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Near-field dilution of a turbulent jet discharged into coastal waters: Effect of regular waves

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ABSTRACT

The effect of regular waves on three-dimensional scalar structures of a vertical round jet in the wave-following-current environment is investigated. The wave effect is represented by two dimensionless parameters, i.e. the wave-to-current velocity ratio R_{wc} and Strouhal number *St*. The jet concentration distribution, including 13 cases in the wave-following-current environment and 1 case in the current-only environment, is obtained using the large eddy simulation method and validated by experimental data. The results show that the characteristics of the distinctive 'effluent clouds' phenomenon, namely the effluent cloud size and the distance between adjacent effluent clouds, are strongly dependent on R_{wc} and *St*. As a result, different structures of the time-averaged concentration distribution are found in the transverse planes, and they are classified into three types: one-peak type, two-peak type, and three-peak type. The area of the concentration contour of $C = 0.25C_m$, where C_m is the time-averaged cross-sectional maximum concentration, is defined as the jet visual area that represents the jet dilution characteristic. It highlights the existence of an optimal wave-to-current velocity ratio (approximately 0.6 here) for the highest dilution of a jet in the wave-following-current environment, which provides useful guidelines for selecting the sites of wastewater or brine discharge projects.

1. Introduction

There is an urgent global requirement for the ocean disposal of urban treated wastewater and brine from desalination plants via submarine outfalls, as shown in Fig. 1 (Roberts and Snyder, 1993; Yang, 1995; Voutchkov, 2011). However, such plants are point sources of pollution, posing a potential threat to local human and wildlife communities (Roberts et al., 2010; Mendonça et al., 2013; Stark et al., 2016). A vital step in disposal management is selecting the site of submarine outfalls such that the wastewater or brine is quickly and effectively diluted by the ocean currents. Therefore, it is important to understand the effect of coastal waters on the mixing and dispersion of such discharge.

From the viewpoint of environmental hydraulics, the movement of discharged wastewater or brine usually forms a turbulent jet, identified as a near-field process or a far-field process according to different time and distance scales. The time and distance scales in a near-field process are of the order of minutes and tens or hundreds of metres, whereas those in a far-field process are of the order of hours and kilometres, respectively (Roberts, 1999). It is important to study near-field mixing and dispersion, which primarily affects jet dilution in the far field and partially dominates the entire process (Zhao et al., 2011; Chan et al., 2013). In the near field, there are two types of factors that affect the movement and dilution of the wastewater- or brine-formed jet, as shown in Fig. 2. One involves parameters associated with the jet itself, namely the initial velocity w_0, the jet density ρ_0, the geometry/diameter of the jet orifice d (circular or slit), and the discharge angle θ_0. The other involves several ambient fluid parameters, such as water depth D, ambient fluid density ρ_a, and ambient fluid velocity U_a. A certain variable P representing the jet characteristic is determined by the following equation:

$$P = f(w_0, \rho_0, d, \theta_0, D, \rho_a, U_a) \tag{1}$$

By comparing the values of ρ_0 and ρ_a, the jet is classified as a buoyant (e.g. salinity- or temperature-induced buoyancy) or non-buoyant jet. As for the angle θ_0, a jet outfall could be set horizontally, vertically, or obliquely in a discharge project. This study focuses only on the near-field movement and dilution of a vertical non-buoyant jet discharged into coastal waters. It should be noted that understanding such a jet is a prerequisite for studying an oblique buoyant jet.

In coastal areas, the tidal current is one of the leading dynamic factors that affect the jet movement. Its action could be considered as

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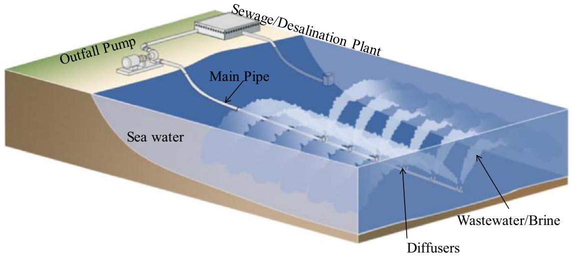

Fig. 1. Ocean disposal of wastewater or brine (modified from the diagram of Voutchkov (2011)).

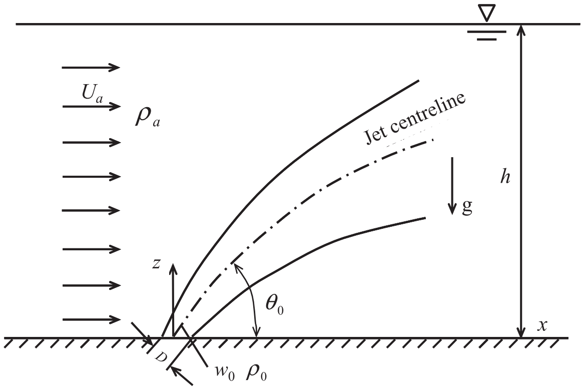

Fig. 2. Factors affecting jet motion in the near field.

the effect of a series of steady currents over a long period. Under the current effect, the vertical jet is deflected and divided into the near zone, curvilinear zone, and vortex zone (Subramanya and Porey, 1984). The deflection is primarily determined by the jet-to-current velocity ratio, R_{jc}. Jets in the current-only environment with R_{jc} in the range of 2–25 have been investigated extensively in previous studies (e.g. Hodgson and Rajaratnam, 1992; Kelso et al., 1996; Moawad and Rajaratnam, 1998; Muppidi and Mahesh, 2005; Megerian et al., 2007). As R_{jc} increases, the jet reaches a greater height and the jet shear layer instability is weakened (Alves et al., 2008). Kelso et al. (1996) experimentally showed that the folding and rolling up of the jet shear layer very close to the jet orifice contribute to the formation of the counter-rotating vortex pair (CVP). Consequently, the jet trajectories and dilution are closely related to R_{jc}. For example, Wong (1991) expressed the vertical centreline minimum dilution S_c of a jet in the current-only environment as

$$\frac{S_c d}{L_m} = 1.271\left(\frac{x}{L_m}\right)^{2/3} \tag{2}$$

where

$$L_m = \frac{M_0^{1/2}}{u_0} = 0.886 R_{jc} d \tag{3}$$

and M_0 is the jet initial momentum flux. Nevertheless, the jet flow structure remains virtually unchanged with increasing R_{jc}. Four large-scale coherent structures can be identified from a vertical jet in the current-only environment: jet shear layer vortices, horseshoe vortices, wake vortices, and CVP. Among these, CVP is a salient feature of the jet, which leads to a kidney-shaped and bifurcated cross-sectional scalar field, with distinct double concentration maxima (Lee et al., 2002).

In addition to the tidal current, wave motion is a common dynamic factor in coastal areas. It usually coexists with the tidal current. As discussed by Xu et al. (2016), the three-dimensional flow structure of a vertical round jet in the wave-current coexisting environment is significantly distinct from that in the current-only environment, e.g. the ‘effluent clouds’ phenomenon. This indicates that the wave action has a significant influence on the jet movement in the wave-current coexisting environment. However, only one case of a jet in such an environment was considered in their study. Xia and Lam (2004) studied a downward jet in an oscillating crossflow and found that the unsteadiness in the oscillating crossflow leads to an increase in the time-averaged jet width in the symmetrical plane. At present, there remains a lack of knowledge regarding the effect of wave periods and wave heights on the jet structure (particularly the three-dimensional structure) in the wave-current coexisting environment. Actually, instead of focusing on the jet-wave-current interaction, many researchers (e.g. Chyan and Hwung, 1993; Koole and Swan, 1994; Hsiao et al., 2011) have studied different flow structures of a jet in the wave-only environment by considering the relative strength between jets and waves. Mori and Chang (2003), Ryu et al. (2005), Chang et al. (2009) defined the wave-to-jet momentum ratio R_M and identified it as a key parameter for describing the wave-jet interaction. With increasing R_M, the horizontal jet in waves (similar to the vertical jet in waves) can be classified into three patterns: symmetric motion, asymmetric motion, and discontinuous motion (Mori and Chang, 2003). When the wave action is weak, the distribution of the time-averaged axial velocity or concentration in the cross sections follows a Gaussian shape. When the wave action is sufficiently enough, such a distribution will be flat-topped or bi-peaked, especially in the jet deflection region. This has been confirmed by Chyan and Hwung (1993), Koole and Swan (1994), Hsiao et al. (2011), Xu et al. (2014). Thus, the jet undergoes a faster decay of centreline velocity, with a larger spreading width and higher dilution rate at higher R_M. These conclusions serve as valuable references for the studies of the wave effect on the jet structure in the wave-current coexisting environment.

Following the work of Xu et al. (2016), this study aims to investigate the three-dimensional scalar structure of a vertical round jet in the wave-current coexisting environment, using the method of large eddy simulation (LES). Initially, the wave-current coexisting environment is set to the regular wave-following-current flow. This paper provides a detailed description of the wave effects on the jet initial dilution as well as some guidelines for selecting sites for wastewater or brine discharge projects.

2. Methodology

2.1. Dimensional analysis of jet characteristic parameters

The characteristic parameters affecting the jet motion are shown in Fig. 2 and expressed by Eq. (1). For a vertical round jet, dimensional analysis yields the following dimensionless parameters:

$$P = f\left(\mathrm{Re}_j, \frac{\rho_a}{\rho_0}, \frac{d}{D}, \frac{w_0}{U_a}\right) \tag{4}$$

where d is the jet diameter and Re_j is the jet Reynolds number, which is defined as

$$\mathrm{Re}_j = \rho_0 \frac{w_0 d}{\upsilon} \tag{5}$$

where υ is the kinematic coefficient of viscosity. The Reynolds number is sufficiently large in this study, and the jet motion belongs to the turbulent flow. The jet is non-buoyant, i.e. $\rho_a/\rho_0=1$, and the ratio of the jet diameter to the water depth is assumed to be extremely small, i.e. $d/D \approx 0$. From these assumptions, Eq. (4) is simplified into

$$P = f\left(\frac{w_0}{U_a}\right) \tag{6}$$

It can be seen that the velocity ratio w_0/U_a is a key factor that determines the movement and dilution of the non-buoyant vertical round jet. For a jet in the current-only environment, the velocity ratio