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Three-dimensional flow structure of a non-buoyant jet in a wave-current coexisting environment

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ABSTRACT

The three-dimensional flow structure of a non-buoyant vertical round jet in a wave-current coexisting environment is investigated. Laboratory experiments are first conducted to measure instantaneous flow patterns and mean velocity fields of the jet in a wave-current coexisting environment and a current-only environment for comparison. The distinctive 'effluent clouds' phenomenon is clearly observed in the wave-current coexisting environment but scarcely observed in the current-only environment. Moreover, the mean velocity vectors bend further toward the bottom when the wave effect is present. To reveal a more detailed flow structure of the jet in the wave-current coexisting environment, a large eddy simulation (LES) model is developed and validated against the experimental data. The mechanisms of formation and development of 'effluent clouds' are unravelled based on in-depth analysis of the vorticity contours and the high-pass filtered flow fields on the vertical symmetrical plane. With the variation of instantaneous jet-to-current velocity ratio, the 'effluent clouds' dynamically interact with the current-induced counter-rotating vortex pair (CVP), resulting in an inverted pear-shaped distribution of mean flow field above the CVP structure centre. This study highlights that the existence of 'effluent clouds' can lead to a significant enhancement of jet spread and dilution in the wave-current coexisting environment.
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1. Introduction

Offshore wastewater discharge is receiving increasing public attention due to its adverse impacts on coastal environments and ecosystems. To understand the movement of wastewater, which is usually in the form of a turbulent jet, it is essential to accurately assess its impacts on the surrounding environment. The jet movement is not only driven by its initial discharge momentum but also affected by the wave and current dynamics in sea waters. These factors may significantly affect the initial dilution of the jet in the near field and also alter its movement in the far field. It is therefore important to study the flow characteristics of the jet in the wave and/or current environment.

Previous studies mainly focused on two topics: a jet in the current-only environment and a jet in the wave-only environment. A vertical round jet in crossflow, which is a typical example of a jet in the current-only environment, has been investigated extensively by many researchers, with a focus either on the jet trajectory (Subramanya and Porey, 1984; Yuan and Street, 1998; Hasselbrink and Mungal, 2001; Muppidi and Mahesh, 2005) or on the jet flow and/or vorticity fields (Kelso et al., 1996; Yuan et al., 1999; Lim et al., 2001; Hsieh and Huang, 2003; Gopalan et al., 2004). According to these studies, the flow structure of a vertical round jet in crossflow can be divided into three zones from its exit, namely, near zone, curvilinear zone and vortex zone. In the near zone, the jet maintains its own structure because it is mainly driven by its initial discharge momentum. In the curvilinear zone, the jet centreline is deflected under the drag force of the crossflow, with a rapid decrease of jet momentum along the centreline. In the vortex zone, the jet moves along with the crossflow, forming the characteristic counter-rotating vortex pair (CVP) structure on the jet transverse planes. A jet in the wave environment has also been studied both experimentally (Chyan and Hwung, 1993; Koole and Swan, 1994a, b; Mori and Chang, 2003; Mossa, 2004; Ryu et al., 2005, Hsiao et al., 2011) and numerically (Dai and Wang, 2005; Chen et al., 2008, 2012). Unlike that in the crossflow environment, the jet body in the wave environment moves back and forth under the effect of wavy forces, forming three distinct zones: the deflection, transition and developed zones (Chyan and Hwung, 1993). In the deflection zone, the jet

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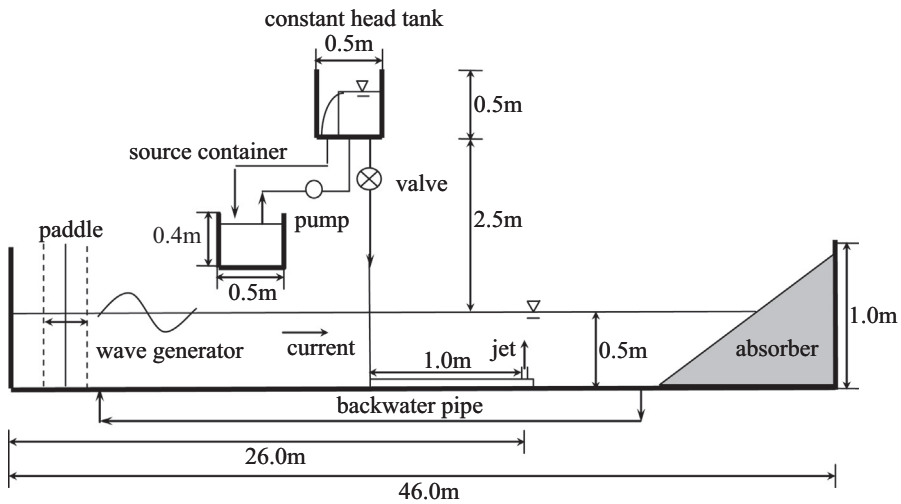

Fig. 1. Schematic design of the experimental setup.

preserves its identity and exhibits a large gradient of flow velocity with the ambient water, which is similar to the deflection of jet in crossflow. In the developed zone, the jet loses its rigidity and just oscillates with the water particles (Mossa, 2004). In the transition zone, the jet gradually changes from the 'deflection' mode to the 'developed' mode.

Limited work has been conducted thus far on a jet in the wave-current coexisting environment, although such type of dynamic condition is commonly found in real sea waters. Abdel-Rahman and Eleshaky (2004) conducted an experimental study on the interaction of a plane jet in a wavy crossflow environment and presented the mean velocity and the turbulent intensity profiles at six different downstream sections. Their study was only two-dimensional, but the significant changes of the jet velocity profiles demonstrate the necessity for further research on the three-dimensional flow structure of the jet in such type of environment. Other relevant work was carried out by Lam and Xia (2001) and Xia and Lam (1997, 2004), in which a downward jet discharged into an oscillating crossflow environment was studied. The oscillating environment was generated by the sinusoidal movement of the jet orifice in a steady crossflow; therefore, the oscillating velocity was uniform along the vertical direction. In their studies, the jet body was found to be periodically organised with the presence of 'effluent clouds', resulting in the gradual evolution of concentration profiles along the downstream, from a Gaussian to a double-peaked to a skewed distribution. In comparison with those in the steady crossflow, the width and the dilution of the jet in the oscillating crossflow environment were significantly enhanced. It should be noted that the above experimental setup was designed for the simulation of waves and currents in very shallow waters. However, to reduce the environmental impacts on coastal waters, sewage outfall is often allocated in a relatively deep water area, where the wave oscillation exhibits a strong variation in the vertical direction. To understand the jet characteristics in such an environment, a more genuine wave and current condition should be provided.

The objective of this study is to investigate the flow structure of a non-buoyant vertical round jet in a wave-current flume with relatively deep water depth. It is understood that the buoyancy may play an important role in the construction of a jet flow structure, either in the crossflow environment (Chu and Lee, 1996; Yu and Li, 1998; Kaminski et al., 2005) or in the wave environment (Chin, 1987; Natale and Vicinanza, 2001; Lin et al., 2013), particularly for the heated wastewaters; however, for the wastewater from the urban sewage, its density is usually not much different from that of the ambient water. In such a circumstance, the jet flow is mainly dominated by the discharge momentum as well as the external forces in the surrounding area, and the buoyancy effect can be roughly ignored. Moreover, understanding of the non-buoyant jet is a type of pre-knowledge for the study of buoyant jet, and this study will therefore focus on the non-buoyant jet only, while the buoyancy effect will be considered in our future work.

2. Experimental study

2.1. Experimental setup

The experiments were conducted in a wave-current flume that was 46.0 m long, 0.5 m wide and 1.0 m deep at the laboratory of the College of Harbor, Coastal and Offshore Engineering, Hohai University. A round acrylic pipe, with an inner diameter (d) of 1.0 cm, was installed at the mid-section of the flume. The jet was discharged vertically through the pipe at the centre of the flume, with the jet orifice 10.0 cm above the bottom. The jet water was supplied from a constant head tank above the flume, using an adjustable valve to control the volume flow rate. The wave was generated via a piston-type paddle. The current was generated via a flow control valve at one end and a V-notch weir at the other end. After propagating through the experimental section, the wave was dissipated by a wave absorber installed at the end of the flume. The wave reflection coefficient of the flume was less than 6%. The schematic design of the experimental setup is shown in Fig. 1.

The static water depth in the flume was kept at 0.5 m throughout the experiments. The free surface elevation was measured using two resistance wave gauges located at the upstream and downstream sides 1.0 m away from the jet centreline. A 16-MHz side-looking Micro Acoustic Doppler Velocimeter (ADV) was used to measure the flow velocity. The sampling volume for the ADV measurement was less than 0.09 cm^3, which was adequate for the measurements of the round jet with the diameter of 1 cm. A three-dimensional measurement frame was used to install the ADV, ensuring the accurate positioning of the ADV system. The maximum positioning error was 1 mm by use of this frame. The sampling rate was 25 Hz, and the sampling period was 20 times the wave period (1.4 s in this study), so there were 700 measured data points to calculate the mean velocity in the wave-current environment. The accuracy of the calibrated ADV probe was $\pm 1\%$ of the measured range. Before the

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