MULTI-FLUID MODELING OF TURBULENT FLOW WITH AIR ENTRAINMENT IN A HYDRAULIC JUMP

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ABSTRACT

A hydraulic jump is numerically reproduced by a multifluid method at a Froude number of 7.5 and at the Reynolds number of 66,000. A large-eddy simulation with a localized dynamic sub-grid model is carried out for resolving the turbulence flow. The free surface fluctuation, intense air entrainment, and segregated and dispersed flow behaviors are modeled by a hybrid VOF (volume of fluid) multifluid method. Our numerical results clearly reveal the location of jump toe, the length of hydraulic jump, significant air entrainment and intense pressure and velocity fluctuations which are comparable with experimental measurements. Based on the good agreement of computed time-averaged velocity and pressure fields and their turbulence statistics with the measurement, the present numerical solutions further elucidate the rich, three-dimensional dynamics of the free surface, shear layer near the bottom and jump roller above the shear layer.

Keywords: Hydraulic jump, turbulent flow, air entrainment, numerical modeling

1. INTRODUCTION

The hydraulic jump is a rapidly varied open channel flow through a sudden transition from a supercritical to subcritical regime, which is characterized by the discontinuities in flow depth, velocity and hydrostatic pressure fields. The flow recirculation region, located immediately downstream of the jump toe and between the upper border of turbulent wall jet and the free surface, is called by the jump roller. The roller exhibits very complex flow behaviors, including interfacial exchange of air and water along the free surface and strong air entrainment at the jump toe at sufficiently high Froude number. The flow near along the free surface and insider the rollers is dominated by large-scale turbulent fluctuations in pseudo-periodic manners (Wang and Chanson, 2014).

A combined modeling approach based on a hybrid volume of fluid (VOF) and large eddy simulation (LES) methods is applied to investigate the turbulence characteristics of the strong hydraulic jump with substantial air entrainment and intense dynamic deformation of free surface. A synthetic eddy method is used to impose turbulent unsteady inflow conditions for the LES. The model is applied to the hydraulic jump generated in a laboratory flume by Wang and Chanson (2014) at the Froude number of 7.5 and the Reynolds number of 66,000. The numerical results are compared with the experimental measurements of time-averaged velocity, turbulence intensity and void fraction distributions in the hydraulic jump.

2. NUMERICAL APPROACHES

A Large eddy simulation (LES) with a localized dynamic subgrid kinetic energy model (LDKM) of Kim and Menon (1995) to reproduce the turbulence open channel flow with a hydraulic channel. The LDKM approach is dynamic as it implicitly takes into account the local energy transfer between the resolved and unresolved motions for the ongoing simulation and requires no special near-wall treatment for wall-bounded complex turbulent flow. The localized dynamic evaluation is stable in both attached and separated flow regions near the wall (Patel and Menon, 2014).

A hybrid VOF (hVOF) multifluid method is used for modeling the free surface fluctuations and intense air entrainment. It solves separate flow and phase transport equations for each phase for modeling both the segregated and dispersed flow behaviors that are dominant around and inside the jump roller.

The fully turbulent inflow conditions in the LES are imposed by a synthetic eddy method (SEM) which generates the turbulent velocity condition with synthesized eddies based on the Reynolds stresses, velocity and turbulence length scale at the inlet. The computation domain for present LES starts at the cross section of gate open, and the flow and turbulence quantities at the inlet are extract from a Reynolds-averaged Navier-Stokes (RANS) solutions for the application of SEM. The preliminary RANS computation was carried out at the same configurations in the computational domain of which the dimensions are exactly same to the experimental flume of Wang and Chanson (2014), as depicted in Figure 1.

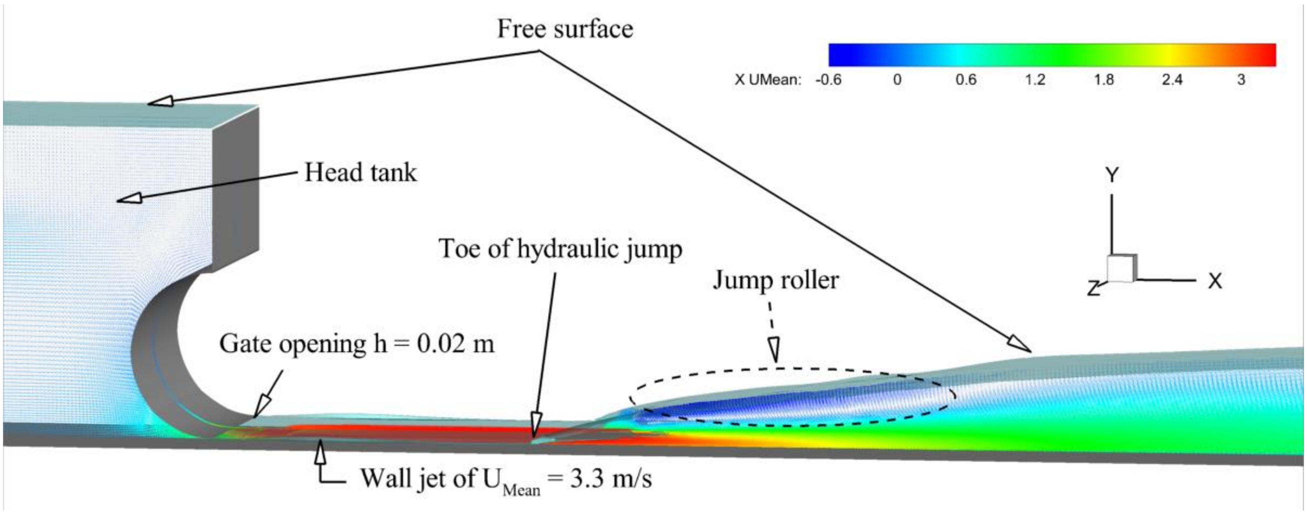

Figure 1. A snapshot of computed mean open channel flow field with a hydraulic jump at Froude number of 7.5.

3. RESULTS

Numerical solutions of time-averaged streamwise velocity profiles and turbulence intensity distributions at selected locations and free surface variation are compared with the experimental data. To evaluate the present LES-hVOF modeling approach, the profiles of time-averaged void fraction standing for the volume of air per unit volume of air and water mixture and the longitudinal decrease in local maximum void fraction in the turbulent shear region are compared with the measurement of Wang and Chanson (2014). The void fraction exhibits the extent of the air entrainment induced by the jump roller and its profiles reveal distinct distributions in the jump region which consists of the turbulent shear layer on the channel bottom and the recirculation zone, known as the roller, over the shear layer. Numerical solutions show that the void fraction rapidly increases in the recirculation zone near the free surface and reveals the second peak of void fraction induced by the intense air entrainment from the jump toe. The power spectral density functions of velocity and void fraction computed in the shear layer support that the LES resolves the turbulent flow fields in the jump region and well reproduces some dominant frequencies of the flow evolutions.

4. CONCLUSIONS

Our numerical results clearly reveal the location of jump toe, the length of hydraulic jump, significant air entrainment and intense pressure and velocity fluctuations which are comparable with experimental measurements. Based on the good agreement of computed time-averaged velocity and pressure fields and their turbulence statistics with the measurement, the present numerical solutions further elucidate the rich, three-dimensional dynamics of the free surface, jump roller and air entrainment in the jump region.

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