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Applications of Three-Dimensional LBM-LES Combined Model for Pump Intakes

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Abstract. Lattice Boltzmann model (LBM) in conjunction with an accurate Large Eddy Simulation (LES) technology was proposed to simulate various vortical structures and their evolutions in open pump intakes. The strain rate tensor in the LES model is locally calculated by means of non-equilibrium moments based on Chapman-Enskog expansion, and bounce-back scheme was used for non-slip condition on solid walls and reflection scheme for free surface. The presented model was applied to investigate free-surface and wall-attached vortices for different water levels and flow rate. The vortex position, shapes and vorticities were predicted successfully under three flowing cases (i.e. critical water level (CWL), lower water level, lower flow rate), and the numerical velocity and streamline distribution were analyzed systematically. For CWL based on Froude number considering open channel flows, the shape and the location of various dynamic vortices were captured. Compare to the experimental results of CWL, more vortices were predicted for lower water level, and less vortices were observed for lower flow rate. The predicted velocities and vortex locations are in good agreement with the experimental of a small physical model. The comparisons demonstrated the feasibility and stability of above-mentioned model and numerical method in predicting vortex flows inside open pump intakes.

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Key words: Lattice Boltzmann model, Large Eddy Simulation, free-surface vortices, wall-attached vortices, open pump intakes.

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1 Introduction

The flows inside pump intakes are generally very complex and contains commonly many coherent structures. Poor designs of pump intakes and improper combinations of geometric parameters including pump bell give rise to bad flow pattern with various vortices, such as free surface vortices and wall-attached vortices [1], which influence safe and steady operation in pump stations, such as noise and vibration, impeller damage due to cavitation, and uneven impeller loadings [2–4].

Experimental techniques are effective and intuitive tools to investigate various vortices and corresponding generation causes and find practical solutions to eliminate or suppress them. Rajendran [5] used conventional flow visualization to identify the vortices, and obtained quantitative information on the number, location, shape, size, and strength of vortices by PIV technology in a simple but representative intake. Tomoyoshi et al. [6] studied the velocity and vorticity distribution in the sump using PIV method and visualization method, the experimental data show that the critical submergence for the free surface vortex and the wall-attached vortices are almost proportional to the flow rate in the intake. But experiments have some disadvantages such as high cost and long periods, and now numerical methods are useful and promising tools to investigate the flow field in pump intake and to optimize geometry parameters.

Tokyay et al. confirmed that LES model with a sufficiently fine mesh can accurately capture not only qualitatively but also quantitatively most of flow features in a pump intake [7]. Tang et al. [8] investigated the feasibility and applicability of turbulence models in predicting flows in the pump sump, and analyzed various vortex streamlines and strength in the sump. Aljaz Skerlavaj et al. [9] focused on the choice of a suitable turbulence model for flow simulations in an industrial pump intake, and successfully predicted the gas-core length of vortex for different submergence.

In recent years, emerging LBM becomes a popular tool to solve fluid flow problems. Tang et al. [10] used 2D LBM-SGS model to study the flow characteristics in a forebay, and compared with the experimental data, the numerical results show that the model scheme has the capacity to simulate complex flows in shallow water with reasonable accuracy and reliability. D. Bespalko et al. [11] simulated a turbulent channel flow by using the D3Q19 athermal LBM, and compared these numerical results to those calculated using Navier-Stokes-based solvers, the comparisons suggested that the athermal LBM should not be suitable for predictions of large fluctuations of density and temperature. Van Treek [12] presented the hybrid LBM to simulate a 3D turbulent heat transfer by using Smagorinsky sub-grid scale (SGS) model and validated laminar and turbulent natural convection in a cavity at various Rayleigh numbers up to 5×10^{10} for Prandtl number $Pr=0.71$ by means of relevant benchmark data. Sajjadi et al. [13] investigated the turbulent natural convection flow based on LBM coupled with LES. In this research, streamlines, local and average Nusselt numbers, and isotherm counters have been studied in different Rayleigh numbers. M. Fernandino et al. [14] carried out simulations of free surface duct flow with a flat interface with the LBM in combination with the Smagorinsky