

Measurements in a turbulent boundary layer with intense free stream turbulence

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Abstract

Most flows in nature and in engineering applications are inherently turbulent. An analytic description of such fluid motion is impossible, yet engineers still require an understanding of these flows. The turbulent boundary layer is a flow that, though not fully understood, is nonetheless well-documented. How the turbulent boundary layer behaves in the presence of free stream turbulence is even less well-understood, despite many turbulent boundary layers occurring without laminar free streams.

Here we present results of hotwire anemometry studies demonstrating the influence of free stream turbulence on a boundary layer. In particular, we focus on new results that indicate a strong dependence on free stream conditions even very close to the wall, where one might expect the free stream to play very little role.

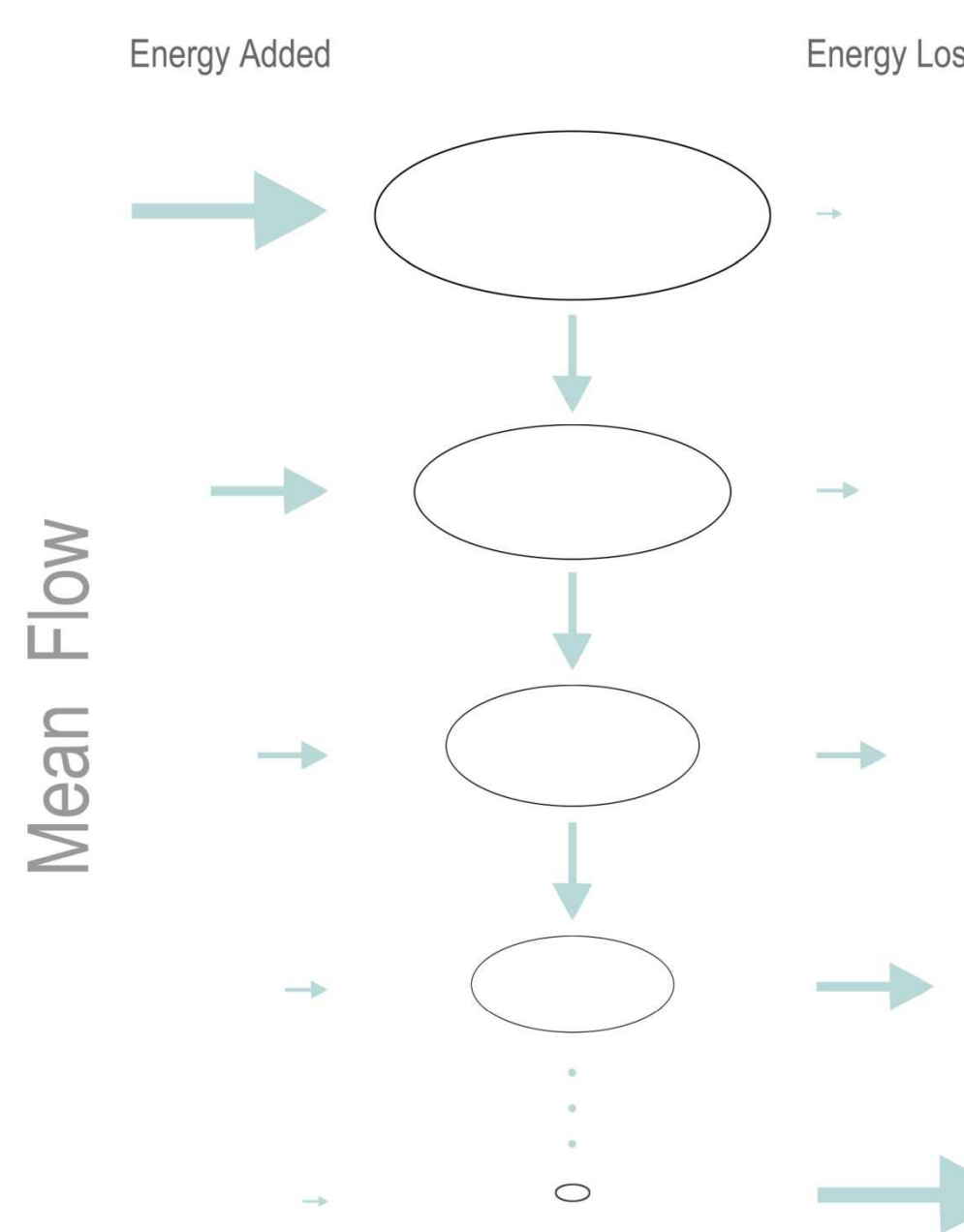
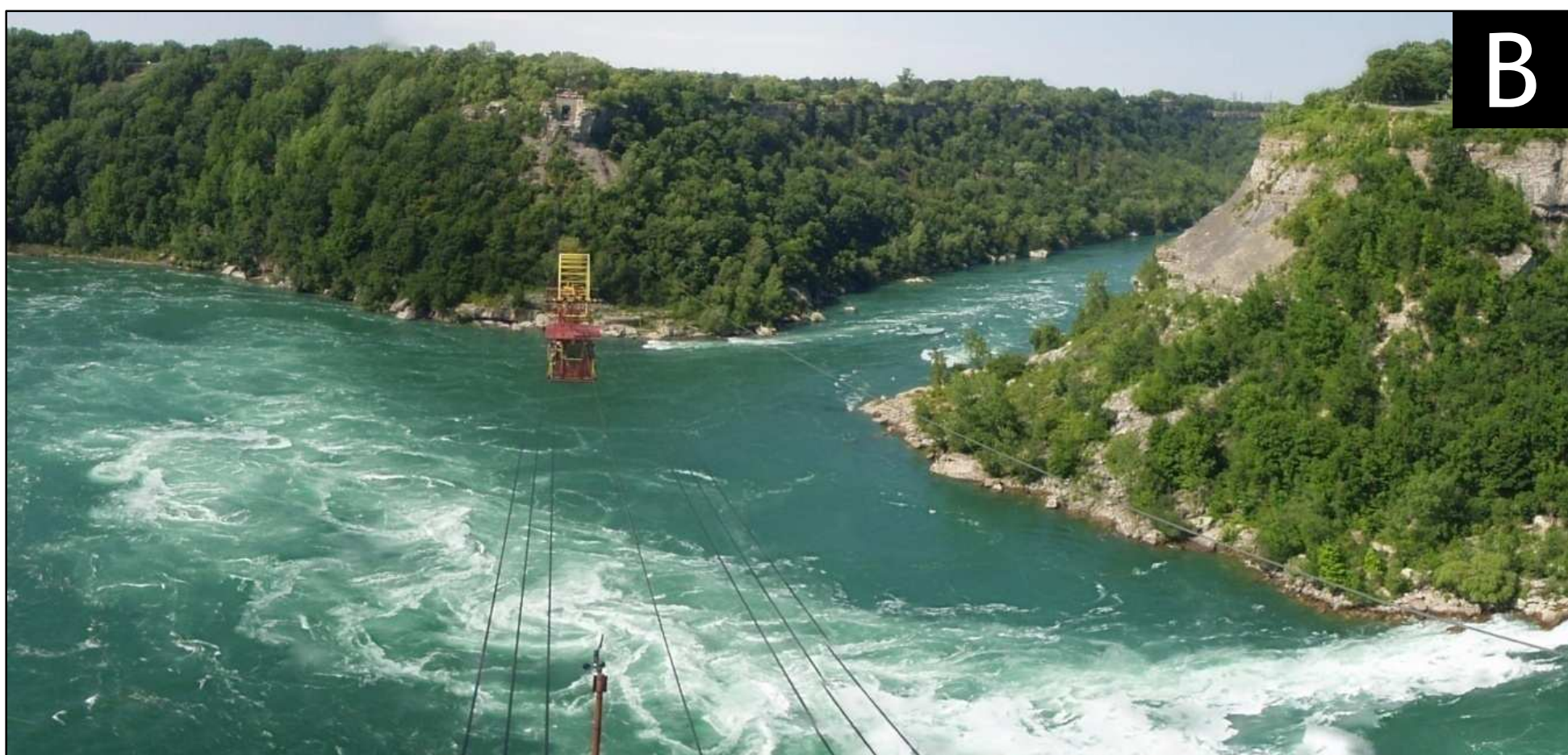
Turbulent Flows



Turbulent flows exhibit unsteady and seemingly random behavior. They are also characterized by multiple scales.

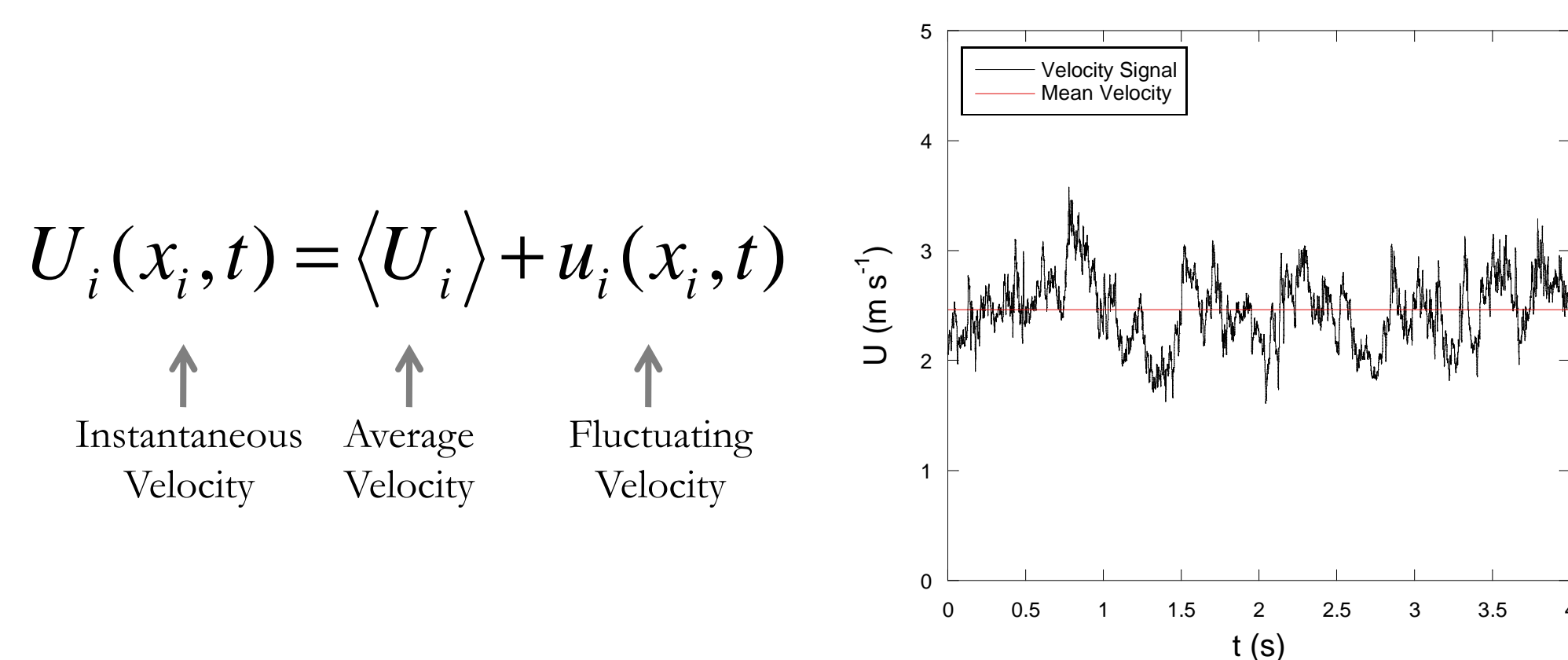
- A. A space shuttle launch leaves exhaust that swirls with eddies of many scales.
- B. The Niagara River flows into a cul-de-sac, creating a turbulent “whirlpool”.

Image A courtesy of NASA.



The different sizes of turbulent eddies are connected through what is known as the energy cascade. Energy is added to the largest eddies by the mean flow and propagates down through the cascade until the energy is dissipated by viscosity.

Because the velocity and pressure fields in a turbulent flow are constantly changing, the equations of motion are often rewritten in terms of an average and a fluctuation:



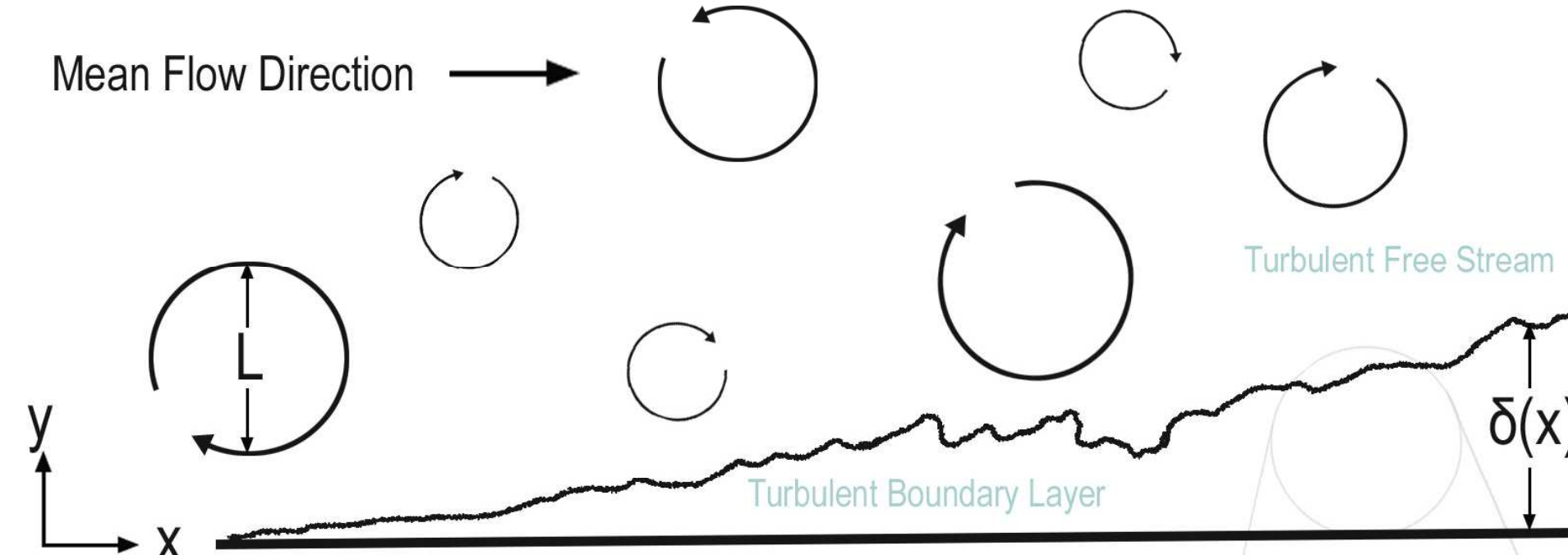
This decomposition can be applied to the Navier-Stokes equations to give:

$$\underbrace{\rho \frac{\partial \langle U_i \rangle}{\partial t}}_{\text{Rate of change of momentum following the mean flow}} + \underbrace{\rho \langle U_j \rangle \frac{\partial \langle U_i \rangle}{\partial x_j}}_{\text{Change in mean viscous stress}} = \underbrace{\mu \frac{\partial}{\partial x_j} \left(\frac{\partial \langle U_i \rangle}{\partial x_j} + \frac{\partial \langle U_j \rangle}{\partial x_i} \right)}_{\text{Change in mean pressure stress}} - \underbrace{\frac{\partial}{\partial x_j} \langle \langle p \rangle \delta_{ij} \rangle}_{\text{Change in Reynolds stress}} - \underbrace{\rho \frac{\partial \langle u_i u_j \rangle}{\partial x_j}}_{\text{Change in Reynolds stress}}$$

References

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Boundary Layers With Free Stream Turbulence



Important Parameters:

- $U_0 \sim$ mean free stream velocity
- $L \sim$ characteristic free stream eddy size
- $(u_{rms}/\langle U \rangle)_0 \sim$ turbulent intensity of free stream
- $\delta(x) \sim$ thickness of the boundary layer

Turbomachinery

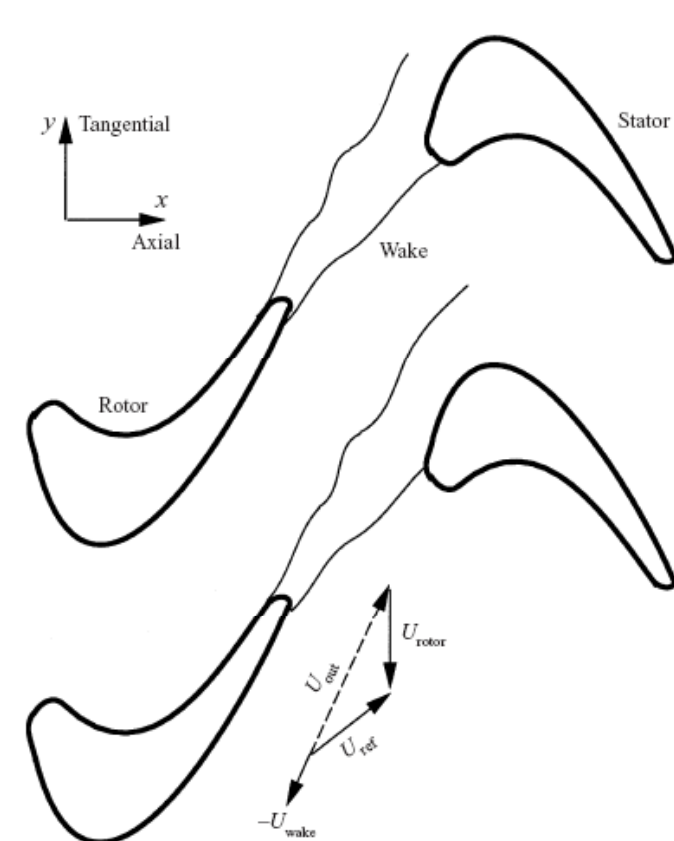
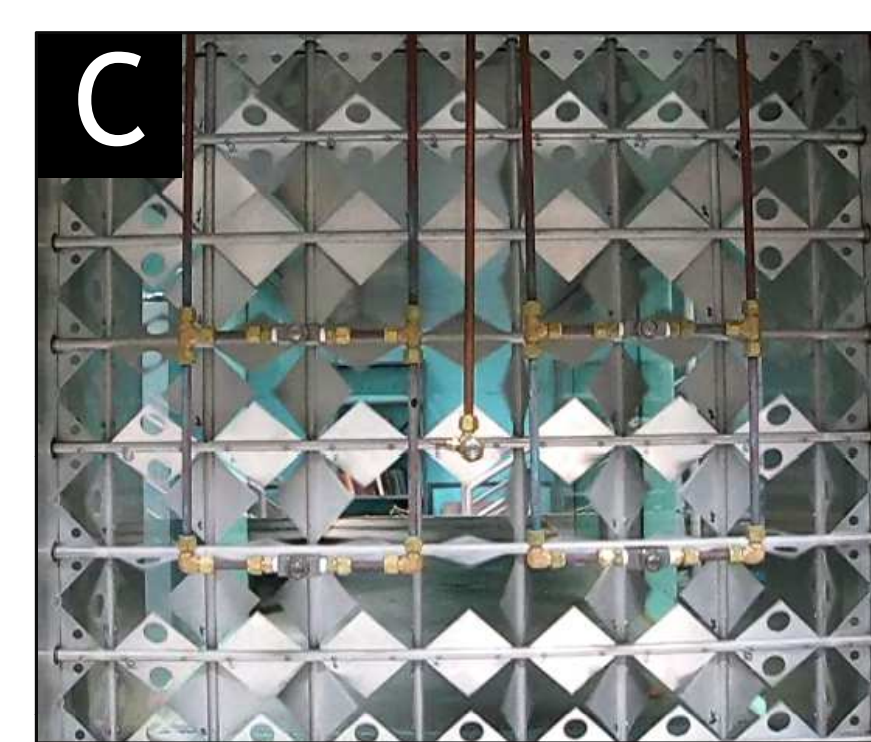


FIGURE 1. Sketch of rotor-stator wake interaction: U_{wake} , rotor velocity in the stator reference frame; U_{rot} , rotor exit flow velocity in the rotor reference frame; U_{stat} , stator inflow velocity in the stator reference frame.

A turbulent boundary layer with free stream turbulence is a simplification of flow over rotors and stators in turbines, compressors, and other parts inside turbomachines.

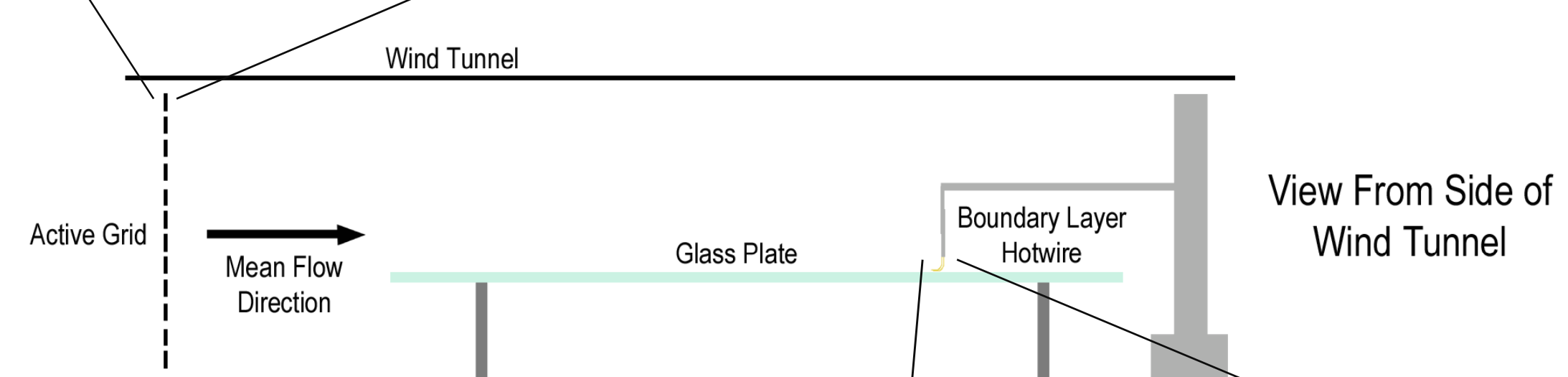
Figure from Wu, Jacobs, Hunt, and Durbin.

Experimental Set-Up

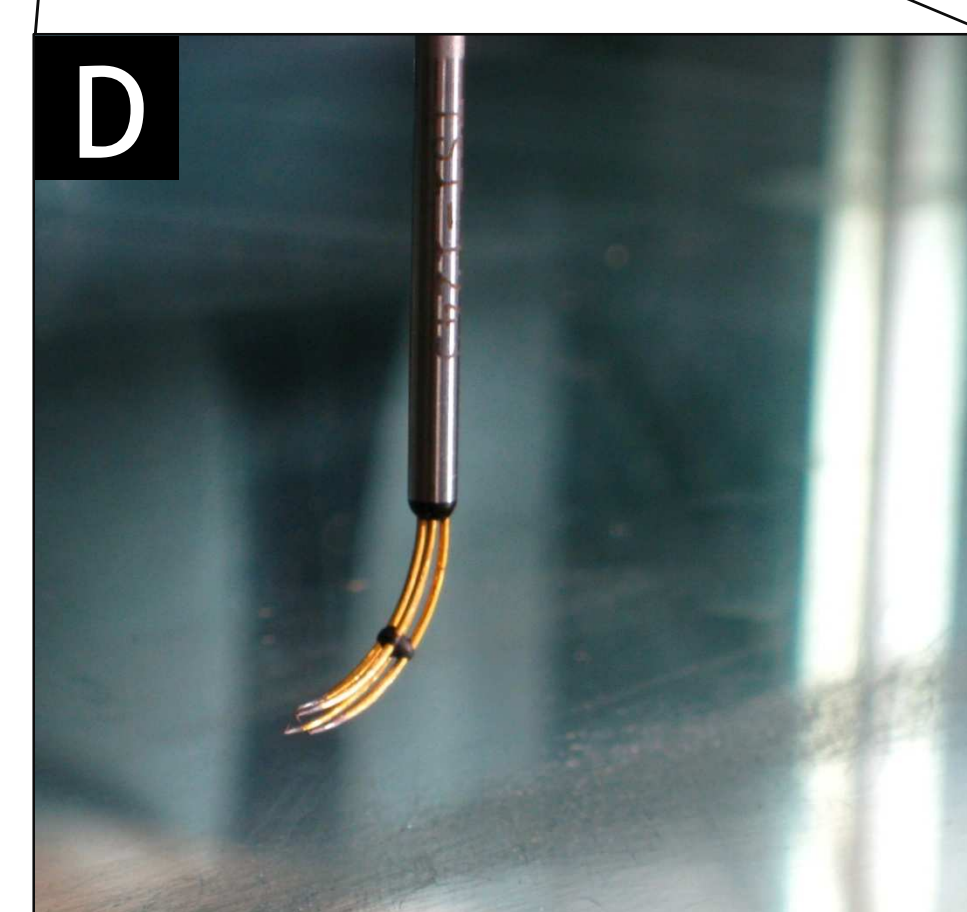


Isotropic turbulence can be created in a wind tunnel by placing a grid of bars at the mouth of the tunnel.

C. Our “active” grid uses randomly rotating flaps to greatly increase the Reynolds number of the turbulence we produce. With the grid off and the flaps turned to lie in the plane of the bar, we can reproduce the effect of “passive” grids.

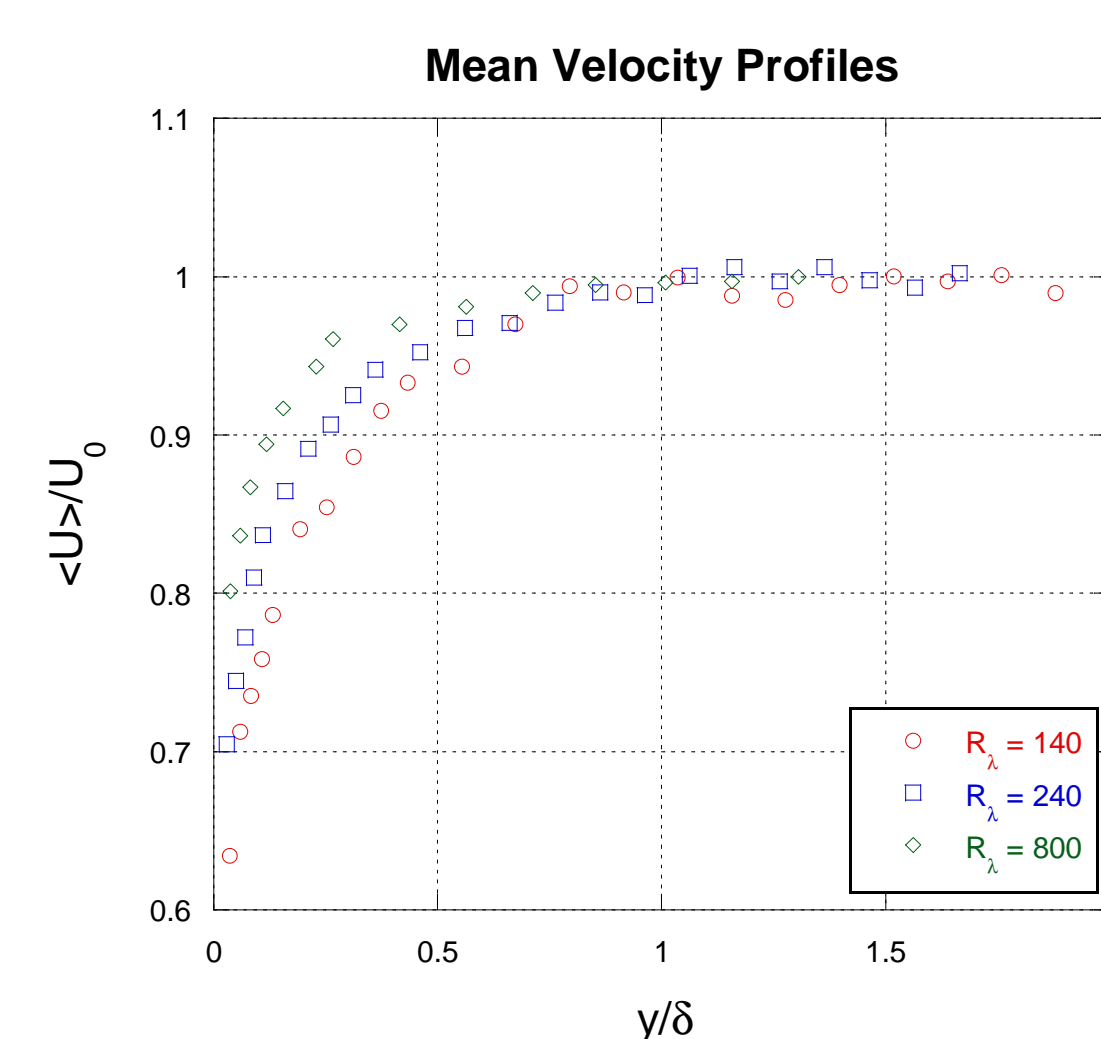


D. The boundary layer hotwire probe used in our experiments. Hotwire anemometry provides accurate measurements of the velocity fluctuations of the air flowing past the probe.



Results

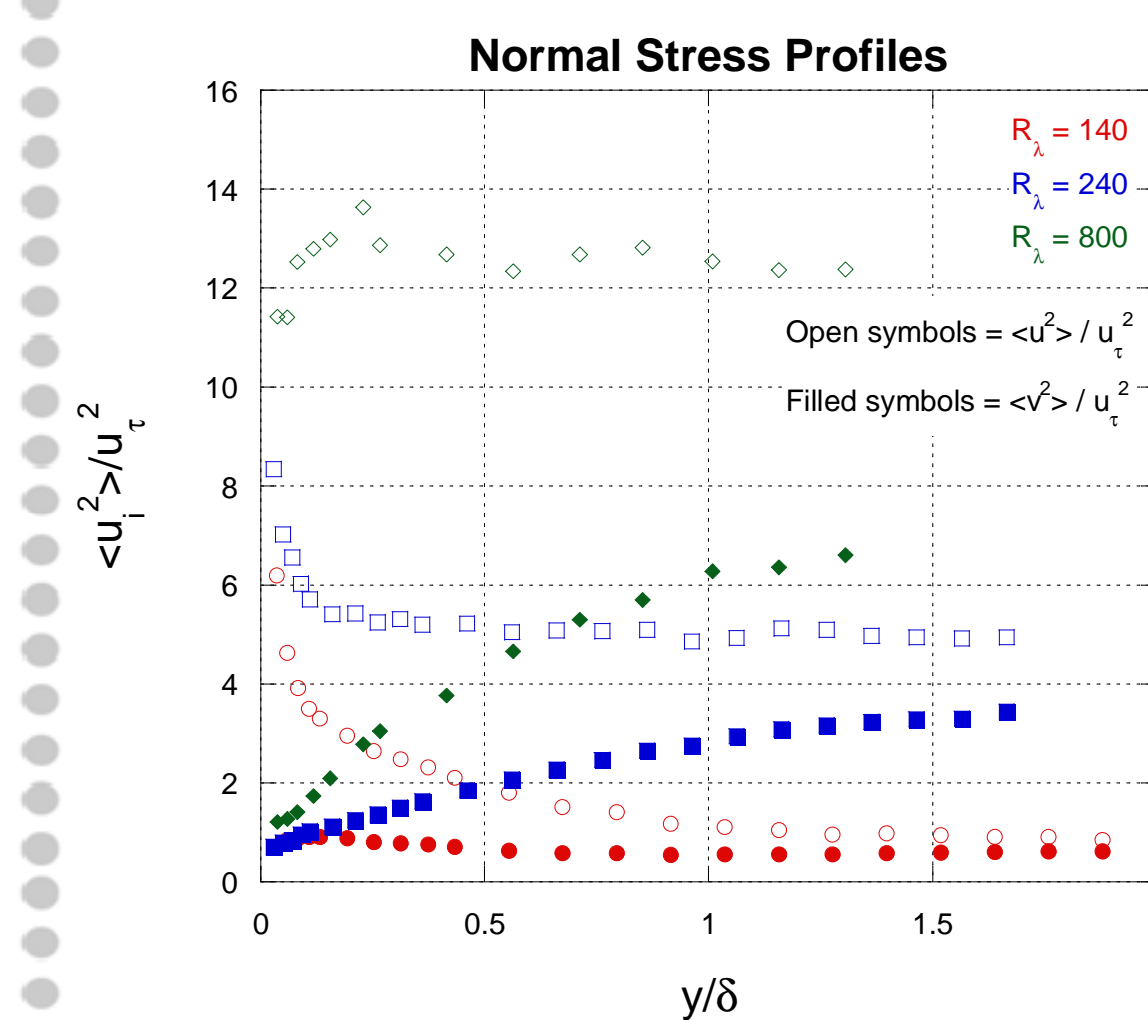
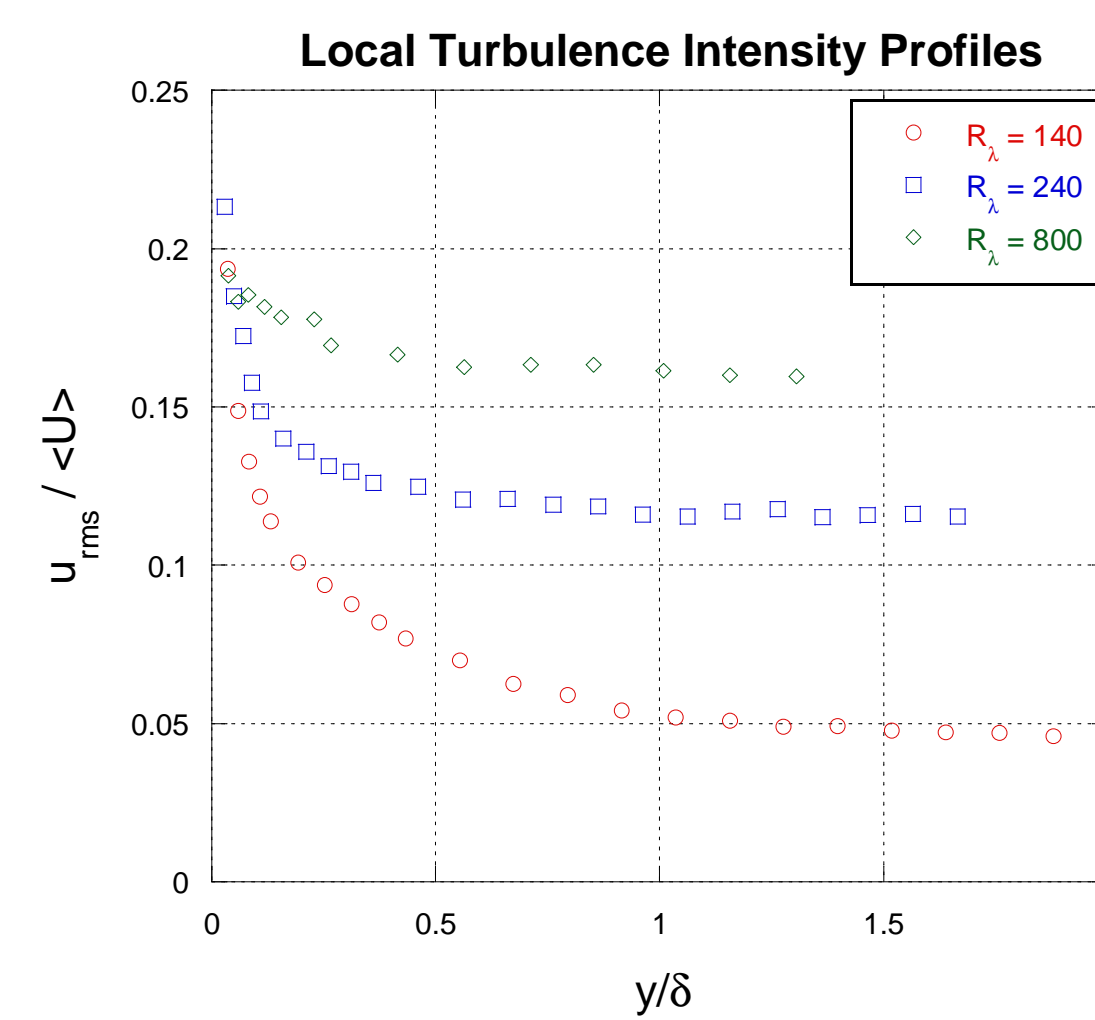
Left: The first two flows differ very little in terms of free stream velocity and lengthscale relative to the thickness of the boundary layer. Their primary difference is in the intensity of the free stream’s turbulence.



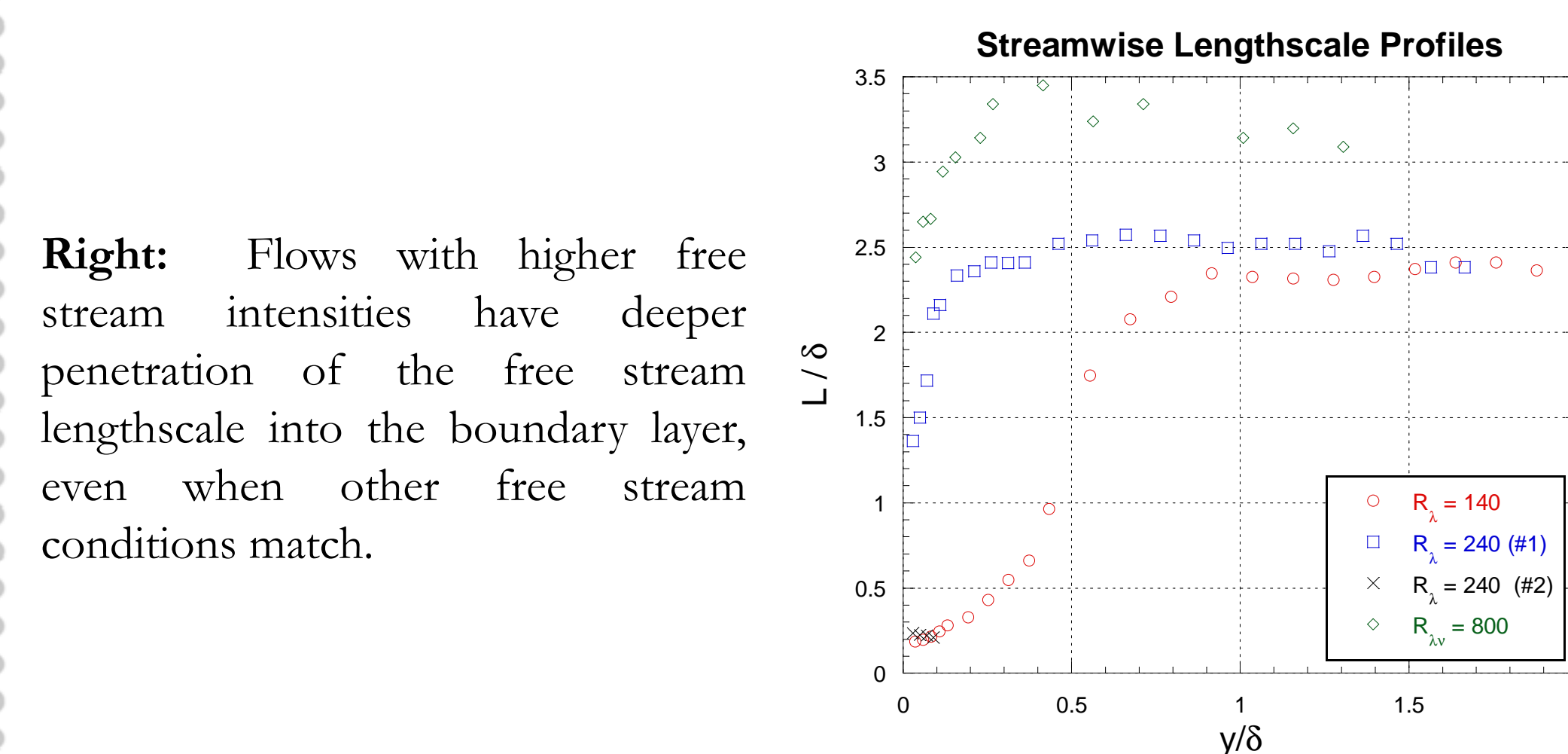
Right: Increasing the intensity of the turbulence in the free stream creates a flatter profile in the outer layer of the boundary layer and sharper velocity gradients close to the wall.

Results (cont.)

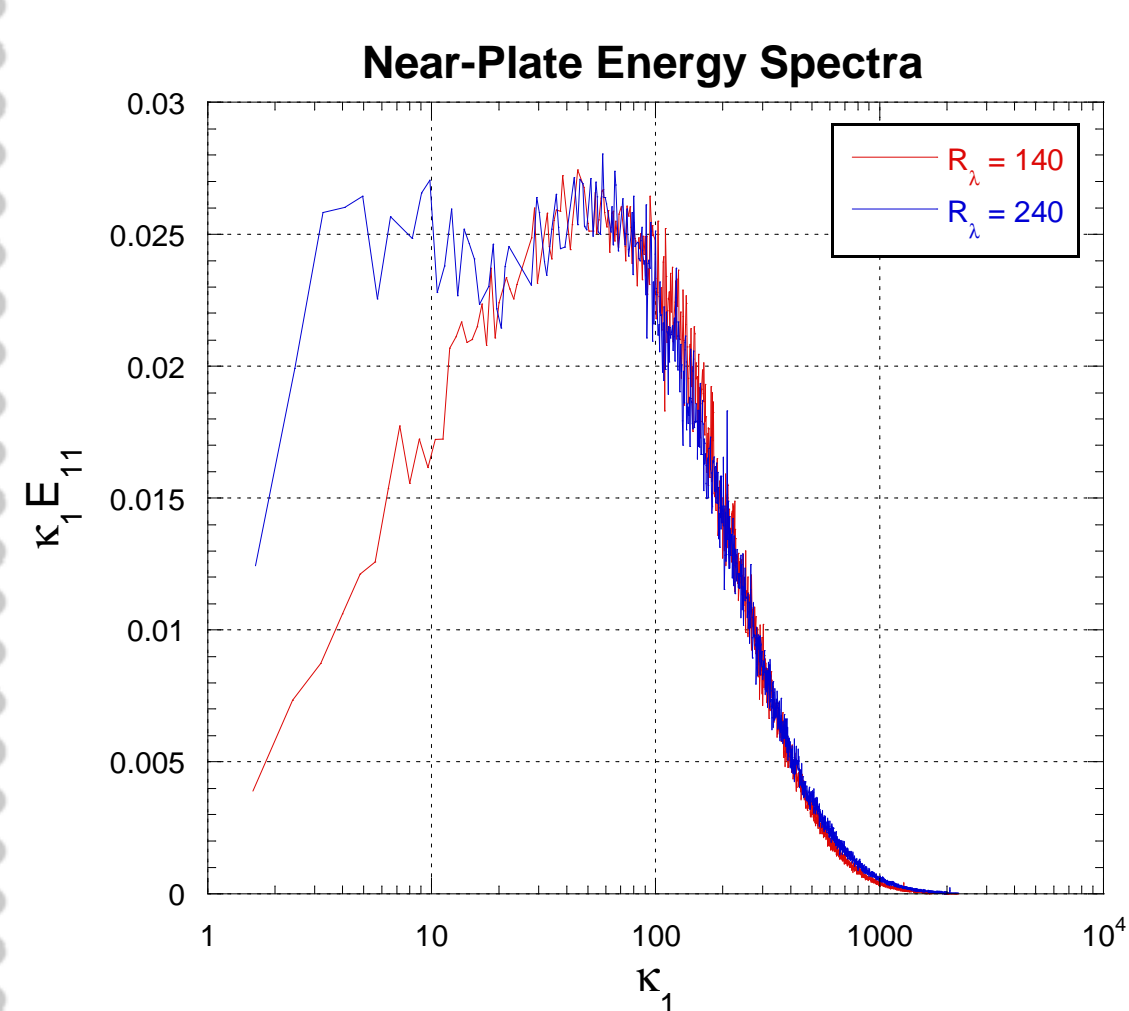
Right: The turbulence’s intensity increases closer to the wall. In the higher R_L cases, the free stream turbulence intensity penetrates further into the boundary layer.



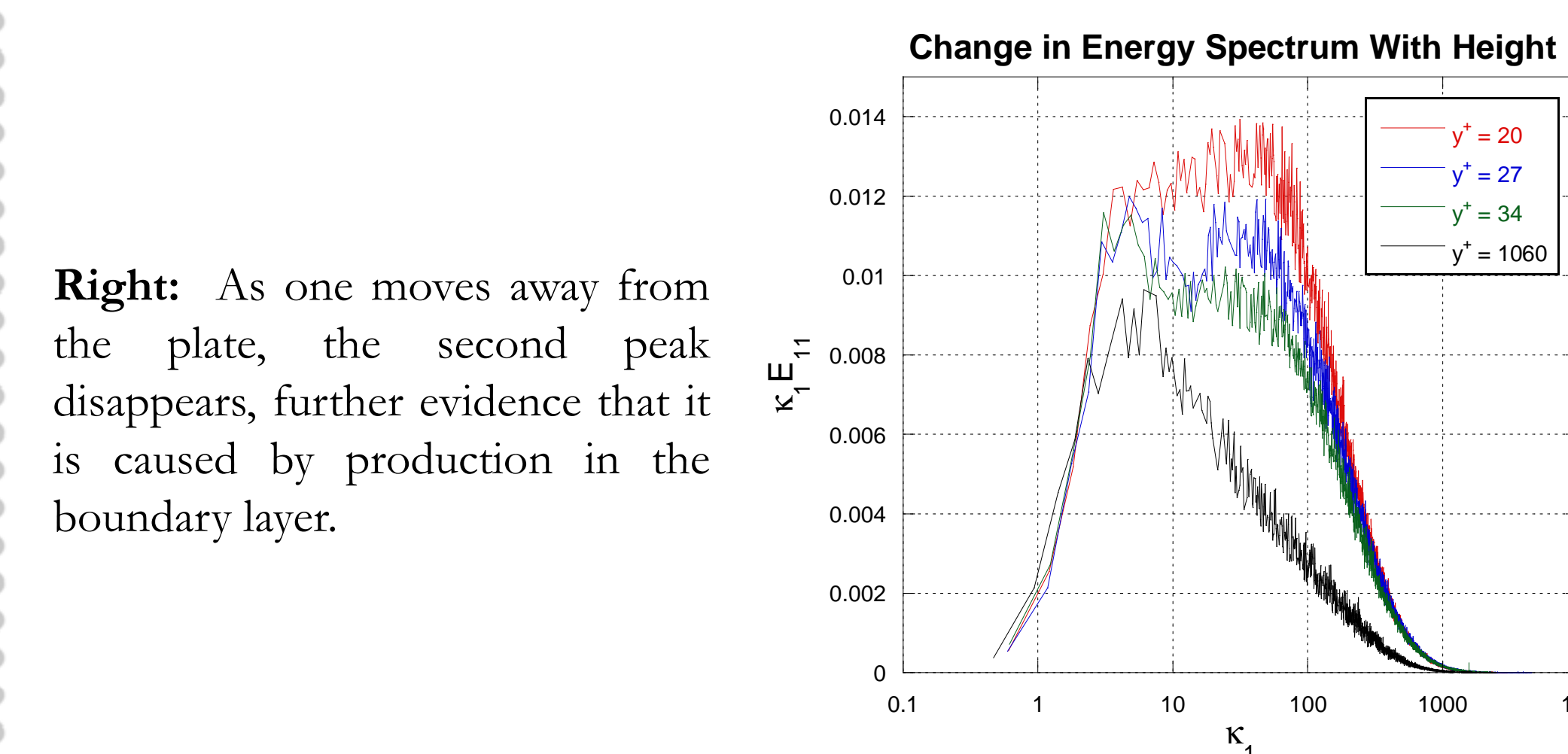
Left: Unlike in a canonical boundary layer, $\langle u^2 \rangle$ and $\langle v^2 \rangle$ do not go to zero in the free stream. For the cases with higher free stream turbulence intensity, $\langle v^2 \rangle$ actually decreases inside the boundary layer. This behavior is due to a constraint caused by the presence of the wall (Hunt and Graham).



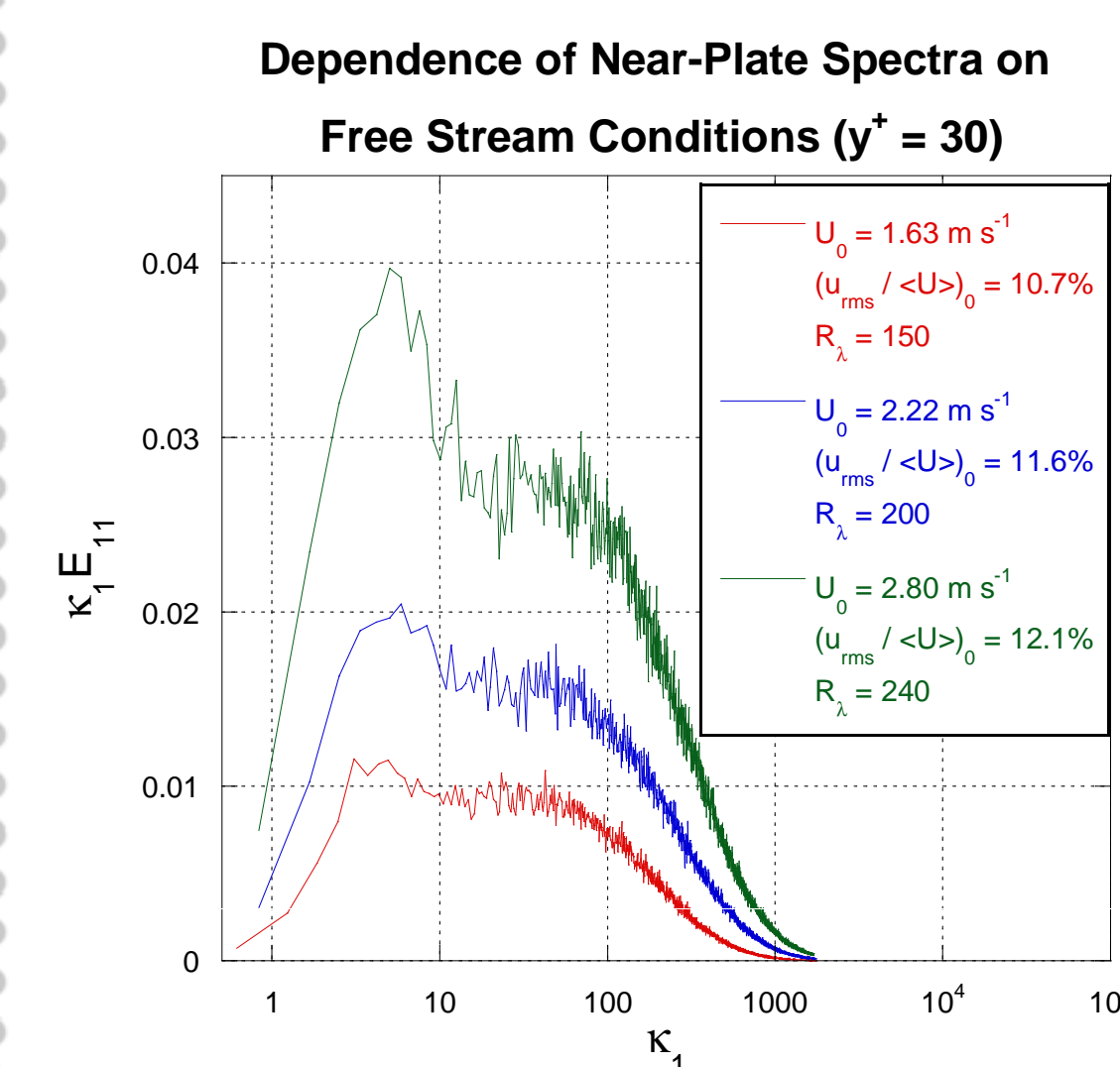
Right: Flows with higher free stream intensities have deeper penetration of the free stream lengthscale into the boundary layer, even when other free stream conditions match.



Left: Near the plate ($20 < y^+ < 100$), the $R_L = 240$ case has two peaks in its energy spectra, indicating two major energy-containing lengthscales. The $R_L = 140$ flow has only one peak. The peak shared by both flows corresponds to energy produced by lengthscales in the boundary layer while the second peak represents energy from the free stream reaching deep into the boundary layer.



Right: As one moves away from the plate, the second peak disappears, further evidence that it is caused by production in the boundary layer.



Left: Flows with very similar free stream intensities show substantial difference in the relative amounts of energy in the two lengthscales. This may be related to the difference in free stream velocities.

Conclusions

The turbulent boundary layer with free stream turbulence is an important non-canonical flow, representing a simplification of flow over blades in turbomachinery. Our recent experiments show that conditions very close to the wall in this flow can still depend strongly on the free stream conditions. Penetration of free stream conditions into the near-wall region seems to be dependent on the intensity of the turbulence in the free stream, but other free stream factors—such as velocity—may impact the near-wall region as well.

Our current experiments aim to decouple the influence of free stream velocity versus that of free stream intensity on this near-wall behavior.