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Letter

Numerical investigation of air-entrainment in skimming flow over stepped spillways

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HIGHLIGHTS

- Simulation is performed of the air-entrainment in skimming flow using the volume of fluid (VOF), mixture and Eulerian.
- The VOF+large eddy simulation (LES) method is able to capture the splashing water droplets.
- The mixture+LES method predicts the inception of air entrainment most accurately.
- The Eulerian+Reynolds-averaged Navier–Stokes (RANS) method fails to capture the free-surface aeration.

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ABSTRACT

As a widely used flood energy dissipator, the stepped spillway can significantly dissipate the kinetic or hydraulic energy due to the air-entrainment in skimming flow over the steps. The free-surface aeration involves the sharp deformation of the free surface and the complex turbulent shear flows. In this study, the volume of fluid (VOF), mixture, and Eulerian methods are utilized to simulate the air-entrainment by coupling with the Reynolds-averaged Navier–Stokes/large eddy simulation (RANS/LES) turbulence models. The free surface deformation, air volume fraction, pressure, and velocity are compared for the three different numerical methods. Only the Eulerian+RANS method fails to capture the free-surface aeration. The air volume fraction predicted by the VOF+LES method best matches the experimental measurement, while the mixture+LES method predicts the inception point of the air entrainment more accurately.

The stepped spillway at the toe of a dam is one of the widely seen energy dissipation structures in hydro-power projects [1]. Energy of the flood is dissipated due to the air-entrainment in skimming flow, together with the generated vortexes on the steps [2]. The experimental investigation in the laboratory is not able to capture the vortex structures in the flow. Hence, researchers have been devoted to the numerical investigation of the flow aeration in skimming flow, with the development of high-performance computers and parallel computation methods [3].

Limited by the computation condition, the earlier numerical studies of the stepped spillway overflow did not consider the coupling of the turbulence model [1]. Then, the Reynolds-averaged Navier–Stokes (RANS) turbulence models, including the standard $k-\varepsilon$ model and the re-normalisation group (RNG) $k-\varepsilon$ model, are widely utilized in conjunction with the volume of fluid (VOF) method [4,5]. The VOF+RANS method is able to capture the free surface in good agreement with the experimental results. However, the time averaged RANS method is not able to capture the fluctuating instantaneous flow characteristics. Different to RANS method, the large eddy simulation (LES) method resolves the spatial-filtered Navier–Stokes equations, such that it is able to capture the small scale eddies [6].

In this study, the LES sub-grid scale (SGS) Smagorinsky–Lilly model will be used to resolve the turbulent structures in skimming flow over the stepped spillways using a commercial computational fluid dynamics (CFD) tool, ANSYS FLUENT [7]. Three multiphase models are available in FLUENT: the VOF model [8], the mixture model [9], and the Eulerian model [10]. The VOF method captures the gasliquid interface by calculating the volume fraction of water through each computing cell, but it does not reflect the phase interaction very well. The mixture method considers the interactions between phases (can be more than two) by introducing the relative velocity into the mixed momentum equation. The most complex Eulerian method resolves the governing equations for each phase with coupled pressure and

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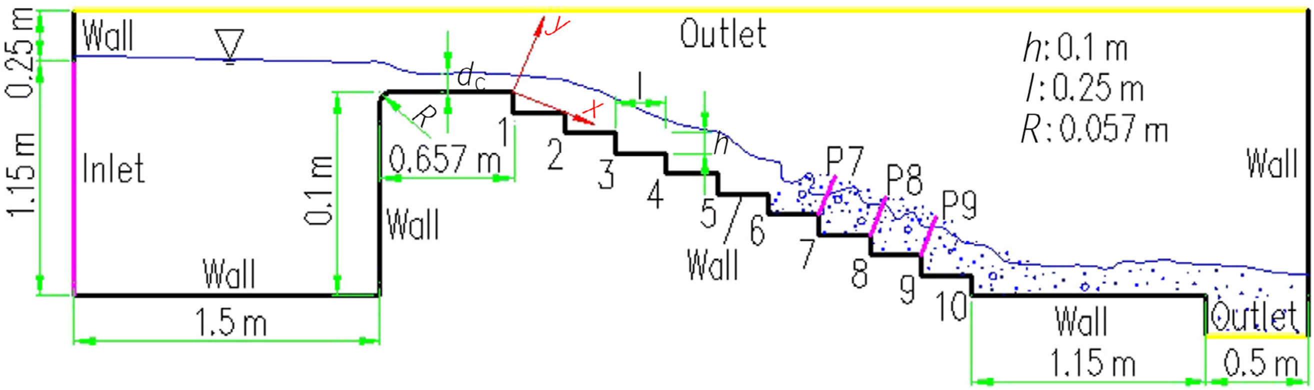

Fig. 1. Computation domain and boundary conditions [12].

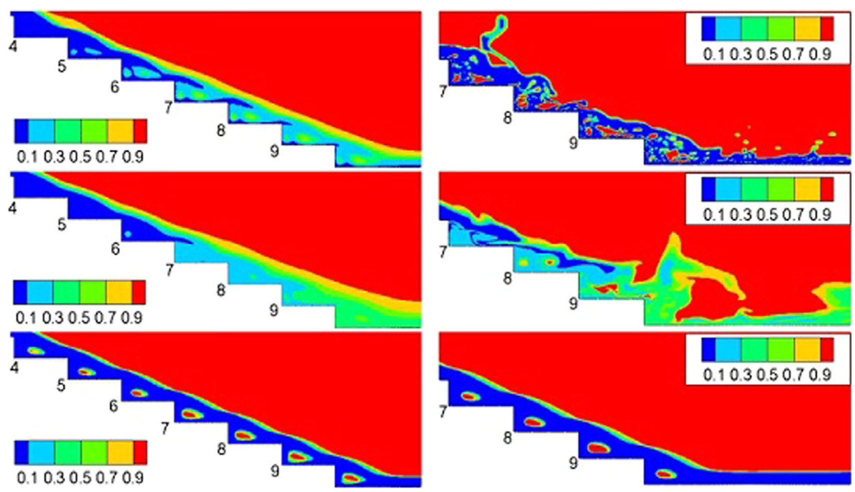

Fig. 2. (Color online) Air volume fraction distribution above the steps. Left: time averaged air volume fraction above No. 4–10 steps; right: instantaneous air volume fraction above No. 7–9 steps at 60 s.

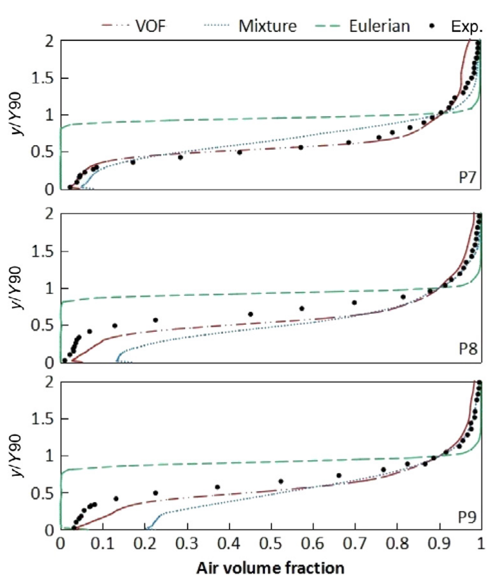

Fig. 3. Air volume fraction distribution on probes P7–P9 with distance y measured normal to the pseudo-bottom and $Y90$ the characteristic distance where the air volume fraction is 90%.

interface interaction. More details of the three multiphase methods refer to Ref. [11].

To compare the three typical multi-phase models, the skimming flow will be simulated using three different numerical methods with details shown in Table 1. Because the LES turbulence option is not allowed for the Eulerian method in FLUENT, we use the RNG $k-\varepsilon$ model for turbulence in the Eulerian case. The two fluids in the VOF model share a single set of momentum equations, the liquid phase volume fraction is resolved throughout the whole computation domain and the gas–liquid interface is build using the Geo-reconstruct method. For each multiphase method, pressure–velocity coupling is coordinated via the Pressure Implicit with the Splitting of Operators (PISO) scheme for LES or the Semi-Implicit Method for Pressure Linked (SIMPLE) scheme for RANS. Different combinations of the computation algorithms are tested for each method, and the best performers are listed in Table 1, where pressure staggering option (PRESTO) scheme calculates the "staggered" pressure using the discrete continuity balance for pressure discretization, quadratic upstream interpolation for convective kinematics (QUICK) is a quadratic-upwind differencing scheme [7]. Note that the velocity fields resolved by the VOF and mixture method are the mixture velocity of the air–water flow, while the Eulerian method predicts the fluid velocity instead.

As shown in Fig. 1, the tested stepped spillway model is positioned 1.5 m from the inlet, 0.4 m from the top boundary and 0.5 m from the right boundary. The stepped spillway includes ten identical steps with height h and width l. In a skimming flow, water enters the inlet at a fixed mass flow rate q_w, and then flows over the dam with a critical flow depth of d_c. The mass flow rate q_w is adjusted such that $d_c/h = 1.15$. Then, air is continuously entrained and released the free surface above the steps, and lastly the aerated flow leaves the downstream outlet freely.

The skimming flow is simulated using the three different numerical methods listed in Table 1, and the calculated air volume