Boundary layer transition induced by a roughness element

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Funding agency: Deutsche Forschungsgemeinschaft, INEEL LDRD program, FY 1998

In many technical applications, laminar boundary layers are induced, by roughnesses, to undergo transition to a turbulent flow at lower Reynolds numbers than the natural flow transition. The present studies were undertaken to extend the knowledge of the spatial and temporal structure of the transition process induced by a single square roughness element. Particular emphasis was placed on the evolution of the viscous layer since it usually dominates the convective resistance to heat transfer (and momentum transfer) to/from a surface. The aim is to reach a better understanding of the fluid physics structure which evolves in a transition process induced by roughnesses, especially in the near-wall region. The results should also be valuable for benchmarking Direct Numerical Simulations of transition enhanced by the presence of roughness elements.

To measure the wall-normal component close to the surface, two-component laser Doppler anemometry (LDA) was used with the INEEL Matched-Index-of-Refraction (MIR) flow system. With hot-wire and hot-film X- or slant-probes to deduce Reynolds shear stresses, the sensor volume required has a dimension of the order of a millimeter perpendicular to the surface plus the additional space necessary for the support prongs. With LDA, an effective sensor diameter of about 60 µm or less can be achieved so measurements can be obtained to y ≈ 30 µm before "intersecting" the surface. However, the wall can interfere with the laser beams of an LDA system, especially when systems for two- and three-component measurements are employed. One way to eliminate these problems is to use a liquid possessing a refractive index that is matched to that of the wall material. The INEEL MIR flow system provides a basic test facility to study boundary layer transition in detail. The length of the test section is about 2.4 m and it has a cross section of about 0.61 m × 0.61 m, compared to other MIR facilities which have characteristic dimensions of a few centimeters.

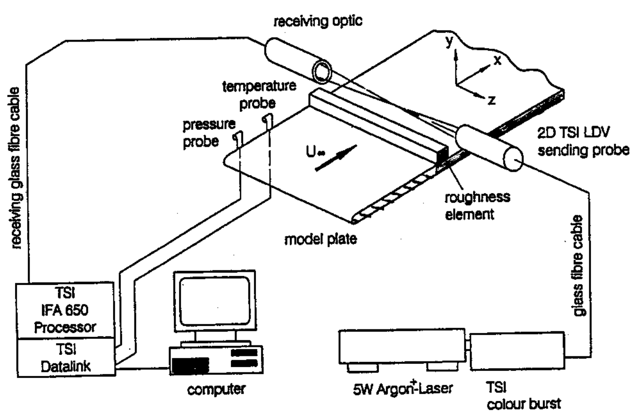

Figure 1. Experimental apparatus and model configuration

Measurements of flat plate boundary layers were carried out with three different roughness heights k and three different freestream velocities, resulting in the following ranges of parameters:

$$k^+ = 5.5 \text{ to } 21, \; 0.3 < k/\delta_1 < 1, \; 180 < Re_k < 740,$$

$$6 \times 10^4 < Re_{x,k} < 1.5 \times 10^5, \; Re_\Theta < 660, \; -125 < (x - x_k)/k < 580$$

Consequently, results covered boundary layers which retained their laminar characteristics through those where a turbulent boundary layer was established shortly after reattachment beyond the forcing rib. For "large" elements, evolution of turbulent statistics of the viscous layer for a turbulent boundary layer ($y^+ < \sim 30$) was rapid even in flows where the mean velocity profile still showed laminar behavior. The LDA system yielded data to a distance as near to the wall as $y^+ = 0.1$ and less. Thus, it was possible to estimate the local apparent wall shear stress accurately from the measured gradient $\partial U/\partial y$.

Most of the data were acquired with a two-component LDA operating in the forward scattering mode, thereby permitting simultaneous streamwise and normal velocity component measurements and calculation of their higher-order moments to be performed.

Figure 2. Dr. Stefan Becker of the Lehrstuhl für Strömungsmechanik of Univerität Erlangen-Nürnberg, Germany, using INEEL MIR flow system to measure boundary layer transition induced by a roughness element. The horizontal model is barely visible above the black horizontal support stringer since the refractive indices are matched for the blue and green beams of the LDA system.

New measurements of the evolution of the Reynolds stresses, v^2 and $\overline{uv}$, have been obtained at $y^+ < 30$ in transitional boundary layers on a flat plate. To our knowledge, such data were not previously available so close to the wall (in non-dimensional terms) for transitional boundary layers. Tabulated mean results are available for eight sets of experimental conditions, spanning a range from flows that do not undergo significant transition to ones which become turbulent in a short distance. These measurements extend the study of Klebanoff and Tidstrom to larger non-dimensional roughnesses, square ribs, moderate freestream turbulence levels and larger downstream distances. For small ribs (e.g., $k^+ \approx 11$), turbulence evolved from the inflectional region above the separated region downstream of the rib but laminar mean velocity profiles were recovered as in their case. For larger ribs ($k^+ > 14$) significant turbulence appeared in the reattaching shear layer as well and the viscous layer of a turbulent boundary layer began evolving soon after reattachment. The new data showed the development of the turbulent momentum transport across the boundary layer.

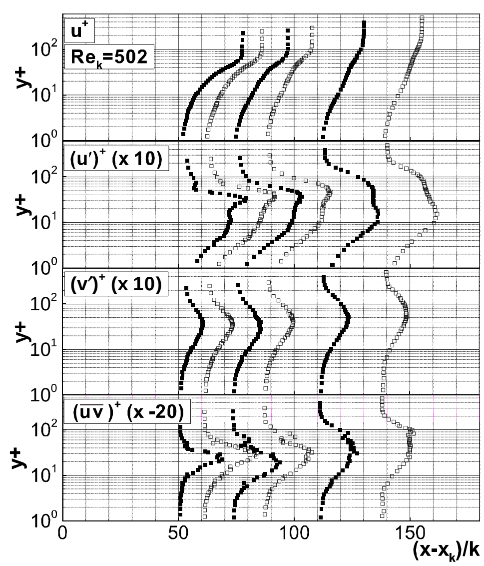

Figure 3. Evolution of turbulent boundary downstream of the square roughness element. Results normalized by wall coordinates: (a) streamwise mean velocity, (b) rms streamwise fluctuations, (c) rms wall-normal fluctuations and (d) Reynolds shear stress.

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