International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 32, No. 1, March 2022, pp. 31–38; https://doi.org/10.17736/ijope.2022.jc838

http://www.isope.org/publications

A Hybrid Volume-of-Fluid/Euler–Lagrange Method for Vertical Plunging Jet Flows

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The vertical plunging jet is a typical multiscale two-phase flow problem in which a large number of microbubbles are formed by the impingement of a liquid jet with a free surface. Traditional numerical simulation methods experience difficulty reproducing both the large-scale phase interface evolution and the small-scale microbubbles at the same time. In this paper, a hybrid volume-of-fluid (VOF)/Euler–Lagrange method is adopted to simulate the vertical plunging jet flow problem. The large-scale air-water interface is captured by the VOF method, and the microbubbles are modeled as Lagrange points. Special algorithms are designed to realize a smooth transformation between two frameworks. Results indicate that satisfactory multiscale two-phase flow capture accuracy can be achieved with high efficiency by using the new method.

INTRODUCTION

Although computational fluid dynamics (CFD) algorithms have made great progress in recent years, the prediction of multiphase flow problems remains a unique challenge for numerical simulation. One of the most important reasons is that many multiphase flow problems involve a broad range of scales. This is also common in ocean-related problems, such as wave breaking. The evolution of waves is a typical large-scale flow phenomenon, whereas the bubbles and droplets that appear near the free surface are typical small-scale flow phenomena. Traditionally, there are limitations in the simulation methods for two-phase flow phenomena at different scales. For example, free surface flows were usually simulated by some mature interface capturing methods such as the volume of fluids, level-set, and front-tracking methods. These methods rely on computational grids to describe the phase interface, which needs extreme high computational cost to capture large numbers of bubbles and droplets at small scales. On the other hand, there are two well-known simulation methods designed for discrete multiphase flow problems: the Euler–Euler method and Euler–Lagrange method. In both methods, the discrete phase such as bubbles and droplets are modeled according to specific assumptions. The computational cost is obviously reduced, but it cannot simulate phase interface evolution. Therefore, there is a strong need to develop a hybrid method to solve the multiscale two-phase problems.

The vertical plunging jet is a typical multiscale two-phase flow problem in which a large number of microbubbles are formed by the impingement of a liquid jet with a free surface. Many experimental studies in recent years have analyzed the air entrainment characteristics of this problem. To analyze the air entrainment mechanism, some studies focus on the evolution of the air-water interface during the initial impact process (Soh et al., 2005; Qu et al., 2013). It has been found that when the jet makes impact with the free surface, the free surface collapses, and an air cavity is formed. Under the action of turbulent flow, the air cavity is broken, leading to air entrainment. Some studies focus on the evolution of underwater microbubbles. Roy et al. (2013) carried out a comprehensive visualization study to analyze the trajectory of entrained bubbles. Bigger bubbles caused by coalescence were found to move upward. Belden et al. (2012) used an advanced synthetic aperture imaging technology to make detailed measurements of the bubble distribution. For the flow field, particle image velocimetry was utilized by Kendil et al. (2012) to analyze the development of the impinging region and recirculation zone. Harby et al. (2014) proposed that the axial underwater velocity distribution satisfies the Gaussian distribution. Recently, Miwa et al. (2018) performed a more complex study of the interaction between a vertical plunging jet and an underwater inclined plate. Many mechanisms and characteristics have been elucidated by these experimental studies, which are also the main focus of relevant research at present.

There are mainly two ways to carry out numerical simulations for a vertical plunging jet. The first is the general interface capturing method. As mentioned above, this method relies on grid resolution, resulting in a large amount of computational cost. Therefore, previous studies usually used the two-dimensional domain (Qu et al., 2011; Brouilliot and Lubin, 2013). In spite of this, only the initial impact process could be simulated. The air entrainment phenomenon was hard to reproduce. Qu et al. (2012) also performed a three-dimensional simulation for a vertical plunging jet using 4 million grids. Physical quantities of the initial impact process were in good agreement with experimental data, but discrete bubbles were not captured either. Recently, Karnakov et al. (2019) carried out a direct numerical simulation (DNS) study using 67 million grids. Air entrainment and discrete bubbles were simulated obviously better than in previous studies, but the simulation was also very expensive. The second way of simulation is the hybrid method. Ma et al. (2010, 2011, 2012) built a hybrid method by combining the level-set model and two-fluid model, and they proposed a comprehensive subgrid air entrainment model. By using this numerical method, they carried out vertical plunging jet simulation and analyzed the distribution of bubbles on the millimeter scale. Shonibare and Wardle (2015) combined Euler–Euler multifluid methodology with the interface sharpening the volume of fluid (VOF) method. Both the initial impingement and the long-time entrained bubble plume phenomena were simulated. Although there are some parameter implications that need to be discussed further, this method has demonstrated unique advantages.

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Received August 2, 2021; updated and further revised manuscript received by the editors October 19, 2021. The original version (prior to the final updated and revised manuscript) was presented at the Thirty-first International Ocean and Polar Engineering Conference (ISOPE-2021), Rhodes, Greece (virtual), June 20–25, 2021.

KEY WORDS: Vertical plunging jet, multiscale problem, hybrid VOF/Euler–Lagrange method, high efficiency.