

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,

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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.^[4] 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^[5], Nezu & Rodi^[6], Dickey et al.^[7] and Komori et al.^[8] performed important experiments studying the turbulence near gas-liquid interfaces, and valuable information was obtained. Both Dickey et al.^[7] and Komori et al.^[8] 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^[9] 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^[10]. The airflow speeds V_∞ 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

set at $y = 1.5$ cm beneath the water surface ($y = 0$) to measure instantaneous streamwise velocities in the water flow. The sampling frequency was 1.6 kHz, and the sampling duration was 20 s and 300 s respectively for the air and water flows.

To visualize flow structures, the hydrogen bubble technique was adopted. Tiny hydrogen bubbles were generated either from a platinum wire about $20\text{ }\mu\text{m}$ in diameter that was positioned vertically, or from a wire held parallel to the air-water interface and normal to the flow direction. By pulsing the voltage applied to the wire, time-lines can be formed. Flow patterns of the bubble could be viewed from the top and side of the wind-water channel for the parallel and vertical generating wires respectively. At the same time, the visualization results were recorded by a CCD camera for playback analyses.

As is well known, the hydrogen bubble technique can not only provide qualitative information concerning flow structures, but also be used to determine instantaneous velocity profiles. Indeed, Kim et al.^[4] pointed out that the ability to observe instantaneous velocity profiles is crucial in understanding the nature of turbulence structures. A detailed description of the measurement of velocity by the bubble method can be found in Ref.[11]. In the discussion that follows, both the quantitative and qualitative output of the hydrogen bubble technique is reported.

3 RESULTS AND DISCUSSION

3.1 Low- and High-Speed Streaks near Sheared Air-Water Interfaces

Many laboratories have documented the existence of longitudinal “streaks” of alternating slow- and fast-moving fluid within turbulent boundary layers at solid walls. Because of its universality, this structure is accepted as a basic feature of turbulent shear flows near smooth walls. On the other hand, Uzkan & Reynolds^[12] examined a shear-free turbulent boundary layer where mean velocity gradients were absent, and showed that no wall-layer streaks appeared.

We now look at the same problem for air-water interfaces. Figure 1 shows the top views of flow patterns as visualized with hydrogen bubble sheets for different shearing air flows. The bubble wire appears at the left extreme of the pictures. Figure 1(a) is for $V_\infty = 0$, namely the zero-shear interface case. The flow seems smooth and steady, and no distortion whatever or disturbance can be observed. This result coincides with the conclusion mentioned above for solid boundaries. As an air flow is imposed on the water surface, striations in the bubble sheet waver slowly in the spanwise direction while the sheet on the whole can keep its entity. When the air speed increases to 2.21 m/s, a quite peculiar phenomenon is revealed: pockets observed as small blank patches of different shapes in the bubble sheet appear abruptly and stochastically; almost simultaneously, a pair of counter-rotating streamwise vortices could be seen on both sides of the pocket. One can assume that the blank pocket is the result of a hairpin vortex, and the counter-rotating vortices may be its two legs while the head lifts away from the observation plane due to vortex induction. Such a picture is similar to the hairpin vortex model for near-wall turbulence, initially proposed by Theodorsen^[13] and subsequently by others (see, for example, Willmarth & Tu^[14], Offen & Kline^[15], Smith et al.^[16]). Shown in Fig.1(b) is an example of the pocket and accompanying vortices. From our observation, it is fair to say that the pockets are a sign of the appearance of turbulence and may correspond to the so-called “turbulent spots” in wall turbulence^[17,18].

As V_∞ increases further, blank pockets appear more frequently, and the bubble sheet can no longer keep as a whole, instead bubbles tend to collect into narrow streamwise streaks that can be clearly seen in Fig.1(c). The “turbulent spots”, if appear, are always on these streaks.

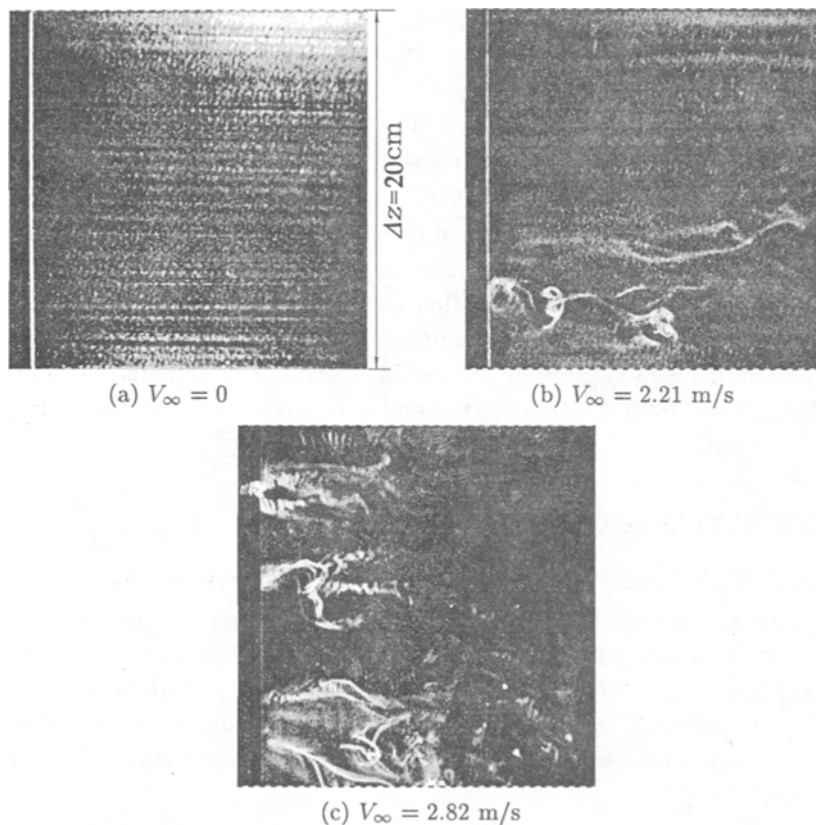


Fig.1 Top views of hydrogen bubble sheets with parallel hydrogen bubble wire at $y_{\text{wire}} = 1.0$ cm. The views are of the same scale; the water flow is from left to right of the pictures

With pulsed generation of hydrogen bubbles, low- and high-speed fluid streaks near the air-water interface were made directly observable in top views of the time-line flow pattern. Figure 2(a) illustrates a streaky structure for $V_\infty = 1.08$ m/s. Though the shear at the interface is very weak, long streamwise streaks of low-speed fluid are evidently present. When the airflow velocity (so that shear stress at the interface) is increased, the streaky structure becomes more visible as shown in Fig.2(b) for $V_\infty = 2.82$ m/s. Moreover, the velocity defect of the low-speed streak becomes greater and the spanwise streak spacing decreases statistically with increased V_∞ . The low-speed streaks are not straight but are observed to meander and oscillate “freely”. The spanwise locations where low-speed streaks occur can not be predicted at all, and the separation between two adjacent streaks changes significantly. It is easy to find out that the features of the streaky structure described herein seem to resemble those well-documented ones near rigid walls. As a quantitative example, Fig.3 shows the typical instantaneous spanwise variation of the streamwise velocities determined by the hydrogen bubble method.

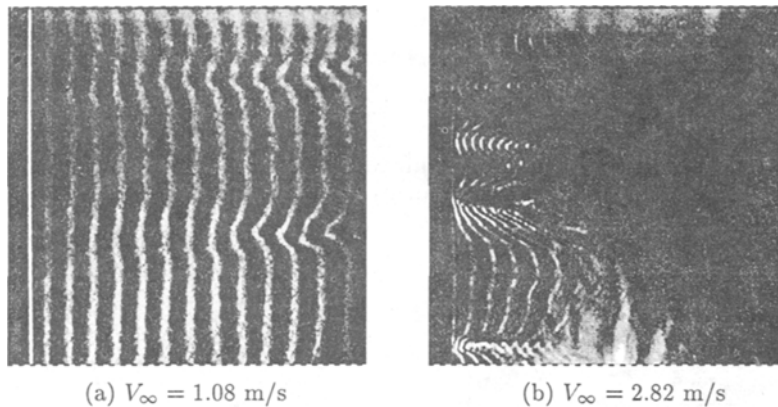


Fig.2 Top views of the hydrogen bubble time-line patterns showing the streaky structure. Bubble pulse frequency is 4 Hz; the views are of the same scale as those in Fig.1. $y_{\text{wire}} = 1.0$ cm

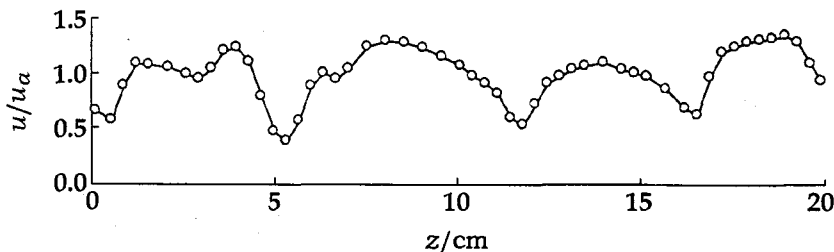


Fig.3 Typical instantaneous spanwise variation in the streamwise velocity u , obtained using the bubble method. Here, u_a is the spanwise average velocity. $V_{\infty} = 2.75$ m/s

3.2 Bursting Events

For a free-surface flow, hydrogen bubble time-lines (side view for the vertical bubble-generating wire) showed a uniform velocity profile, which is straight except for a slight velocity defect immediately beneath the water surface. When the water surface is sheared by low speed countercurrent airflows ($V_{\infty} < 2.63$ m/s), boundary layers near air-water interfaces begin to thicken, and the velocity at the water surface approaches zero or even turns in the air flow direction momentarily. The thickness of the interface boundary layer varies frequently, and so did the corresponding velocity profile in the layer. However, under weak shear conditions, the boundary layer flow keeps relatively quiescent and is quasi-steady all the time.

The present experiments showed that a turning-point is reached at the wind speed of about 2.63 m/s, from which on flow patterns near the interface are increasingly dominated by a kind of large scale, intermittent structure—turbulent bursting events. Such events, whenever they happen, usually evolve in a loosely ordered way from one stage to another, showing certain repeatability, but are by no means wholly deterministic. Figure 4 is a series of 5 side-view pictures of hydrogen bubble time-lines obtained with the vertical bubble wire, which illustrate the process of a typical bursting phenomenon.

The initial stage of bursting is characterized by the appearance of an inflectional zone in the instantaneous velocity profile. The inflection may be an indication of the arrival of a low-speed fluid streak, as examined and explained by Kim et al.^[4] in their study on near-wall turbulence structures. Shown in Fig.5 are instantaneous velocity profiles over a

bursting cycle. It is obvious that the profiles are dramatically deformed and very different from those either during the quiescent period between bursting processes or in cases where no bursts occur. It should be noticed that, while the instantaneous inflexional profile is often a precursor of bursting sequence, it does not necessarily lead to an actual occurrence of bursting. The deformation of velocity profile may gradually weaken and vanish in its later evolution, and finally a shape qualitatively like the one in quiescent periods is resumed.

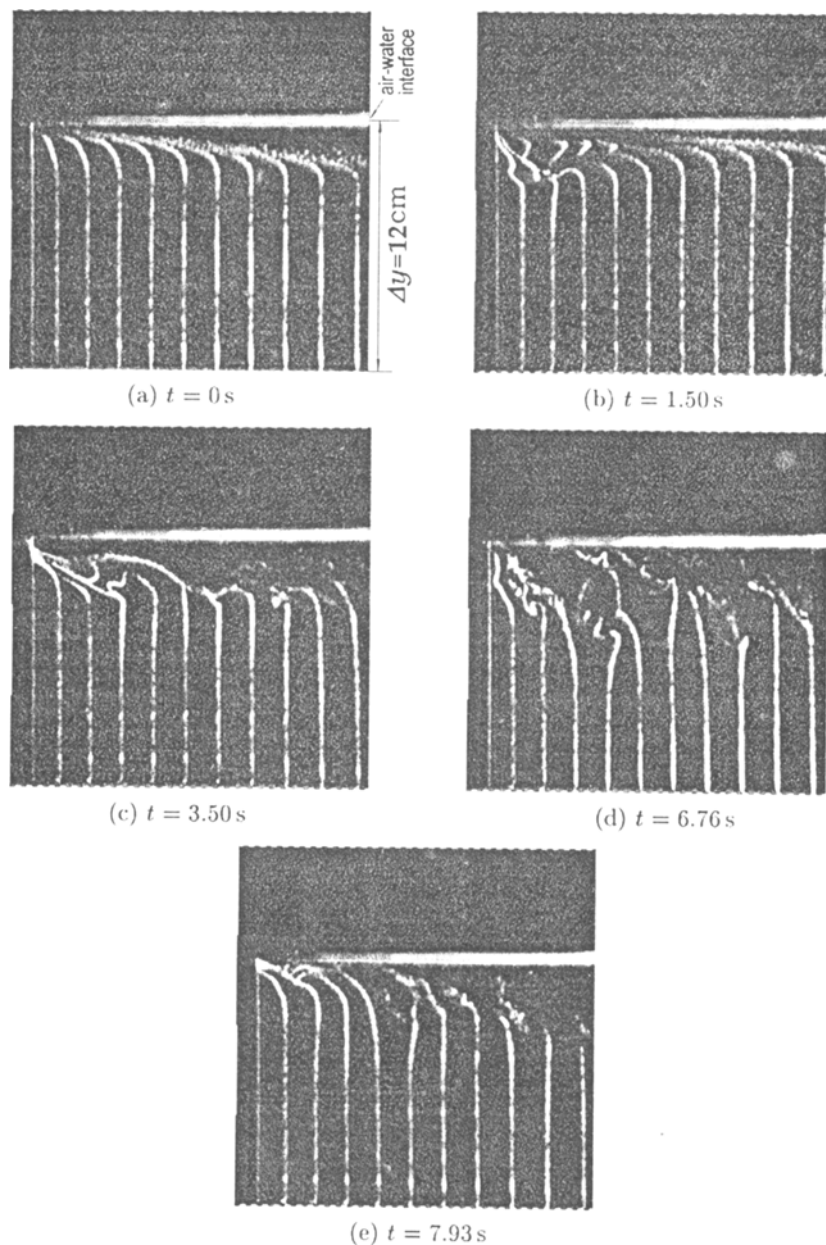


Fig.4 Side views of a typical bursting process illustrated by hydrogen bubble time-lines. Bubble pulse frequency is 4 Hz; all views are of the same scale; the flow is from left to right of the pictures

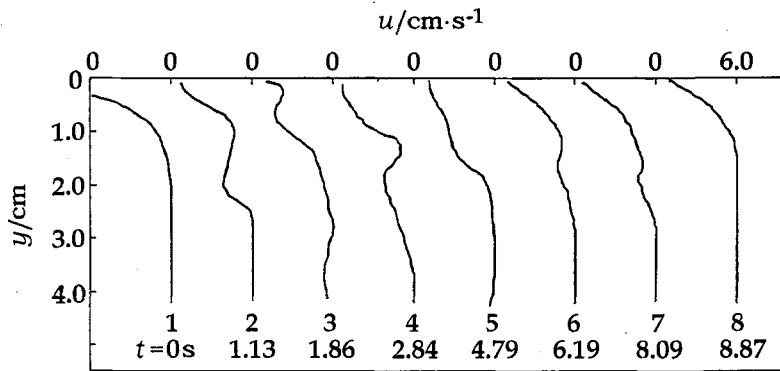


Fig.5 Instantaneous velocity profiles over a typical burst cycle, determined by the bubble method

Following the occurrence of instantaneous inflexional velocity profiles, vortex structures of various intensities and orientations were often observed to develop just downstream. The dominant mode is a streamwise vortex motion which swirls very close to the water surface, or slants away from the interface downstream at a small angle as shown in Fig.4(c) and Fig.4(d). This means the vortex motion can deeply penetrate into the nonviscous flow region, implying that the burst may play an important role in the transport process at gas-liquid interfaces. Transverse and vertical vortices were also seen during bursting processes, and the latter was somewhat more common. The vertical vortex extends from the neighborhood of the water surface into the bulk water, whose axis usually turns to the stream direction quickly owing to velocity gradient near the interface. The appearance of vertical vortices is one of the features specific to interface turbulence. They have not equivalents in near-wall turbulence. It is the much lower density and viscosity of the air that leave fluctuations parallel to the interface essentially unrestrained and allow of the formation of vertical vortices. For free-surface turbulence whose origin lies in the bottom wall shear region in a shallow channel flow, Kumar et al.^[19] experimentally showed "spiral eddies" as one of the persistent structures. While considerable difference exists between "spiral eddies" and the vertical vortices near sheared air-water interfaces, both their presence should be closely related with characteristics of air-water interfaces.

Vortical structures would eventually break up as they proceed downstream in the sense that large scale organized structures are replaced by a less coherent and small scale motion. With the viscous dissipation of small scale motions, the interface boundary layer becomes progressively less chaotic. Finally the flow reverts to a relatively quiescent state accompanied with the disappearance of inflexional zones in the instantaneous velocity profile; the cycle of the intermittent bursting process comes to an end, and will in due course start again. As observed in experiments the duration of bursting varies from one case to another, and some may last as long as 20 seconds. The intermission between bursting events also exhibits significant variation. However, the general trend is clear: the interval decreases as the air flow speed increases. Because of the large fluctuation of burst "period" and the difficulty in bursting identification, it seems to need longer video sequences in order to obtain faithful burst statistics than that actually recorded in the present study (usually 5~8 minutes duration for each experimental condition).

3.3 Variations of the Thickness of Water Surface Boundary Layer

Boundary layer thickness is a familiar concept in fluid mechanics. Our flow-visualization study, however, shows some rather unexpected features of the boundary layer under sheared air-water interfaces. Even when the airflow speed is less than 2.63 m/s, the boundary layer thickness as defined by instantaneous velocity profiles varies constantly, though the flow state is entirely laminar. The variation process occurs intermittently, and its duration appears random, usually lasting several seconds. For higher wind speeds ($V_\infty > 2.63$ m/s), the boundary layer thickness varies in greater amplitude. But the more remarkable is, with high interface shear, thickened interface boundary layers may trigger off bursting events now and then. Figure 6 shows the comparison of instantaneous velocity profiles during a typical thickening process, in which no burst is produced.

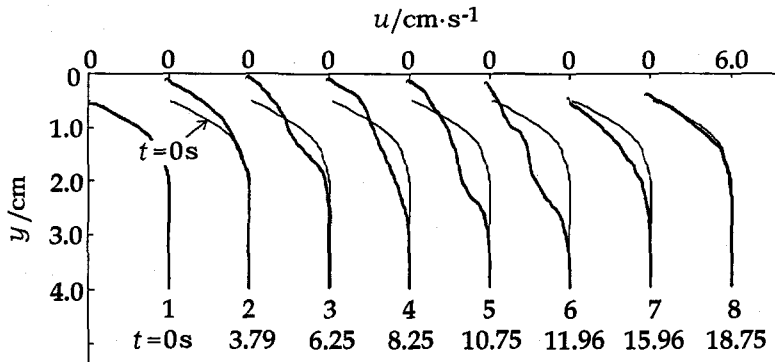


Fig.6 Comparison of instantaneous velocity profiles during a typical thickening process of the interface boundary layer. $V_\infty = 2.68$ m/s

The observations described above suggest that the transition from a literal laminar boundary layer to a turbulent one does not occur in an abrupt manner. The fluctuating thickness of the interface boundary layer could be a manifestation of some kind of initial disturbances. As the surface shear gradually increases, the thickness variations occur more frequently and intensely. Such disturbances may lead to bursting events at relatively high interface shear. However, the boundary layer thickening does not always result in bursting even at the highest wind speed employed in the experiments. Therefore the distinction between flows with and without bursting events in the boundary layer is not absolute.

4 CONCLUDING REMARKS

The visualization examination of turbulence structures near a sheared air-water interface leads to the following speculative ideas:

- (1) The shear rate at the interface is the chief factor bringing about streaky structure and bursting phenomenon. With certain airflow velocities, "turbulent spots" appear randomly on low-speed streaks, accompanied by vortex motions that are proposed to be the footprint of hairpin vortices. If the shearing airflow is sufficiently strong, water flow near the interface is controlled mainly by intermittent turbulent bursts.
- (2) Despite the quite different boundary conditions, the streaky structure and bursting process observed in interface boundary layers are qualitatively similar to their counterparts in near-wall turbulence. The bursting processes do show repeatable features and undergo

similar evolution stages though the details vary among realizations.

- (3) The constant variation of the boundary layer thickness was clearly revealed, and could be regarded as a kind of disturbance. The frequency and amplitude of the thickness fluctuation increase with increased speed of the shearing air flow, and in the region of $V_\infty > 2.63$ m/s, thickened boundary layers may lead to bursting events. It is suggested that the transition from laminar to turbulent flow is a progressive process rather than a sudden one.
- (4) More work is needed before a better understanding on the present problem can be gained. Further experimental study is now under way, and parts of the measurements are in processing.

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