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Effects of upstream tetrahedron length on flow characteristics around juncture of circular cylinder and flat plate

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ABSTRACT

The influences of the length of tetrahedron juncture flow controller (JFC) and Reynolds number on the flow in the vertical symmetrical plane of the upstream region and near wake of a circular cylinder-flat plate juncture were studied experimentally in a towing water tank. The flow was analyzed by the particle-tracking flow visualization method and particle image velocimetry. The Reynolds number ranged from 500 to 6000. The inverse of nondimensional boundary-layer displacement thickness was from 3.27 to 10.33. The tetrahedron length-to-circular cylinder diameter ratio ranged from 0 to 1.4. The natural flow presented single-vortex, dual-vortex, triple-vortex, and unsteady vortical flow modes in different ranges of Reynolds numbers. The effects of the tetrahedron JFC installed at the leading edge of the juncture on the flow patterns significantly depended on the tetrahedron length and a little on the Reynolds number. Larger tetrahedron length was required to change flow modes and eliminate horseshoe vortices at larger Reynolds number. Within the range of Reynolds numbers < 6000, the tetrahedron length-to-cylinder diameter ratio must be larger than about 1, so all flows near the upstream region of the juncture directed forward without reversal or vortices. The tetrahedron JFC significantly reduced the wall shear stress in the near wake of the juncture when compared with that of the natural flow.

1. Introduction

Many research results have shown that as a flow near a surface approaches an obstacle extruded from that surface, a complex three-dimensional vortical flow field would develop around the juncture [1–24]. The complex flow field around the juncture of the obstacle and surface consisted of one, two, or three horseshoe vortices located upstream of the obstacle. The horseshoe vortices wrapped around the obstacle and extended to the downstream area, forming a large wake. The number of horseshoe vortices depended on the Reynolds number $Re_D = UD/\nu$ (where U is the freestream velocity, D is the equivalent diameter of the obstacle, and ν is the kinetic viscosity of the fluid) and the inverse of the dimensionless boundary-layer thickness $\delta^* = D/\delta_1$ (where δ_1 is the boundary-layer displacement thickness at the cylinder position when the cylinder is not present). The horseshoe vortices were induced by the adverse pressure gradient due to the existence of the obstacle.

The juncture flow may induce negative effects in many applications. For instance, horseshoe vortices often induce scour phenomenon of bridge pier foundations in river sand beds and, therefore, threaten the safety of the bridge [25–27]. Noise and vibration induced by the unsteadiness of horseshoe vortices around the sail-hull juncture of a submarine presented an unfavorable feature from the military viewpoint [28]. Around the juncture of the wing and body of an airplane, the horseshoe vortices could lead to decreased aerodynamic performance [29,30]. Some studies have reported methods of reducing the negative effects of the horseshoe vortices. Suction applied at the upstream area of the surface near the cylinder-surface juncture and fillet installed at the corner of the juncture were the most frequently used methods. Applying suction at the surface upstream of a wing-body juncture reduced the size of horseshoe vortices [29,30]. Suction from a slot arranged upstream of a circular cylinder-surface juncture mitigated some of the negative effects of the horseshoe vortices [31]. A delta wing–like fillet attached to a rectangular pier surface juncture could modify the horseshoe vortex's development [32]. A fillet wrapping around the entire base of a wing-body juncture did not prevent formation of horseshoe vortices [33]. A leading-edge fillet could eliminate boundary-layer separation upstream of an appendage-body juncture, but the traces of vortex legs were still observed downstream of the juncture [34]. Strake fillets attached to the wing-surface juncture have

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Nomenclature

D	diameter of circular cylinder, 50 mm
f	vortex shedding frequency
Re_D	Reynolds number ($=UD/\nu$)
St	Strouhal number of vortex shedding ($=fD/U$)
U	towing velocity
u	local axial velocity
x, y, z	Cartesian coordinates originated at leading edge of juncture
Φ	power spectrum density function
τ_w	wall-shear stress
ρ	density of water
δ_1	displacement boundary layer thickness
δ^*	inverse of non-dimensional boundary layer thickness ($=D/\delta_1$)
ν	kinematic viscosity of water

been proven to present no significant reduction in vortex structure [30]. The upstream longitudinal triangular ribs placed ahead of a wing-surface juncture could displace the horseshoe vortices away from the juncture and reduce their strength [35]. Mounting an inclined circular rod to the upstream area of the cylinder-surface juncture, the horseshoe vortices could be weakened [36]. A properly designed tetrahedron installed at the upstream corner of the cylinder-surface juncture could eliminate the horseshoe vortices [37].

In Huang et al.'s work [37], the horseshoe vortices in the upstream region around the juncture of a circular cylinder and a flat plate could be suppressed by installing a tetrahedron JFC at the upstream corner of the juncture. They discussed that the primary parameters affecting the flow field were the tetrahedron length at small tilt and expansion angles. However, little information on the effect of tetrahedron length as well as the characteristics of flow behaviors, vortex shedding, and shear stress could be found in that work and other literature. To extend Huang et al.'s work [37], the present study used a water towing tank to investigate the effects of tetrahedron length and Reynolds number on flow characteristics in the upstream and downstream regions around the juncture of a circular cylinder and a flat plate with a tetrahedron JFC by particle-tracking flow visualization method and particle image velocimetry. The wall-shear stress and vortex shedding in the wake region were simultaneously presented and discussed.

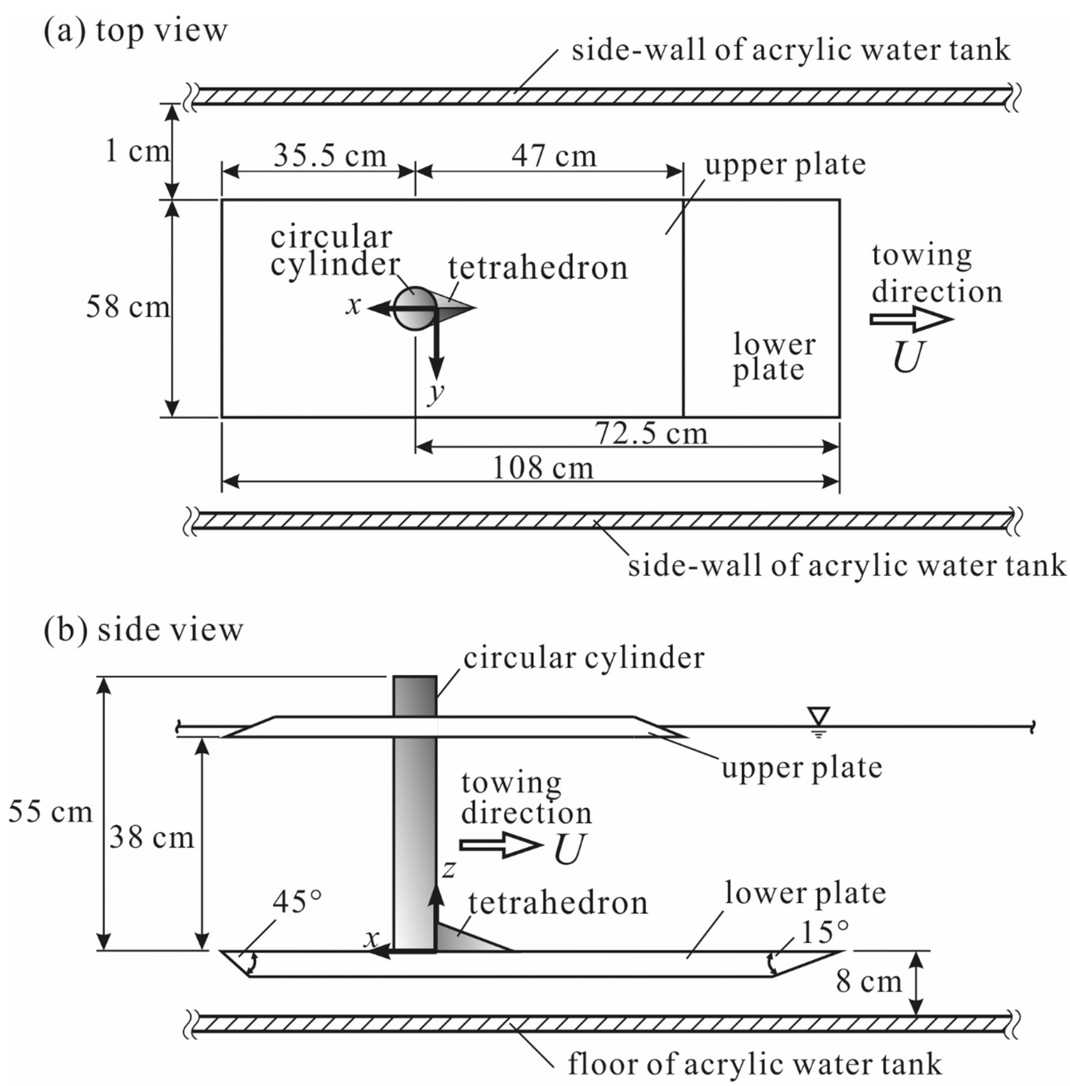

Fig. 1. Arrangement of experimental setup.