

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/174924/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Xu, Zhenshan, Zhang, Wanru, Chen, Yongping and Pan, Shunqi 2025. Numerical study on mean and turbulent characteristics of an oscillating jet under the effect of currents. Ocean Engineering 317 , 120035. 10.1016/j.oceaneng.2024.120035

Publishers page: <http://dx.doi.org/10.1016/j.oceaneng.2024.120035>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



Numerical study on mean and turbulent characteristics of an oscillating jet under the effect of currents

Zhenshan Xu^{a,*}, Wanru Zhang^a, Yongping Chen^a, Shunqi Pan^b

^aCollege of Harbor, Coastal and Offshore Engineering, Hohai University, Nanjing 210098, China

^bHydro-environmental Research Centre, School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK

Abstract

The mean flow and turbulent characteristics of oscillating jets in the current environment are investigated using a three-dimensional large eddy simulation (LES) model. The effect of dimensionless parameters on oscillating jets is analyzed. Moreover, the mean flow velocity distributions of the downstream sections in the oscillating jet in the current environment and wave-current coexisting environment are compared. The results show that increasing the jet-current velocity ratio (R_{jc}) and the amplitude-jet velocity ratio (R_{aj}) can significantly increase the impact height and spreading range of the jet column, reduce its bending degree, and increase turbulence intensity, whereas the Strouhal number (S_r) has a minimal effect on the motion of the oscillating jet. Oscillating jets in a current environment and non-oscillating jets in a wave-current coexisting environment exhibit similar flow characteristics and mean velocity distributions, particularly when R_{aj}/R_{wc} is small, but the inconsistency in the range of action leads to stronger vertical penetration of the oscillating jets. This study reveals that the oscillating jet has a positive effect on mixing and dilution.

Keywords: oscillating jet; flow structure; vertical velocity distribution; turbulence characteristics; current environment

Nomenclature

CVP counter-rotating vortex pairs

d	pipe diameter
LES	large eddy simulation
PIV	particle image velocimetry
R_{aj}	amplitude-jet velocity ratio
R_{jc}	jet-to-current velocity ratio
R_{wc}	amplitude-to-current velocity ratio
SEM	synthetic eddy method
S_t	Strouhal number
T	oscillation/wave period
u_0	current velocity
u_w	wave amplitude
w_0	jet mean velocity (oscillating jet in a current environment)
	jet initial velocity (non-oscillating jet)
w_A	oscillating jet amplitude
x	horizontal distance from the center of the jet exit
y	transverse distance from the center of the jet exit
z	vertical distance from the center of the jet exit

23

24 1. Introduction

25 In recent years, with the rapid development of the global economy, a considerable quantity of domestic
26 sewage, industrial wastewater, and other pollutants have been discharged into the ocean worldwide. The pollutants
27 in the discharged wastewater will lead to the lowering of the quality of seawater, the aggravation of eutrophication,
28 and the threat to the reproduction and growth of marine organisms, which seriously affects the ecological structure
29 of the oceans and the quality of the environment. Jet discharge is the predominant method for introducing sewage
30 from rivers into the sea. It is extensively employed in the disposal of treated wastewater, thermal and nuclear
31 power plant thermal effluents, and concentrated brine from seawater desalination plants. The dilution and
32 diffusion process of pollutants in the jet discharge process is divided into two stages: initial dilution and
33 subsequent diffusion. The initial dilution stage of the jet affects the subsequent diffusion stage of the pollutant
34 concentration in the jet (Zhao et al., 2011). Consequently, analyzing the jet in the near section of the movement
35 and diffusion characteristics is crucial for enhancing the initial dilution of pollutants during jet discharge,
36 minimizing the wastewater mixing zone, and upholding water quality standards and marine environmental
37 protection.

Currently, the predominant form of wastewater discharge, such as industrial wastewater, is a non-oscillatory jet with a constant discharge rate. Extensive research has focused on the motion laws of non-oscillatory jets in current environments, particularly on jet trajectories (Muldoon and Acharya, 2010; Muppidi and Mahesh, 2005; Sau et al., 2004; Yuan and Street, 1998) and vortical fields (Karagozian, 2014; Mahesh, 2013). Sau et al. (2004) summarized four distinct vortical structures observed in non-oscillatory jets: shear layer vortices, horseshoe vortices, counter-rotating vortex pairs (CVP), and wake vortices. The CVP structure is considered the defining feature of jets in current environments. Fan et al. (2009) conducted an experimental investigation into the vortical formation and entrainment characteristics of shallow-water circular current jets using LIF flow visualization and PIV measurements. Their findings indicated that the behavior of current jets is influenced by the formation of the shear layer and the subsequent vortical structures generated by the jet and the surrounding ambient water body. Among these factors, the jet-to-current velocity ratio (R_{jc}) is the primary determinant of the motion and diffusion patterns of non-oscillatory jets in a current environment. An increase in the R_{jc} reduces the curvature of the motion trajectory and elevates the impact height (Kalifa et al., 2014; Plesniak and Cusano, 2005). Megerian et al. (2007) conducted experiments on R_{jc} ranging from 1 to 10. Their findings indicated that the transverse jet shear layer variation depends on the R_{jc} .

Two main factors affect the initial motion law of the jet: the parameters of the jet, including the initial velocity, jet density, the diameter/geometry of the jet orifice, and the angle of the jet discharge; and the background flow field parameters. The marine environment where these effluents are discharged is rarely stationary. The jet motion is driven not only by its initial discharge momentum but also by wave and current dynamics in seawater (De Padova et al., 2020). The surrounding water is strongly mixed with the buoyant jets and waves (Sharp et al., 2014; Webb and Tomlinson, 1992). Consequently, wastewater discharge projects to the sea are often sited in areas with strong ocean dynamics, such as waves and currents (especially tidal currents). Numerous scholars have researched the characteristics of jet motion under the influence of periodic wave motion. The jet

61 region can be subdivided into three sections according to the influence of wave action: the deflection, transition,
62 and developed zones (Mori and Chang, 2003). As wave action increases, the lateral distribution of the jet velocity
63 can exhibit three distinct forms: Gaussian, flat-topped, or double-peaked. The oscillatory nature of the waves,
64 which move back and forth, alters the jet's motion law. This periodic motion increases the degree of velocity
65 change in the ambient flow field. Furthermore, wave parameters such as wave height, wave period, and wave
66 phase affect the jet's motion and dilution characteristics. Ryu et al. (2005) employed the particle image
67 velocimetry (PIV) technique to quantify the instantaneous velocity field of a horizontal circular pipe jet in a
68 shallow water environment. Their findings indicated that surface wave amplitude exerted a more pronounced
69 influence on the jet's diffusion effect, while wave phase exhibited a comparatively minor influence. Yuan (2009)
70 established a three-dimensional numerical model of a vertical turbulent jet in waves and discovered that the effect
71 of waves on jet dilution depends on the ratio of the wave trace amplitude to the jet's expanded half-width along the
72 water depth. Chang et al. (2009) experimentally measured the jet velocity field under different wave conditions in
73 deep and shallow water. They found that jet mixing is stronger in shallow water and larger wave steepness,
74 concluding that the most important factor affecting the intensity of jet mixing is the momentum ratio of the wave
75 and the jet. Hsiao et al. (2011) investigated the jet process of a turbulent round tube jet under the action of regular
76 waves based on the PIV technique and concluded that the jet width, turbulence intensity and Reynolds stresses
77 increase significantly under the action of waves.

78 The combined effect of waves and currents can also significantly alter the motion characteristics of the jet.
79 Abdel-Rahman and Eleshaky (2004), Xia and Lam (2004), and Dong and Yu (2014) primarily analyzed the flow
80 structure and diffusion law on the two-dimensional symmetric longitudinal profile and found that several
81 large-scale "water clusters" appeared on one side of the jet in this environment. These "water clusters" indicate
82 that the combined action of waves and currents can enhance the mixing between the jet and the surrounding water
83 body. In recent years, Xu et al. (2016b, 2017, 2018) numerically simulated the three-dimensional motion and

dilution in a wave-current coexisting environment using a large eddy simulation model. Fang et al. (2024) explored the positive effects of increasing wave height and buoyancy on the mixing behavior of buoyant jets in a wave-current coexisting environment. Similar to the periodic oscillations of waves, studies on the motion and dilution effects of periodically oscillating jets in current environments have gradually increased. Hsu and Huang (2011) found that an oscillating jet in a current environment disperses faster and wider than a non-oscillating jet and that the smaller the Strouhal number, the better the jet's diffusion dispersion effect. Marcum et al. (2015) discovered that the jet's oscillation amplitude and frequency can affect the jet's motion and diffusion characteristics through physical experiments. Oscillating jets in current environments have been shown to have stronger lateral penetration and can be applied to film cooling (Mohammadshahi et al., 2020; Mohammadshahi et al., 2021). However, most studies on oscillating jets have been limited to the two-dimensional level, with fewer studies on the three-dimensional motion properties.

The objective of this research is to present a detailed description of the three-dimensional mean and turbulent characteristics of an oscillating jet under the effect of current using the method of large eddy simulation (LES). This manuscript is organized as follows. The numerical model, boundary conditions, model validation, dimensional analysis and numerical cases are outlined in Section 2. Section 3 includes the results and discussion on instantaneous and mean flow structure, turbulence characteristics, effect of dimensionless parameters and the comparison of mean characteristics between the oscillating jets in the current environment and jets in wave-current coexisting environment. Summary conclusions are provided in Section 4.

102

103 **2. Methodology**

104 2.1. Governing equations and numerical methods

105 A σ -coordinate three-dimensional large eddy simulation (LES) model was developed based on the spatially
106 filtered Navier–Stokes equations by Chen et al. (2008). Following Chen et al. (2008), Xu et al. (2016b, 2017)

107 further developed the model to investigate the three-dimensional flow structure and concentration behavior of jets
 108 in a wave-current coexisting environment. In this study, the flow structure of an oscillating jet in a current
 109 environment is examined using this LES model. The boundary conditions at the jet outlet are modified to enable
 110 sinusoidal oscillations, and the jet is embedded in a numerical current environmental flume. The governing
 111 equations are as follows:

$$112 \quad \frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$113 \quad \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + g_i + (\nu + \nu_t) \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \quad (2)$$

$$114 \quad \nu_t = l \cdot q = l^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}} = (C_s \Delta)^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}} \quad (3)$$

$$115 \quad \Delta = \sqrt[3]{\Delta x \Delta y \Delta z} \quad (4)$$

116 where u_i ($i=1, 2, 3$) are the velocity in the x_i direction; x_i ($i=1, 2, 3$) are the spatial coordinates x, y, z in horizontal,
 117 transverse, and vertical directions, respectively; t is the time; p is the pressure; ρ is the water density; g_i is the
 118 acceleration due to gravity; l is the characteristic length; q is the characteristic velocity; S_{ij} is the resolved strain
 119 rate tensor; C_s is the Smagorinsky constant; Δ is the grid spacing; $\Delta x, \Delta y, \Delta z$ are the spatial steps in the x, y , and z
 120 directions, respectively.

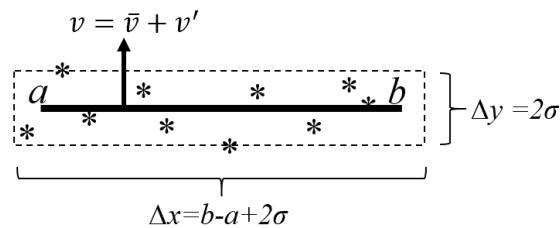
121 The model introduces the Lagrange-Euler numerical scheme to solve the free surface tracking problem. The
 122 numerical method employs the operator splitting method (Lin and Li, 2002), which divides the model solution
 123 into three steps: convection, diffusion, and pressure propagation. The convective term is solved discretely using
 124 the quadratic backward eigenline method and Lax-Wendroff format averaging, the diffusion term is solved
 125 discretely using the time-ahead, spatial-centered difference format, and Poisson's equation is solved using the
 126 conjugate gradient algorithm. A detailed study of the flow structure of a jet in a wave-current coexisting
 127 environment based on this model has been conducted and more details about the model can be found in Xu et al.
 128 (2016b, 2017, 2018).

129 2.2. Boundary conditions

130 The current inlet boundary follows a logarithmic flow vertical distribution and hydrostatic pressure
 131 conditions. The current outlet boundaries use the modified artificial sponge layer method with zero gradient
 132 conditions. The lateral boundaries are defined by impermeable boundary conditions, where the wall-normal
 133 component of each physical quantity is zero. The bottom boundary employs the wall function method for the
 134 pressure boundary and the slip condition for the velocity boundary. A damping zone is imposed to reduce the
 135 numerical reflection.

136 The exit turbulence of the oscillating jet is generated using the synthetic eddy method (SEM) (Shi et al., 2016)
 137 to fulfill the requirement of stochasticity of the components of the turbulent velocity. The SEM method is based
 138 on the following assumptions: turbulence is an ensemble of proposed sequential structures generated directly at
 139 the inlet boundaries; the spatiotemporal properties of these structures are defined by the shape function; and
 140 turbulence can be modeled based on stochastic eddies with specific positions and directions. The SEM method is
 141 described as follows.

142 Take the simpler one-dimensional turbulence boundary as an example, as shown in Fig. 1. To generate a
 143 unidirectional velocity signal in the interval $[a, b]$, it is necessary to construct a vortex motion plane $\Delta x \times \Delta y$. Each
 144 vortex has two attributes: coordinates (x_i, y_i) and length scale σ_i . The vortex center position in the figure is denoted
 145 by ‘*’. For simplicity, each vortex scale is temporarily defined as being equal to σ . The synthetic vortices are
 146 randomly distributed on the vortex plane, ensuring that every point on the turbulence boundary has a chance to be
 147 surrounded by vortices.



149

150

Fig.1. Vortex plane of motion.

151

152 Define f_σ to be the shape function of the vortex, which is tightly supported in the interval $[a-\sigma, b+\sigma, -\sigma, \sigma]$ and
 153 satisfies the normalization condition, as shown in Eq. 5. Each eddy is given a random variable characterizing the
 154 direction of the disturbance ε_i , which is chosen randomly only between +1 and -1 to ensure that the expectation of
 155 the velocity field pulsation is 0. Therefore, the velocity contribution of a particular eddy (with coordinate x_i and i
 156 denoting the number of the eddy) to a point (with coordinate x) on the turbulence boundary is shown in Eq. 6,
 157 where $f_\sigma(x-x_i)f_\sigma(y_i)$ denotes the distribution of the velocity of the i th eddy at that point. Similarly, the velocity of
 158 the superposition of N eddies at a point (with coordinates x) on the turbulent boundary can be derived (Eq. 7).

$$159 \quad \frac{1}{\Delta x \Delta y} \int_{-\Delta x/2}^{\Delta x/2} \int_{-\Delta y/2}^{\Delta y/2} f_\sigma(x) f_\sigma(y) dy dx = 1 \quad (5)$$

$$160 \quad v^{(i)}(x) = \varepsilon_i f_\sigma(x_i - x) f_\sigma(y_i) \quad (6)$$

$$161 \quad v'(x) = (1/\sqrt{N}) \sum_{i=1}^N \varepsilon_i f_\sigma(x_i - x) f_\sigma(y_i) \quad (7)$$

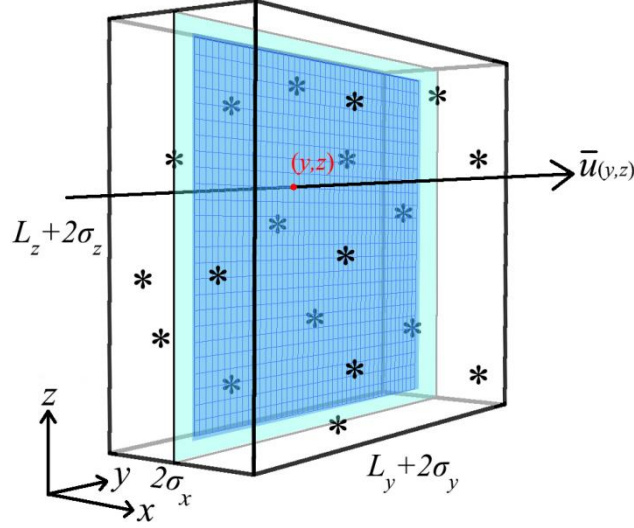
162 The number of eddies in the computational domain is determined by $(b - a) / \sigma$ to ensure that the turbulence
 163 boundary is fully covered by eddies. The autocorrelation function at any two points on the turbulent boundary can
 164 be calculated using Eq. 8.

$$165 \quad R_{vv}(r) = \frac{1}{\Delta x} \int_{-\Delta x/2}^{\Delta x/2} f_\sigma(x) f_\sigma(x+r) dx \quad (8)$$

166 In the following, the one-dimensional turbulence boundary $[a, b]$ is expanded to a two-dimensional planar
 167 turbulence boundary $[0, 0; L_y, 0; L_z]$ (shown as a blue area in Fig. 2), assuming that there is a mean flow velocity
 168 along the x -direction only. It is first necessary to construct a space for the motion of eddies in three-dimensional
 169 space, referred to as the vortex box, which has a volume of $[-\sigma_x, \sigma_x] \times [-\sigma_y, L_y + \sigma_x] \times [-\sigma_x, L_z + \sigma_x]$ to ensure that
 170 every point on the turbulence boundary can be surrounded by eddies. Similarly, the shape function of the eddies is
 171 tightly supported within the vortex box and satisfies the normalization condition. The vortices are randomly
 172 distributed throughout the vortex box and convect at a constant characteristic velocity. Assume that the coordinate
 173 of the i th vortex at moment t is (x_i, y_i, z_i) , and that the horizontal coordinate of this vortex changes to

174 $x_i(t + dt) = x_i(t) + \bar{u}(y_i, z_i) dt$ moment $t + dt$. When a vortex moves out of the vortex box, it will randomly generate
 175 a vortex with the same length scale at an arbitrary position on the inlet boundary of the vortex box.

176



177

178

Fig.2. Vortex box.

179

180 The instantaneous and turbulent velocities resulting from the superposition of N vortices at a specific point
 181 on the turbulent plane at time t (with coordinates $(0, y, z)$). It can be expressed as follows,

$$182 \quad u_i(x, t) = \bar{u}_i(x) + a_{ij} u'_j(x, t) \quad (i, j=1, 2, 3) \quad (9)$$

$$183 \quad u'_j(x, t) = \frac{\delta}{\sqrt{N}} \sum_{k=1}^N \epsilon_j^k f_\sigma(x - x^k(t)) \quad (j=1, 2, 3) \quad (10)$$

$$184 \quad f_\sigma(x - x^k(t)) = \sqrt{\frac{V_B}{\sigma_x \sigma_y \sigma_z}} f\left(\frac{x - x^k(t)}{\sigma_x}\right) f\left(\frac{y - y^k}{\sigma_y}\right) f\left(\frac{z - z^k}{\sigma_z}\right) \quad (11)$$

$$185 \quad f(\zeta) = \begin{cases} \sqrt{1.5}(1 - |\zeta|) & |\zeta| \leq 1 \\ 0 & |\zeta| > 1 \end{cases} \quad (12)$$

$$186 \quad a_{ij} = \begin{pmatrix} \sqrt{R_{11}} & 0 & 0 \\ R_{21}/a_{11} & \sqrt{R_{22} - a_{21}^2} & 0 \\ R_{31}/a_{11} & (R_{32} - a_{21}a_{31})/a_{22} & \sqrt{R_{33} - a_{31}^2 - a_{32}^2} \end{pmatrix} \quad (13)$$

$$187 \quad N \approx \frac{L_y \cdot L_z}{\sigma_y \cdot \sigma_z} \quad (14)$$

$$188 \quad dt \approx 0.1 \sigma_i / \bar{u}_i \quad (15)$$

189 Where u_i , $\bar{u}_i$ and u'_i is the instantaneous flow rate, mean flow rate and turbulent flow rate in the i -direction,

190 respectively; a_{ij} is the Cholesky decomposition of the Reynolds stress tensor; δ is the turbulence amplification
191 factor, set by default at 1.0; N is the number of vortices; ε_j^k is a random variable that characterizes the direction of
192 the perturbation, which is randomly chosen between +1 and -1; V_B is the volume of the vortex box; $f(\zeta)$ is the
193 shape function, which, according to Lu and Dai (2016), is selected as the trigonometric function; dt is the time
194 step.

195 In this study, the jet outlet is round with a diameter of 1.0 cm. However, for the numerical simulation of the
196 jet outlet fitting process, a rectangular outlet is employed. To approximate the actual situation, this geometry is
197 simplified to a square with an equivalent cross-sectional area, resulting in a side length of 0.886 cm. The mean
198 flow velocity at the outlet boundary is characterized by velocities of 0 m/s in the y and z directions and 0.5 m/s in
199 the x direction. The outlet is discretized into 1010 grids, and the simulation includes 25 vortices, each with a
200 characteristic length of 0.004 m. The time step dt is set to 0.001 s. The Reynolds number for this configuration is
201 calculated to be 4393, indicating that the flow mode is turbulent. During the simulation experiments, the
202 turbulence amplification factor was set to 1.5, and the boundary condition on the jet outlet was established at 0.96.

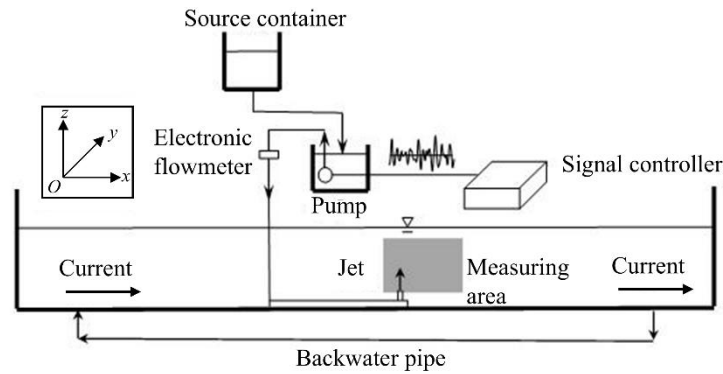
203 2.3. Model validation

204 2.3.1 Experimental description

205 The schematic design of the experimental setup is shown in Fig. 3. Experiments designed to validate the
206 numerical model were conducted using a 46.0-m-long, 0.5-m-wide, and 1.0-m-deep wave flume with a water
207 depth of 0.5 m. A round acrylic pipe with a diameter of 0.01 m is installed at the mid-section of the flume. The jet
208 is discharged vertically through the pipe along the centerline of the flume, with the jet orifice positioned 0.10 m
209 above the bottom. The sinusoidal oscillating jet is generated by a specialized controller that regulates the pump
210 based on an input signal. Flow velocity measurements were conducted using a Vectrino Profiler. The experiments
211 were performed under three conditions: a jet in a still water environment, a jet in a current-only environment, and
212 an oscillating jet in a still water environment. The parameters for the experiments are as follows: the initial

213 velocity of the jet w_0 is 0.5 m/s, the average velocity of the current u_c is 0.066 m/s, and the amplitude of the
 214 oscillating jet in a still water environment is 0.25 m/s with a period of 2 s. The three-dimensional Cartesian
 215 coordinate system (x, y, z) is defined such that x represents the transverse coordinate along the direction of current,
 216 y is the transverse coordinate, and z is the longitudinal coordinate. The origin of the coordinate system is located at
 217 the center of the jet outlet. All experimental data were used to validate the numerical model.

218



219

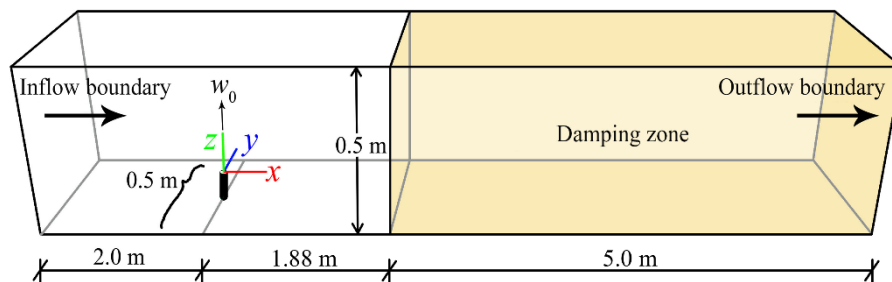
220

Fig.3 Schematic diagram of experimental device.

221

222 2.3.2 Computational domain and grid sensitive tests

223 The consistency of each parameter of the jet and current is ensured for the corresponding groups of
 224 experimental and numerical simulations. Fig. 4 shows the computational domain of the numerical model, which
 225 has a length of 8.88 m, a width of 0.5 m, and a height of 0.5 m. The length of the damping zone is 5 m, and the jet
 226 outlet is located 2.0 m from the inflow boundary.



227

228

Fig.4. Computational domain.

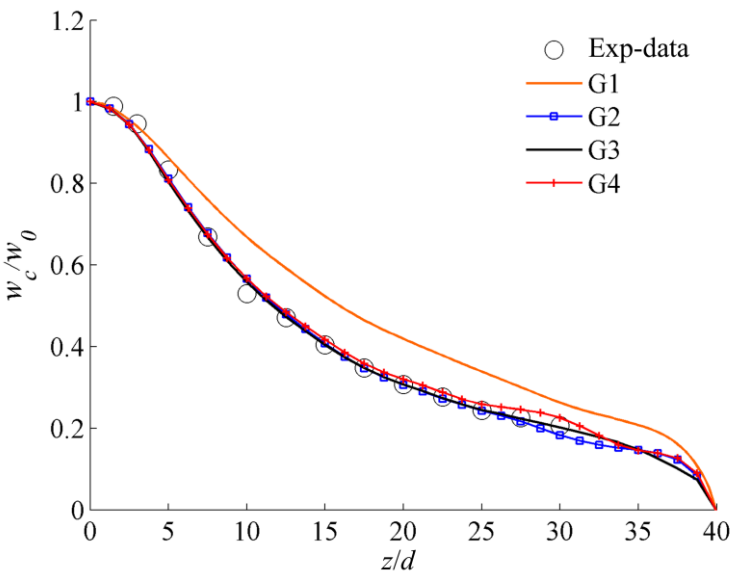
229

230 Grid sensitivity tests were conducted using four sets of non-uniform grid systems, named G1 to G4. All grid
231 systems made the grid refinement gradually near the jet center on the x - y plane, with the detailed grid information
232 presented in Table 1. The time step for all grid systems is set to 0.002 s. The mean vertical velocity distribution of
233 the jet in still water is plotted in Fig.5. The vertical profiles of the mean velocity at three different downstream
234 locations for the jet in the current-only environment are shown in Fig. 6. Among all numerical results, the result of
235 G1 exhibits the largest discrepancy with the experimental data, indicating that the grid configuration of the jet
236 outlet is critical to the outcomes of the jet simulation. The results for G3 and G4 align well with the experimental
237 data. It indicate that the grid size of G3 is fine enough for the numerical simulation. Therefore, the results using
238 the grid system G3 are used to validate the model accuracy against the experimental data.

239

Table 1. Grid information

Grid system	Grid nodes	Grid division
G1	$217 \times 81 \times 126$	6×6
G2	$228 \times 91 \times 126$	8×8
G3	$236 \times 99 \times 126$	10×10
G4	$242 \times 107 \times 126$	12×12



240

241

Fig.5. Grid convergence test under a still water environment.

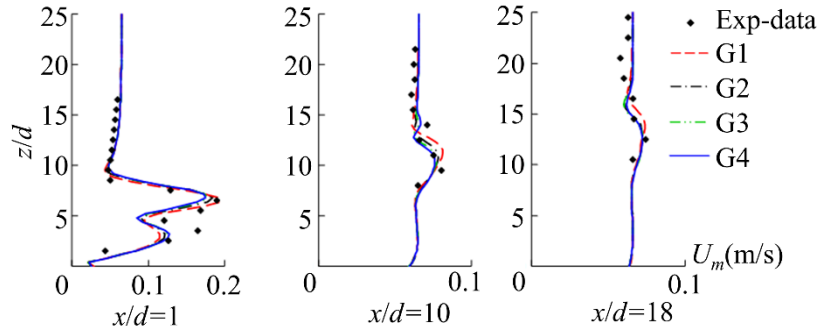


Fig.6. Grid convergence test under a current-only environment.

2.3.3 Model validation

Figs. 7 and 8 show the comparison between numerical results and experimental data in the non-oscillating jet in still water environment and oscillating jet in still water environment. Numerical results on the vertical velocity decay of jets in both environments align well with the experimental data. For the vertical velocity distributions at the $z/d = 15$ and $z/d = 25$ sections, the numerical simulation results are slightly higher than the experimental results near the location of $x/d = 0$. However, the simulation results in the near zone, excluding the jet outlet, are consistent with the experimental data and accurately reflect the vertical velocity distribution. This validates the applicability of the LES model for both non-oscillating and oscillating jets in still water environments.

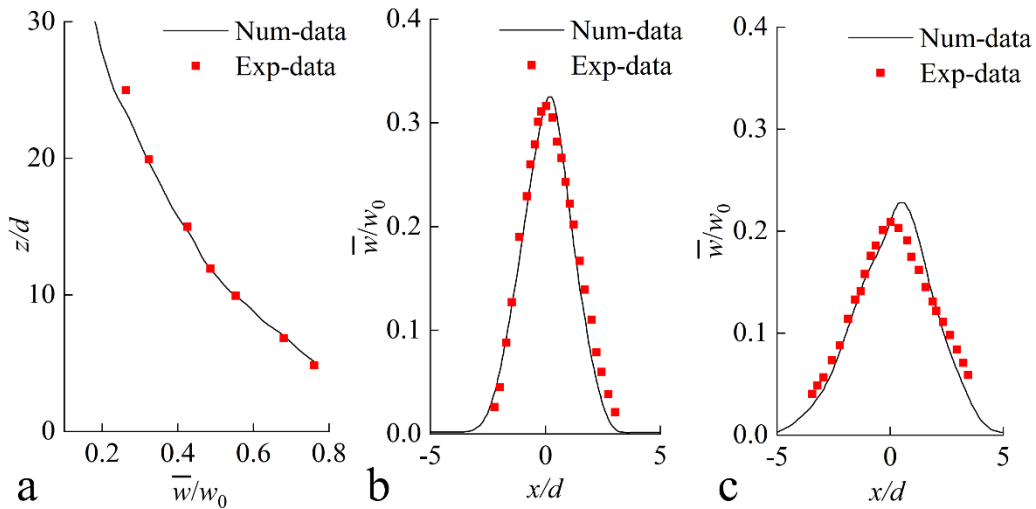


Fig.7. Comparison between numerical model results and experimental data of non-oscillating jet in still water environment: (a)

vertical velocity decay, (b) velocity distribution on section $z/d=15$, (c) velocity distribution on section $z/d=25$, more validations of jets in still water environment were shown in Zhou et al. (2011).

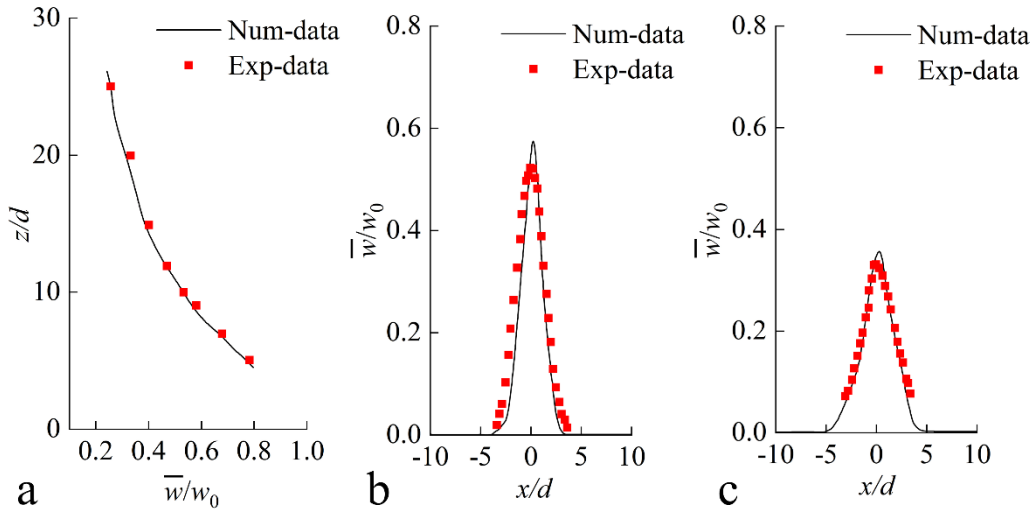


Fig.8. Comparison between numerical model results and experimental data of oscillating jet in the still water environment: (a)

vertical velocity decay, (b) velocity distribution on section $z/d=15$, (c) velocity distribution on section $z/d=25$.

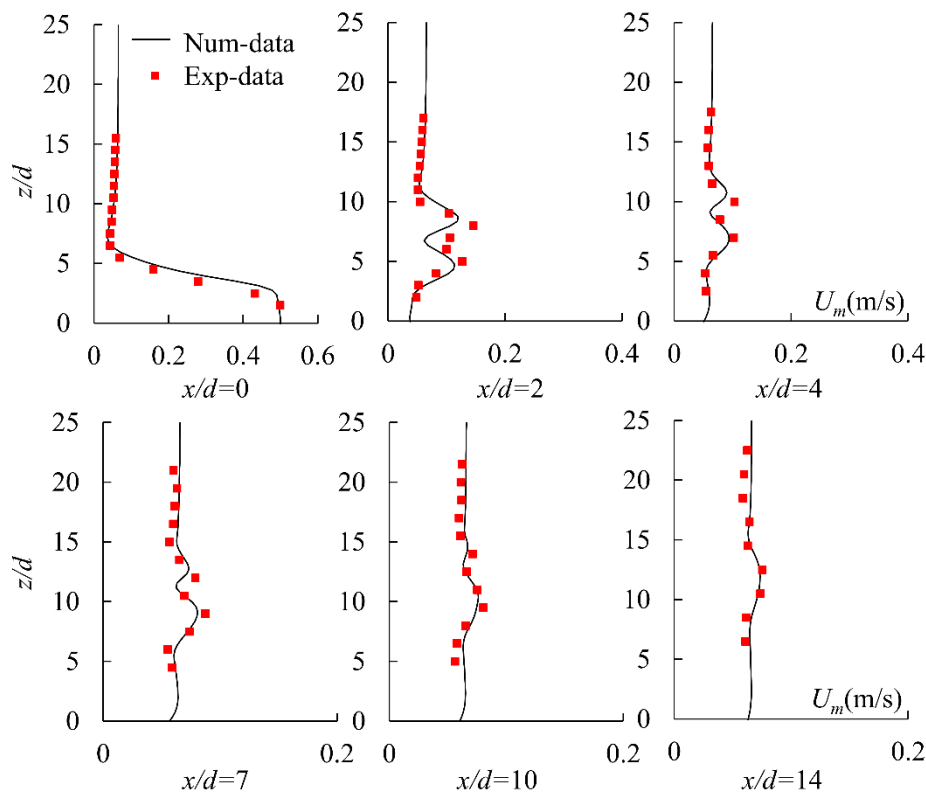
Fig. 9 shows the comparison of vertical profiles of the velocity magnitude on the symmetrical plane ($y/d=0$)

between the numerical results and the experimental data at six downstream sections. It can be observed that the location of the maximum vertical velocity varies across different longitudinal sections. The strong agreement between the simulation and experimental results indicates that the LES model can accurately simulate jet near-field behavior in a current-only environment. In addition to mean velocities, the turbulent properties obtained from both numerical and experimental methods are also compared, as shown in Fig. 10. The comparison shows that the model successfully reproduces the variation of turbulence intensity along the water depth at each downstream section.

Above all, the good agreement between the numerical and experimental results demonstrates the general accuracy of the LES model. It proves that the model can reasonably predict the distribution of vertical flow

274 velocity along the water depth at different sections of the jet.

275



276

277 **Fig.9.** Comparison of mean vertical magnitude on the vertical symmetrical plane ($y/d=0$) between numerical results and
278 experimental data at six downstream locations ($x/d=0, 2, 4, 7, 10, 14$) for the jet in the current-only environment, more validations
279 were shown in Xu et al. (2016a).

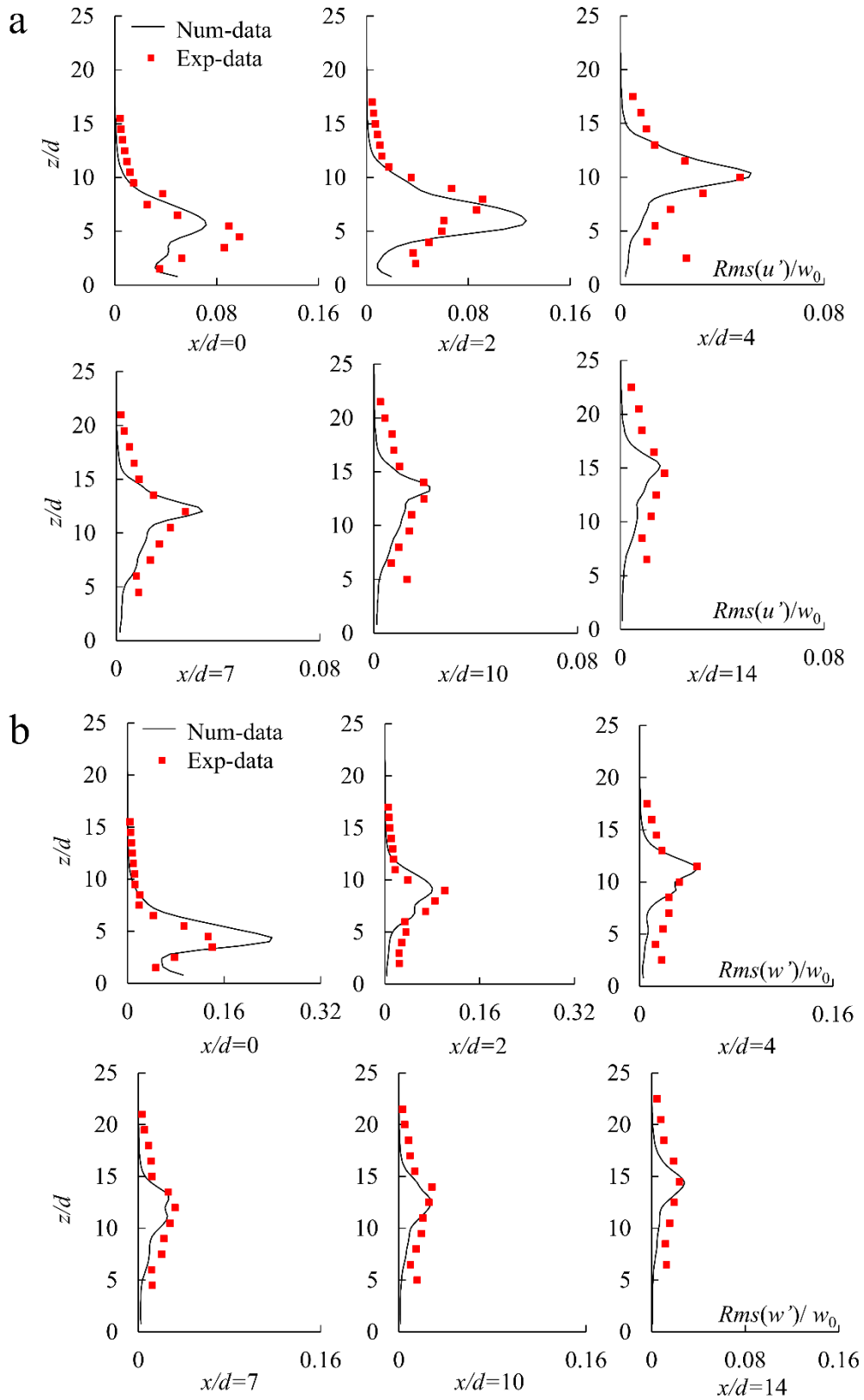


Fig.10. Comparison of Velocity turbulence fluctuations on the vertical symmetrical plane ($y/d=0$) between numerical results and

experimental data at six downstream locations ($x/d=0, 2, 4, 7, 10, 14$) for the jet in the current-only environment: (a) turbulence

fluctuations rms (u'), (b) turbulence fluctuations rms (w'), more validations were shown in Xu et al. (2016a).

284

285 2.4. Dimensional analysis and Numerical cases

286 The motion of an oscillating jet in a current environment is influenced by two distinct factors. The first factor
 287 is the intrinsic properties of the jet, including the pipe diameter (d), mean velocity (w_0), oscillation period (T), and
 288 amplitude (w_A). The second factor is the background flow field parameters, specifically the current velocity (u_0).
 289 The above parameters are the most basic factors affecting jet motion characteristics. By combining these
 290 parameters, dimensionless parameters can be derived to describe the jet's motion characteristics. The jet-to-current
 291 velocity ratio (R_{jc}) is a key parameter for describing jet flow and mixing characteristics. The amplitude-to-jet
 292 velocity ratio (R_{aj}) reflects the influence of oscillation amplitude, and the Strouhal number (S_t) reflects the
 293 influence of the oscillation period. The formulas for these three dimensionless parameters are as follows:

$$294 R_{jc} = w_0 / u_0 \quad (16)$$

$$295 R_{aj} = w_A / w_0 \quad (17)$$

$$296 S_t = d / (u_0 T) \quad (18)$$

297 The combined characteristic parameters of the non-oscillatory jet in a current environment mainly include the
 298 initial momentum of the jet and characteristic length. Similar combined characteristic parameters can be used to
 299 analyze the dilution law of the oscillatory jet. Considering the oscillatory nature of the jet, the characteristic
 300 velocity (w_{ch}) is defined as follows:

$$301 w_{ch} = w_0 \left(1 + \alpha_{wc} \frac{w_A}{w_0} \right), \alpha_{wc} = \frac{4}{T} \int_0^{T/4} \cos \omega t dt \quad (19)$$

302 where ω is the oscillation frequency of the jet ($\omega = 2\pi/T$). By integrating the calculation, we can obtain α_{wc} as
 303 0.637, which characterizes the degree of contribution of the oscillation velocity to the characteristic velocity. The
 304 characteristic momentum M_{ch} of the oscillating jet is:

$$305 M_{ch} = 0.25 \pi d^2 w_{ch}^2 \quad (20)$$

306 The physical meaning of the characteristic length scale L_m of an oscillating jet in a current environment is the

relative strength of the oscillating jet to the current, which can be expressed by the following equation,

$$L_m = M_{ch}^{0.25} / u_0 \quad (21)$$

In total, 10 cases of numerical experiments are designed to investigate the three-dimensional mean and turbulence characteristics of an oscillating jet in a current environment (Table 2). Various current velocities (w_0), jet amplitudes (w_A), and oscillation periods (T) are considered to examine the effects of R_{jc} , R_{aj} , and S_t on the mean and turbulence characteristics. Additionally, 2 cases of jets in a wave-current coexisting environment (Table 3) are included to compare the differences between the two environments.

Table 2. Parameters of an oscillating jet in a current environment used in numerical simulations.

Case	Jet mean velocity w_0 (m/s)	Current velocity u_0 (m/s)	Jet amplitude w_A (m/s)	Oscillation period T (s)	Amplitude-to-jet velocity ratio (R_{aj})	Strouhal number (S_t)
CJ00	0.50	0.05	/	/	/	/
CJ02	0.50	0.05	0.1	1.0	0.2	0.2
CJ03	0.50	0.05	0.2	1.0	0.4	0.2
CJ06	0.50	0.05	0.1	2.0	0.2	0.1
DJ00	0.40	0.05	/	/	/	/
DJ01	0.40	0.05	0.04	1.0	0.1	0.2
DJ02	0.40	0.05	0.08	1.0	0.2	0.2
DJ03	0.40	0.05	0.16	1.0	0.4	0.2
DJ06	0.40	0.05	0.08	2.0	0.2	0.1
DJ07	0.40	0.05	0.16	2.0	0.4	0.1

Table 3. Parameters of a jet in a wave-current coexisting environment used in numerical simulations

Case	Jet initial velocity w_0 (m/s)	Current velocity u_0 (m/s)	Wave amplitude u_w (m/s)	Wave period T (s)	Wave height H (m)	Amplitude-to-current velocity ratio (R_{wc})	Strouhal number (S_t)
WJ01	0.50	0.05	0.01	1.0	0.011	0.2	0.2
WJ02	0.50	0.05	0.02	1.0	0.021	0.4	0.2

318

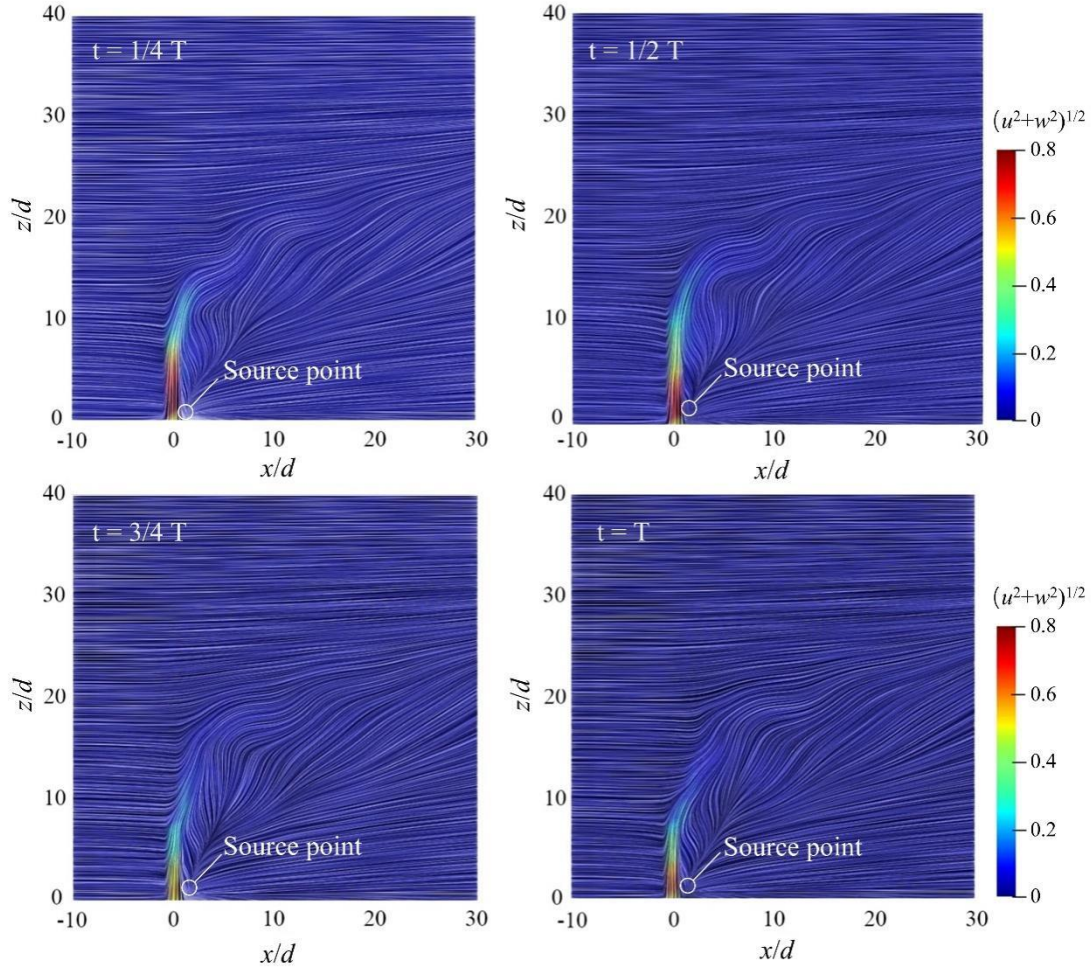
319 3. Result and discussion

320 3.1. Instantaneous flow structure

321 Since the oscillating jet is periodic, the instantaneous flow field of the oscillating jet is phase-averaged to
322 demonstrate its motion characteristics. It is defined that within one cycle, $t=1/4T$ is the moment of maximum jet
323 velocity, $t=1/2T$ is the moment of mean jet velocity with gradually decreasing velocity, $t=3/4T$ is the moment of
324 minimum flow velocity, and $t=T$ is the moment of mean flow velocity with gradually increasing velocity. Fig. 11
325 shows the instantaneous streamlines of the jet on the symmetric longitudinal profile ($y/d=0$) at four typical phases
326 of case DJ06. As the jet is deflected due to the influence of the current, energy and momentum exchange occurs
327 between the jet and the current boundary shear layer (Chang et al., 2019). At $t=1/4T$, the jet has a large vertical
328 momentum, resulting in a greater degree of bending of the jet column. At $t=1/2T$, the vertical momentum of the jet
329 decreases, the degree of bending decreases, the upward tilt deepens, the height of the impact increases, and the
330 degree of mixing intensifies. At $t=3/4T$, the vertical momentum of the jet reaches its minimum, while the impact
331 height of the jet column reaches its maximum, the degree of bending decreases, and the degree of mixing further
332 intensifies. At $t=T$, the jet returns to a mean flow velocity with a gradually increasing velocity, completing the
333 cycle. The streamlines at four representative phases in a cycle illustrate the temporal and spatial instability of
334 oscillating jets in a current environment. Intense mixing between the jet and the current creates a convergence
335 source near the onshore side, spreading out in all directions. New et al. (2006) identified this source as the
336 ‘Unstable Focus’. Due to the high initial kinetic energy of the vertical jet and the negligible impact of drag force
337 on momentum decay, the jet moves in its initial direction with a certain deviation angle. The entire motion field is
338 thus divided into two regions by a flow line near the source point, with opposite flow directions in each region.
339 Kelso et al. (1996) found that the velocity ratio of the jet to the current primarily determines the jet's motion
340 characteristics. However, in the interaction between the current and the oscillating jet, the jet moves sinusoidally,

341 undergoing periodic acceleration and deceleration. This results in a non-constant R_{jc} , leading to periodic deflection
 342 and penetration of the jet within a cycle. Consequently, the wake of the accelerating fluid is pulled, making the
 343 oscillating jet's area of influence larger than that of the non-oscillating jet (Mohammadshahi et al., 2021).

344



345

346 **Fig.11.** Instantaneous streamline of $y/d=0$ section under four typical phases of case DJ06.

347

348 Fig. 12 shows the streamlines in the $x/d=0$ section at four typical phases of case DJ06, exhibiting
 349 symmetrical streamlines on both sides. The velocity characteristics of the jet column align with the symmetric
 350 longitudinal profile. The key factor in jet mixing is the alternating formation and dissipation of vortices caused by
 351 the shear layer (Li et al., 2022). A distinct kidney-shaped symmetric structure can be observed throughout the
 352 cycle, indicative of the CVP structure, which is a characteristic feature of jets in a current environment (Lee et al.,

1999). The formation of the CVP structure significantly impacts flow fluctuation quantities such as turbulence intensity and Reynolds stress (Su and Mungal, 2004). It entrains a large amount of fluid from the surrounding environment into the main jet's impact range, promoting interaction and mixing between the entrained fluid and the jet. At $t=1/4T$, the CVP structure initially forms and is located downward, with the left and right halves showing a regular semicircular shape. At $t=1/2T$, the CVP structure shifts upward, adopting a shape resembling a heart, indicating increased mixing between the jet and the surrounding water. At $t=3/4T$, the CVP structure reaches its highest vertical position, with the heart shape becoming narrower and longer, indicating a decrease in width. At $t=T$, the CVP structure falls back to a position near the jet opening, with its shape becoming wider and shorter, resembling the semicircular shape observed at $t=1/4T$. In addition, we can find that at $z/d=15$ and above, the vertical positions at the four phases are similar, with the flow spreading from the highest position of the jet impact to the top on both sides. Here, the degree of mixing is lower, and the differences between the moments are less pronounced.

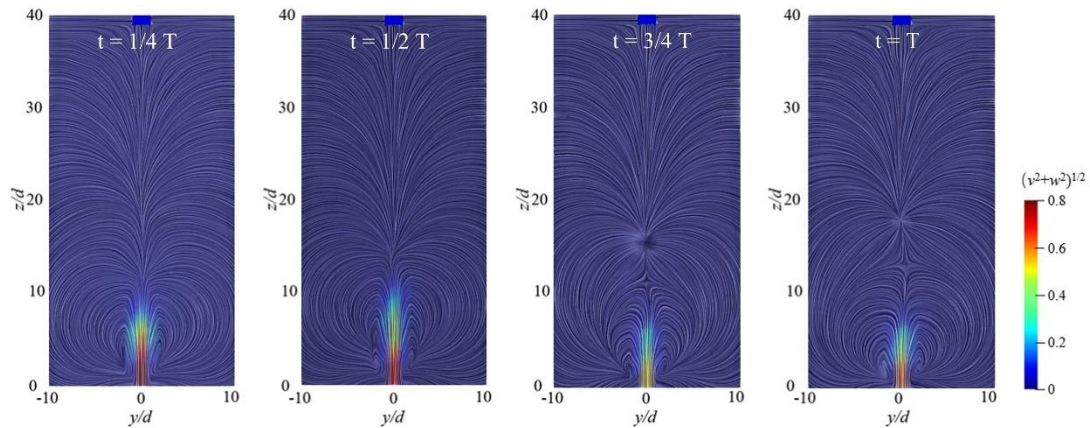


Fig.12. Instantaneous streamline of $x/d=0$ section under four typical phases of case DJ06.

Fig. 13 illustrates the streamlines at four typical phases of case DJ06 at the $z/d=20$ section. As observed, the streamline characteristics in this section are quite similar across all four phases. The streamlines are relatively straight, and no obvious vortex structures are present, indicating that the jet fluid movement and mixing with the

water body have significantly weakened by this point, primarily dominated by the current. At $t=1/4T$, the current starts to move along the jet to the left and right of $y/d=0$, with the diffusion position at $x/d=7$. At $t=1/2T$, this diffusion position shifts to the right to $x/d=10$. At $t=3/4T$, the current diffusion is closest to the jet origin at $x/d=0$. Finally, at $t=T$, the diffusion position shifts right again to $x/d=4$. Overall, the differences in the characteristics of the phases at the $z/d=20$ section are minimal.

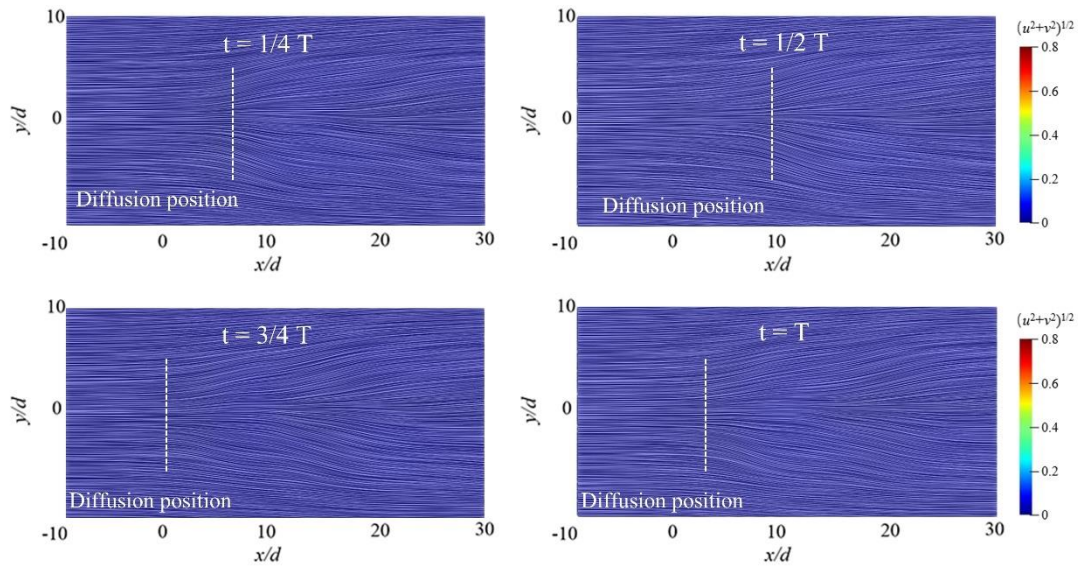


Fig.13. Instantaneous streamline of $z/d=20$ section under four typical phases of case DJ06.

3.2. Mean flow structure

Due to the periodic motion of the oscillating jet, the instantaneous flow structure of the three-dimensional jet fluid significantly influences the mean flow structure. Fig. 14 and Fig. 15 depict the three-dimensional mean flow structure of the non-oscillating jet and oscillating jet in the current environment, respectively, in the symmetric longitudinal section ($y/d=0$), downstream section ($x/d=5$), and horizontal cross-section ($z/d=5$). As the jet enters the current, different transition processes occur. In the flow establishment zone, the initial flow velocity distribution transforms into a strong shear jet-like flow velocity distribution. At this stage, the jet flow volume force mainly dominates the flow regime, and the effect of buoyancy force can be neglected in the jet zone.

389 Subsequently, the flow regime transforms into a plume-like region. The jet bends towards the current direction
390 with decreasing momentum, gradually reaching maximum height, and the effect of buoyancy force and secondary
391 flow mainly controls the mixing process in this plume region (Gharavi et al., 2020). The jet rises and bends under
392 the influence of buoyancy and the current, moving downstream, with buoyancy becoming increasingly important
393 in the final stage.

394 The jet trajectory line presents a complex three-dimensional structure, and both oscillating and
395 non-oscillating jets show relatively similar flow field characteristics. The symmetric longitudinal section diagram
396 indicates that the jet deflects in the direction of the current, exhibiting a source point. The downstream section
397 reveals a clear, typical CVP structure. From the horizontal cross-section, distinct stagnant points and stable
398 focuses are observable at the surface, with smooth flow lines near the stagnant point indicating more stable flow.
399 While the mean flow characteristics of the oscillating and non-oscillating jets in the current environment are
400 generally similar, notable differences exist. In the symmetric longitudinal profile, the main flow line of the
401 non-oscillating jet is positioned closer to the bottom bed, resulting in a lower jet height and reduced mixing. In
402 contrast, the exit velocity of the oscillating jet is significantly higher, and its maximum velocity decays more
403 rapidly, indicating higher momentum transfer. Furthermore, in the downstream section at $x/d=5$, the two pairs of
404 vortex centers of the non-oscillating jet are located at $y/d=2$ and $z/d=12$. In contrast, the vortex centers of the
405 oscillating jet are found at $y/d=4$ and $z/d=15$. This indicates that the CVP structure of the non-oscillating jet has a
406 larger area and a lower vertical position than that of the oscillating jet at this section. Additionally, consistent with
407 the findings of Mohammadshahi et al. (2020), oscillating jets in a current environment exhibit more curved and
408 less smooth mean streamlines than non-oscillating jets, leading to more intense mixing.

409

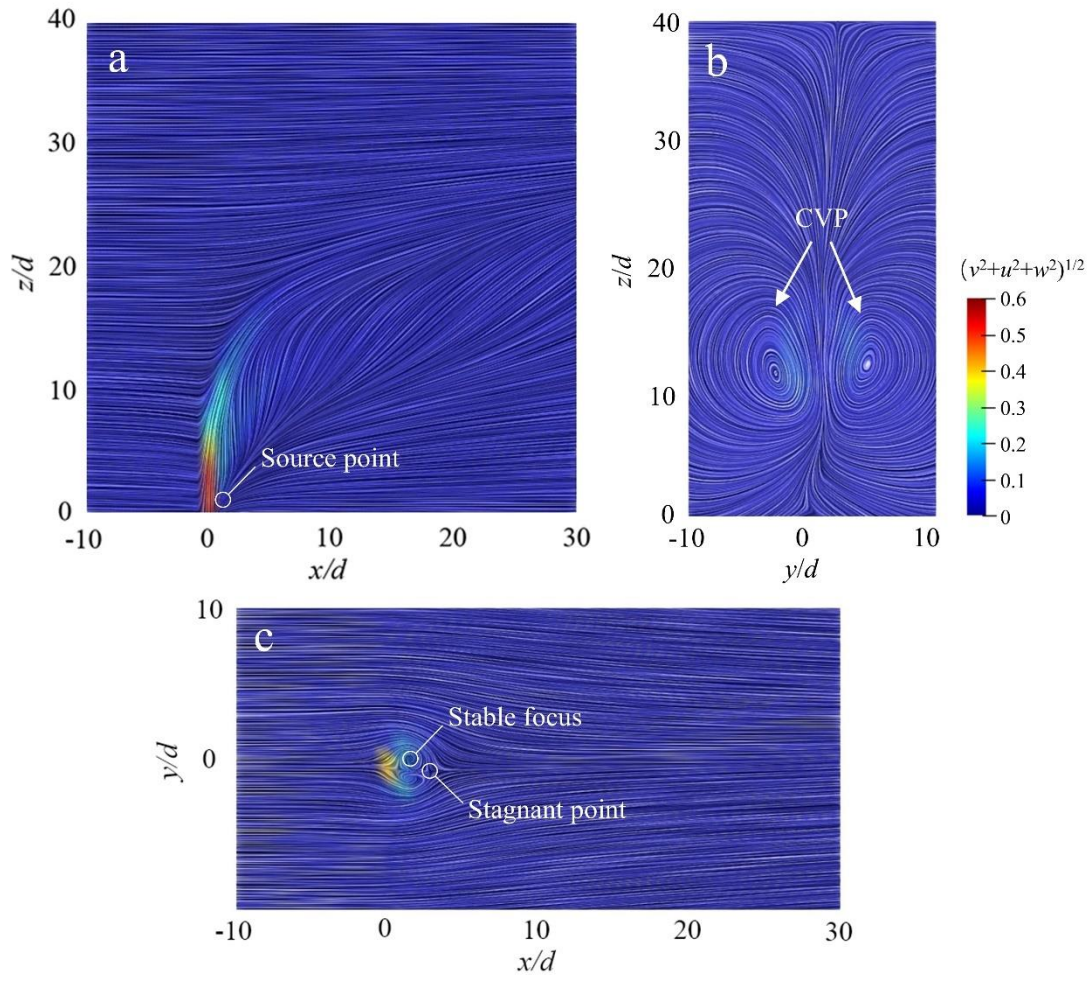


Fig.14. Mean streamlines of non-oscillating jets in a current environment (case DJ00): (a) longitudinal section ($y/d=0$), (b) downstream section ($x/d=5$), (c) horizontal cross-section ($z/d=5$).

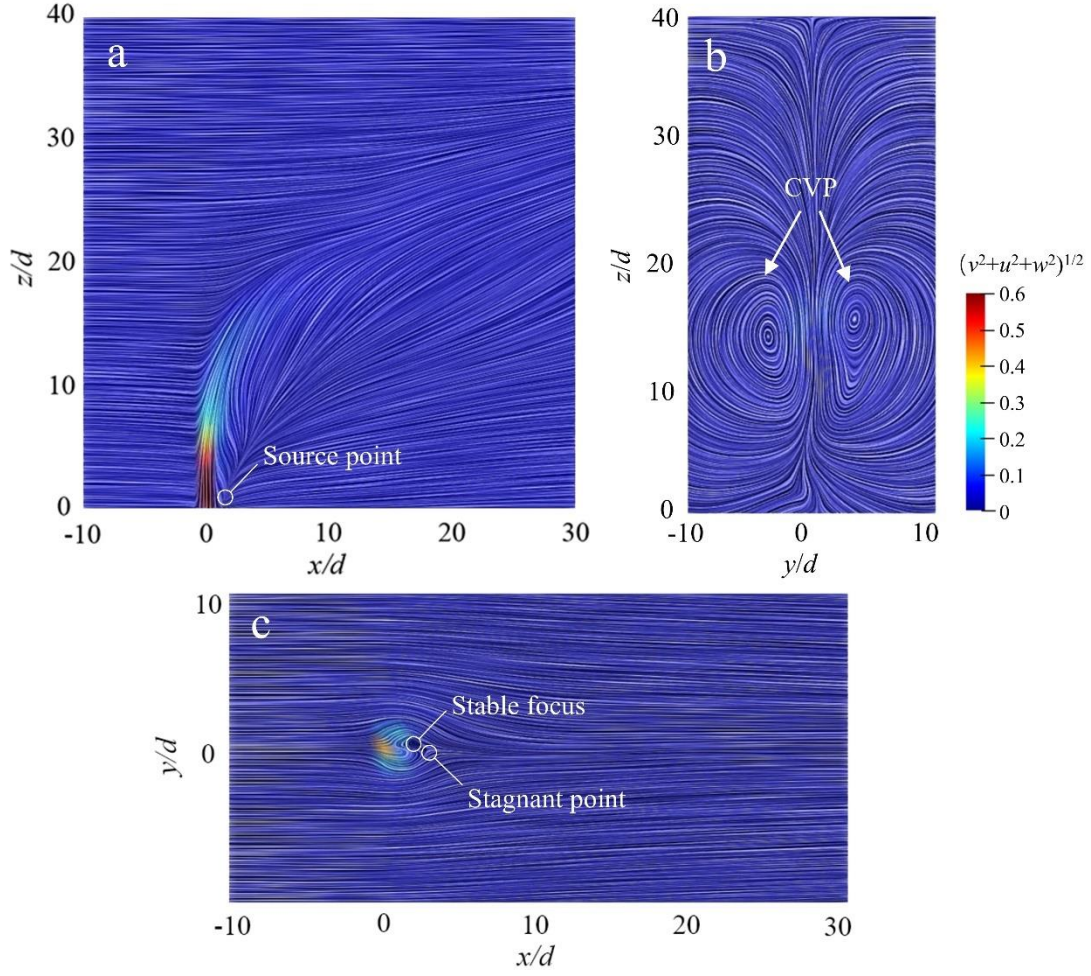


Fig.15. Mean streamlines of oscillating jets in a current environment (case DJ03): (a) longitudinal section ($y/d=0$), (b) downstream section ($x/d=5$), (c) horizontal cross-section ($z/d=5$).

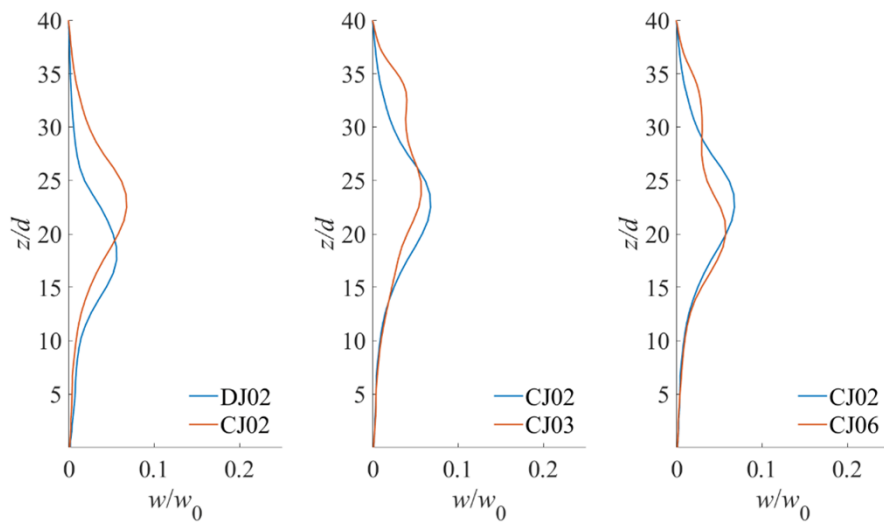
3.3. Effects of R_{jc} , R_{aj} and S_t on flow velocity distribution

Fig. 16 compares the mean velocity distributions of oscillating jets in current environments across different cases at $x/d=30$ sections. Comparing case DJ02 and case CJ02, both of which exhibit clear Gaussian distribution characteristics. For case CJ02, with a larger jet velocity, the section velocity maximum occurs at $z/d=23$, while for case DJ02, it occurs at $z/d=17$. The vertical position of the mean flow velocity maximum at the cross-section in case CJ02 is higher, while the velocity maximum and distribution widths for both groups are very similar. This indicates that an increase in the R_{jc} causes the jet to penetrate more deeply into the current in the vertical direction, due to the increased momentum complicating the flow and vortex structure. An increase in the R_{jc} results in a

426 higher penetration of the jet and a weaker jet deflection, which is a significant reason for the higher vertical
 427 position of the flow velocity maximum in the oscillating jet section.

428 Comparing case CJ02 and case CJ03, an increase in R_{aj} reduces the velocity maximum and raises its vertical
 429 position, with the distribution widths remaining nearly identical. For case CJ03, with a larger R_{aj} , the section
 430 velocity maximum occurs at $z/d=25$, while for case CJ02, it occurs at $z/d=23$. As the R_{aj} increases, the velocity
 431 distribution in this transverse plane shifts from Gaussian to double-peaked, indicating the emergence of an
 432 additional velocity maximum. This suggests that with higher R_{aj} , more jet fluid is transported to higher elevations.
 433 This phenomenon may be related to the CVP structure generated by the periodic motion (Xu et al., 2017).

434 Comparing case CJ02 and case CJ06, the effect of the S_t on the mean flow velocity distribution is not
 435 significant. The maximum velocity in case CJ06 occurs at $z/d=20$, while case CJ02 exhibits slightly higher
 436 maximum velocity and vertical position. In contrast, case CJ06 shows a slightly wider distribution width.
 437 According to Ostermann et al. (2019), the S_t determines the ability of currents to adapt to new flow field
 438 conditions, such as changes in the jet deflection angle. As the S_t increases, the relative duration of the vortex at a
 439 flow position during an oscillation cycle also increases. The effect of the increased S_t , which results in a higher jet
 440 penetration position, on the mixing capacity needs to be further investigated.



441
 442 **Fig. 16.** Comparison of the mean velocity distribution of the oscillating jet in the current environment at $x/d=30$ sections.
 443

444 3.4. Turbulence characteristics

445 3.4.1. Turbulence intensity, Reynolds shear stress and Pulsating mass flux

446 To facilitate the comparison of turbulence characteristics between non-oscillatory and oscillatory jets in a
447 current environment, all turbulence parameters were calculated on the symmetric longitudinal section ($y/d=0$).
448 Turbulence intensity, which describes the relative strength of the pulsation velocity in the shear mixing process
449 between the injected and ambient fluids, is a critical characteristic of turbulent motion. According to the analysis
450 presented in Fig. 17, both non-oscillatory and oscillatory jets exhibit similar patterns in turbulence intensity
451 change. However, notable differences are observed in the horizontal turbulence intensities. For the non-oscillatory
452 jet, the maximum turbulence intensity occurs at the jet's centerline. In contrast, the oscillatory jet, which bends
453 more significantly, shows enhanced shear around the current, causing the maximum turbulence intensity to shift
454 downstream. A maximum horizontal turbulence intensity of approximately 0.14 is maintained between $x/d=0$ and
455 $x/d=2$, as well as between $z/d=0$ and $z/d=4$. Moreover, the maximum vertical turbulence intensity of 0.32 occurs at
456 $x/d=0$ and $z/d=6$ for case DJ00, while a high vertical turbulence intensity of about 0.38 is observed at $z/d=0$ to
457 $z/d=11.5$ for case DJ03, indicating that the oscillating jet maintains a higher vertical turbulence intensity.
458 Additionally, the turbulence intensity of the oscillating jet significantly increases with distance from the jet, and
459 this increase intensifies further away from the source. This is primarily due to the frequency of jet changes under
460 oscillation, enhancing its interaction with the surrounding water column and strengthening turbulence, akin to
461 wave effects. For vertical turbulence, the intensity near the outlet is considerably higher in the oscillating jet, and
462 it decays more slowly over distance. This allows the oscillating jet to maintain a higher turbulence intensity at
463 elevated positions. Thus, the oscillating jet in a current environment exhibits more pronounced changes in
464 turbulence characteristics.

465

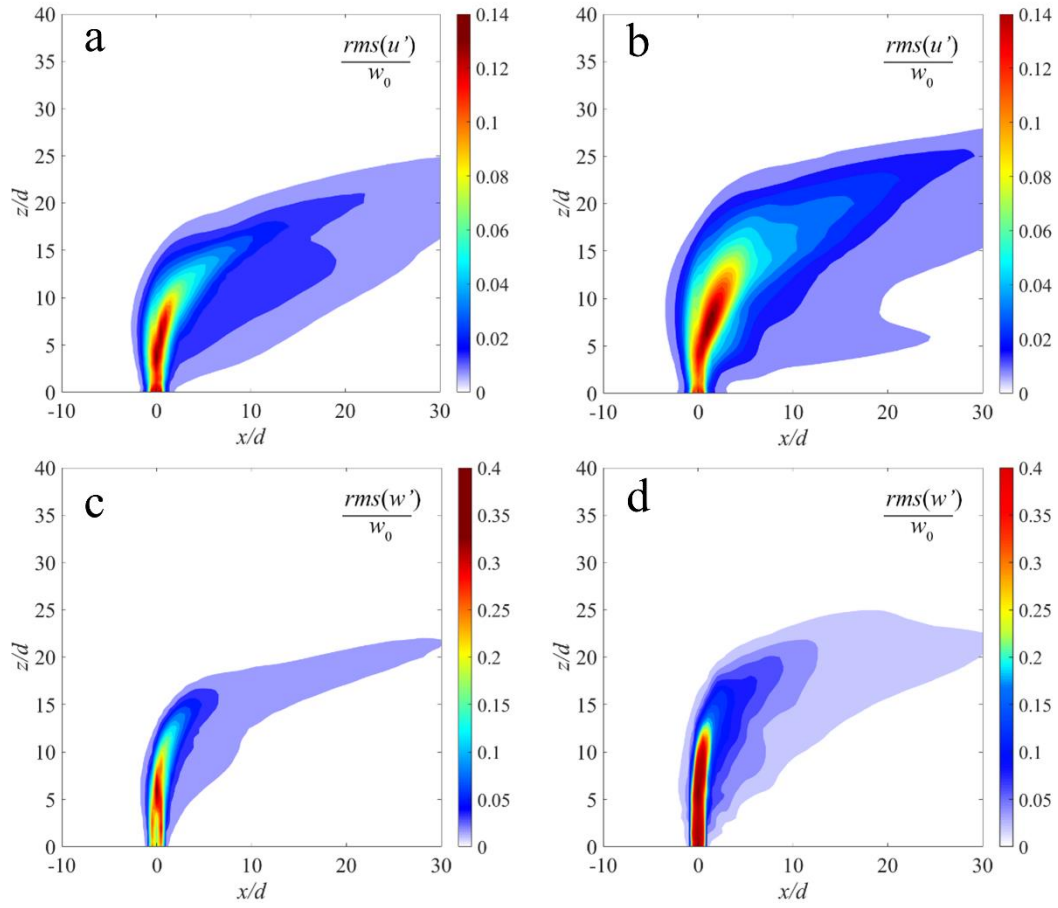


Fig. 17. Comparison of turbulence intensity on the symmetrical longitudinal section ($y/d=0$) of cases DJ00 and DJ03, (a) horizontal turbulence of DJ00, (b) horizontal turbulence of DJ03, (c) vertical turbulence intensity of DJ00, (d) vertical turbulence intensity of DJ03.

Figs. 18 (a) and (b) show the Reynolds stress distribution, which plays an important role in momentum transport. While the locations of shear stress in non-oscillating and oscillating jets are similar, the oscillating jet produces significantly higher shear stress, both in terms of its influence range and magnitude. This indicates a stronger coiling and suction effect in the oscillating jet, leading to more intense mixing with the ambient fluids and rapid momentum transfer to these fluids. Furthermore, as the jet develops, current fluid is entrained, leading to a decrease in jet flow velocity and the formation of a recirculation zone on the back-flow side of the jet. Within this zone, radial pulsations become negative attributed to the effects of the shear layer and the fluid shear within the recirculation zone, and the mixing induced by the coiled section of low-velocity fluid further contributes to the

negative Reynolds stress (Chen et al., 2023). Notably, the area of the recirculation zone is significantly smaller in the oscillating jet, which facilitates the transfer of momentum to higher vertical positions.

Figs. 18 (c) to (d) offer a detailed comparison of horizontal pulsating mass fluxes along the symmetric longitudinal profiles. The distribution patterns of pulsating mass flux closely resemble those of the Reynolds shear stress. There are notable differences in the horizontal pulsating mass flux. Specifically, at the jet exit, the horizontal pulsating mass flux is lower and the rate of lateral decay is significantly less pronounced in the oscillating jet. This indicates that the oscillating jet maintains a relatively stable horizontal pulsating mass flux over a broader range. The persistence of horizontal pulsating mass flux in the oscillating jet can be attributed to the gradual development of the vortex structure. The increasing area and vertical positioning of the CVP structure play critical roles in sustaining this flux across an extended range.

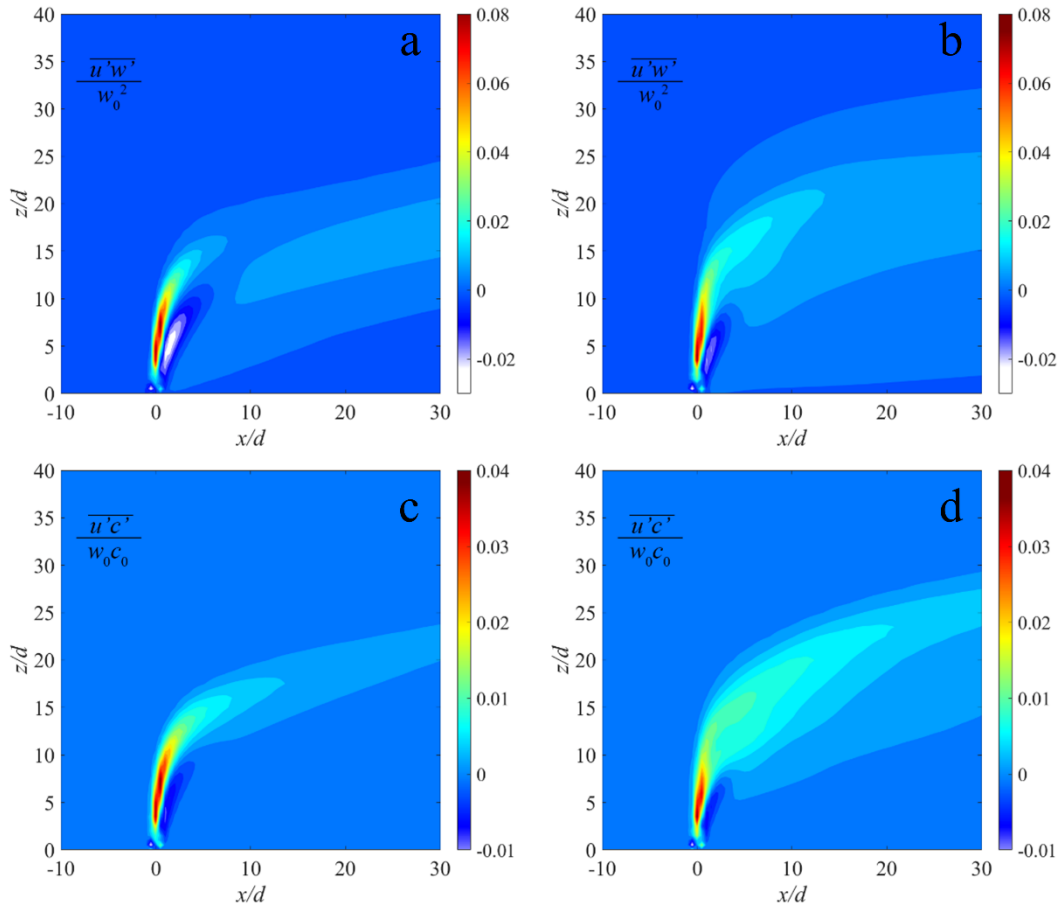


Fig. 18. Comparison of other turbulence parameters on the symmetrical longitudinal section ($y/d=0$) of cases DJ00 and DJ03, (a) Reynolds stress distribution of DJ00, (b) Reynolds stress distribution of DJ03, (c) horizontal pulsating mass fluxes of DJ00, (d) horizontal pulsating mass fluxes of DJ03.

3.4.2. Effects of R_{jc} , R_{aj} and S_t on turbulence intensity

Fig. 19 compares the horizontal turbulence intensity in the sub-symmetric longitudinal section of four cases of oscillating jets in a current environment. The horizontal turbulence intensity of case CJ03 is significantly larger than that of case DJ03, with higher diffusion height and a greater range of influence. This increased turbulence intensity can be attributed to the higher R_{jc} in case CJ03. The larger amplitude in case DJ03 exhibits similar characteristics compared to case DJ01. However, case DJ07, which has a smaller S_t , shows a slightly larger range of turbulence compared to case DJ03. Despite this, the decay rate of turbulence intensity in the x direction is faster for case DJ07. Thus, the effect of the S_t on the oscillating jet cannot be conclusively determined from the comparison of turbulence intensities. This observation supports the law described in the previous section: increasing the R_{jc} and the R_{aj} significantly enhances the turbulence intensity and the range of influence of the oscillating jet. This enhancement effectively increases the mixing of the jet with the surrounding water. In contrast, the effect of the S_t on the jet is not as clear and requires further analysis and investigation.

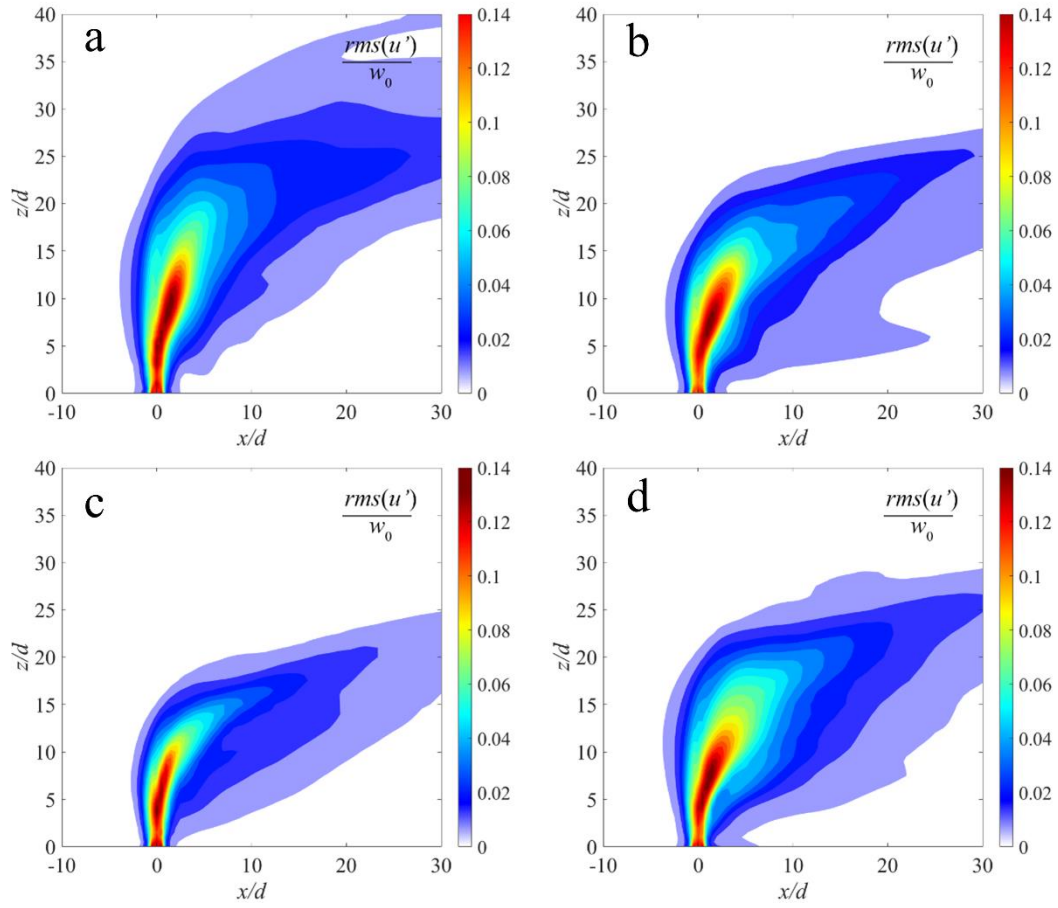


Fig. 19. Horizontal turbulence intensity comparison on symmetrical longitudinal section ($y/d=0$) of oscillation parameter comparison group, (a) CJ03, (b) DJ03, (c) DJ01, (d) DJ07.

3.5. Comparison of motion characteristics of jets in wave-current coexisting environment

Xu et al. (2016b) conducted a detailed analysis of the three-dimensional flow field characteristic of the jet in a wave-current coexisting environment. Comparing the results of this study, similar features include jet body deflection, upstream and downstream sources relative to the vertical symmetry planes, CVP structure in the transverse plane, and stagnant points and stable focuses in the horizontal plane. Overall, the motion development laws of jets in both environments are very similar. However, in the wave-current coexisting environment, the symmetric longitudinal section structure shows that the main flow line is closer to the bottom and the jet deflection angle is larger. While the penetration is greater for oscillating jets in the current environment. From the downstream section, the CVP structure of the oscillating jet is narrower and longer, with a pear-shaped

522 distribution on the waterward side and a kidney-shaped distribution on the backward side. Additionally, the
523 vertical position of the CVP structure is relatively high. From the horizontal longitudinal section, the flow line
524 near the stable node of the oscillating jet is more uneven.

525 To better compare the similarities and differences of motion characteristics in the two environments, we
526 analyzed the mean flow velocity distributions of the downstream sections (Figs. 20,21). The characteristic
527 parameters are constant for the compared cases (for cases CJ02 and WJ01: $R_{aj}/R_{wc}=0.2$, $S_t=0.2$; for cases CJ03
528 and WJ02: R_{aj}/R_{wc} , $S_t=0.2$). There is no significant difference in the vertical maximum flow velocity values
529 between the two at the downstream sections, and both vertical flow velocities are essentially Gaussian distributed.
530 The wave transverse velocity superimposed on the current velocity of the case WJ01 varies between 0.04 m/s and
531 0.06 m/s, resulting in the R_{jc} between 8.33 and 12.50. The jet velocity of the case CJ02 varies between 0.4 m/s and
532 0.6 m/s, resulting in the R_{jc} between 8 and 12. The wave transverse velocity superimposed on the current velocity
533 of the case WJ02 varies between 0.03 m/s and 0.07 m/s, resulting in the R_{jc} between 7.14 and 16.67. The jet
534 velocity of the case CJ03 varies between 0.3 m/s and 0.7 m/s, resulting in the R_{jc} between 6 and 14. When R_{aj}/R_{wc}
535 is small, there is little difference in the vertical flow velocity distribution between the two environments. At the
536 $x/d=10$ section, the maximum vertical velocity for both cases occurs at approximately $z/d=15$. The maximum
537 vertical velocity decreases during downstream propagation and stabilizes at a vertical position near $z/d=25$. The
538 similar ranges of R_{jc} in the two environments account for the extremely similar motion characteristics, indicating
539 that oscillating jets are similar to the periodic changes of waves.

540 However, the vertical position of the maximum velocity of the oscillating jet is significantly higher than that
541 of the jet in the wave-current coexisting environment when R_{aj}/R_{wc} is larger. The vertical positions of the
542 maximum velocity for case WJ02 at sections $x/d=20$ and $x/d=30$ are below $z/d=20$, whereas for case CJ03, they
543 are approximately at $z/d=25$. In terms of distribution width, the jet in the wave-current coexisting environment is
544 narrower than the oscillatory jet in the current environment up to $x/d=30$, but wider beyond $x/d=40$. This

545 discrepancy arises due to the inconsistency in the scope of the two oscillatory effects. The wave uniformly affects
546 the entire water column, from the bottom to the surface, altering the lateral velocity of the background flow field
547 throughout its cycle. Consequently, the jet in the wave-current coexisting environment exhibits greater
548 downstream deflection and slower attenuation, extending its influence over a longer period. In contrast, the
549 oscillating jet primarily affects the area around the jet opening and gradually propagates to the surface. As a result,
550 the vertical penetration ability of the oscillating jet in the current environment is stronger, but it weakens more
551 rapidly downstream. It should be noted that to reduce the environmental impacts on coastal waters, sewage outfall
552 is often allocated in a relatively deep water area, where the wave oscillation exhibits a strong variation in the
553 vertical direction. According to Watanabe et al. (2015), vertical velocity fluctuation is the major source of energy
554 fluctuation that contributes to the development of the highly buoyant jet. In this case, the positive effect of the
555 periodic motion on jet mixing may be more similar in the two environments.

556

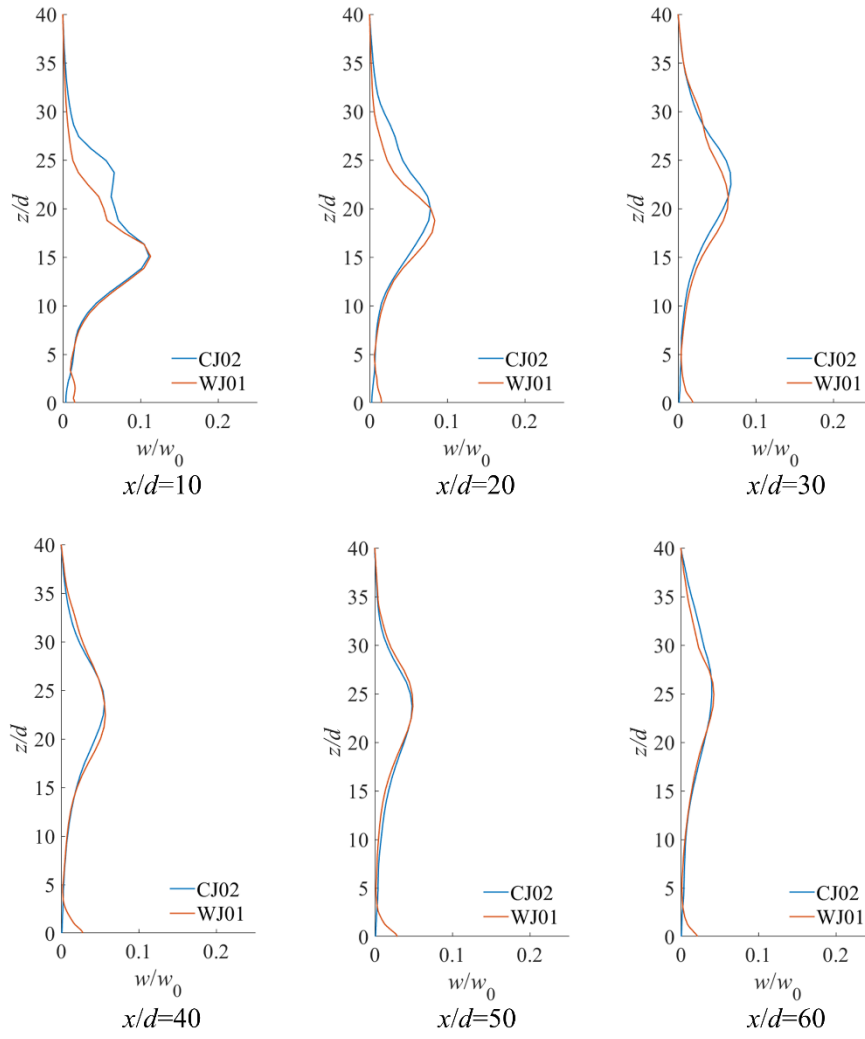


Fig.20. Mean flow velocity distribution in the downstream section of oscillating jet (CJ02) in a current environment and non-oscillating jet (WJ01) in a wave-current coexisting environment.

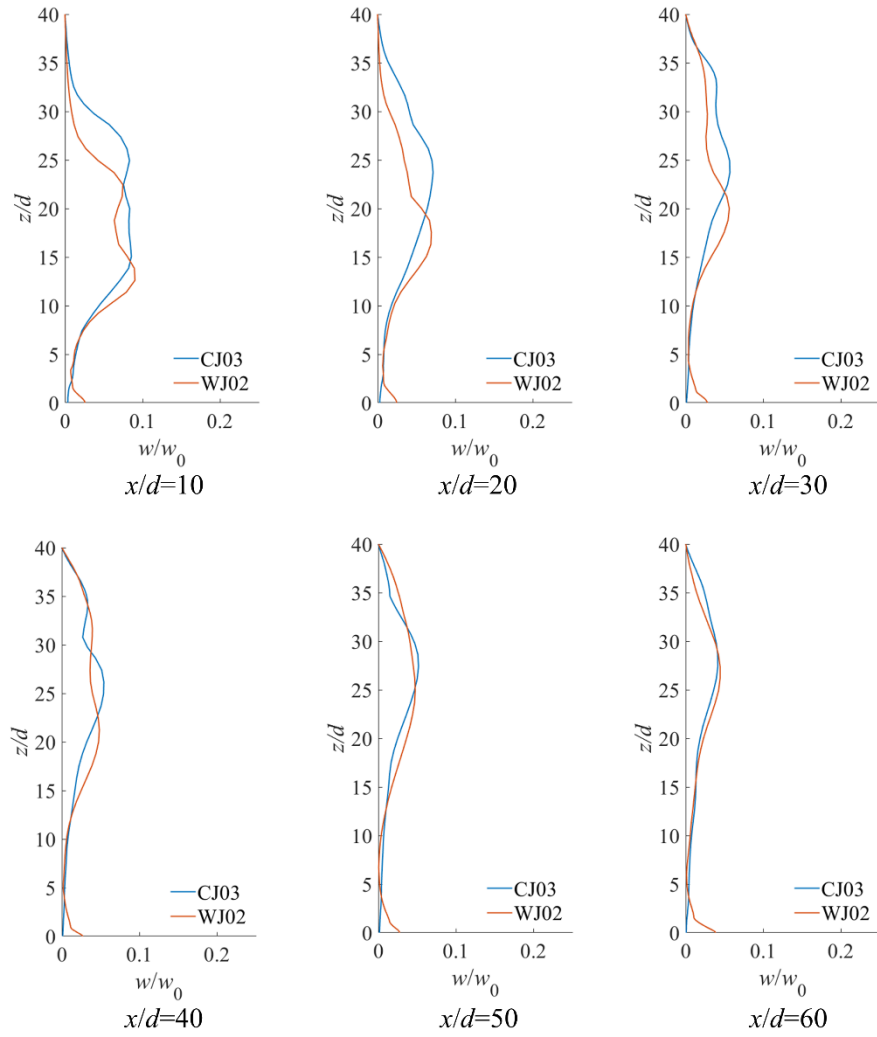


Fig.21. Mean flow velocity distribution in the downstream section of oscillating jet (CJ03) in a current environment and non-oscillating jet (WJ02) in a wave-current coexisting environment.

4. Conclusions

This study presents a detailed analysis of the three-dimensional mean and turbulence characteristics of an oscillating jet under the effect of currents using the large eddy simulation (LES) method. The main conclusions are summarized as follows:

- (1) In current environments, oscillating jets are positioned lower in the downstream section of the CVP structure compared to non-oscillating jets. This results in a higher impact height, greater bending, and wider diffusion of the jet in the symmetric longitudinal profile, leading to more effective mixing with the surrounding

572 water.

573 (2) Increasing the R_{aj} decreases the maximum mean flow velocity in the oscillating jet section and raises its
574 vertical position. Increasing R_{jc} elevates the vertical position of the maximum mean flow velocity. The positive
575 effect of the S_t on jet mixing is not significant.

576 (3) The turbulence intensity, Reynolds shear stress, and horizontal pulsating mass flux of the oscillating jet
577 are significantly higher than those of the non-oscillating jet. When R_{jc} and R_{aj} increase, the turbulence intensity of
578 the oscillating jets is further enhanced.

579 (4) The mean flow structure and velocity distribution of oscillating jets in a current environment are similar
580 to those of non-oscillating jets in a wave-current coexisting environment, particularly when R_{aj}/R_{wc} is small. As
581 R_{aj}/R_{wc} increases, the vertical position of the maximum flow velocity of the oscillating jet in the current
582 environment is higher.

583

584 **Acknowledgments**

585 This work was partly supported by the Fundamental Research Funds for the Central Universities [grant numbers
586 B200202057], the National Natural Science Foundation of China [grant numbers 51709078], and the Natural
587 Science Foundation of Jiangsu Province [grant number BK20170882].

588

589 **References**

590 Abdel-Rahman, A., Eleshaky, M., 2004. Diffusion characteristics of a plane jet discharged in a wavy crossflowing
591 stream. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering
592 Science 218 (4), 411-423.
593 Chang, J., Du, Y., Shao, X., Zhao, Y., Zheng, S., 2019. Investigation and analysis of vortex and application of jet
594 in crossflow. Case Studies in Thermal Engineering 14, 100459.

595 Chang, K.-A., Ryu, Y., Mori, N., 2009. Parameterization of neutrally buoyant horizontal round jet in wave
596 environment. *Journal of waterway, port, coastal, and ocean engineering* 135 (3), 100-107.

597 Chen, Y., Li, C.W., Zhang, C., 2008. Numerical modeling of a round jet discharged into random waves. *Ocean*
598 *Engineering* 35 (1), 77-89.

599 Chen, Y., Xu, Z., Chen, Y., Otoo, E., Xie, Z., 2023. Turbulence properties of a vertical round jet in a
600 wavy-crossflow environment. *Ocean Engineering* 288, 116040.

601 De Padova, D., Mossa, M., Sibilla, S., 2020. Numerical investigation of the behaviour of jets in a wave
602 environment. *Journal of Hydraulic Research* 58 (4), 618-627.

603 Dong, Z.Y., Yu, G.L., 2014. A preliminary study of effects of wave and crossflow on side discharge of wastewater.
604 *Advanced Materials Research* 955, 2041-2045.

605 Fan, J.-y., Zhang, Y., Wang, D.-z., 2009. Experimental study on the vortex formation and entrainment
606 characteristics for a round transverse jet in shallow water. *Journal of Hydrodynamics, Ser. B* 21 (3), 386-393.

607 Fang, S., Chen, Y., Shi, W., Xu, Z., Zhou, X., Xu, X., 2024. Mixing behavior equations created by a buoyant jet in
608 wavy crossflow environments. *Physics of fluids* 36 (2).

609 Gharavi, A., Mohammadian, A., Nistor, I., Peña, E., Anta, J., 2020. Experimental study of surface buoyant jets in
610 crossflow. *Environmental Fluid Mechanics* 20 (4), 1007-1030.

611 Hsiao, S.-C., Hsu, T.-W., Lin, J.-F., Chang, K.-A., 2011. Mean and turbulence properties of a neutrally buoyant
612 round jet in a wave environment. *Journal of waterway, port, coastal, and ocean engineering* 137 (3), 109-122.

613 Hsu, C.M., Huang, R.F., 2011. Effects of acoustic excitation at resonance Strouhal numbers on characteristics of
614 an elevated transverse jet. *Experimental thermal and fluid science* 35 (7), 1370-1382.

615 Kalifa, R.B., Habli, S., Saïd, N.M., Bournot, H., Le Palec, G., 2014. Numerical and experimental study of a jet in
616 a crossflow for different velocity ratio. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*
617 36, 743-762.

618 Karagozian, A.R., 2014. The jet in crossflow. *Physics of fluids* 26 (10).

619 Kelso, R.M., Lim, T., Perry, A., 1996. An experimental study of round jets in cross-flow. *Journal of Fluid*

620 *Mechanics* 306, 111-144.

621 Lee, J.H., Li, L., Cheung, V., 1999. Semianalytical self-similar solution of bent-over jet in cross-flow. *Journal of*

622 *engineering mechanics* 125 (7), 733-746.

623 Lee, J.H.W., Kuang, C.P., Chen, G.Q., 2002. Structure of a turbulent jet in a crossflow-effect of jet-crossflow

624 velocity. *China Ocean Engineering* 16 (1), 1.

625 Li, Z., Liu, Y., Zhou, W., Wen, X., Liu, Y., 2022. Thermal pollution level reduction by sweeping jet-based

626 enhanced heat dissipation: A numerical study with calibrated Generalized k- ω (GEKO) model. *Applied Thermal*

627 *Engineering* 204, 117990.

628 Lin, P., Li, C.W., 2002. A σ -coordinate three-dimensional numerical model for surface wave propagation.

629 *International Journal for Numerical Methods in Fluids* 38 (11), 1045-1068.

630 Lu, J., Dai, H., 2016. Large eddy simulation of flow and mass exchange in an embayment with or without

631 vegetation. *Applied Mathematical Modelling* 40 (17-18), 7751-7767.

632 Mahesh, K., 2013. The interaction of jets with crossflow. *Annual review of fluid mechanics* 45, 379-407.

633 Marcum, W., Cadell, S., Ward, C., 2015. The effect of jet location and duty cycle on the fluid mechanics of an

634 unconfined free jet and its heat transfer on an impinging plate. *International Journal of Heat and Mass Transfer* 88,

635 470-480.

636 Megerian, S., Davitian, J., Alves, L.d.B., Karagozian, A., 2007. Transverse-jet shear-layer instabilities. Part 1.

637 Experimental studies. *Journal of Fluid Mechanics* 593, 93-129.

638 Mohammadshahi, S., Samsam-Khayani, H., Cai, T., Kim, K.C., 2020. Experimental and numerical study on flow

639 characteristics and heat transfer of an oscillating jet in a channel. *International Journal of Heat and Fluid Flow* 86,

640 108701.

641 Mohammadshahi, S., Samsam-Khayani, H., Cai, T., Nili-Ahmadabadi, M., Kim, K.C., 2021. Experimental study
 642 on flow characteristics and heat transfer of an oscillating jet in a cross flow. *International Journal of Heat and*
 643 *Mass Transfer* 173, 121208.

644 Mori, N., Chang, K.-A., 2003. Experimental study of a horizontal jet in a wavy environment. *Journal of*
 645 *engineering mechanics* 129 (10), 1149-1155.

646 Muldoon, F., Acharya, S., 2010. Direct numerical simulation of pulsed jets-in-crossflow. *Computers & Fluids* 39
 647 (10), 1745-1773.

648 Muppidi, S., Mahesh, K., 2005. Study of trajectories of jets in crossflow using direct numerical simulations.
 649 *Journal of Fluid Mechanics* 530, 81-100.

650 New, T., Lim, T., Luo, S., 2006. Effects of jet velocity profiles on a round jet in cross-flow. *Experiments in Fluids*
 651 40, 859-875.

652 Ostermann, F., Woszidlo, R., Nayeri, C.N., Paschereit, C.O., 2019. The interaction between a spatially oscillating
 653 jet emitted by a fluidic oscillator and a cross-flow. *Journal of Fluid Mechanics* 863, 215-241.

654 Plesniak, M., Cusano, D., 2005. Scalar mixing in a confined rectangular jet in crossflow. *Journal of Fluid*
 655 *Mechanics* 524, 1-45.

656 Ryu, Y., Chang, K.-A., Mori, N., 2005. Dispersion of neutrally buoyant horizontal round jet in wave environment.
 657 *Journal of Hydraulic Engineering* 131 (12), 1088-1097.

658 Sau, A., Sheu, T.W., Tsai, S., Hwang, R.R., Chiang, T., 2004. Structural development of vortical flows around a
 659 square jet in cross-flow. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and*
 660 *Engineering Sciences* 460 (2051), 3339-3368.

661 Sharp, D.B., Shawcross, A., Greated, C.A., 2014. LIF measurement of the diluting effect of surface waves on
 662 turbulent buoyant plumes. *Journal of Flow Control, Measurement and Visualization* 2 (3), 77-93.

663 Shi, H., Wang, G., Luo, X., Yang, J., Lu, X.-Y., 2016. Large-eddy simulation of a pulsed jet into a supersonic

664 crossflow. *Computers & Fluids* 140, 320-333.

665 Su, L., Mungal, M., 2004. Simultaneous measurements of scalar and velocity field evolution in turbulent
666 crossflowing jets. *Journal of Fluid Mechanics* 513, 1-45.

667 Watanabe, R., Gono, T., Yamagata, T., Fujisawa, N., 2015. Three-dimensional flow structure in highly buoyant jet
668 by scanning stereo PIV combined with POD analysis. *International Journal of Heat and Fluid Flow* 52, 98-110.

669 Webb, T., Tomlinson, R.B., 1992. Design procedures for effluent discharge to estuaries during ebb tide. *Journal of*
670 *environmental engineering* 118 (3), 338-362.

671 Xia, L., Lam, K.M., 2004. Unsteady effluent dispersion in a round jet interacting with an oscillating cross-flow.
672 *Journal of Hydraulic Engineering* 130 (7), 667-677.

673 Xu, Z.-s., Chen, Y.-p., Tao, J.-f., Yi, P., Zhang, C.-k., Chi-Wei, L., 2016a. Modelling of a non-buoyant vertical jet
674 in waves and currents. *Journal of Hydrodynamics, Ser. B* 28 (5), 778-793.

675 Xu, Z., Chen, Y., Tao, J., Pan, Y., Sowa, D.M., Li, C.-w., 2016b. Three-dimensional flow structure of a
676 non-buoyant jet in a wave-current coexisting environment. *Ocean Engineering* 116, 42-54.

677 Xu, Z., Chen, Y., Wang, Y., Zhang, C., 2017. Near-field dilution of a turbulent jet discharged into coastal waters:
678 Effect of regular waves. *Ocean Engineering* 140, 29-42.

679 Xu, Z., Chen, Y., Pan, Y., 2018. Initial dilution equations for wastewater discharge: Example of non-buoyant jet in
680 wave-following-current environment. *Ocean Engineering* 164, 139-147.

681 Yuan, L., 2009. The three dimensional numerical simulation of vertical jet in waves, *New Trends in Fluid*
682 *Mechanics Research: Proceedings of the Fifth International Conference on Fluid Mechanics (Shanghai, 2007).*
683 Springer, pp. 380-380.

684 Yuan, L.L., Street, R.L., 1998. Trajectory and entrainment of a round jet in crossflow. *Physics of fluids* 10 (9),
685 2323-2335.

686 Zhao, L., Chen, Z., Lee, K., 2011. Modelling the dispersion of wastewater discharges from offshore outfalls: a

687 review. *Environmental Reviews* 19 (NA), 107-120.

688 Zhou, X., Luo, K.H., Williams, J.J., 2001. Large-eddy simulation of a turbulent forced plume. *European Journal of*

689 *Mechanics-B/Fluids* 20 (2), 233-254.