NUMERICAL STUDY ON A TURBULENT BACKWARD-FACING STEP FLOW IN OPEN-CHANNEL

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ABSTRACT

Turbulent open channel flow over a backward-facing step is reproduced at Reynolds number of 23,400 and Froude number of 0.22 using a large-eddy simulation with the localized dynamic subgrid kinetic energy model and a volume of fluid approach for capturing the free surface deformation induced by the Kolk-Boil-type vortices. The numerical solutions are comparable to the experimental measurements in terms of profiles of time-averaged velocity, turbulence intensities and Reynolds shear stress. The three-dimensional dynamic behaviors of turbulent flow structures associated with flow separation, reattachment and two-kind of vortices shedding from the separation and reattachment points, respectively, are elucidated by aid of flow visualization technique and statistical analysis.

Keywords: *Backword-facing step, Open channel flow, large-eddy simulation, coherent structures*

1. INTRODUCTION

The turbulent flow over a backward facing step is characterized by the detachment of boundary layer from the sharp edge of step and its subsequent attachment downstream, called as flow separation and reattachment. The flow separation is accompanied by the shedding of large scale vortices and the high shear layer emanating from the separation point which significantly interact with bottom wall near the reattachment point. The corresponding low-frequency, large scale, unsteady motions of the reattachment point over a distance of mean reattachment length results in the emergence of the so-called Kolk-Boil (KB) vortex that interacts with the free surface (Nakagawa and Nezu, 1987).

We numerically reproduce such complex turbulent flow over a backward-facing step at Reynolds number of 23,400 and Froude number of 0.22 which was experimentally investigated by Nakagawa and (1987) through a large-eddy simulation (LES). Volume of fluid (VOF) method is employed to resolve the formation of KB vortex and its interaction with the free surface. The numerical solutions are evaluated by comparing with the experimental measurements of mean velocity profiles, turbulence intensities and Reynolds shear stress. The present solutions further show the three-dimensional dynamics of recirculating flow and KB vortex by aid of visualization techniques.

2. NUMERICAL METHOD

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 requires no special near-wall treatment for wall-bounded complex turbulent flow. A two-phase volume of fluid (VOF) method is employed to capture the free surface deformation that interacts with the boil vortex shedding from the reattachment. The governing equations are solved by a second-order-accurate finite volume methods using OpenFOAM open source toolbox.

Turbulent inflow conditions including a stochastically-varying eddies at the inlet of computational domain may have a significant effect on the dynamics of flow downstream. In this work, 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 flow and turbulence quantities at the inlet of computational domain for the present LES are extract from a pre-calculated Reynolds-averaged Navier-Stokes (RANS) solutions. The 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 Nakagawa and Nezu (1987), as depicted in Figure 1

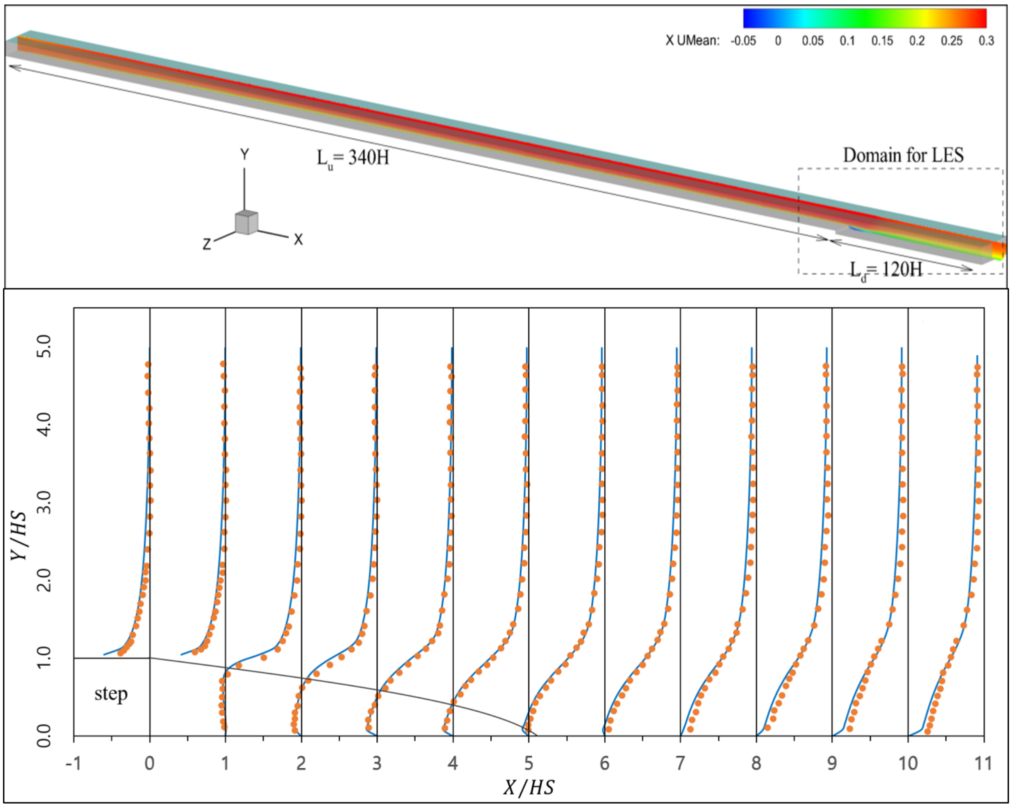

Figure 1. Computational domain and computed time-averaged velocity profiles compared with experimental measurements at selected locations.

3. RESULTS

Numerical solutions computed on a mesh of 1.26×10^7 computational cells are compared with experimental measurements of mean velocity profiles, Reynolds shear stress and turbulence intensity distributions at selected locations. The computed length of reattachment is comparable to the measurement. Present numerical solutions further illustrate the rich dynamics of vortices shedding from the top edge of step and its breakdown in the downstream region. The results reveal that the transition process of the turbulent flow field downstream of the step can be characterized by the Kelvin-Helmholtz instability of the shear layer and its breakdown to three-dimensional small scales vortices. The power spectra of streamwise velocity and pressure fluctuations computed along the shear layer and channel bottom boundary layer underscores that the present LES well revolve the evolution of coherent vortical structures downstream of the backward facing step.

4. CONCLUSIONS

The numerical solutions are comparable to the experimental measurements in terms of profiles of time-averaged velocity, turbulence intensities and Reynolds shear stress. The three-dimensional dynamic behaviors of turbulent flow structures associated with flow separation, reattachment and two-kind of vortices shedding from the separation and reattachment points, respectively, are elucidated by aid of flow visualization technique and statistical analysis.

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