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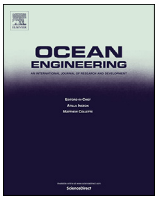

Numerical modeling of a buoyant round jet under regular waves

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ABSTRACT

This paper presents a numerical study on the kinematics of buoyant round jets in a wave environment. A buoyant round jet was horizontally discharged at the mid-depth in regular waves using three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations with the standard $\kappa - \varepsilon$ turbulence model. Three kinds of effluent with various densities were used for the jets. The numerical results were compared with the experimental data, with reasonable agreement observed. The mechanism of the jet oscillation under different wave-to-jet momentum ratios was presented. The effects of relative water depth, the ratio of the wave height to the water depth, and buoyancy on jet diffusion were considered. Among them, the ratio of the wave height to the water depth appears to be the most important factor on jet diffusion processes under the conditions being considered. Finally, the variations of the jet cross-sectional profiles in the potential core region and the near field region were studied.

1. Introduction

Discharging jets into coastal areas is a common practice in many industrial applications. For instance, residential sewage, hot water from power plants, and brine from seawater desalination plants are discharged through marine outfalls located along a coastline. The characteristics of the effluent (e.g., density, temperature) and environmental forces (e.g., currents, tides, and waves) should be considered to understand the process of effluent dispersion.

For a neutrally round jet under a wave environment, the diffusion characteristics have been quantified and qualified via laboratory measurements (Chyan and Hwung, 1993; Mori and Chang, 2003; Mossa, 2004; Ryu et al., 2005; Tam and Li, 2008; Chang et al., 2009; Hsiao et al., 2011; Wang et al., 2015). Mori and Chang (2003) observed various jet oscillation patterns under standing waves and classified them as symmetric, asymmetric, or discontinuous motions depending on the wave-to-jet momentum ratio. Ryu et al. (2005) found that the effect of wave dispersion on jet diffusion under regular progressive waves is dominated by wave height, not by wave phase. The jet centerline velocity decays rapidly and the jet width increases with increasing wave height. Chang et al. (2009) showed that the characteristics of the jet diffusion correlate closely with the wave-to-jet momentum ratio. Interestingly, they found that the jet vertical width is smaller than the jet horizontal width in the potential core region, but the opposite is true in the near field region. Hsiao et al. (2011) quantified the mean and turbulence properties of a jet under regular progressive waves. Their results indicate that the mean jet width, turbulence intensity, and Reynolds stress increased significantly when the jet was acted on by the waves. However, the mechanisms of jet oscillation and the variation of the jet width remain unclear.

A few studies have focused on the problem of a buoyant round jet in a current environment (Jirka, 2004, 2008; Lam et al., 2006) or a wavy environment (Chen et al., 2009; Lin et al., 2013). Jirka (2004) presented an integral model to predict the characteristics of turbulent buoyant jets in various flow fields. Jirka (2008) used the integral model to consider the effect of the discharge angle on a submerged negatively buoyant jet in a flat or sloping seabed. Lam et al. (2006) measured the trajectory, spreading, and dilution of a jet in a counterflow via laser-induced fluorescence. Chen et al. (2009) utilized acoustic Doppler velocimetry to measure the vertical velocity for a vertical buoyant round jet in random waves. They found that the dilution rate increases with increasing wave effect. Lin et al. (2013) measured the velocity field using particle image velocimetry for three kinds of buoyant jet in regular waves. They reported that the buoyancy effect had a considerably smaller influence than the wave dispersion effect on the enhancement of jet diffusion.

Due to limitations of measurement techniques and the use of an integral model, a complete three-dimensional (3D) flow field for a buoyant jet in a wave environment is hard to obtain. Numerical modeling has been used as an alternative to investigate the problem, with high-quality results obtained. For a jet discharging vertically in a wave environment, Chen et al. (2008) simulated a neutrally buoyant vertical round jet under random waves using a 3D LES model. Later, Chen et al. (2012) extended

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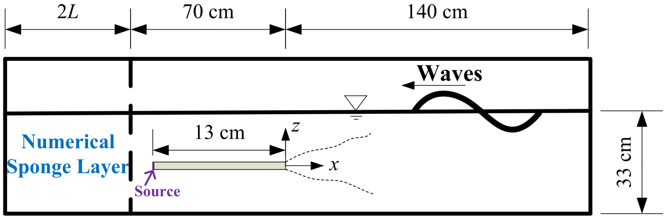

Fig. 1. An illustrative sketch of numerical wave tank (not to scale); L is the wavelength.

the model to consider the buoyancy effect. They found that the buoyant force weakens wave effect on the jet entrainment and mixing, leading to a slower decay rate of the maximum velocity and a narrower jet width. Recently, Xu et al. (2014) investigated the variation of the jet half-width in random waves and regular waves using the LES model, and found that a jet has a smaller width in regular waves.

A jet discharged in the direction opposite that of wave propagation has been investigated (Chen et al., 2015, 2017). Chen et al. (2015) used a 3D RANS equations model to discuss the wave effects for a neutrally buoyant horizontal round jet under regular waves. They found that the jet vertical-to-horizontal width ratio is insensitive to the wave period; with increasing wave height, it decreased in the potential core region and increased in the near field region. Chen et al. (2017) simulated a buoyant horizontal round jet in a stagnant environment. They reported that the buoyant force influences the jet vertical-to-horizontal width ratio in the near field, but not in the potential core region. However, the cause of vertical-to-horizontal width ratio for the buoyant jet in a wave environment remains unclear.

The objective of the present study is to investigate the kinematic characteristics of a buoyant round jet in a wave environment. As mentioned previously, the mechanisms of jet oscillating motion, the characteristics of diffusion, and the variation of the jet shape are not fully known, especially in the lateral direction. In this study, the 3D features of buoyant jets are obtained using a 3D numerical model named FLOW-3D. The model has been used to successfully simulate a neutrally buoyant jet in a wave environment (Chen et al., 2015) and buoyant jets in a stagnant ambient environment (Chen et al., 2017). The numerical model solves the RANS equations combined with the standard $\kappa - \varepsilon$ turbulence model, and the water surface deformation is captured using the volume of fluid method. The setup of the numerical tank is based on a previous physical experiment (Hsiao et al., 2011; Lin et al., 2013). The properties of jet diffusion and the cross-sectional profile under the effect of buoyancy and waves are discussed due to a lack of a 3D velocity field in the experiment.

2. Numerical model

2.1. *Governing equations*

A three-dimensional computational fluid dynamics code, FLOW-3D, solves Navier-Stokes type equations embedded with various turbulence closure models. In this study, RANS equations are solved with the standard $\kappa - \varepsilon$ turbulence model and the volume of fluid method is applied to track the water surface elevation (Hirt and Nichols, 1981). The interface between the fluid and solid boundaries is treated with the fractional area-volume obstacle representation (FAVOR) method, which computes the open area and volume in each cell to define the area that is occupied by an obstacle. The continuity equation, the momentum equation with Boussinesq approximation, and the turbulent advection-diffusion equation for density in tensor form are respectively:

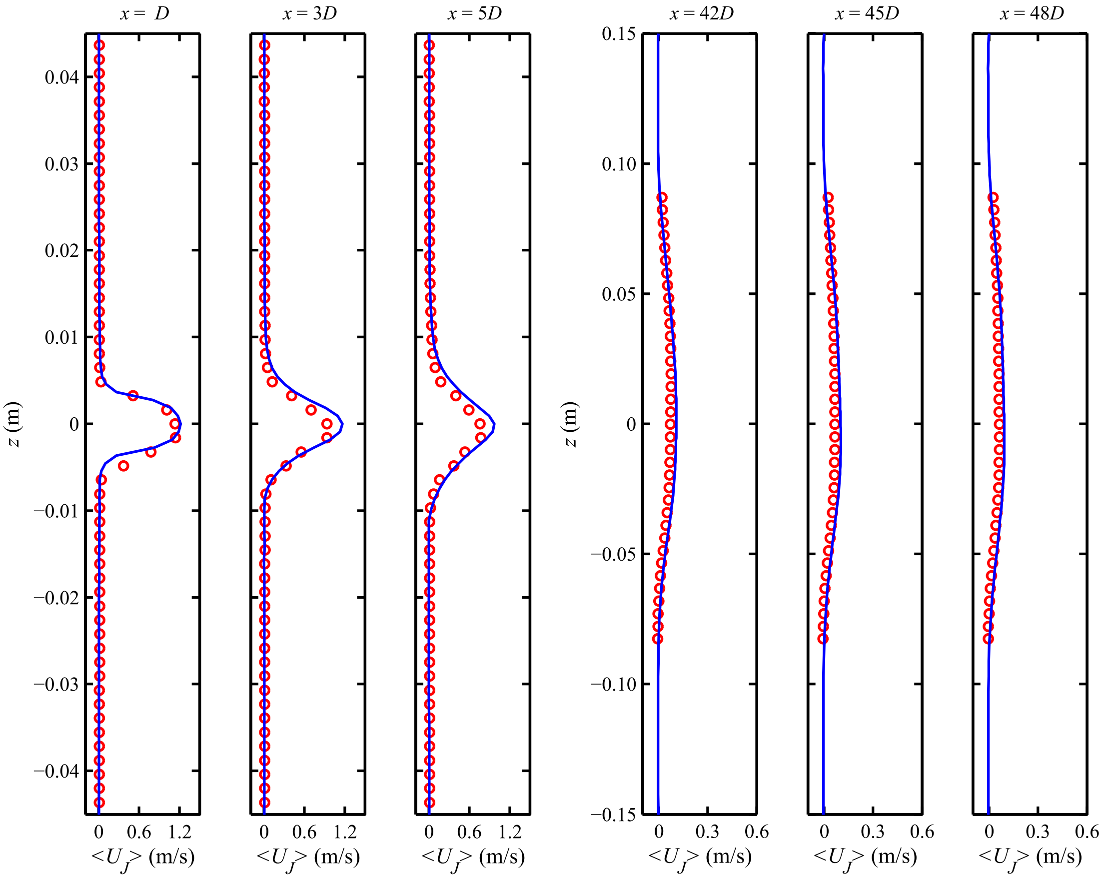

Fig. 2. Horizontal velocity profile for a neutrally buoyant jet under water waves (line: numerical model; circle: experimental data).