Investigation of Density Effect on Turbulent Round Jet in Wave Environment (2/3)

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ABSTRACT

An experimental study of a turbulent round jet discharged into a regular wave field is presented. The particle image velocimetry (PIV) technique was employed to measure quantitative mean and turbulence properties of the flow. Three kinds of effluent are used to examine the effects of buoyancy on the interactions of the horizontal round jet under regular waves. By comparing the buoyant jet in a stagnant ambient and in a wave field, the experiment demonstrates that the turbulence intensity and Reynolds stress of the buoyant jet receives significant influence when the jet is acted on by waves. It is also found that the turbulence production, advection, and dissipation terms of the buoyant jet under waves are greater than those of a buoyant jet in a stagnant environment, owing to the greater interaction between the buoyancy effects and the water waves near the free surface.

Keywords: Buoyant jet; Turbulence; Buoyancy effect; PIV

紊流射流於波浪場下與密度之效應研究 (2/3)

林建鋒 從文碩 蕭士俊 許泰文

摘要

本研究應用質點影像測速儀 (Particle Image Velocimetry, PIV) 量測水平浮昇射流與波浪交互作用後平均流場與紊流特性之變化，試驗中並改變三種不同紊流射流之初始密度，進而探討不同密度的射流與周邊流體交互作用後浮力與波浪之效應影響。經由試驗結果顯示，射流紊流強度除了受到本身初始密度差異之影響外，亦會受到波浪作用後而加速其擴散之分佈。最後，本研究比較波浪場作用下浮昇射流的紊流能量收支平衡中之生成項、對流項及能量消散項，其特性皆會受到浮力與波浪效應之交互作用而有增大的現象。

關鍵詞: 浮昇射流、紊流、浮力效應、質點影像測速儀

1. Introduction

In many industry and engineering projects in coastal regions, effluent is released into the vast ambient coastal water, such as brine discharge from a desalination plant and hot water discharge from a power plant. Most work on effluent mixing and transport focuses on the behavior of neutrally-buoyant turbulent jets in a stagnant environment or in a uniform current. In reality, initial buoyancy induced mixing and wave effect may play an important role in the mixing processes. It is thus important to understand the complex behavior of the flow in order to determine its possible adverse environmental...
impact. In the past, several studies on neutrally buoyant turbulent jets injected into a wave environment have been performed using laboratory measurements (Ryu et al., 2005; Chang et al., 2009; Hsiao et al., 2011). The buoyancy effect was not included in those studies.

Most existing studies on buoyant jets have been focused on jets discharged vertically and horizontally into a stagnant environment or a uniform current. Recently, an experimental study was conducted to investigate the behavior of a buoyant round jet in a counterflow using the LIF technique (Lam et al., 2006). The results demonstrate a combined forcing of momentum and buoyancy, aiding the design of ocean outfalls. A combined PIV and planar laser-induced fluorescence (PLIF) technique was also applied to investigate the turbulence properties of horizontal dense jets (Shao and Law, 2009). All the studies mentioned above either focus on neutrally buoyant jets in a wave environment or buoyant jets in a stagnant environment or uniform flow. There have been few studies on buoyant jets in a wave environment that include the wave dispersion effect.

The objective of the present study is to fill the gap by investigating the wave effects on buoyant jet behavior. In the approach, the previous study of Hsiao et al. (2011) that examined neutrally buoyant jets in waves is extended to positively and negatively buoyant jets in waves. Quantitative comparisons among the neutrally buoyant jet and the positively and negatively buoyant jets in a stagnant environment and under waves are made to demonstrate the jet buoyancy and wave dispersion effects.

2. Experimental Setup

The experiments were carried out in a glass-walled, glass-bottomed wave tank located in the Department of Hydraulic and Ocean Engineering at National Cheng Kung University. The tank is 25-m long, 0.5-m wide, and 0.6-m deep. A computer-controlled piston-type wavemaker is located at one end of the tank to generate the waves, and a sloping beach is located at the other end to absorb and dissipate the incident wave energy. The wave flume was filled with fresh water and kept at a constant depth of 0.33 m in the water throughout the experiment. Along the tank centerline, a round jet injected from a stainless steel tube with an inner diameter $D = 6.2 \text{ mm}$ was discharged horizontally at mid-depth in the direction towards the wavemaker. A water supply system controlled by a constant-head tank was installed to provide a constant head and exit velocity for the jet.

The PIV technique was used to measure two-dimensional flow velocities included a dual-head pulsed laser, laser light sheet optics, a CCD camera, and a synchronizer. The dual-head pulsed laser is a Nd:YAG laser that has a 20 Hz repetition rate and 120 mJ/pulse maximum energy output. It was used as the PIV illumination source. Images were recorded using a 12-bit CCD camera that has a 1600×1200 pixels resolution and 30 frames per second (fps) maximum framing rate. Water in the wave tank and the jet head tanks was seeded with nearly neutrally buoyant hollow glass sphere particles with a mean diameter of 9μm and specific gravity of 1.1.

Five fields of view (FOVs) were used in the PIV measurements, as shown in Fig. 1. The coordinate systems, where $x$ is the axial direction of the jet and $z$ is the vertically upward direction, and the origin at the jet exit are also shown in the figure. The size of the FOVs is $0.128 \times 0.096$ m$^2$, and their resolution is 0.08 mm/pixel. These four FOVs are slightly overlapped in order to cover the entire depth because the jet oscillates owing to the wave motion and the

![Fig. 1 Fields of view in PIV measurements](image-url)
The jet had a fixed exit velocity of $u_e = 1.28 \text{ m/s}$ throughout the experiment. The corresponding Reynolds number, defined as $Re = u_e D / \nu$ where $\nu$ is the kinematic viscosity of water, is 7,900. The waves generated in the experiment were regular progressive waves with a fixed wave period of $T = 1.0 \text{ s}$. The wave height $H$ was kept constant at 30 mm throughout the experiment. Three kinds of initial effluent were used to examine the effects of buoyancy on the interactions of a turbulent jet under water waves. Salt water was used as the negatively buoyant jet effluent. It was prepared in a salt-water tank by dissolving pure table salt (NaCl) in fresh water and the relative density of the salt water was kept at 1.02. In addition, positive buoyant jet was achieved by mixing water with alcohol and the relative density of the alcohol water was kept at 0.98.

The experimental conditions are summarized in Table 1, in which $L$ is the wavelength and $A(=H/2)$ is the wave amplitude. For turbulence statistics, all of the statistical velocity fields were obtained from 1,320 instantaneous vector fields at the fixed phase for each experimental condition.

Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Effluent Density</th>
<th>$H$ (mm)</th>
<th>$T$ (s)</th>
<th>$L$ (m)</th>
<th>$kA$</th>
<th>$kb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>water</td>
<td>1</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2*</td>
<td>salt</td>
<td>1.02</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3*</td>
<td>alcohol</td>
<td>0.98</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>water</td>
<td>1</td>
<td>30</td>
<td>1.0</td>
<td>1.4</td>
<td>0.067</td>
</tr>
<tr>
<td>5</td>
<td>salt</td>
<td>1.02</td>
<td>30</td>
<td>1.0</td>
<td>1.4</td>
<td>0.067</td>
</tr>
<tr>
<td>6</td>
<td>alcohol</td>
<td>0.98</td>
<td>30</td>
<td>1.0</td>
<td>1.4</td>
<td>0.067</td>
</tr>
</tbody>
</table>

* The free jet case

3. Results

The mean velocity was obtained by phase averaging the measured instantaneous velocities at the fixed phase for each experimental condition. Following Hsiao et al. (2011), the instantaneous velocity could be decomposed into the mean quantity and turbulent fluctuation as follows:

$$u_i = \langle u_{ni} \rangle + u'_i = \left( \langle u_i \rangle + \langle U_{ni} \rangle \right) + u'_i$$  \hspace{1cm} (1)

where $u_i$ represents the instantaneous velocity of the $i$th component while the superscript $j$ denotes the $j$th measurement, $\langle u_{ni} \rangle$ is the combined jet and wave phase-averaged mean velocity, $\langle u_i \rangle$ is the phase-averaged mean jet velocity, $U_{ni}$ is the (phase averaged) wave particle velocity, $u'_i$ represents the turbulent fluctuation, and $N$ is the total number of instantaneous velocities. In this study, $N = 1,320$ and $U_{ni}$ was directly measured using PIV under the same test conditions but without the jet.

Fig. 2 shows the measured mean flow fields for the cases of the neutrally buoyant jet and the buoyant jet using flow visualization and the PIV technique. To examine the effect of buoyancy on jet diffusion in the wave field and to better demonstrate the behavior of the jets, jet velocity profiles were extracted at five cross sections. The wave velocity $U_{ni}$ in Eq. (1) was removed from the figure so that only the jet velocity $\langle u_i \rangle$ is plotted. Note that the velocity maps cover the region indicated in the pictures (i.e., FOV 1). The jet centerline oscillation and velocity decay due to the wave motion can be clearly observed in the figure.

As the distance from the jet increases, the jet width spreads, jet momentum decreases, and the jet centerline becomes skewed owing to the buoyancy effect. Fig. 3 shows the normalized (by the centerline velocity $\langle u_e \rangle$) horizontal turbulence intensity $\langle u'^2 \rangle^{1/2}$, the vertical turbulence intensity $\langle w'^2 \rangle^{1/2}$, and the Reynolds stress $-\langle u'w' \rangle$ at $x/D = 47.0$. Each map is a combination of the four velocity maps obtained in FOVs 2-5. As shown in the figure, all three quantities for the neutrally buoyant free-jet case agree well with the measurements of Hussein et al. (1994), indicating that the turbulence measurements in the present study were performed accurately. The turbulence properties of the buoyant jets in a stagnant environment in Fig. 3 show only minor deviations from those of the neutrally buoyant jet, and no noticeable increase was observed in their
magnitude, except for a slight increase in turbulence intensity in the axial (horizontal) direction in Fig. 3(a).

Fig. 3 also shows the plots of the jet-under-wave cases. As expected, the width and magnitude of the jet turbulence properties increased significantly when the jets were under the waves. The averaged magnitudes in $<u'^2>^{1/2}$ and $<w'^2>^{1/2}$ increased by 74% and 65% for the neutrally buoyant jet, 35% and 37% for the negatively buoyant jet, and 46% and 53% for the positively buoyant jet. For Reynolds stress $\tau' = \rho \left( \frac{1}{2} \frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right)$, the zero value at the jet centerline in the free-jet cases does not appear at the center in the jet-under-wave cases; the zero value is slightly off-center owing to the asymmetric wave motion above and below the jets. On comparing the maximum values of $<\tau'>$, we observe that the averaged magnitude increases 1.6, 0.8, and 1.4 times for the neutrally buoyant, negatively buoyant, and positively buoyant jets, respectively.

The equation for the turbulence kinetic energy in tensorial form for a quasi-steady flow can be written as follows (Tennekes and Lumley, 1972):

$$
\begin{align*}
 & \frac{\partial k_i}{\partial t} + u'_i \frac{\partial k_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial}{\partial x_j} \left( \frac{\tau_{ij}}{\rho} \right) - 2\nu \frac{\partial u'_j}{\partial x_i} + S_{ij} + 2\nu \frac{\partial u'_j}{\partial x_i} \frac{\partial u'_j}{\partial x_i} \\
 & - \frac{1}{2} \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_j}{\partial x_i} \\
 & = 0
\end{align*}
$$

where $k_i$ is the turbulent kinetic energy, $S_{ij}$ is the Cartesian coordinates, $u'_i$ is the mean velocity, $u'_j$ and $\rho'$ represent the velocity and pressure fluctuations, $v$ is the kinematic viscosity, and $\rho$ is the fluid density. The mean rate of strain $S_{ij}$, the fluctuation rate of strain $S_{ij}$, and $k_i$ are defined as

$$
S_{ij} = \frac{1}{2} \left( \frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right)
$$

$$
S_{ij} = \frac{1}{2} \left( \frac{\partial u'_i}{\partial x_j} - \frac{\partial u'_j}{\partial x_i} \right)
$$

Since the velocity measurements in the present study are only two dimensional, the third component of turbulent kinetic energy was approximated as $<v'^2> <w'^2>$ by assuming the turbulent jet is axisymmetric. The turbulent diffusion cannot be determined due to the fact that the pressure transport was not measured. To calculate each term in the turbulent kinetic energy budget, the horizontal and vertical spatial derivatives in the energy budget equation were curve fitted to a self-similar profile using a least-square method. More detailed analysis can be found in Hsiao et al. (2011).

Fig. 4 shows the turbulent kinetic energy budget in the near field at $x/D = 47.0$ for the jets with the vertical axis normalized by $u'_i/L_w$, where $L_w$ is the half-width of the dimensional local jet. The diffusion and dissipation terms were combined and indirectly calculated using Eq. (3) after the advection term $<u'_i> \left( \frac{\partial k_i}{\partial x_j} \right)$ and production term $<u'_i u'_j> S_{ij}$ were obtained.
For the free-jet cases in Fig. 4(a1, b1, c1), the measurements of the neutrally buoyant jet without waves agree well with those reported by Panchapakesan and Lumley (1993). Following their approach, we neglected the pressure diffusion term and indirectly calculated the combined diffusion and dissipation profile on the basis of the turbulence energy budget in Eq. (3). Noted that even though the turbulence dissipation was not measured directly and was combined with the turbulent diffusion, the combined magnitude may be quite close to that of the dissipation term owing to the small ratio between the diffusion term and the dissipation term in a turbulent round jet, as reported by Panchapakesan and Lumley.

Fig. 4(a1, b1, c1) also shows the kinetic energy budgets of the buoyant jets in a stagnant environment. The magnitudes and widths of the advection, production, and combined diffusion and dissipation terms are significantly greater and wider for the alcohol jet and are skewed towards its positive buoyancy direction. The results show that the averaged peak value of the advection increases 0.5 and 1.5 times for the salt jet and alcohol jet, respectively, over the value for the neutrally buoyant jet. Furthermore, the averaged production decreases by 8% and increases by 22%, and the combined diffusion and dissipation increases by 16% and 73% for the salt jet and alcohol jet, respectively, over the corresponding values for the neutrally buoyant jet.

Fig. 4(a2, b2, c2) illustrates the turbulent advection, production, and combined diffusion and dissipation terms for the jets under waves. It clearly shows that their magnitudes are greater than those of the corresponding free jet. Among the plots, the turbulent production term in Fig. 4(b1, b2) gives perhaps the most direct measure of the wave effect; the average peak values in the jet-under-wave cases (the average of the two peaks) increase 2.0, 1.4, and 1.6 times those in the free-jet cases for the alcohol, salt, and neutrally buoyant jets, respectively. These increments due to the wave effect are much higher than those due to the buoyancy effect mentioned above. Furthermore, the averaged peak values of the advection and combined diffusion and dissipation terms for the jet-under-wave cases increase approximately 1.9 and 1.9 times, 3.2 and 2.1 times, and 3.7 and 2.5 times those in the free-jet cases for the alcohol, salt, and neutrally buoyant jets, respectively. These results further indicate that the wave motion significantly enhances the turbulence properties.

4. Conclusions

In the present study, buoyancy effects on a turbulent round jet in a stagnant environment and under regular waves were examined using particle image velocimetry. Positive (alcohol) and negative (salt) buoyancy of 2% difference in density were used to form two buoyant jets, along with a neutrally buoyant (water) jet. In the potential core region, the jets were affected by the buoyancy effect and were skewed in the direction of buoyancy. In the near field, the turbulence intensity and Reynolds stress of the buoyant jets in a stagnant environment showed no noticeable increase in their magnitudes over that of the
neutral buoyant jet, whereas the axial and vertical turbulence intensities increased by approximately 48% and 56%, respectively, and the maximum value of the Reynolds stress increased 1.3 times when the buoyant jets were under the wave motion, as compared to the free-jet cases. An examination of the turbulent kinetic energy budget indicates that the turbulence properties were more enhanced by the wave effect than by the buoyancy effect. Specifically, the turbulent production increased more significantly when the buoyant jets were under waves.

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References