Journal of Hydro-environment Research 21 (2018) 118–130

Contents lists available at ScienceDirect

Journal of Hydro-environment Research

journal homepage: www.elsevier.com/locate/jher

Mixing of swirling inclined dense jets – A numerical study

Mingtao Jiang[a,b], Adrian Wing-Keung Law[b,c,*]

[a] Interdisciplinary Graduate School, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[b] Environmental Process Modelling Centre (EPMC), Nanyang Environment and Water Research Institute (NEWRI), Nanyang Technological University, 1 Cleantechloop, Singapore 637141, Singapore
[c] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Keywords:
Inclined dense jet
Swirl
LES
Dynamic Smargorinsky SGS
RANS
$K-\varepsilon$ closure
Turbulence kinetic energy spectrum

ABSTRACT

Recent experimental investigations demonstrated the possibility that the addition of swirls at the discharge outlet can lower the terminal rise height of inclined dense jets and increase the dilution at the return point, which can potentially influence the outfall design in coastal waters. In the present study, we further examined the effect of swirls on the mixing characteristics of 45 degree inclined dense jets using numerical simulations with two different approaches. The first approach was the Large Eddy Simulation (LES) with the dynamic Smargorinsky Sub-grid Model, and the second one was the Reynolds-Averaged Navier-Stokes (RANS) with the standard $k-\varepsilon$ turbulence closure. The comparison showed that the trajectories of the non-swirling inclined dense jet predicted by LES were closer to the experimental results, while RANS underpredicted the centreline peak height. This was consistent with the previous findings and can be attributed to the fact that the turbulence characteristics of non-swirling dense jets were highly anisotropic. Both approaches however underestimated the additional spreading in the lower half of the inclined dense jet due to the convective mixing by the buoyancy induced instability, and also the dilution in general. With swirls, the RANS predictions matched the jet trajectory better compared to LES, which was probably because the turbulence anisotropy was reduced and the distributions were more axisymmetric. The dilutions of swirling jets remained underestimated by both approaches, until the Swirl Number became sufficiently large at 0.33. Finally, strong swirls up to twice the highest value in the experiments were attempted in the numerical simulations to explore the possibility of jet breakup and disintegration at the outlet. It was found that the high swirl intensity did not lead to significant changes beyond what were observed at $G = 0.33$. The turbulence kinetic energy spectrum of the swirling inclined dense jet was also analysed along the trajectory based on the LES results. The spectral analysis confirmed that the effects of swirls were different depending on the magnitude, with strong swirls producing turbulence energy at the range of frequencies just before the inertial range probably due to eddy break up around the vortical layer, while extremely strong swirls increased the turbulence energy production range overall with the additional formation of large eddies.

1. Introduction

An inclined dense jet is formed by the upward discharge of dense effluents at an inclined angle relative to the bottom. The configuration has been shown to be effective in the effluent mixing with the surrounding ambient water so as to minimize the environmental impact, and it is now a standard practice in outfall designs e.g. for the discharge of brine from desalination plants (Milione and Zeng, 2008; Drami et al., 2011). In the design considerations for the outfall, two key parameters are typically analysed for the near field mixing, namely the terminal rise height and return point dilution. The ideal scenario calls for the terminal rise height to be lower than the water surface i.e. a full submergence of the inclined dense jet, while the return point dilution satisfies the requirements towards the mixing zone compliance (Jiang et al., 2014).

Fig. 1 shows a schematic diagram of a typical inclined dense jet discharging into a quiescent ambient. The intersection of the jet centreline with the discharge datum is defined as the return point. The angle of inclination is θ, the jet exit velocity is U_o, and the velocity along the centerline is U_m. The horizontal and vertical coordinates of the centerline peak are x_m and z_m, respectively. Previous studies (Roberts and Toms, 1987; Roberts et al., 1997; Cipollina et al., 2005;

---

* Corresponding author at: Environmental Process Modelling Centre (EPMC), Nanyang Environment and Water Research Institute (NEWRI), Nanyang Technological University, 1 Cleantechloop, Singapore 637141, Singapore.
E-mail address: cwklaw@ntu.edu.sg (A.W.-K. Law).

https://doi.org/10.1016/j.jher.2018.09.004
Received 3 February 2018; Received in revised form 2 July 2018; Accepted 24 September 2018

Nomenclature

Symbols

b_c	Concentration 1/e width
C_0	Initial concentration
C_m	Centerline concentration
C_S	Smagorinsky constant
C_Φ	Correction term in dynamic Smagorinsky SGS model
D	Nozzle diameter
Fr	Densimetric Froude number
g	Gravitational acceleration
g'	Reduced gravitational acceleration
G	Swirl number
h	Port height
H	Distance from the port to the water surface
L_1, L_2	Distance from the port to the back and front vertical boundary
L_M	Jet characteristic length scale
L_{ij}	Resolved turbulent stress
m	ratio between x_m of swirling and non-swirling jets
M_{ij}	Anisotropic part of the turbulent stress
r	Radial distance
R_j	Coefficient in dynamic Smagorinsky SGS model
Re	Reynolds number
p	Pressure
Q_j	SGS scalar flux or turbulent scalar flux
s	Stream-wise distance from the nozzle
S	Dilution
S	Local strain rate
Sc_t	Turbulent Schmidt number
S_m	Dilution at the centerline peak
S_r	Dilution at the return point
S_{ij}	Rate of strain tensor for the resolved scale
t	Time
U	Stream-wise velocity
U_0	Discharge velocity
U_m	Jet velocity along the centerline
u_i, u_j	Velocity in i, j direction, respectively
W_0	Initial tangential velocity
W	Tangential velocity
W_{d1},W_{d2}	Distances from the nozzle center to the left and right sides
x, y, z	Cartesian Coordinates in the horizontal, lateral and vertical direction, respectively
x_m	Horizontal locations of the centerline peak
z_m	Centreline peak height
ρ	Fluid density
ρ_a	Ambient density
ρ_b	Effluent density
Φ	Scalar concentration
μ	Fluid viscosity
μ_t	SGS viscosity
θ	Inclined angle relative to the horizontal plane
Δ	LES filter width
ε_j	Resloved flux
δ_{ij}	Kronecker delta
τ_{ij}	SGS Reynolds stresses or Reynolds stresses
τ_{kk}	Isotropic part of SGS stress
Γ	Scalar diffusivity

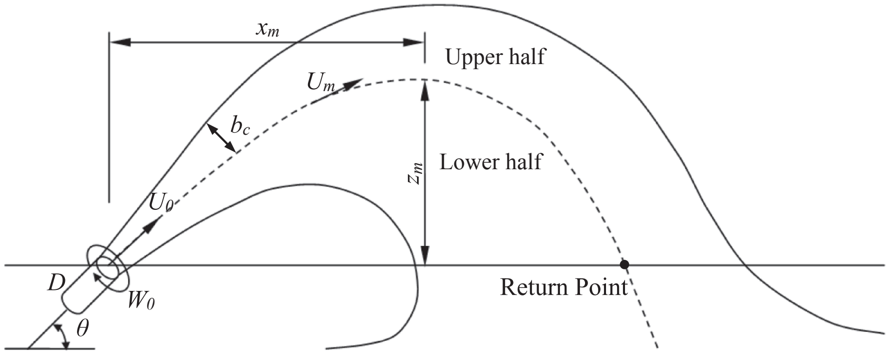

Fig. 1. Schematic side view of a swirling inclined dense jet discharged into stagnant ambient.

Kikkert et al., 2007; Shao and Law, 2010; Papakonstantis et al., 2011; Lai and Lee, 2012; Oliver et al., 2013) showed that the mixing characteristics can be linked to the inclination angle as well as the Densimetric Froude number Fr, defined as:

$$Fr = \frac{U_0}{\sqrt{\frac{\rho_b-\rho_a}{\rho_a}gD}} = \frac{U_0}{\sqrt{g'D}} \tag{1}$$

where ρ_a and ρ_b are the ambient and effluent density, respectively, g is the gravitational acceleration, g' is the reduced gravitational acceleration and D is the nozzle diameter.

As discussed previously in Jiang and Law (2013) and Jiang et al. (2014), large scale desalination plants now have to cope with a wide range of brine discharge flowrate due to different operation modes (e.g. full operation, standby, etc), and the corresponding wide range of Fr is a challenge to the outfall design. In addition, the consideration of full submergence implies that the outfall needs to be located in deeper waters to avoid the surface interactions. The construction cost would thus increase correspondingly, which would also translate to a higher unit water cost for the desalination with the typical financial arrangement of cost recovery upon operation.

A possible enhancement to the brine outfall is to impart a swirl to the effluent discharge. This can be accomplished in the form of a swirl valve installed at the outlet as proposed in Jiang and Law (2013). Previous experimental studies with non-buoyant jets had shown that the addition of swirls can affect the mixing behavior significantly. Park and Shin (1993) investigated the entrainment of a gas jet by using the Schlieren flow visualization method. They showed that for swirling jets with $G < 0.6$ (where G is the Swirl Number defined as the maximum tangential velocity over the discharge velocity at the outlet), the entrainment rate was fairly independent of the Reynolds number. For