Numerical Study of Air Entrainment and Energy Dissipation Mechanisms of Plunging Breaking Waves

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ABSTRACT

High-fidelity simulations of plunging breaking waves are performed through direct numerical simulations of the two-phase air-water flow. We investigate how air is entrained during plunging breaking waves in the present study. It is responsible for the formation of numerous bubbles owing to the breakup of the entrained air. The energy dissipation due to viscosity is under consideration. It is found that most of the wave energy is lost after the wave breaking for a relatively large initial steepness. A coupled Level-Set and Volume of Fluid (CLSVOF) interface capturing method combining a high-order scheme based on WENO are adopted to compute moving interface. In order to gain more details, the block-based adaptive mesh refinement is used. Share surface tension model and a mass-momentum consistent scheme are also adopted for simulating high-density-ratio flows such as breaking waves. In addition, some wave breaking process including steep wave formation, jet overturning, air entrainment and splash up are well reproduced in the present study. The goal of the present research is to provide a detailed quantitative description of the air entrainment and energy dissipation in the plunging breaking waves.

KEY WORDS: Plunging wave breaking; air entrainment; energy dissipation; direct numerical simulation;

INTRODUCTION

Numerical simulation of breaking waves is more challenging. Two-dimensional plunging breakers were simulated and detailed breaking process are obtained by the Chen et al. (1999). Dalrymple and Rogers (2006) and Landrini et al. (2007) conducted the simulation of 2D plunging breakers using smooth particle hydrodynamics techniques. They concluded that the jet does not penetrate the free surface and bound up to form a forward splash. A plunging breaking wave without surface tension and viscous effects was simulated by Adams et al. (2010) using VOF method with 134 million grids. The overall plunging wave breaking process including the formation of vertical jet and oblique splash in the plunging wave breaking over a submerged bump was simulated by Kang et al. (2012). Recently, with the raid development of numerical methods and computer capability, more and more researchers’ interests focus the small structures in wave breaking. In the study by Wang et al. (2012), up to 2.2 billion grids were used by Lubin & Glockner (2015) to study the fine vortex filaments which are generated at the early wave breaking stage. Wang et al. (2016) used very large grid (up to 12 billion grids) to perform the simulation of wave breaking process which focus on the small-scale structures such as bubble/droplet size distributions.

Air entrainment in wave breaking is of great importance to ship hydrodynamics and ocean engineering. The entrained air brakes into numerous bubbles which provide a source of acoustic and wake of ships that is easy to detect. It is also important to provide the transport of oxygen and carbon dioxide. Two different large-scale air entrainment process were observed in the experiment observation by Deane and Stokes (1999). Two main reasons which are responsible for the generation of bubble clouds: the relatively small bubbles are created by the jet impacting the free surface and the larger bubbles forms owing to the collapses of the cavity are summarized by Deane and Stokes (2002). The air entrainment occurring when wave breaks was described accurately by Lubin et al. (2006). Several air entrainment mechanisms including the jet impact entrainment, the splash-impact entrainment and turbulent entrainment in plunging jet and breaking waves were explained in detail by Kiger and Duncan et al. (2012). Deike et al. (2016) investigated the air entrainment and proposed a predictive model to estimate the amount of air entrained in three-dimensional breaking waves through direct numerical simulation and then is extended to open ocean in Deike et al. (2017).

Energy dissipation is significant in wave breaking process. Horikawa and Kuo (1966) proposed that bubbles entrained by breakers has important effect on energy dissipation in at initial stages. The energy dissipated by wave breaking could be up to 40% of the initial energy was concluded by Rapp and Melville (1990). Up to 50% of the wave energy is dissipated because of the entraining air and the rising bubbles intensify this process according to Lamarre and Melville (1991). Loewen and Melville (1994) pointed out that the amount of entrapped air can be related with the energy dissipation in breaking waves. The time evolution of the total energy shows three distinct stages which indicates different regimes of wave energy decay which is shown by Chen et al. (1999). Hoque (2002) demonstrated that wave steepness is important for the volume of entrained air and energy dissipation rate. The entraining air could account for a fraction between 10 to 35% of the energy dissipated by a wave breaking event was concluded by Iafrati (2011). Deike et al. (2015) discussed the influence of steepness and surface tension on the total energy dissipation through a 2-D numerical simulation.