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Flow Characteristics of Flapping Motion of a Plane Water Jet Impinging onto Free Surface

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Abstract. A submerged turbulent plane jet in shallow water impinging vertically onto the free surface will produce a large-scale flapping motion when the jet exit velocity is larger than a critical one. The flapping phenomenon is verified in this paper through a large eddy simulation where the free surface is modeled by volume of fluid approach. The quantitative results for flapping jet are found to be in good agreement with available experimental data in terms of mean velocity, flapping-induced velocity and turbulence intensity. Results show that the flapping motion is a new flow pattern with characteristic flapping frequency for submerged turbulent plane jets, the mean centerline velocity decay is considerably faster than that of the stable impinging jet without flapping motion, and the flapping-induced velocities are as important as the turbulent fluctuations.

AMS subject classifications: 76D25

Key words: Turbulent plane jet, flapping motion, volume of fluid, large eddy simulation.

1 Introduction

For a submerged turbulent plane jet in shallow water impinging vertically onto the free surface, the jet will be self-excited into a flapping oscillation when the jet velocity, exiting the jet orifice, exceeds a critical value. One important characteristic of the flapping jet is to enhance mixing by flapping-induced Reynolds stress [1].In some cases, the instability of jet can be utilized to enhance the dilution. There is therefore a considerable interest in the design, performance and flow control of diffusers or mixers in chemical engineering, environmental engineering, and so on.

The flapping motion is a transverse oscillation of turbulent plane jet impinging onto free surface. A few parametric studies have been done to characterize the onset of flapping instability. Madarame et al. [2] established a relation between the flapping frequency

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and the water depth. Wu et al. [3] performed experiments to delineate the critical jet exit velocity and the jet flapping frequency. All the experimental results in [2] and [3] were presented in dimensional form. Hsu et al. [4] and Sun [5] provided more general dimensionless parametric relations for the onset of flapping instability. In [4] and [5], the critical jet exit velocity W_{oc} was found to increase linearly with the water depth H and to decrease with the square root of the jet orifice width d. Meanwhile, the critical flapping frequency, f_0, was found to decrease with the root square of the water depth H, that is $f_0 \propto \sqrt{g/H}$. On the other hand, there remain debates on the mechanics of flapping motion. Hsu et al. [4] suggested that the flapping behavior was attributed to the self-excited jet instability, associated with the pressure restoring force increased by surface deformation due to gravity. However, in earlier research work, the flapping behavior was confirmed as the unstable motion due to the coherent turbulent structure [6, 7]. Recently, Espa et al. [8] conducted experiments and smoothed particle hydrodynamics simulation to study the instability of a vertical plane jet introduced from the bottom of a finite depth laterally-confined water environment. It should be noted that the flow region in [8] was lateral confined and the ratio of water depth to orifice width was too small to reach the self-similar regime [9] for a submerged plane jet.

There are several kinds of self-induced oscillations coupled with jet flow and relatively few investigations have been conducted on them. The impingement of turbulent plane jets, upon an edge of a solid plate (a wedge of zero degree) in parallel to the jet flow was studied by Rockwell [10] and analyzed numerically by Ohring [11]. Ohring [11] predicted that the flapping oscillation of the impinging jet occurs at the subharmonic mode associated with the coherent large eddies. Gutmark et al. [12] studied the impingement of a plane jet onto a solid plate normal to the jet flow (a wedge of 180 degree) and did not detect any subharmonic transverse oscillations of the jets. Recently, the velocity oscillation phenomena in the far field region for plane jet at low Reynolds number was studied by Zhao et al. [13]. In comparison, the transverse flapping oscillation of turbulent jets in shallow water and more generally the detailed flow characteristics in this condition have so far received little attention in the specialized literature: only few experimental works [1–5, 8] and very little numerical study [8, 14] have addressed this topic.

In this paper, a large eddy simulation (LES) technique coupled with the volume of fluid (VOF) interface capturing method is utilized to investigate the flow characteristics of flapping motion. The purpose is to achieve an improved understanding of some of the fundamental characteristics in this flow, including the mean centerline velocity decay, flapping-induced velocities and frequency of the flapping motion.

2 Governing equations and numerical methodology

Large eddy simulation is implemented in the present work for turbulence closure, in which large-scale motions are explicitly calculated and the eddies with scale smaller than the grid or filter size are modeled to represent the effects of unresolved motions on re-