitivity analysis and to enhance the numerical solution accordingly (Roache 1998,2009).

The best practice for the design of spillway aerators is based upon some solid physical modelling associated with some relevant mathematical modelling (Volkart et al. 1986, Wood 1985,1991). A physical model study must be performed under controlled flow conditions with geometrically similar models. In a dimensional analysis, the relevant parameters include the fluid properties and physical constants, the channel geometry and inflow conditions, the air-water flow properties including the entrained air bubble characteristics and turbulence characteristics. Considering a spillway aerator (Fig. 1), a simplified dimensional analysis shows that the parameters affecting the air-water flow properties at a position (x, y, z) are: (a) the fluid properties including the air and water densities ρ_{air} and ρ_w, the air and water dynamic viscosities μ_{air} and μ_w, the surface tension σ, and the gravity acceleration g, (b) the channel properties including the width B, chute slope α, aerator ramp angel θ and height t_r and offset t_s, (c) the inflow properties such as the inflow depth d_o, the inflow velocity V_o, a characteristic turbulent velocity u'_o, and (d) the cavity subpressure ΔP (Fig. 4) The dimensionless air-water flow properties may be expressed as :

[1] $$C, \frac{V}{\sqrt{g\, d_o}}, \frac{u'}{V_o}, \frac{d_{ab}}{d_o} ... =$$

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$$F_1\left(\frac{x}{d_o},\frac{y}{d_o},\frac{z}{d_o},\frac{V_o}{\sqrt{g\,d_o}},\frac{u_o'}{V_o},\rho_w\frac{V_o\,d_o}{\mu_w},\frac{g\,\mu_w^{\ 4}}{\rho_w\,\sigma^3},\frac{\Delta P}{\rho_w g\,d_o},\alpha,\theta,\frac{t_r}{d_o},\frac{t_s}{d_o},\frac{B}{d_o},...\right)$$

where C is the void fraction, V is the velocity, u' is a characteristic turbulent velocity, d_{ab} is a bubble size, x is the coordinate in the flow direction measured from the nozzle, y is the normal coordinate, z is the transverse coordinate measured from the channel centreline. Note that, if the local void fraction C is known, the density and viscosity of the air-water mixture may be expressed in terms of the water properties and void fraction only; hence the parameters ρ_{air} and μ_{air} may be ignored in Equation [1].

In Equation [1], the dimensionless air-water flow properties (left handside terms) at a dimensionless position (x/d_o, y/d_o, z/d_o) are expressed as functions of the dimensionless inflow properties and channel geometry. In the right handside of Equation [1], the fourth, sixth, seventh and eight terms are the inflow Froude (Fr) and Reynolds (Re) numbers, the Morton number (Mo) and the cavity pressure gradient number (P_N) respectively. Any combination of these numbers is also dimensionless and may be used to replace one of the combinations. For example, the Morton number may be rewritten as a combination of Froude, Reynolds and Weber number (Wood 1991). Since the same fluids (air and water) are used in both laboratory model and prototype, the Morton number is an invariant, and only the Froude and Reynolds numbers are relevant parameters. The Weber number is not an independent parameter for example. For a given spillway aerator geometry (α, θ, t_r, t_s, B fixed), the cavity subpressure may be controlled in the model (e.g. Laali and Michel 1984, Tan 1984, Chanson 1990), and Equation [1] becomes:

$$[2] \qquad C,\frac{V}{\sqrt{g\,d_o}},\frac{u'}{V_o},\frac{d_{ab}}{d_o}... = F_2\left(\frac{x}{d_o},\frac{y}{d_o},\frac{z}{d_o},\frac{V_o}{\sqrt{g\,d_o}},\frac{u_o'}{V_o},\rho_w\frac{V_o\,d_o}{\mu_w},\frac{g\,\mu_w^{\ 4}}{\rho_w\,\sigma^3},...\right)$$

In any geometrically similar model, a true dynamic similarity is achieved if and only if each dimensionless parameter has the same value in both model and prototype. Scale effects may exist when one or more dimensionless terms have different values between model and prototype. In the study of free-surface flows including spillway aerators, a Froude similitude is commonly used because the gravity effects are dominant (e.g., Low 1986, Chanson 1988, Kramer 2004). That is, the model and prototype Froude numbers must be equal. However the entrapment of air bubbles and the mechanisms of air bubble breakup and coalescence are dominated by surface tension effects, while turbulent processes in the shear region are dominated by viscous forces (Rao and Kobus 1971, Wood 1991, Chanson 1997). Dynamic similarity of air bubble entrainment in spillway aerators becomes impossible because of too many relevant parameters (e.g., Froude, Reynolds numbers) in Equation [2]. For example, with the same fluids (air and water) in model and prototype, the air entrainment process is adversely affected by significant scale effects in small size models (Laali and Michel 1984, Pinto 1984, Wood 1985,1991). Figure 2 illustrates a physical model and a prototype spillway, both equipped with several spillway aerators and operating with similar inflow Froude numbers but different Reynolds numbers. In the small laboratory model (Fig. 2a), drastically lesser bubble entrainment was observed compared to the prototype spillway operation (Fig. 2b). In practice, air entrainment at spillway aerators is studied in relatively large physical models with a geometric scaling ratio less than 10:1 to 20:1 (Pinto 1984, Chanson 1997,2009, Kramer 2004).

In summary, we believe that the validation and certification of the Authors' numerical results were improper. These should be conducted on the detailed air-water flow properties of the flow above and downstream of the spillway aerators, and several extensive data sets are freely accessible (e.g. Chanson 1988, Kramer 2004, Toombes 2002). The physical modelling and theoretical calculations remain the basic tools of the design engineers to size the spillway aeration devices on a large spillway, although the physical model dimensions must be carefully selected to address the potential scale effects (e.g. Kramer 2004, Chanson 2009).

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Fig. 1 - Sketch of spillway bottom aeration device and main flow regions

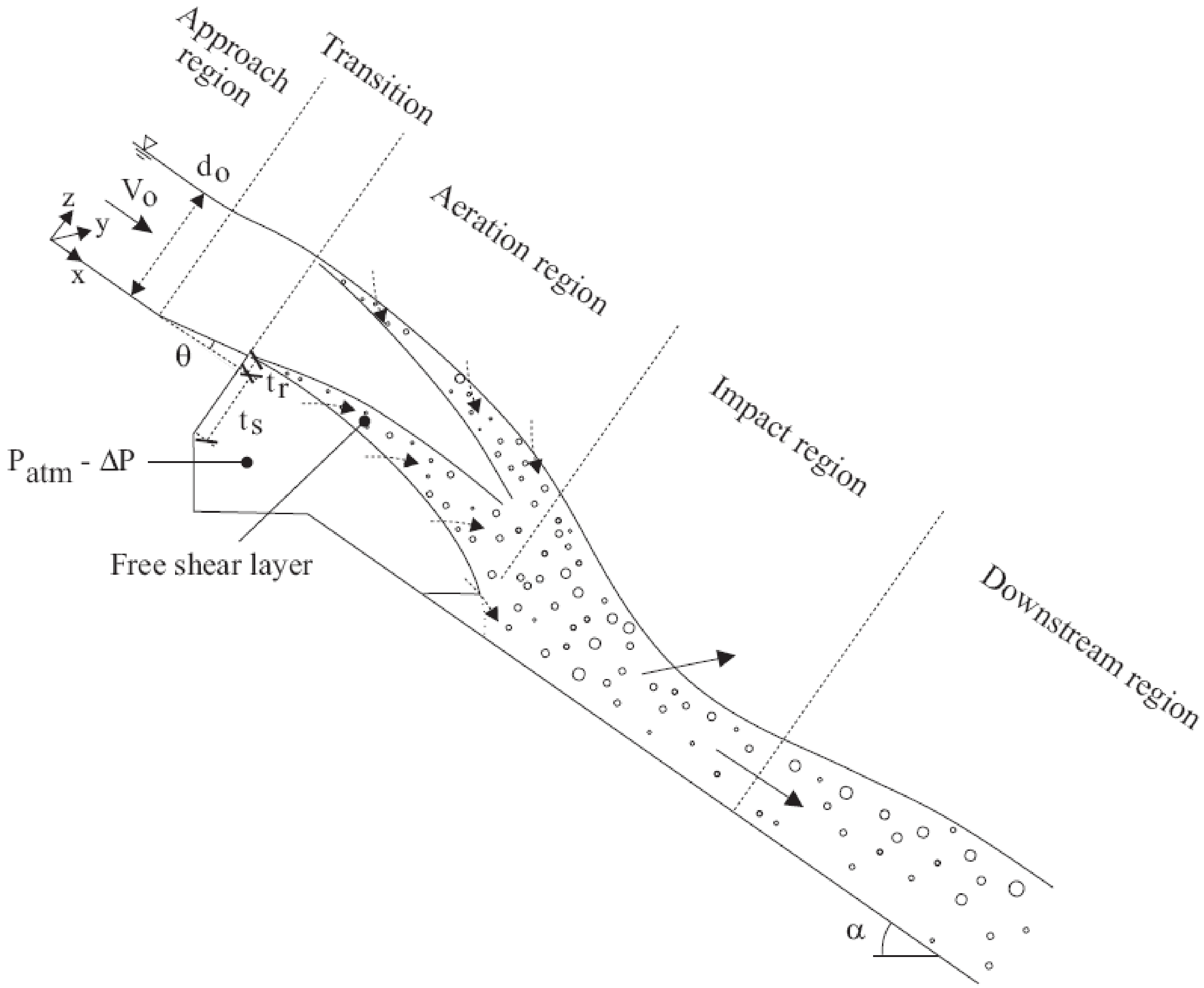

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Fig. 2 - Photographs of spillway aerators

(a) Physical model of El Cajon dam spillway, Mexico in January 2002 - Note the four aerators installed in the model in operation (see air duct intakes) and the negligible free-surface aeration in the small size model - Prototype design discharge: 14,864 m^3/s, Dam height: 188 m

(b) Foz do Areia dam spillway (Brazil) and aeration device in operation (note the air duct intakes) - Note the massive flow aeration from the first set of ducts - Design discharge: 11,000 m^3/s, Dam height: 160 m