BY-PASS LAMINAR-TURBULENT TRANSITION OF THE WIND-DRIVEN FREE SURFACE FLOW

Guillemette Caulliez*, Richard Dupont*, Victor I. Shrira**
**Institut de Recherche sur les Phénomènes Hors Equilibre*
163 av. de Luminy, 13009 Marseille, France
***Dept. of Mathematics, Keele University, Keele, Staffordshire, ST5 5BG, UK.*

Summary The laminar-turbulent transition of a wind-driven surface boundary layer is investigated experimentally. Two stages in the development of the perturbations have been clearly identified. First, a slow growth of streamwise longitudinal vortices is followed by rapid development of secondary instabilities. The picture is similar to a by-pass rigid wall transition to turbulence. At the second stage, peculiar to this flow, an explosive deepening of the boundary layer and the fast development of inflexional instabilities occur.

Turbulent motions generated in boundary layers induced by wind at the free surface of natural basins play a key role in heat and mass exchanges at the water-atmosphere interfaces. However, the properties and the origin of this small-scale turbulence as well as its interaction with the atmospheric turbulence above the interface, wind waves, mean shear current or other motions of larger scales present in water are poorly known. This situation is largely due to the fact that all these processes coexist and overlap in space-time domain, making the observations extremely difficult to perform and to interpret. Then, to shed light on the complex structure of the natural free surface boundary layers, a first step may consist in a thorough investigation of the individual basic processes controlling their formation. In that way, the laminar-turbulent transition in wind-driven flows was identified by Okuda et al.[5] and Kawai[3] in an early laboratory study of the temporally-developing boundary layer while a more detailed investigation of the temporal evolution of this boundary layer and its interaction with wind waves was made later by Melville et al[4] and Veron and Melville[6]. Due to the intrinsic difficulties of these temporal measurements, the main processes of the transition to turbulence have not been entirely clarified, in particular the role of waves in this phenomenon. The later was discarded by Tsai[7] on the basis of direct numerical simulations for the temporal case and by Caulliez et al.[2] as a result of a preliminary study of the spatially-developing drift current. The present work is concerned with the laminar-turbulent transition of a spatially-developing boundary layer. Based on precise laboratory experiments performed in steady conditions, it aims at establishing the main features of this phenomenon and at identifying the fundamental mechanisms at the origin of its development.

The observations were carried out in the large and small IRPHE-Luminy wind-wave facilities, for wind speeds ranging from 2.5 to 7 m/s. The structure of the velocity field in the water surface boundary layer was explored at various fetches (distance from the leading edge of the water tank) and depths just downstream the air-water junction plate, using both flow visualisation technique based upon dye injection and laser Doppler velocimeter measurements. The water surface displacements were measured simultaneously by means of a thin wire capacitance wave probe. Special measures were taken to minimise perturbations in the air and the water at the entrance of the tank and the air flow parameters were monitored by pressure and hot-wire probes.

A first description of the overall behaviour of the water flow was provided by means of the dye visualisations (Fig.1). First, just downstream of the air-water junction, the straight marked streamlines parallel to the flat water surface indicate that the surface wind induced current is laminar. Long wavy instabilities appear from time to time but they evolve to a very small extent before vanishing. Then, further downstream, there is a relatively long stage where the perturbations present a consistent tendency to grow. Finally, at a certain fetch, the flow disturbances start to evolve quite rapidly. The dye trajectory first develops instantaneous steep contortions mainly oriented downward. The presence of large oscillations of the residual dye filaments associated with the rapid dye diffusion into a deep layer suggests the formation of turbulent spots. Often after the streamline overturning the resulting turbulent spot disappears, washed up downstream, and the laminar flow is restored until breaking down again, creating an intermittent pattern. Sometimes, the transition to turbulent flow occurs even faster, when the still rectilinear dye filament stops abruptly at a definite fetch and bursts in wreath of dye disseminating into the whole boundary layer. It is also noticeable that small-scale waves ruffling the free surface

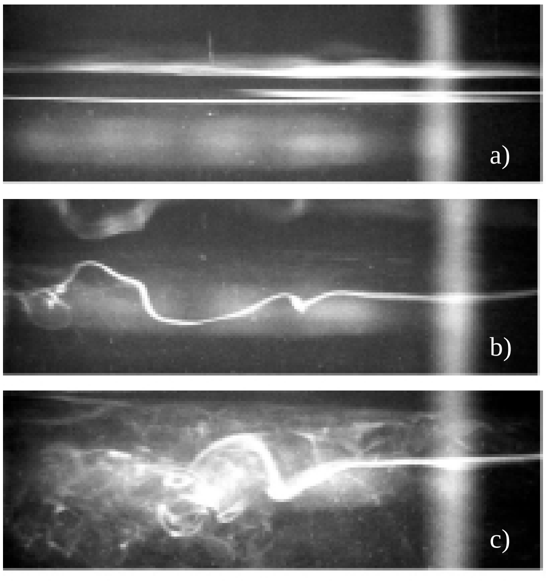

Fig. 1: Sideview of the typical evolution with fetch of the water flow instabilities traced by colored dye injected 30 cm upstream at a depth of 3mm, for a 5m/s wind speed blowing from the right to the left: a) laminar region, b) development of streamwise vortices at the first stage of the transition, c) formation of a turbulent spot at the second stage of the transition.

become visible at the point of the boundary layer breakdown. They mark the downstream regions where the turbulent spots develop and clearly show how the spots slowly expand spanwise until they merge. Thus the characteristic V-shaped streaks are created on the water surface.

Quantitative measurements first show that the thin water boundary layer induced by wind at the leading edge of the water sheet is indeed laminar. The drift current surface velocity and the boundary layer depth increase gradually with fetch, following 1/3 power laws characteristic of the accelerated flat-plate laminar boundary layers. The evolution with fetch of the mean velocity vertical profiles is well described by the self-similar profiles of the Falkner-Skan type. The first low frequency perturbations of the streamwise velocity field observed further downstream are much greater than the vertical one, suggesting the formation and the development of longitudinal vortices within the laminar boundary layer. The laminar-turbulent transition manifests itself by a sudden development of turbulent motions of large amplitude and high frequency localised both in space and time. The critical fetch where the first turbulent spots appear is not linked to any critical Reynolds number, but was found to depend on friction velocity as u^{*-2} (Fig. 2). Then, these turbulent spots evolve with fetch inside longitudinal elongated patches characterised by a slow crosswise expansion, while the boundary layer thickness inside these patches increases with fetch explosively (Fig. 3).

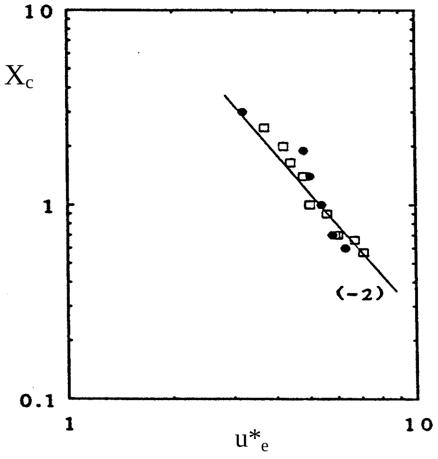

Fig. 2: The critical fetch X_c *vs* the friction velocity u^*_e in water for the different wind conditions observed in the large (open squares) and the small tank (closed circles).

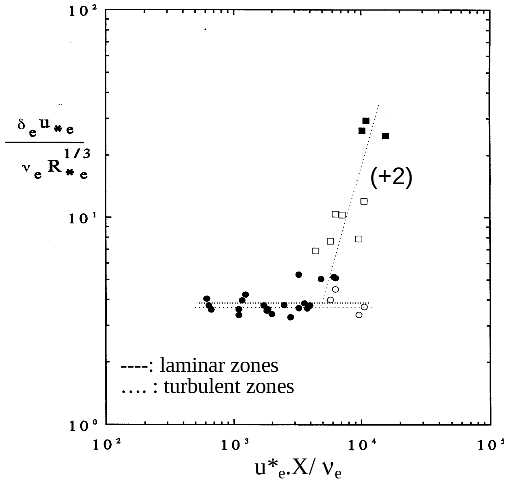

Fig. 3: Boundary layer thickness in water δ_e *vs* non-dimensional fetch ($u^*_e.X/ \nu_e = R^*_e$) shown by closed circles in the laminar region, by open symbols in the transitional region, and by closed squares in the fully-developed turbulent region.

These observations then suggest a plausible scenario of the transition to turbulence of the wind-driven boundary layer essentially characterised by two distinct stages. At the first stage, streamwise elongated structures emerge from natural noise disturbances and grow slowly without significant alteration of the mean field flow till their breakdown at a critical fetch. The picture is similar to the scenario of rigid plate laminar-turbulent transition caused a by-pass mechanism as reported by Andersson et al.[1]. In contrast, the second stage, where the turbulent spots created by the collapse of the shear boundary layer expand and merge, differs dramatically from the rigid plate scenario, in particular by the abruptness and the intensity with which the vertical mixing phenomena occur. The observed differences can be attributed to the coexistence of accelerated-decelerated mean flow regions leading to an enhancement of the turbulent diffusion in the vertical direction and its inhibition in the spanwise direction.

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