New aspects of turbulent boundary-layer structure

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Research Objectives

• To present new findings of turbulent boundary-layer structures that differ from generally accepted ideas, for $500 < R_e < 10,500$
  – Especially in relation to features and formations of vortex pairs
  – Earlier proposals “intuitively appealing hypotheses, supported only indirectly by experimental evidence”
  – Validation of techniques used
Experimental Techniques

- Two flumes
- Flow visualization
  - Smoke (condensed light-oil vapor)
  - Laser (4 W argon-ion)
- Hot wire
Results and Discussion

- Characteristic angle of 45°
- Corroborated by longitudinal light plane, hot wire, and inclined light plane downstream

\[ Re_\theta = 1700. \]
Results and Discussion

• Scale effects

![Diagram showing scale effects](image)

**Figure 17.** Effect of Reynolds number on features composing an outer region of turbulent boundary layer. (a) *Very low* $Re$ (loops); (b) low–moderate $Re$ (elongated loops or horseshoes); (c) moderate–high $Re$ (elongated hairpins or vortex pairs).

• Width of loops scale with $10-100\nu/U_T$

![Image showing width scale](image)
Results and Discussion

• At higher Reynolds numbers hairpin tips form approx. 20° with the surface.

Figure 13. 20° interface formed by 45° features.

Figure 14. (a) Examples of features with interface inclined at approximately 20° to surface. (b) Example of 20° interface at $Re_\theta = 17500$ (this is a composite of two frames because of the restricted length of the light plane).
Results and Discussion

• Tips of hairpins inclined forward into flow
  – Due to lack of shear

Figure 38. Example of curled-over hairpin in developing spot.
Results and Discussion

- At higher $R_e (> 9,400)$ vortex pairs and hairpins are sparse in outer region of BL
  - Large scale features are made up of many small scale hairpins

Figure 15. Boundary-layer structure at high Reynolds numbers. (a) $Re_\theta = 7500$; (b) $Re_\theta = 10500$. 
Questions/Comments

• Data and analysis gives strong evidence
• How do hot-wire measurements tell us direction of flow?
• Interesting to see older analysis techniques