NUMERICAL SIMULATION OF STEPPED SPILLWAY FLOW

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Abstract. *The main purpose of this study is to demostrate the application of the bubbles over a self-areated stepped spillway flow and wave description. The numerical simulation was conducted using opensource softwares for mesh generation and Computational Fluid Dynamic, CFD, modeling. The results were compared with literature data. Enttrained air contributes greatly to oxygen absortion.*

Keywords: *Multiphase flow, void ratio, turbulent transport, entrained air*

1. INTRODUCTION

Stepped channels are extensively used in hydraulic and environmental engineering. The main purpose of such structures is to increase the energy dissipation of the flows and to protect the bed of the spillways from cavitation, by air inception. While the steps significantly increase the energy dissipation rate, they also generate more turbulence and increase the air inception which, as mentioned, reduces the risk of cavitation. Additionally, the steps reduce the size of the energy dissipation basin at the toe of the spillway, implying in reduction of the total costs of spillway structures.

The main purpose of this study was to evaluate numerically the performance of stepped spillways related to air inception and the reduction of risk of cavitation. The velocity profiles along the flow direction were compared with literature data.

Self-areation is a predominant phenomenon of flow on stepped spillways. The process of air entrainment and bubble formation along the flow is initially due to the conducted by entrapment of air volume at the surface of flow, which is then "closed into bubbles", or really entrained in the flow. At the upstream end the flow is smooth and no air entrainment occurs, so that it is called briefly as "black water". The flow turns into the so called "white water" or two-phase flow only after a distance has been traversed, which may involve a distance of several steps. The inception point is defined as the point where the fluid dynamic boundary layer intercepts the flow surface. The location of the inception point is commonly decribed as: black water length.

Far downstream from the inception point the flow remains uniform. “Fig. 1” ilustrates the uniform downstream flow (in this case, it is impossible to attest for the uniformity of the velocity profiles, but is is possible to verify that the white-water global characteristics are maintained). The air inception is a consequence of the appearance of turbulence on the water surface.

Figure 1. Uniform downstream flow over a stepped spillway

2. NUMERICAL MODEL SETUP

Numerical procedures were used in this study, adequately conducted using the open softwares Salome and OpenFoam® for mesh generation and CFD, respectively. The difficulties that arise for the mesh generation in such structures is associated with the form of the crest of the inlet structure that provide a sub-critical inflow condition.

The flows are inherently turbulent and their characteristics were investigated here using the k-ε model of turbulence and adequate wall functions for the wall boundaries.

Table 1. Empirical constants of $k-\varepsilon$ model.

C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	σ_k	σ_ε
0,09	1,44	1,92	1,0	1,3

The VOF method was used to model the free surface of the flows. A scalar value is used to define the volume of fluid 1, as V_1 in each element. In this way, V_2 are simplified as $1-\alpha$. Alpha is a fluid fraction in a cell so $\alpha = V_1/V$. It means that, if the cell is completely filled, then alpha is equal to 1, or, if the cell is filled with the void phase, alpha is equal zero. At the interface the alpha range is between zero and one. The air-water interface is calculated by the transport equation of mass conservation, Eq. (1).

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \tilde{\mathbf{u}}) = 0 \tag{1}$$

The solver surface compression is introduced, as in Eq. (2). Being $\tilde{\mathbf{u_R}}$ the velocity field.

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \tilde{\mathbf{u}}) + \nabla \cdot (\alpha(1-\alpha)\tilde{\mathbf{u_R}}) = 0 \tag{2}$$

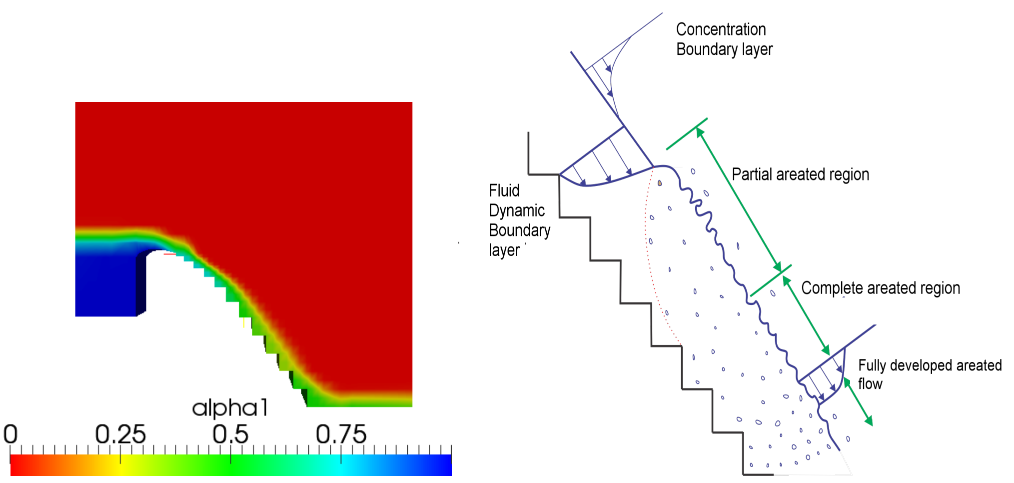
The Eq. (3) represent the Navier-Stokes equations for incompressible, viscous fluids (it is represented here in vectorial form, thus for the usual three components).

$$\frac{\partial \tilde{\mathbf{u}}}{\partial t} + (\tilde{\mathbf{u}} \cdot \nabla)\tilde{\mathbf{u}} = -\frac{1}{\rho}\nabla p + \nu \cdot \nabla^2 \tilde{\mathbf{u}} + \tilde{\mathbf{g}} \tag{3}$$

The PISO method (Pressure-Implicit with Splitting of Operators) was used as the pressure-velocity coupling scheme.

3. PRELIMINARY RESULTS

A steady-state simulation was developed to predict air concentrations, and the phase fraction diagram is ilustrated by “fig. 2“.



(a) Volumetric fraction
(b) Areatted regions

Figure 2. Simulation of flow over a stepped spillway)

3.1 The air model distribution

The air concentration distribution, downstream of the inception point, may be described by a advection diffusion model, proposed by (Chanson, 2000):

$$C = 1 - \tanh^2\left(K' - \frac{y}{2D'Y_{90}}\right) \tag{4}$$

C is the void fraction, $tanh$ is a hyperbolic tangent, y it is a transverse coordenate with origin at the pseudobottom, D' is a dimensionless turbulent diffusivity, K' is an integration constant, Y_{90} is the normal distance to the pseudo-bottom for $C = 90\%$. D' e K' are functions of the depth-averaged air concentration, $\bar{C}$.

From (Peterka, 1953), the air concentration necessary to avoid some cavitation damage is about $5 - 8\%$. The inlet of air increases the compressibility of the mixture and the flow becomes able to absorb the impact of the collapsing vaporized bubbles.

From (Chanson, 1997) the concentration profiles are classified into three main regions as shown in “Tab. 2”

Table 2. Main regions of concentration profiles.

Rate	Classification
$C < 0.3$ to 0.4	Clear water comprising air bubbles
$C > 0.6$ to 0.7	Air flow comprising water droplets
$C > 0.7$	Two-phase flow with equal air and water contents

“Fig. 3” is a representation of the contour of isosurfaces considering the range of concentrations mentioned in “Tab. 2”.

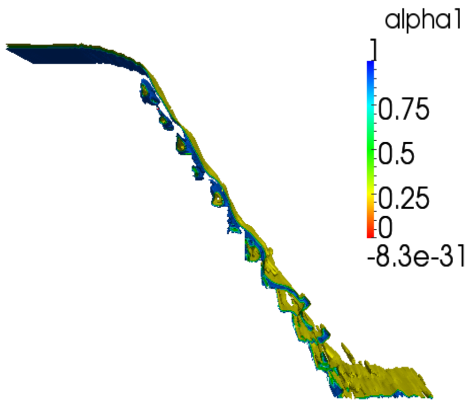


Figure 3. Phase fraction isosurfaces

After the bubble inception the distribution of the bubble sizes change due to breakup and coaescence along the flow. Bubble transport is directely dependent of fluid viscosity and the breakup is Froude-number dependent. So, combined dependences on the Reynolds and the Froude number is expected.

In “Fig. 4”, the simulation results can be visualized as a graphical histogram of the volumetric fracition along the flow.

The velocity of an areated flow is expected to be greater than the velocity of an unaerated flow because the entrained air reduces the wall friction, (Steven and Gulliver, 2007). “Fig. 5” shows a velocity diagram obtained in the present simulations.

3.2 FINAL CONSIDERATIONS

First results of air entrainment at any location of the spillway are presented, allowing the prediction of the air concentration profiles (void fraction profiles). With the distribution of entrained air, the gas transfer along the flow can be estimated. This quantification is relevant, because allows to check experimental results and predictive equations obtained from simplified models, conducting to a better understanding of the air entrainment phenomena on stepped chutes. In addition, it is possible to correlate pressure distributions to recognize cavitation regions where air content is not enough to reduce cavitation damage.

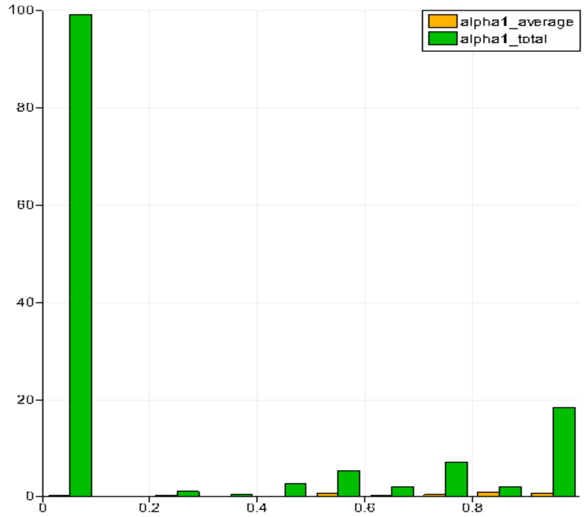


Figure 4. Steady-state volume fraction histogram

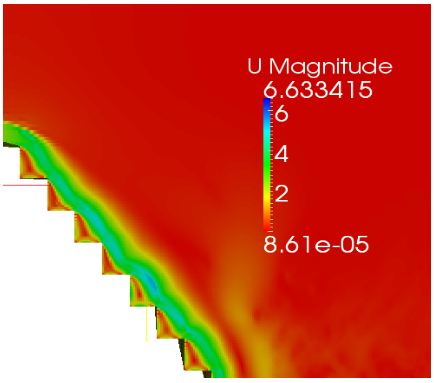


Figure 5. Velocity diagram

4. ACKNOWLEDGEMENTS

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