International Journal of Heat and Fluid Flow 70 (2018) 114–124

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Large eddy simulation of a vertical buoyant jet in a vegetated channel

Meng Gao, Wenxin Huai*, Yizhou Xiao, Zhonghua Yang, Bin Ji

State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, PR China

A R T I C L E I N F O

Keywords:
Large eddy simulation
Coherent structure
Buoyant jet
Emergent vegetation

A B S T R A C T

Predicting the flow and dilution of a buoyant jet in vegetated regions is widely applied in ecology and engineering practices. Large eddy simulation is used to study a vertical buoyant jet that was injected into a cross-flow with emergent rigid vegetation. This simulation successfully reproduces the jet behaviour and the spatio-temporal evolution of vortex structures of turbulent jet with vegetation. The time-averaged velocity and temperature field are compared with the experimental results. The similarities and differences between the tests with and without vegetation are also studied. The existence of vegetation diminishes the channel velocity, thereby significantly increasing the jet penetration height and dilution. Spectral analysis is used to investigate the lengths of the vortices corresponding to the dominant frequency at different locations in the flow field.

1. Introduction

The effluent discharge in a receiving water body via outfalls and diffusers reflects several complex phenomena and affects the ecosystem services. When a jet normally discharges to a cross-flow, an intense interaction occurs between the two flows and consequently deflects the jet in the direction of the cross-flow.

Previous studies on jet focused on time-averaged patterns, including jet trajectory and the spread and dilution of jet effluent (Kelso et al., 1996; Smith and Mungal, 1998; Zeng and Huai, 2008). Lim et al. (2001) and Guan and Wu (2007) studied the dynamic processes of generating and transforming of the large-scale structures of a normal jet into a cross-flow. Their results show that the basic vortex structures, such as the counter-rotating vortex pair, leading-edge vortices and lee-side vortices, are not independent physical substances, and the 3D stretching vortex rings originate from the orifice of the nozzle. Large eddy simulation (LES) model is widely applied to investigate jets within a cross-flow environment (Yuan et al., 1999; Majander and Siikonen, 2006; Guan and Wu, 2007; Cavar and Meyer, 2012; Chai et al., 2015; Zhang et al., 2015). Many numerical studies successfully reproduced the complex dynamics of the jet in a cross-flow field.

Vegetation is a sensitive and key environmental factor that significantly affects the flow velocity distributions, turbulence structures and solute mixing in an open channel in aquatic ecosystems. Studies on flow-vegetation interactions were recently conducted. Cotton et al. (2006) and Naden et al. (2006) studied the influence of vegetation distribution on the mean velocity and turbulence characteristics in specific natural channels. Huai et al. (2009) proposed a three-layer model for the vertical velocity profile with rigid vegetation in an open channel flow. Siniscalchi et al. (2012) examined the effects of aquatic vegetation on flow turbulence, drag forces and flow-drag interrelations in a finite-sized characteristic patch. The LES model has also been used to study the vegetated flow in an open channel (Stoesser et al., 2009; Pan et al., 2014; Huai et al., 2011, 2015; Lu and Dai, 2016; Zhao and Huai, 2016). These simulations show the enormous potential of LES in accurately predicting flow and its associated time-dependent structures.

Despite the ecological importance of vegetation on turbulent jets, relatively few studies examined the influence of vegetation on the evolution of a round turbulent jet by conducting laboratory flume experiments (Ben Meftah et al., 2015; Malcangio and Mossa, 2016; Mossa and De Serio, 2016; Mossa et al., 2017). The results of the laboratory experiments revealed that the interaction between a round buoyant jet and background turbulence generated by rigid emergent vegetation can significantly affect the spread and internal structure of the jet. However, experimental studies cannot produce detailed flow information and elucidate the evolution of vortex structures. The LES model not only can predict the time-averaged velocity fields, but also provide instantaneous velocity fields and resolve the turbulence structures.

Most numerical models were developed either for the jet in a cross-flow or for the vegetation in an open channel. Few simulated studies simultaneously consider these two factors, namely, the turbulent jet and the effect of vegetation. In this paper, we utilize LES to further explore the effect of vegetation on the buoyant jet. The flow around the circular cylinders, which is needed to simulate the vegetation, is fully resolved by a high-resolution grid. The time-averaged velocity and

* Corresponding author.
E-mail address: wxhuai@whu.edu.cn (W. Huai).

https://doi.org/10.1016/j.ijheatfluidflow.2018.02.003
Received 19 July 2017; Received in revised form 7 February 2018; Accepted 7 February 2018

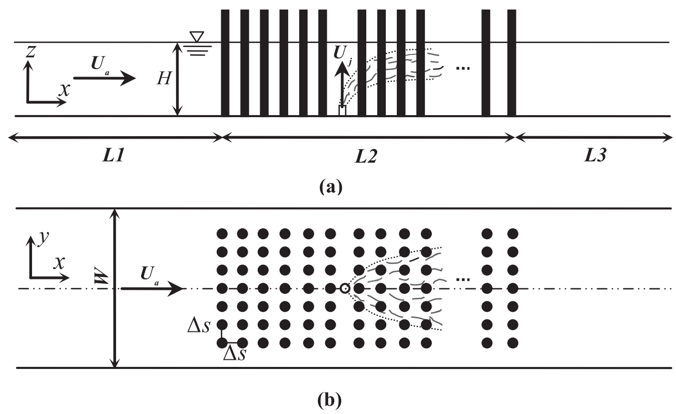

Fig. 1. Schematic diagram of the simulation domain. (a) side view (b) up view.

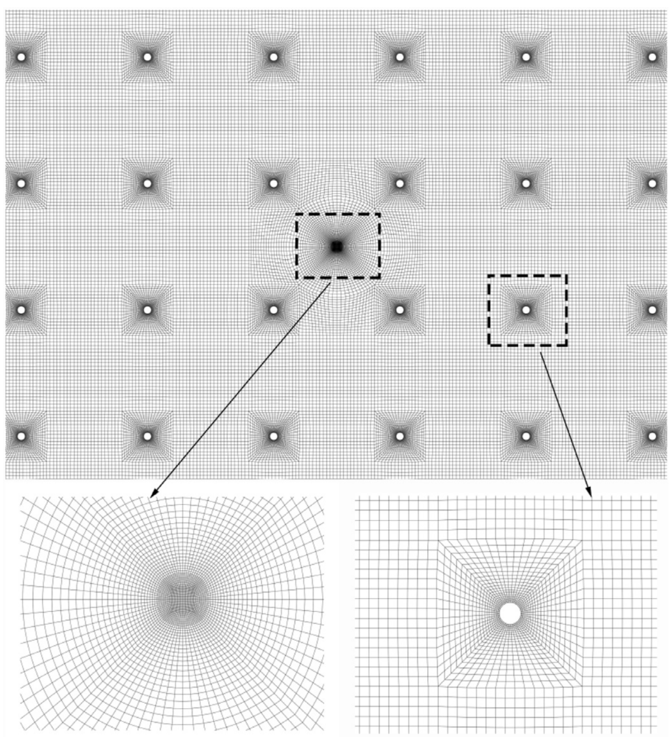

Fig. 2. Computational mesh around the jet orifice and individual vegetation stems.

Table 1
Parameters of computed cases.

Run	Ambient velocity U_a (m/s)	Jet velocity U_j (m/s)	$\triangle T$ (°C)	Vegetation height (m)	R	Re_0
Run 1	0.0826	1.440	35	–	17.4	15,060
Run 2	0.0826	1.875	35	–	22.7	19,610
Run 3	0.0826	1.440	35	0.26	17.4	15,060
Run 4	0.0826	1.875	35	0.26	22.7	19,610

Table 2
Information about the three meshes.

Mesh	Mesh nodes (million)
I	20.58
II	62.54
III	91.20

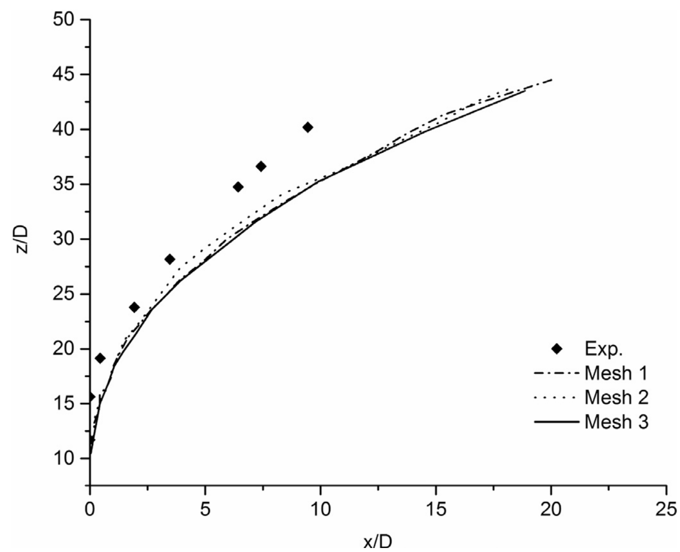

Fig. 3. Effect of grid size on the jet trajectory for Run 4.

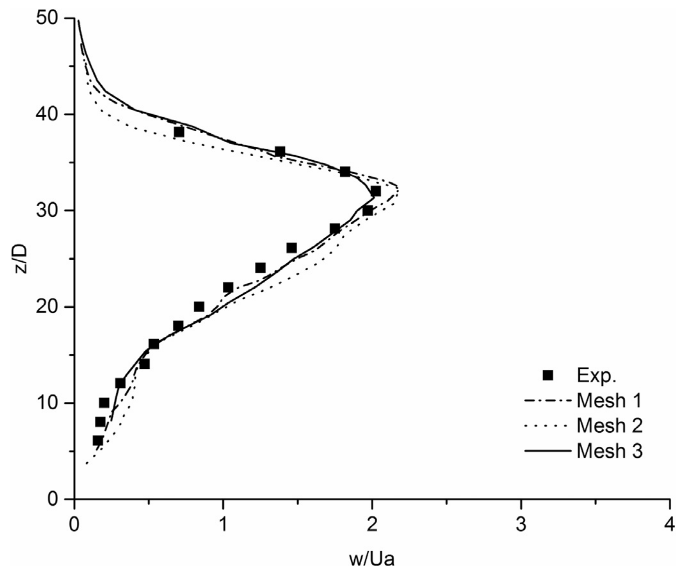

Fig. 4. Effect of grid size on the normalized vertical velocity w/Ua on the centre plane ($y/D = 0$) at $x/D = 10$ for Run 4.

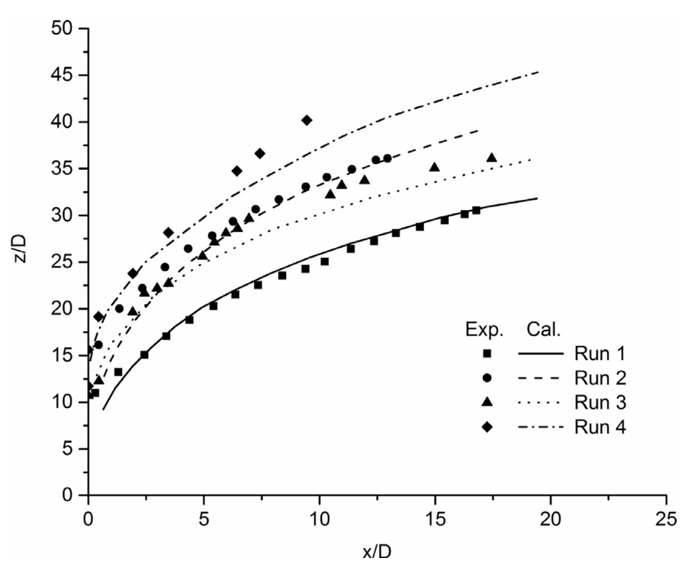

Fig. 5. Comparison of jet trajectory scaled with D. Symbols: experimental data. Line: LES data.