AN EXPERIMENTAL STUDY ON TURBULENT COHERENT STRUCTURES NEAR A SHEARED AIR-WATER INTERFACE*

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ABSTRACT: The turbulence structures near a sheared air-water interface were experimentally investigated with the hydrogen bubble visualization technique. Surface shear was imposed by an airflow over the water flow which was kept free from surface waves. Results show that the wind shear has the main influence on coherent structures under air-water interfaces. Low- and high-speed streaks form in the region close to the interface as a result of the imposed shear stress. When a certain airflow velocity is reached, “turbulent spots” appear randomly at low-speed streaks with some characteristics of hairpin vortices. At even higher shear rates, the flow near the interface is dominated primarily by intermittent bursting events. The coherent structures observed near sheared air-water interfaces show qualitative similarities with those occurring in near-wall turbulence. However, a few distinctive phenomena were also observed, including the fluctuating thickness of the instantaneous boundary layer and vertical vortices in bursting processes, which appear to be associated with the characteristics of air-water interfaces.

KEY WORDS: air-water interface, surface shear, coherent structures, flow visualization

1 INTRODUCTION

Turbulent transport of mass, heat, and momentum across gas-liquid interfaces exists in various engineering applications as well as in environmental flow systems. Recently, the issue of gas transfer rate has received world-wide concern in view of the global-warming problem, which is related to the exchange of carbon dioxide between the atmosphere and the sea. Transport processes at a gas-liquid interface, particularly of sparingly soluble gases, are usually governed by the transfer coefficients on the liquid side, which in turn are dependent on turbulence structures near the interface.

The organized structures in near-wall turbulent flows have been extensively investigated over the past four decades[1~3]. Some few significant findings now are widely accepted, including the understanding that low-speed streaks and the subsequent bursting phenomenon are chief characteristics of the wall region of turbulent boundary layers. During a burst,
individual low-speed streaks lift away from the wall, and eventually break up resulting in a substantial portion of the low momentum fluid being ejected into the outer flow. Such processes play a dominant role in the turbulent transfer of mass, heat and momentum between the inner and outer regions of the boundary layer. Kim et al. have shown that "essentially all the turbulence production occurs during bursting times in the zone $0 < y^+ < 100$".

Compared with the knowledge available for the near-wall situation, the turbulence behavior close to gas-liquid interfaces is poorly understood, and the conducted observations are much less. This could be partially attributed to the complexity of such boundaries, as well as to the special difficulty in taking accurate measurements very close to the interface. As late as the early eighties, Brumley & Jirka, Nezu & Rodi, Dickey et al. and Komori et al. performed important experiments studying the turbulence near gas-liquid interfaces, and valuable information was obtained. Both Dickey et al. and Komori et al. made careful measurements near free-surfaces (with no shear at the interface). Primarily due to their work, it is known that, on the average, fluctuations normal to the interface are damped whereas the tangential components are enhanced. This is a remarkable feature that distinguishes free-surface turbulence from that near a rigid boundary, and implies the very different effect of the interfacial boundary conditions.

For a sheared smooth air-water interface where the turbulence is generated both by the wind shear and by the bottom wall, Rashidi & Banerjee investigated the turbulence structures in a thin open-channel flow. They reported an interesting discovery that streaky structures and turbulent bursts exist in the interface region likewise, which turned out quite similar to the wall turbulence. However, the small depth of the water flow (the maximum less than 3.5 cm) in Rashidi and Banerjee experiments made it very difficult to extract only the action of the interface shear, and the turbulence structures generated independently at sheared gas-liquid interfaces have not yet been examined.

The present paper describes some flow-visualization results of the turbulence structures appearing under a sheared air-water interface. To exclude the interference of wall turbulence, experiments were carried out using a large water depth. In addition, the gas flows were kept at low velocities, and a great care was taken to eliminate surface waves.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were conducted in the SKLTR low turbulence (turbulence intensity $\leq 0.3\%$) circulating water tunnel in Peking University. Mounted on the Plexiglas working section of this tunnel was a rectangular conduit, through which an air flow was created by an axial-flow fan operating at the downwind end. The capacity of the variable-speed motor that drove the fan was controlled by a frequency inverter. The wind-water flow system is 3.5 m long, 0.4 m wide by 0.85 m high with water depth of 0.38 m. The observation position is at $x = 2.0$ m downstream from the entrance of the air flow ($x = 0$).

The water and air flows were set in opposite directions, and a constant water flow velocity of 6.0 cm/s was used in all the experiments. Mean streamwise velocities of the air flows were measured by means of a constant-temperature hot-wire anemometer (TSI 1050-2C) with a single-sensor probe (TSI 1201-20) which was calibrated by using the vortex shedding method. The airflow speeds $V_\infty$ employed in experiments were limited to less than 3.06 m/s in order not to excite surface waves. A hot-film probe (TSI 1210-20w) was