Experimental study of steady concentration fields in turbulent wakes

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Abstract  The pollutant transportation process in turbulent wakes is studied experimentally using planar laser-induced fluorescence (PLIF). The concentration fields in the very near wake region behind typical bluff bodies are measured for steady flow. The characteristics of the mean and instantaneous concentration fields behind circular and sinusoidal island and peninsular are investigated. The results indicate that the pollutant distribution is closely related with the unsteady vortex shedding in the flow field. Compared with that of the circular island, more pollutants enter into the wake generated by the sinusoidal-shaped island. The time needed for pollutants to accumulate in or drain out of the wake region after the peninsular before reaching a relatively constant value is longer than that for the islands, regardless of the island or peninsular shape. The results will facilitate pollutant control behind sea islands and other natural or man-made structures in water. Also the results provide some fundamental data for checking numerical models.

List of Symbols

\( C \) Instant concentration
\( \bar{C} \) Average concentration
\( C_0 \) Concentration at the injection orifice
\( C_i \) Turbulent fluctuation of the concentration
\( S(t) \) Dimensionless concentration value, defined as 
\( S(t) = \frac{C(t) - C_0}{100} \)
\( \bar{S} \) Mean value of \( S(t) \)
\( d \) Island diameter
\( D \) Island transverse dimension
\( i \) Digital time step
\( F \) Laser beam intensity
\( f \) Signal noise
\( H_m \) Parameter relating the concentration and the laser beam intensity
\( H \) Water depth
\( h \) Distance from the bottom of the flume to the light sheet
\( N \) Number of the digital image steps
\( R_{cfl} \) Reynolds number based on the water depth \( H \)
\( R_{cd} \) Reynolds number based on the island diameter
\( R \) Radius of circular island
\( R_x \) Radius of sinusoidal island in the flow direction
\( R_y \) Radius of sinusoidal island in the direction perpendicular to the flow direction
\( t \) Time
\( U_\infty \) Freestream velocity
\( X, Y \) Cartesian coordinates for light system, with \( Y \) in the laser beam direction, \( X \) in the lateral direction (perpendicular to \( Y \))
\( x', y' \) Cartesian coordinates for the flow field, with \( x' \) in the flow direction, \( y' \) in the lateral direction (perpendicular to the flow direction)
\( x, y \) Dimensionless coordinates for \( x', y' \)
\( Y_0 \) Distance from lens to the water flume
\( \alpha, \beta \) Parameters relating the concentration and the laser beam intensity
\( \nu \) Viscosity of water

1 Introduction

Turbulent wakes generated by the flow past bluff bodies have been the subject of many investigations (e.g., Cantwell and Coles 1983, Perry and Steiner 1987, Cimbala et al. 1988, Williamson 1996; Li et al. 1999). The three-dimensional wake transition phenomenon was studied by Williamson (1996), who measured the velocity fluctuations with a miniature hot wire in the wake region. The results indicated that the wake transition regime \( (Re = 190–260) \) is characterized by two distinct three-dimensional instability modes. Both modes involve the generation of streamwise vortex pairs in the wake, which reside and are stretched in the streamwise direction in the braid regions, between the primary Karman vortex structures. The turbulent wake in shallow water has also been studied experimentally by Chen and Jirka (1995), who found that the flow pattern depends mainly on the shallow-water stability parameter, \( S = C_f d/h \), where \( C_f \) is the bottom friction coefficient, \( d \) is the island diameter, and \( h \) is the water depth. They suggested two critical values, \( S_{c1} = 0.20 \) and \( S_{c2} = 0.50 \). When \( S < S_{c1} \), eddy shedding is observed in the wake as a Karman vortex street. For \( S_{c1} < S < S_{c2} \), the wake undergoes a transition from vortex shedding to unsteady bubbles. For \( S > S_{c2} \), the transverse disturbances lessen and the wake is characterized by a pair of steady
wake bubbles with slowly recirculating flow, which is referred as shallow-water wakes. Chen and Jirka (1997) investigated the absolute and convective instabilities of the plane turbulent wakes in shallow water using the shallow-water stability equation. This analysis confirmed that the flow pattern depends mainly on the shallow water stability parameter $S$. The velocity field in the wake zone behind different types of islands has also been experimentally investigated using digital particle image velocimetry (DPIV) (Willert and Gharib 1991, Lloyd et al. 1995, Huang et al. 1993a, b, Lloyd and Stansby 1997a, b, Tian 1998). It is well known that the turbulent wake behind a circular cylinder is closely related to the Reynolds number, especially in the critical range. The shift of the flow separation point and, as a consequence, the hydrodynamic characteristics, such as the drag coefficient and the Strouhal number, are dependent on the flow Reynolds number. Most experimental results have measured velocities in the far wake, indicating the existence of a larger scale motion there.

Numerous measurements of the velocity field in the wake region of a circular cylinder have been reported (e.g., Lloyd et al. 1995, Lloyd and Stansby 1997). The particle image velocity (PIV) system has also been applied to measure the velocity distribution in shallow-water flow. 2D and 3D shallow-water numerical models using the hydrostatic pressure assumption are always used for comparison with laboratory data. The velocity time histories at various points measured by the PIV system can be compared with simultaneous laser Doppler anemometry measurements to assess the accuracy of the measurement system. Until now, relatively little research has been published on the examination of the pollutant transport processes in the very near wake region besides the measurement of the velocity fields. Scalars such as temperature have been measured in the far wake behind circular cylinders (LaRue and Libby 1974, Antonia and Britz 1989) and in the intermediate wake (Freyimuth and Uberoi 1971). The structures of the turbulent wake have been studied with regard to the spectra of temperature fluctuations. Very recent results from Balachandar et al. (1997) demonstrate some significant new results for measuring the concentration distribution in a turbulent wake generated by a flat plate. Dye is introduced behind the plate as the tracer with measurements of the dye concentration in the near wake using an optical colorimeter. A phase average method is used to determine the structure of large-scale eddies. Advanced experimental techniques can be used to measure the entire instantaneous scalar distribution and vector field. Both DPIV and planar laser-induced fluorescence (PLIF) experimental system have been used to measure the concentration fields of steady turbulent jets and turbulent jets in cross-flow (Huang 1993, Li et al. 1999). PLIF images have also been used to analyze the fractal dimension of round turbulent jets in cross-flow (Chen and Jirka 1997). These studies provide a new tool and point of view for understanding turbulence.

This paper studies the turbulent wakes generated by vertical cylindrical objects extending above the water surface. The water depth is much larger than the characteristic length of the bluff bodies, which ensures that the wake stability parameter $S$ is much less than 0.2, so the influence of the bed friction can be neglected and the flow is considered to be two-dimensional. The measurement plane is at about mid-depth to avoid the bottom and surface effects. The velocity is measured by the DPIV method, with the concentration field measured by the PLIF technique. The present study focuses on the characteristics of the concentration field in the near wakes of various types of islands and peninsulas. The mean and instantaneous concentration fields are obtained, and the pollutant transportation mechanism is analyzed. The results are of considerable interest to scientists and engineers involved in coastal water management. Accurate and quantitative experimental measurements of the fluid flow and pollutant transportation processes enable more effective environmental control programs.

2 Experimental arrangement

2.1 Experimental setup

Experiments were conducted in a water flume with horizontal dimensions of 26 m × 0.6 m and a depth of 0.8 m.

![Experimental setup](image-url)