Heat Transfer in Boundary Layer Transition

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Experiments have been performed to investigate the effects of elevated free-stream turbulence and streamwise acceleration on flow and thermal structures in transitional boundary layers. The free-stream turbulence ranges from 0.5 to 6.4 % and the streamwise acceleration ranges from K= 0 to $0.8x10^{-6}$. The onset of transition, transition length and the turbulent spot formation rate are determined. The statistical results and conditionally sampled results of the streamwise and cross-stream velocity fluctuations, temperature fluctuations, Reynolds stress and Reynolds heat fluxes are presented. The eddy viscosity, turbulent thermal diffusivity and the turbulent Prandtl number are calculated. Different distributions of eddy viscosity and turbulent thermal diffusivity across the boundary layer reflect the apparent disparity between the momentum and thermal transports in the transitional boundary layer. Very mild acceleration ($K=0.07x10^{-6}$) can significantly delay the onset and length of transition, while a further increase of acceleration to $k=0.25x10^{-6}$ only slightly changes the onset of transition. In comparison with the acceleration, elevated free-stream turbulence is dominant in advancing the onset of transition. Acceleration only slightly delays the transition but significantly extends the length of transition at highly elevated free-stream turbulence levels. In terms of conditional sampling techniques, nine separate criterion functions are investigated. The results indicate that using a criterion function based on Reynolds shear stress for turbulent/nonturbulent discrimination in a heated transitional boundary layer is superior to a single velocity or temperature scheme. To match the universal intermittency distribution of Dhawan and Narasimha, the minimum values of intermittency at about $y/\delta=0.1$ should be used as the representative "near-wall" value.

FLUID MECHANICS AND HEAT TRASFER IN TRANSITIONAL BOUNDARY LAYERS

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Blue Mountain Lake, New York

On-going projects related to boundary layer transition at Clemson University

1. Baseline: Natural transition
2. Effects of favorable streamwise pressure gradients
3. Effects of Free-stream turbulence intensity (FSTI)
4. Combined effects of favorable gradients and FSTI.
5. Effects of roughness
6. Effects of adverse pressure gradients

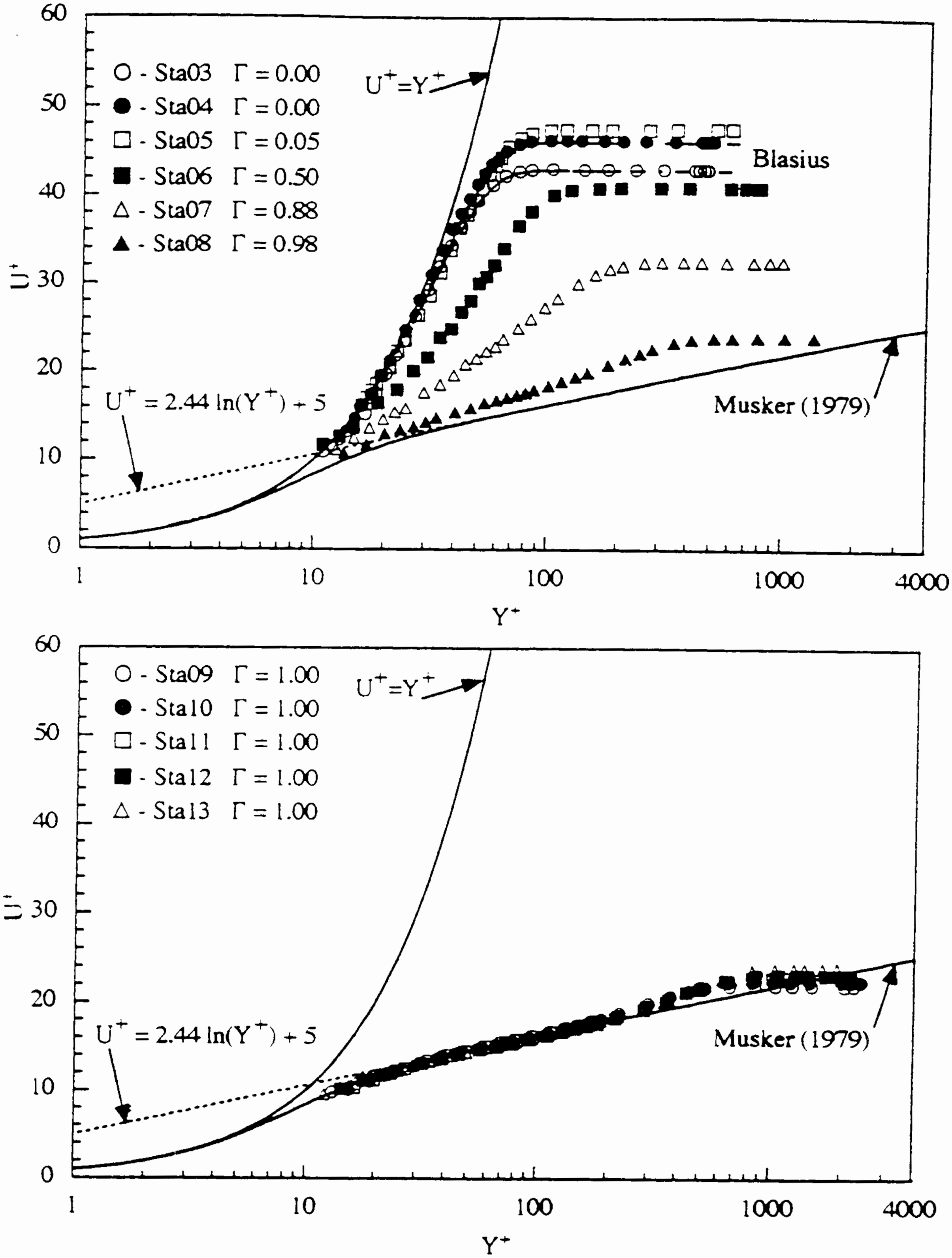


Figure 4.4 Mean velocity profiles for the baseline case in wall coordinates measured by the three-wire probe.

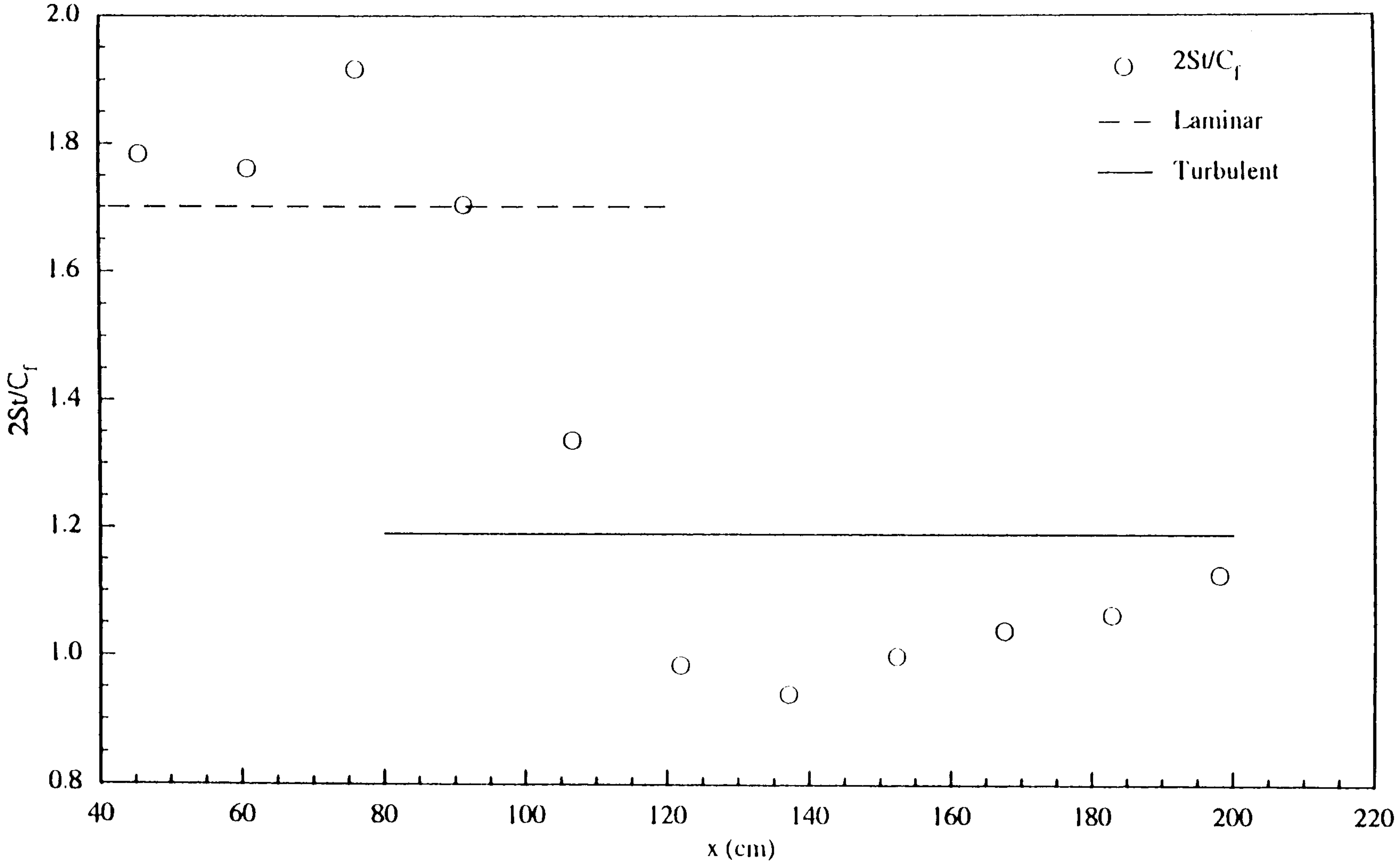


Figure 4.10 Reynolds analogy factor, $2St/C_f$, for the baseline case.

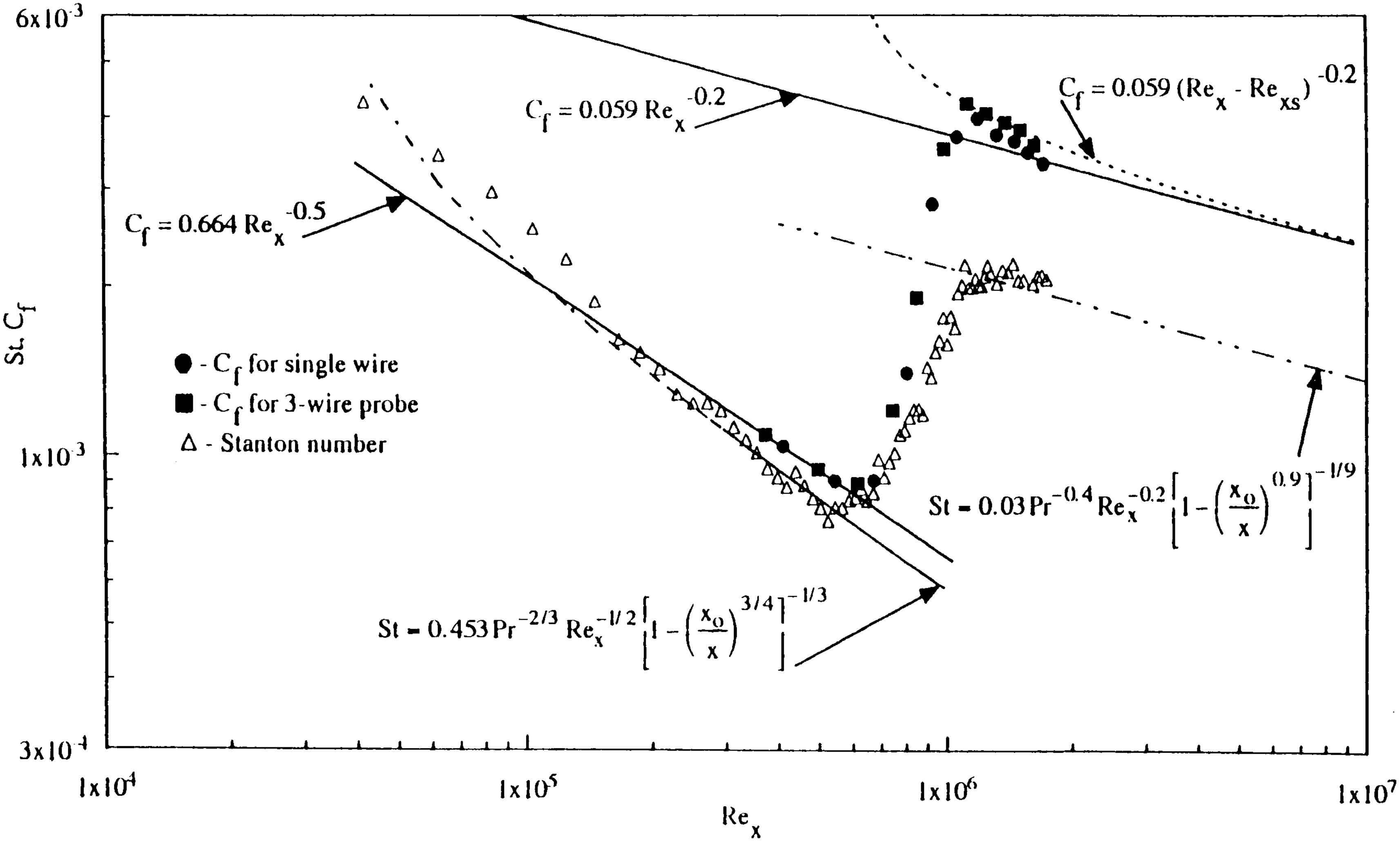
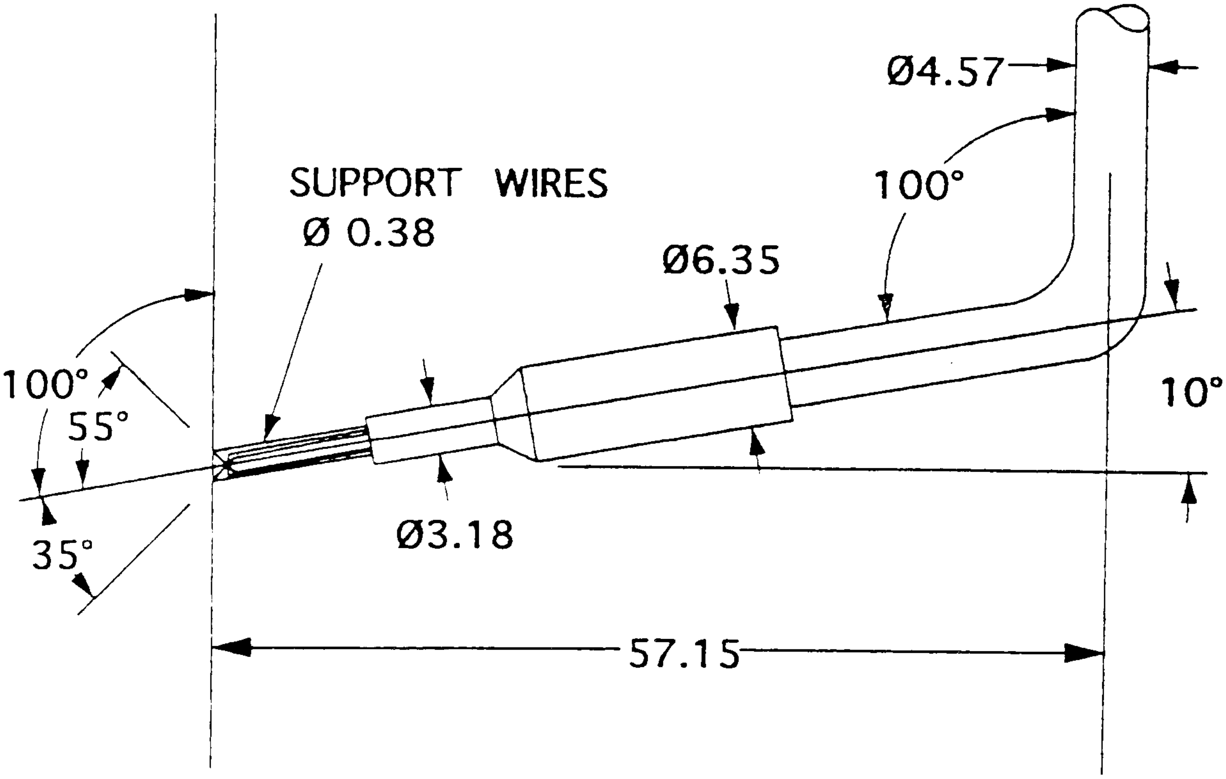
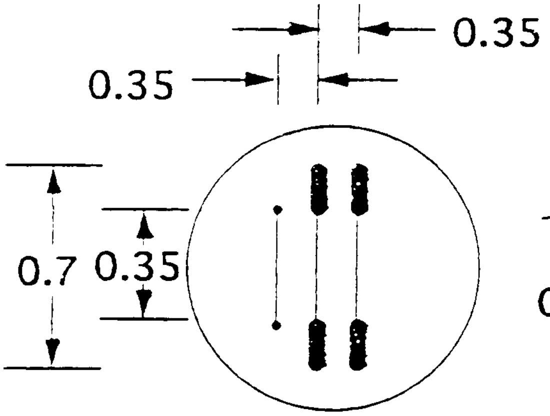


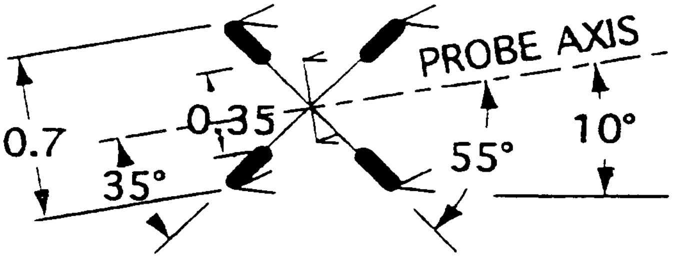
Figure 4.7 Centerline Stanton number and skin friction coefficient distributions for the baseline case.

3-WIRE BOUNDARY LAYER SENSOR



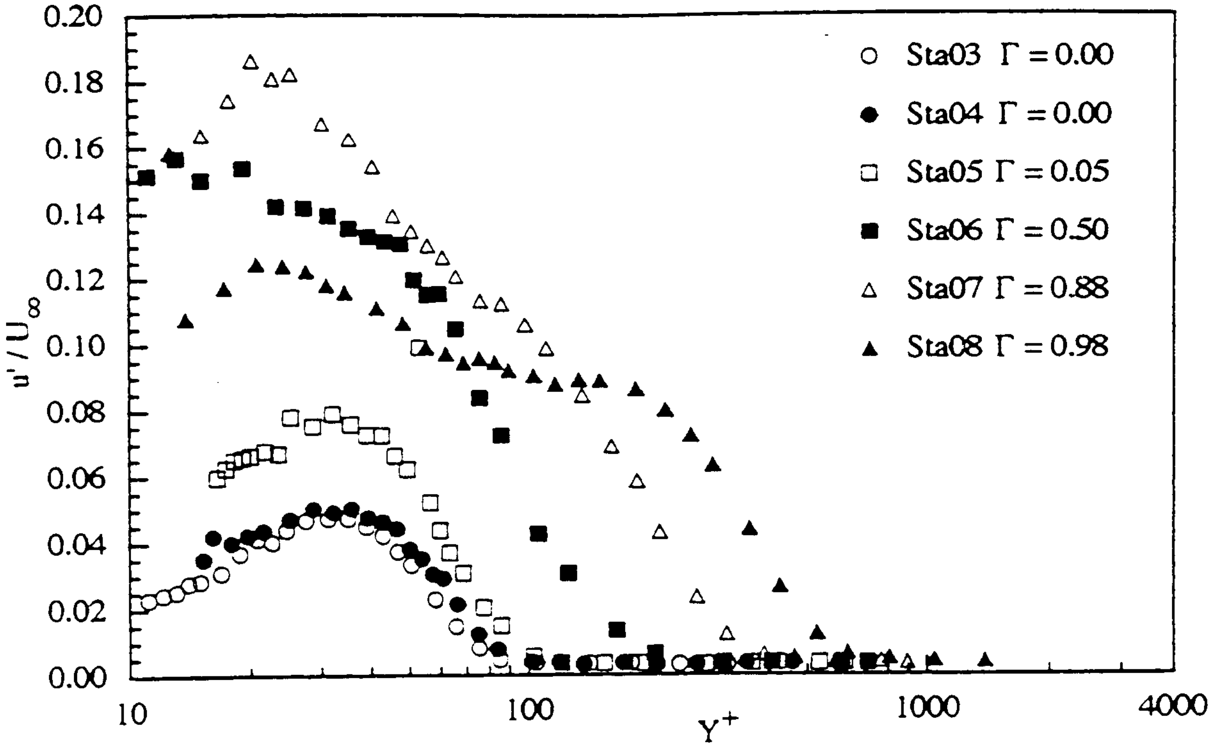


SIDE VIEW



PLANE VIEW

DIMENSIONS IN mm



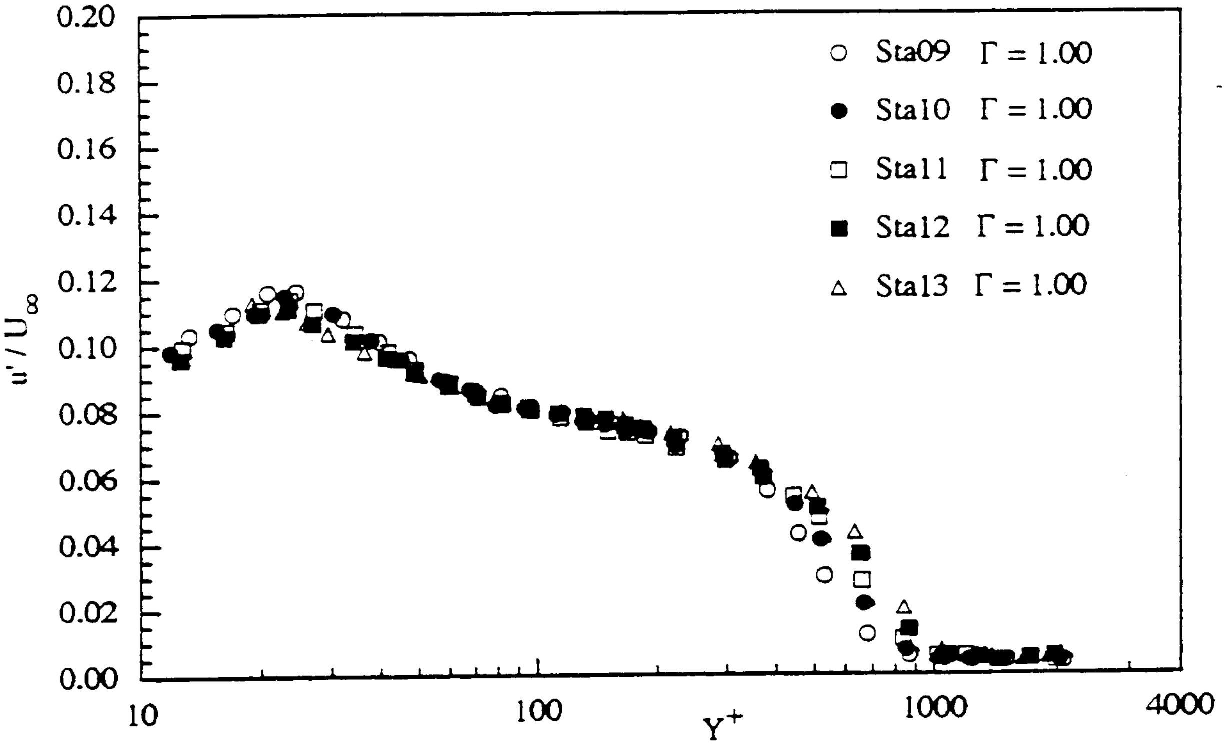


Figure 4.13 Streamwise Reynolds normal stress distribution for the baseline case in wall units.

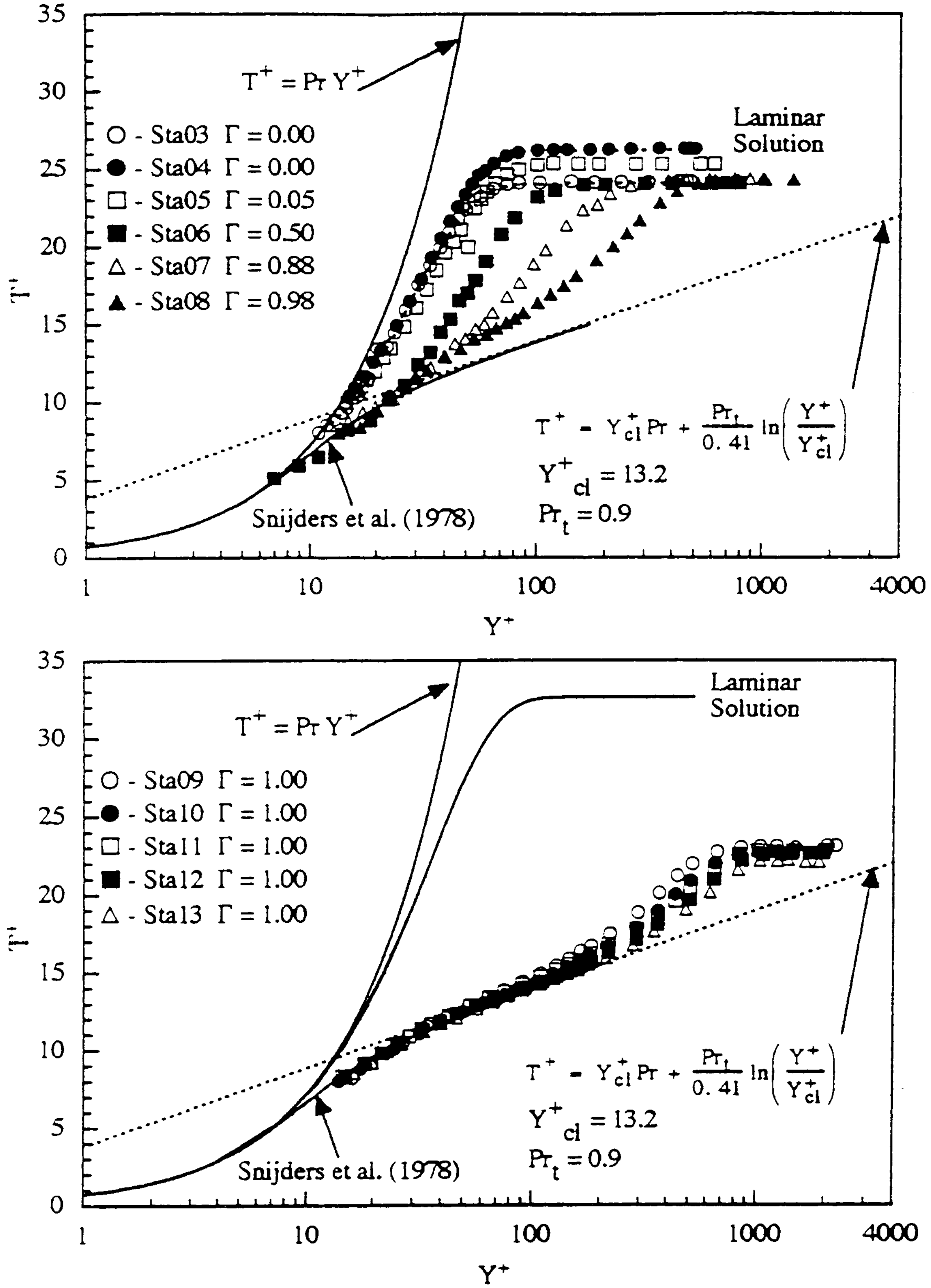


Figure 4.22 Mean temperature profiles for the baseline case in wall coordinates measured by the three-wire probe.

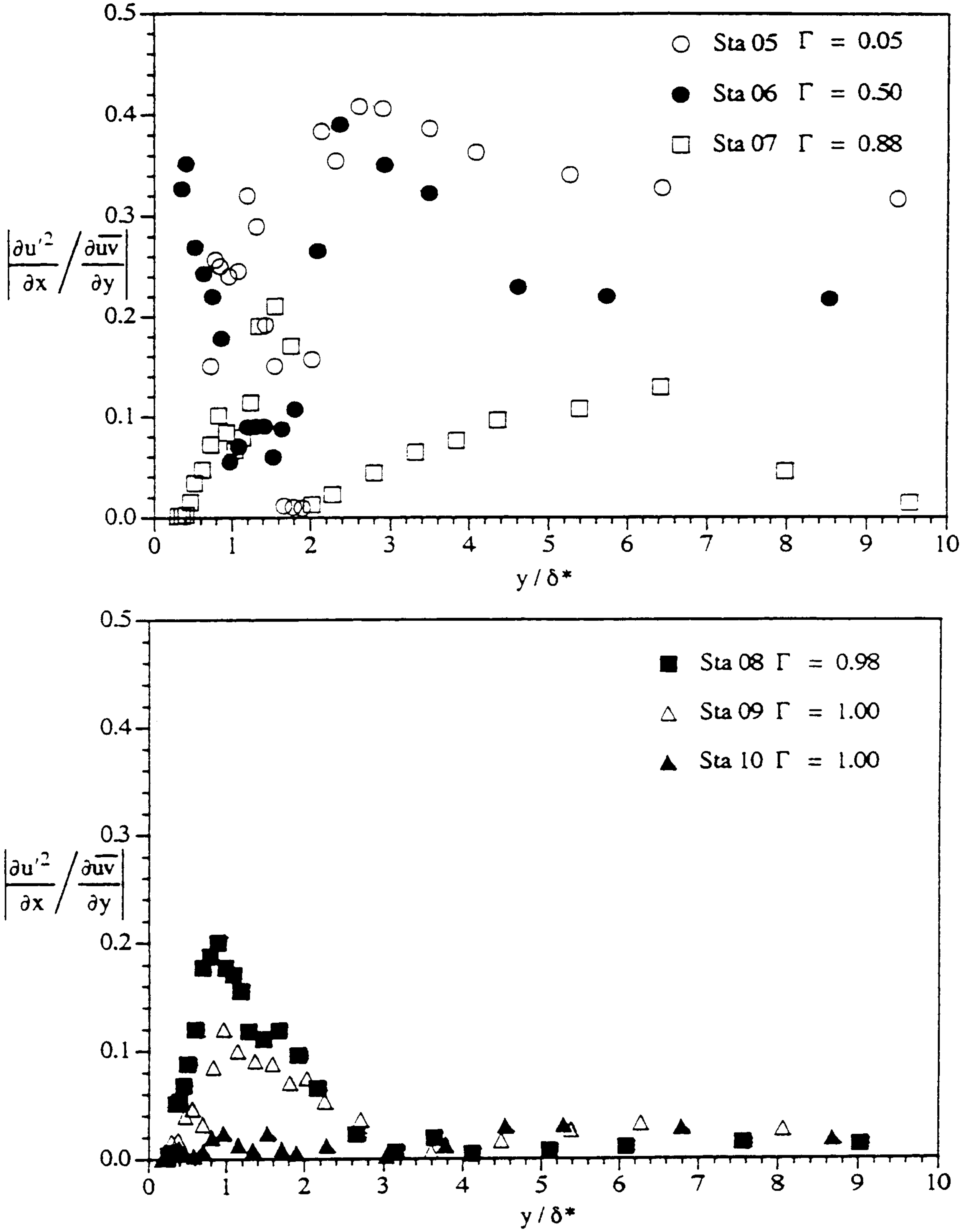


Figure 4.15 Ratio of streamwise gradient of Reynolds normal stress to cross-stream gradient of Reynolds shear stress for the baseline case.

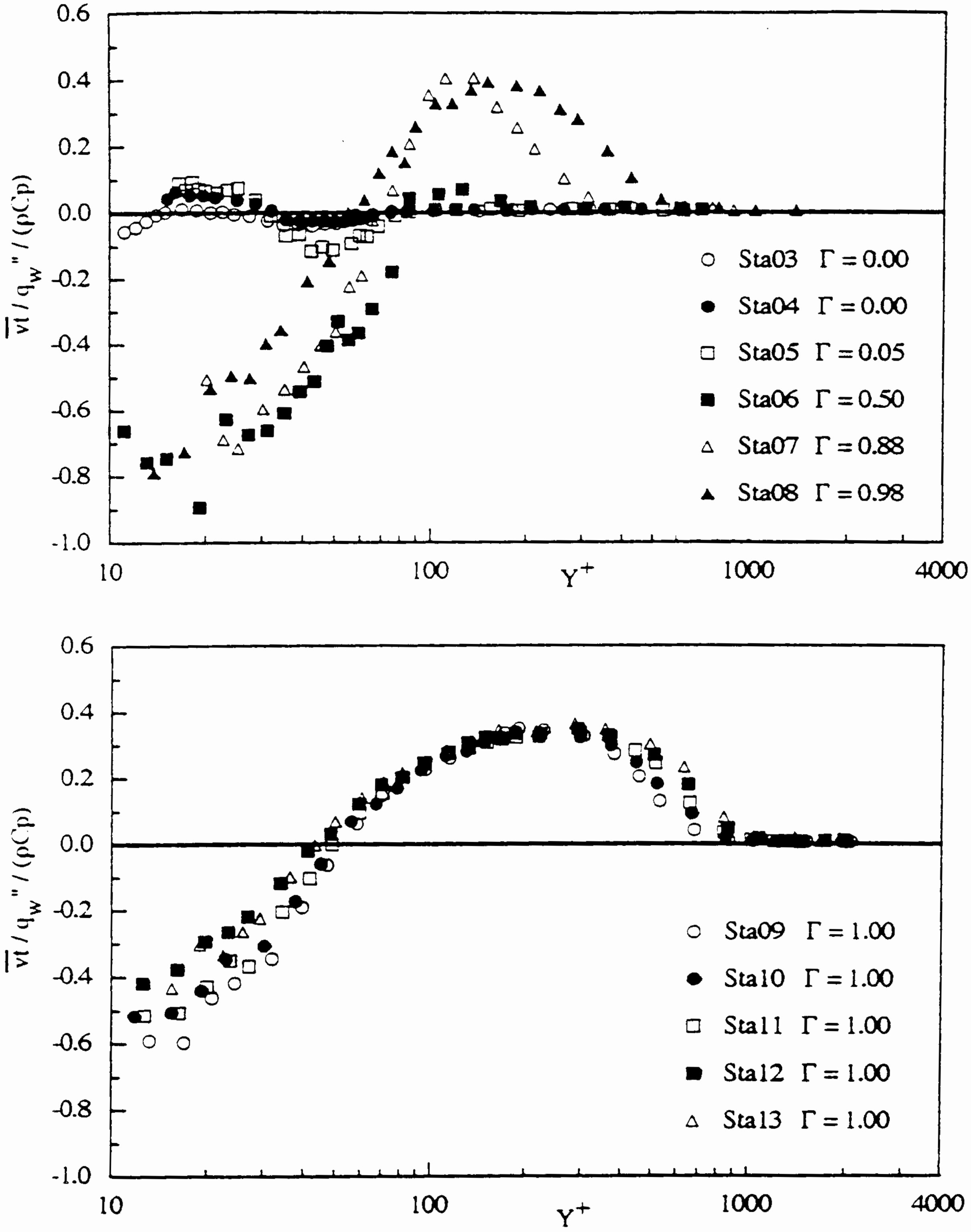


Figure 4.25 Reynolds cross-stream heat flux distribution for the baseline case in wall units.

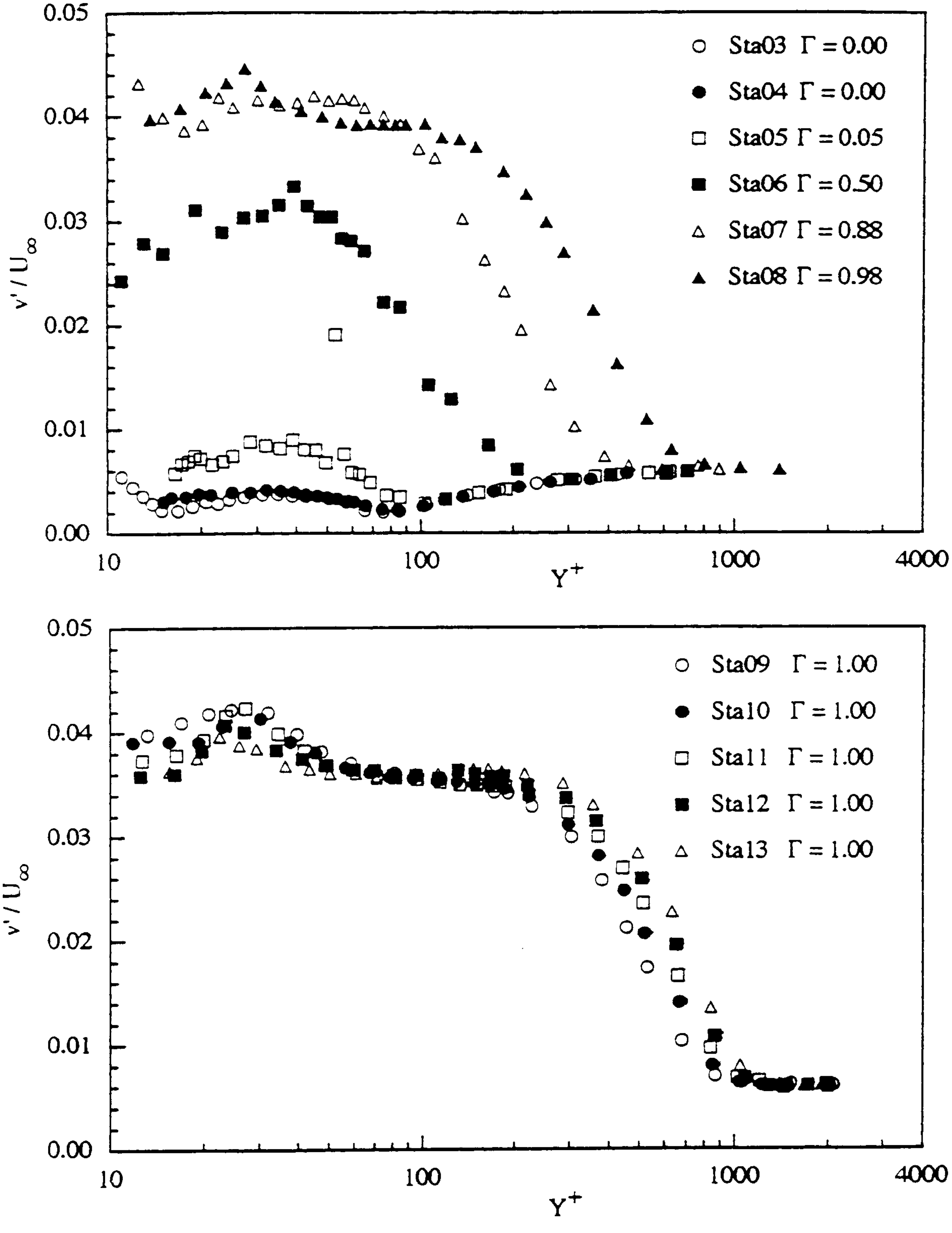


Figure 4.16 Reynolds cross-stream stress distribution for the baseline case in wall units.

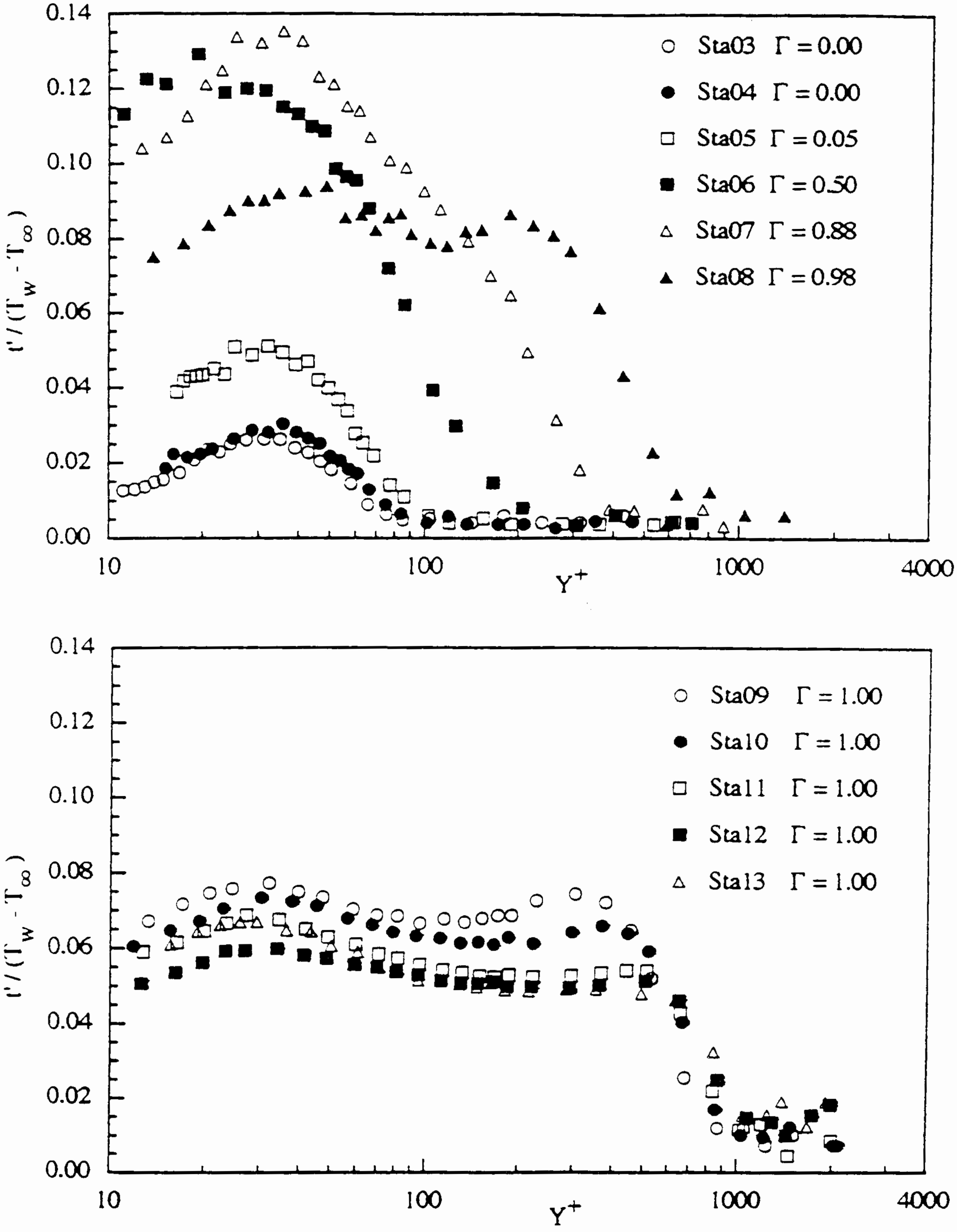


Figure 4.23 RMS temperature distribution for the baseline case in wall units.

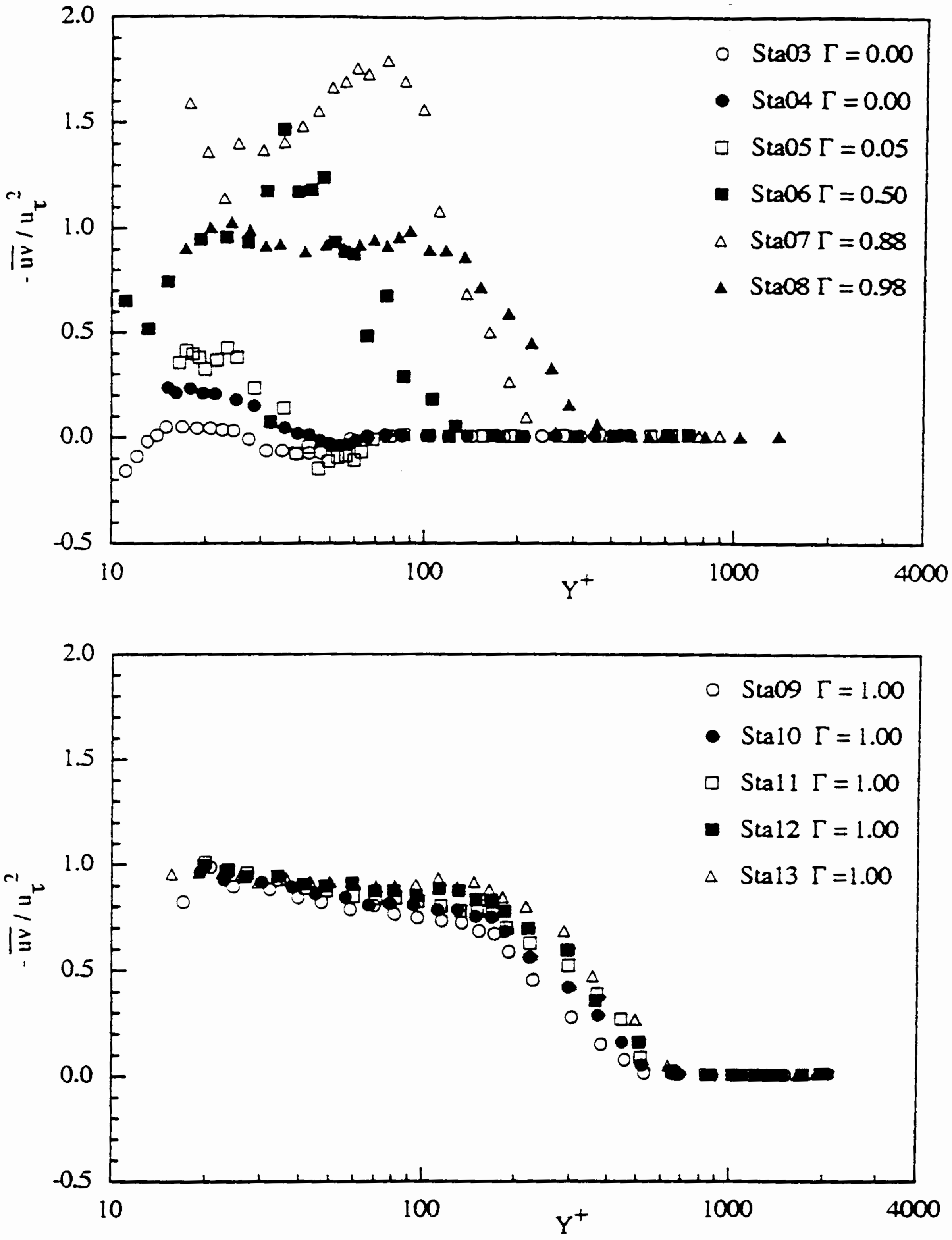
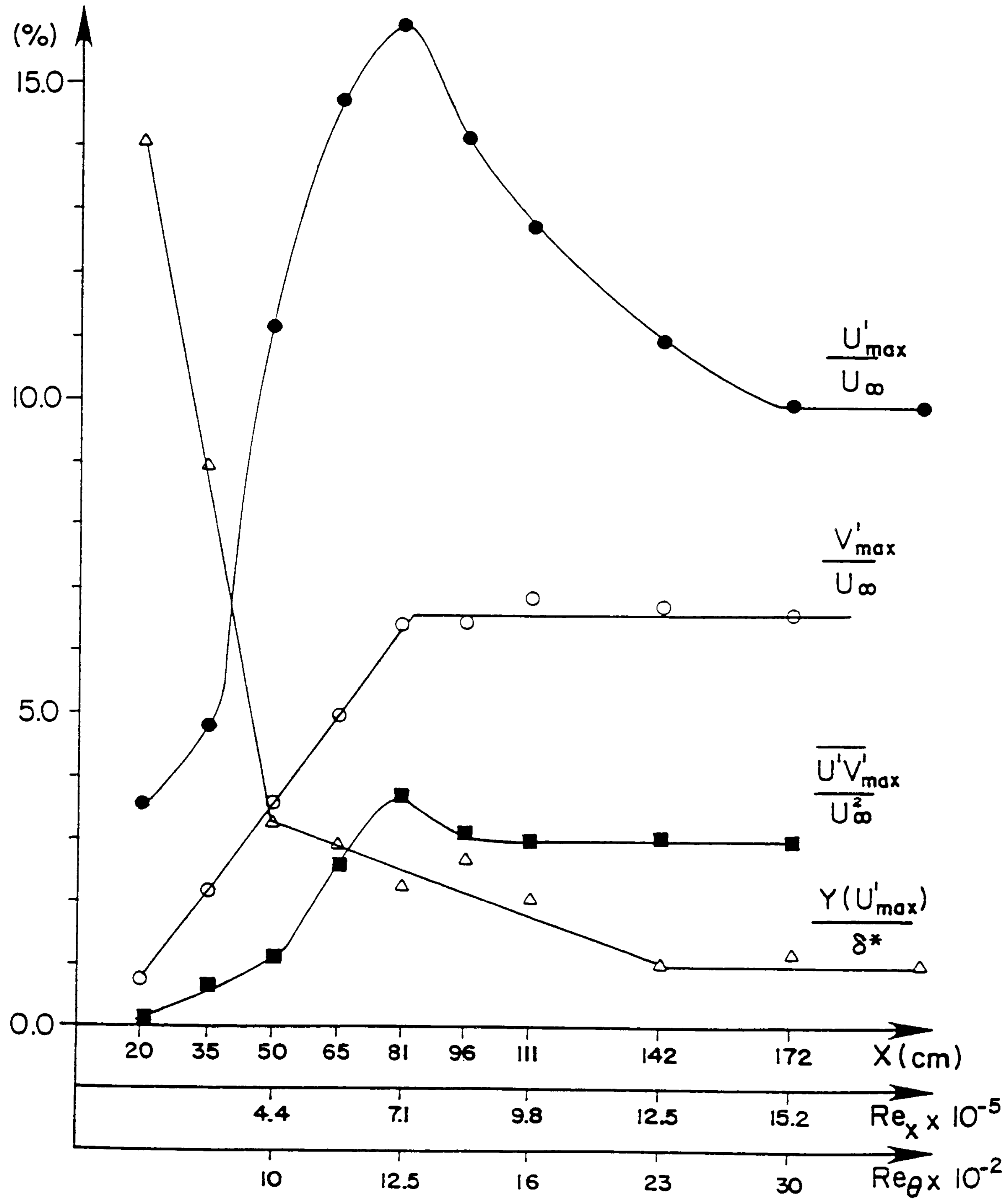


Figure 4.19 Reynolds shear stress distribution for the baseline case in wall units.



Distribution of maximum Reynolds normal stress and the corresponding y-position in the streamwise direction.

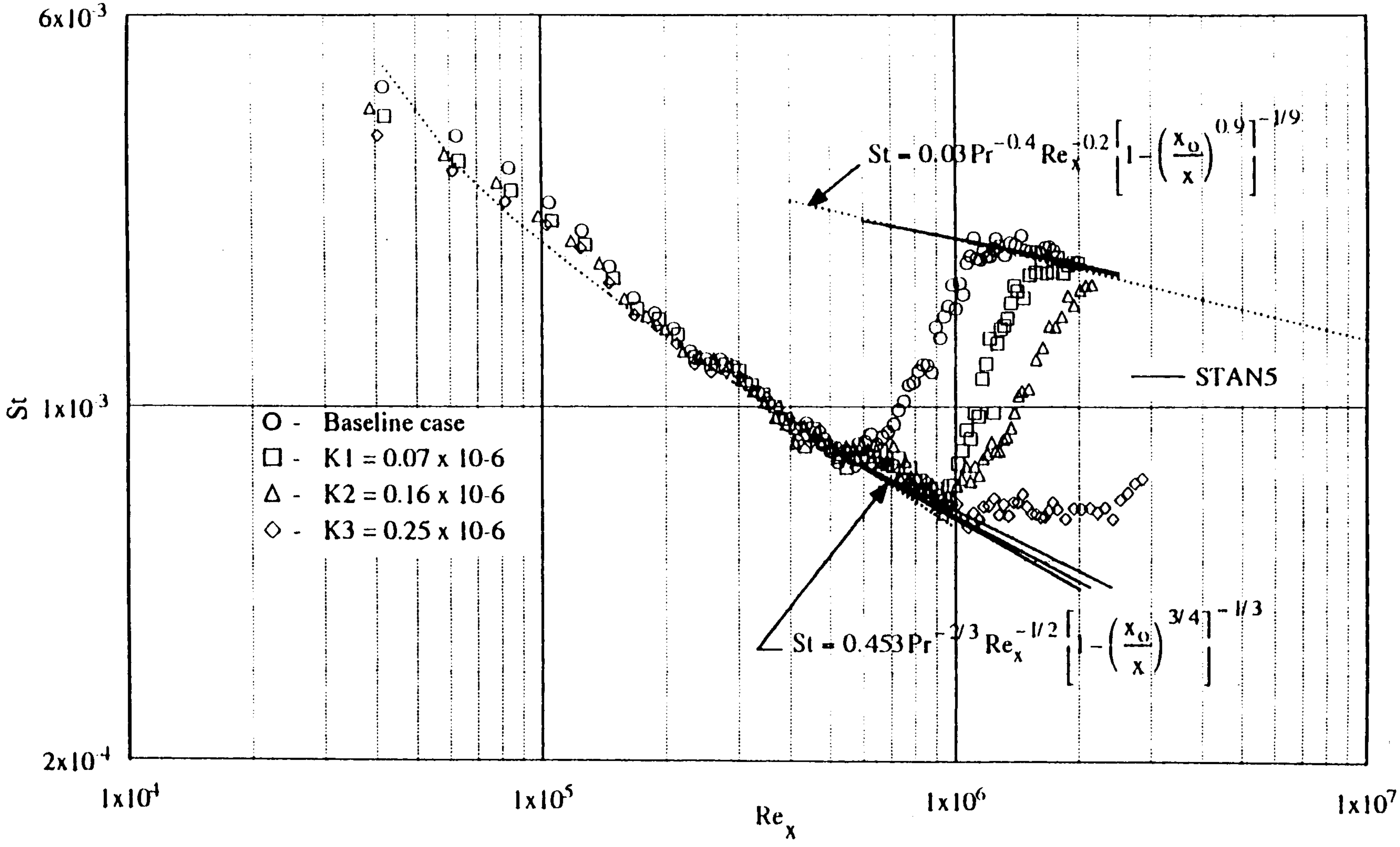
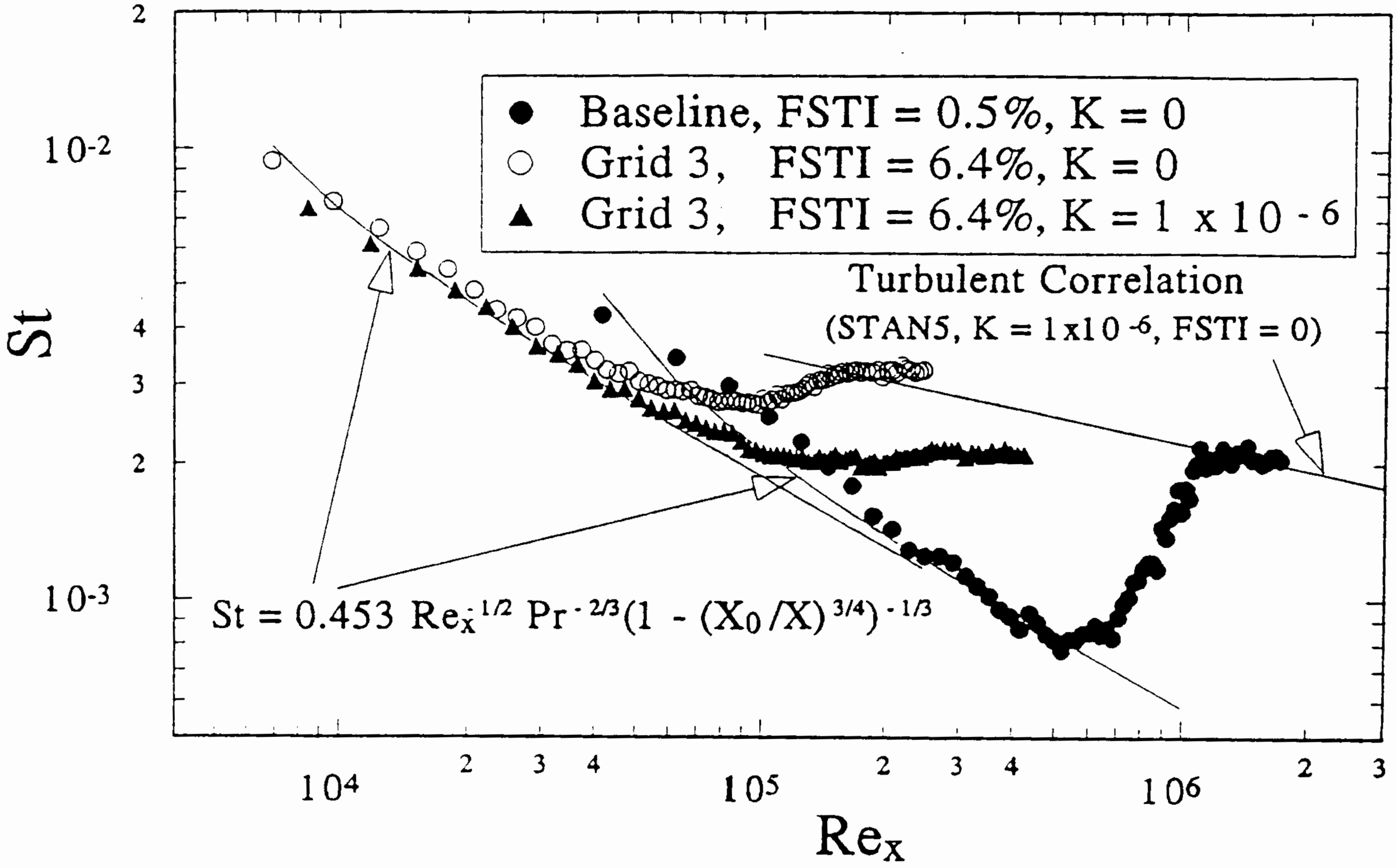
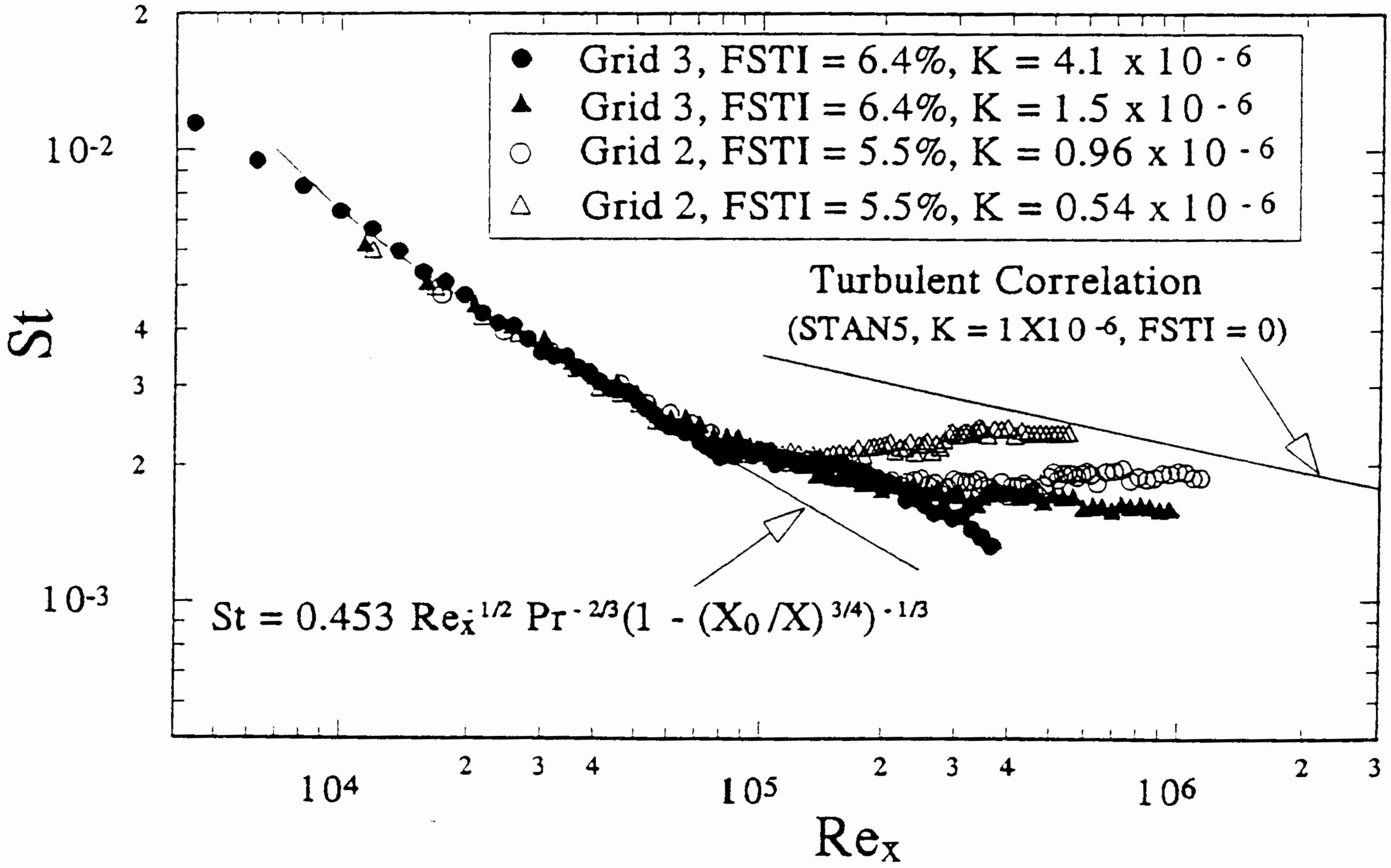


Figure 5.4 Centerline stanton number distribution for all cases.


Baseline, FSTI = 0.5%, K = 0
Grid 3, FSTI = 6.4%, K = 0
Grid 3, FSTI = 6.4%, K = 1 x 10 - 6
Turbulent Correlation
(STAN5, K = 1x10 -6, FSTI = 0)
St = 0.453 Rex -1/2 Pr -2/3 (1 - (X0 /X) 3/4) -1/3
St
2
10-2
4
3
2
10-3
Rex
104
2
3
4
105
2
3
4
106
2
3


Grid 3, FSTI = 6.4%, K = 4.1 x 10 - 6
Grid 3, FSTI = 6.4%, K = 1.5 x 10 - 6
Grid 2, FSTI = 5.5%, K = 0.96 x 10 - 6
Grid 2, FSTI = 5.5%, K = 0.54 x 10 - 6
Turbulent Correlation
(STAN5, K = 1X10 -6, FSTI = 0)
St = 0.453 Rex -1/2 Pr -2/3 (1 - (X0 /X) 3/4) -1/3
St
2
10-2
4
3
2
10-3
Rex
104
2
3
4
105
2
3
4
106
2
3

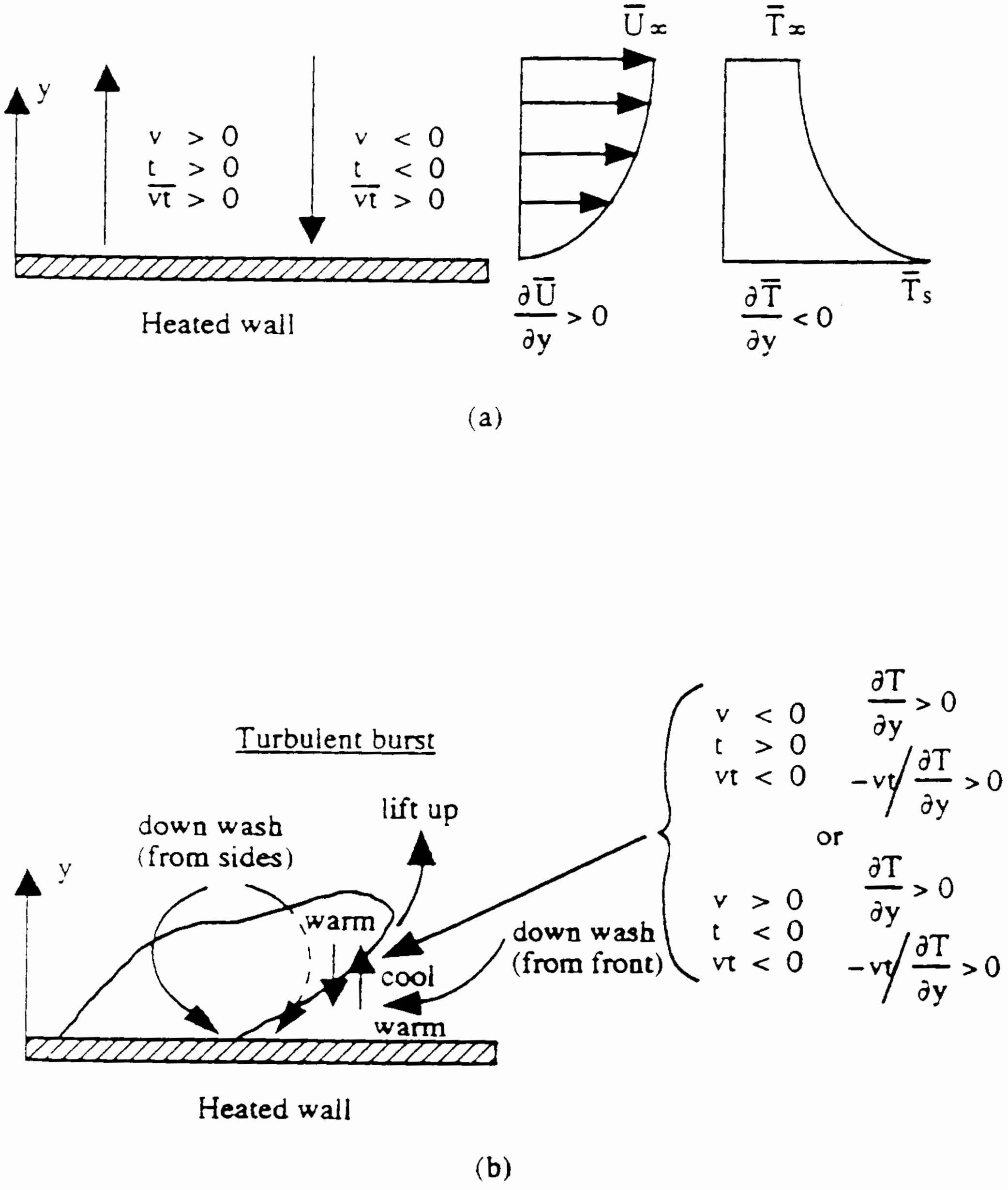


Figure 4.26 (a) Scenario of statistical transport correlation between v' and t' and (b) Scenario of instantaneous view of cross-stream Reynolds heat flux disribution.

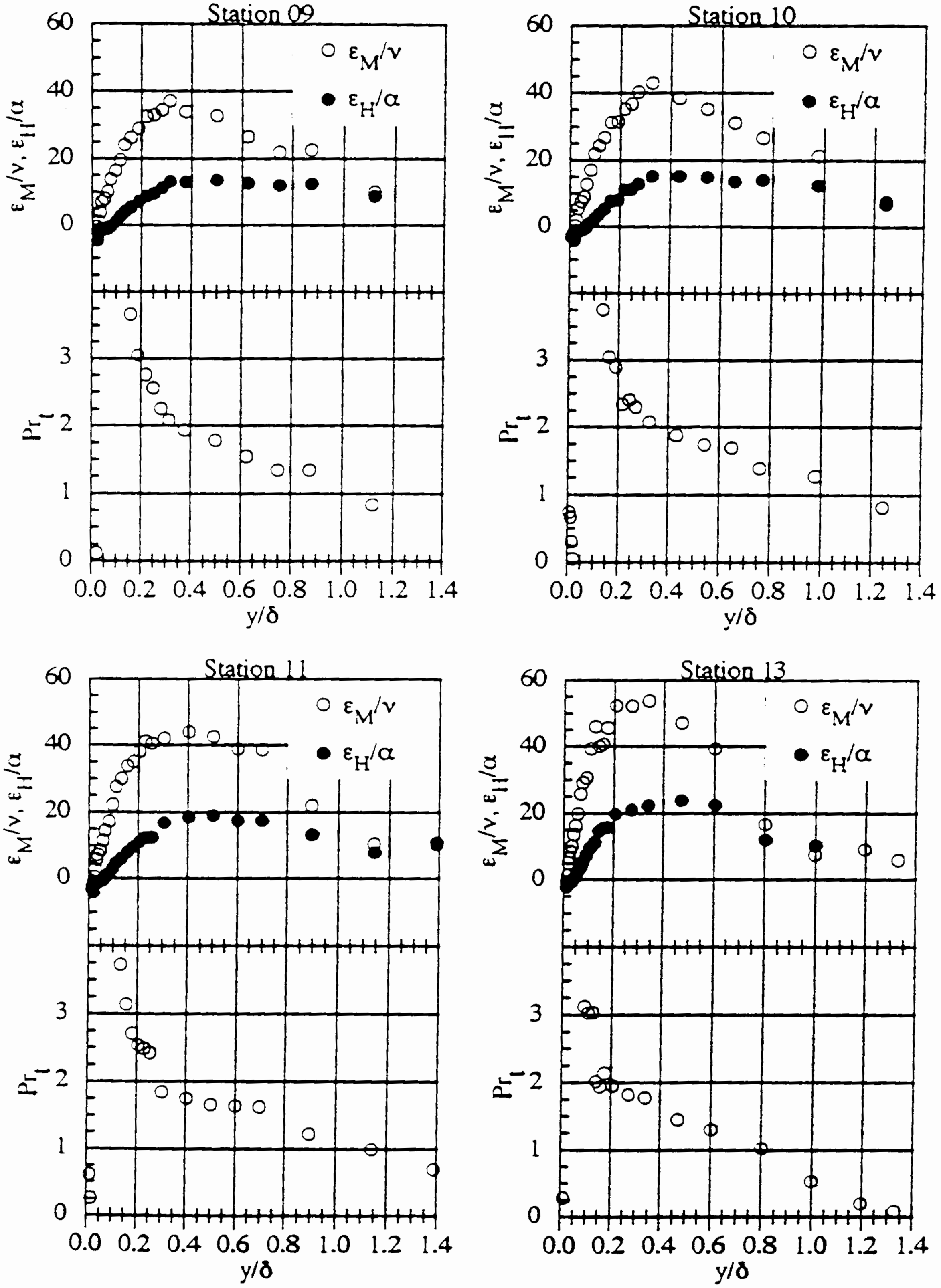


Figure 4.31 Distribution of eddy viscosity, turbulent thermal diffusivity and turbulent Prandtl number for baseline case (stations 9-11,13).

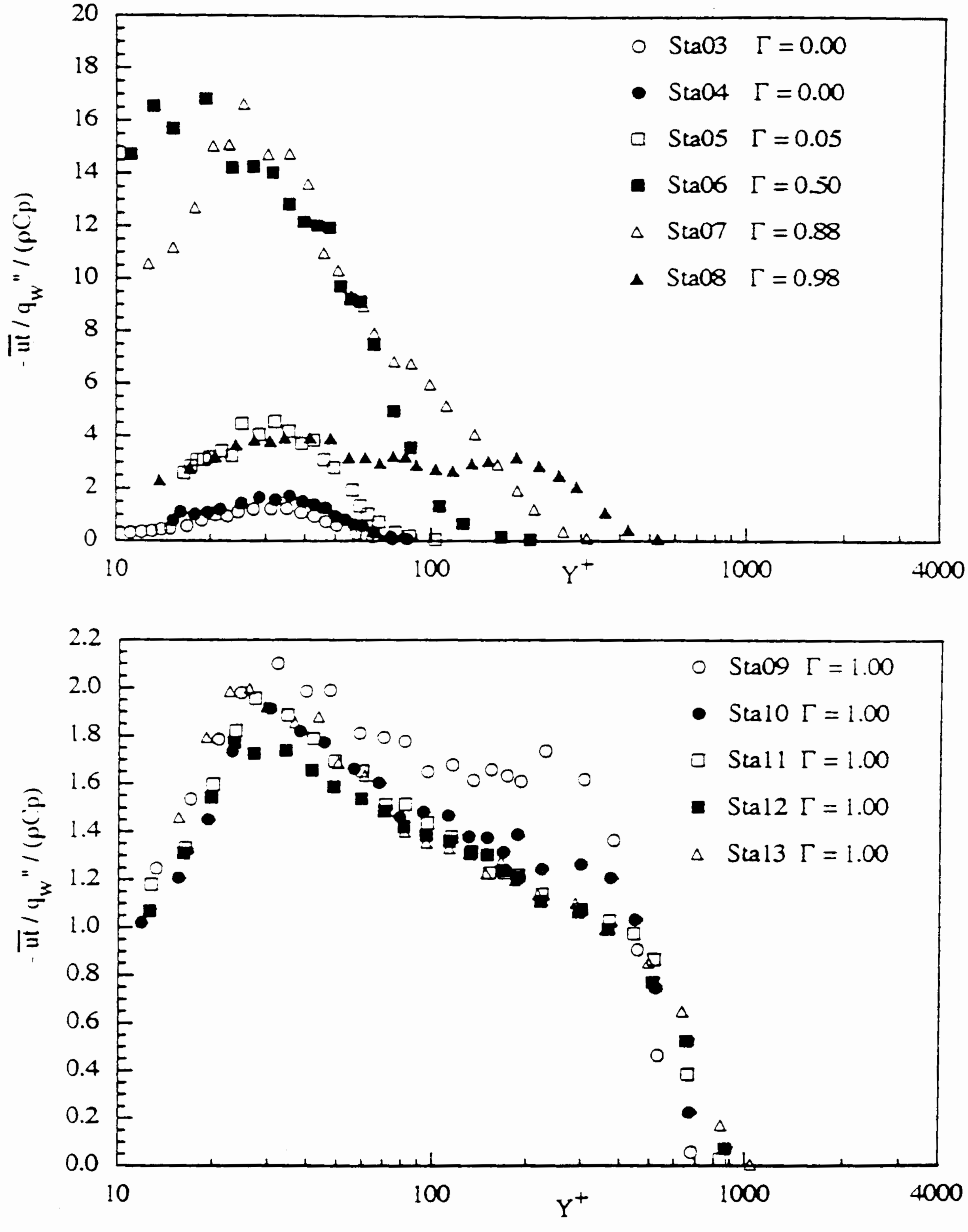


Figure 4.28 Reynolds streamwise heat flux distribution for the baseline case in wall units.

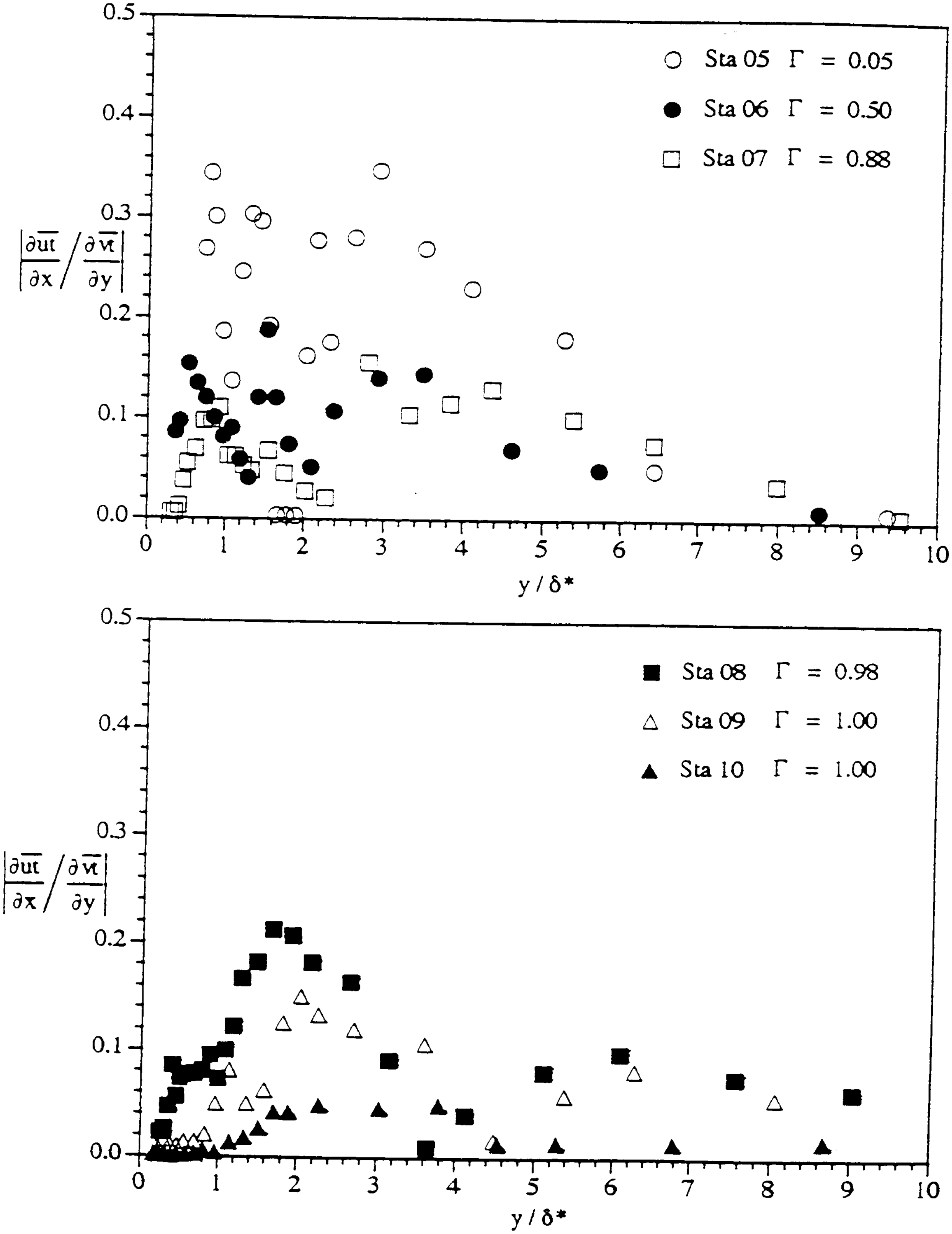
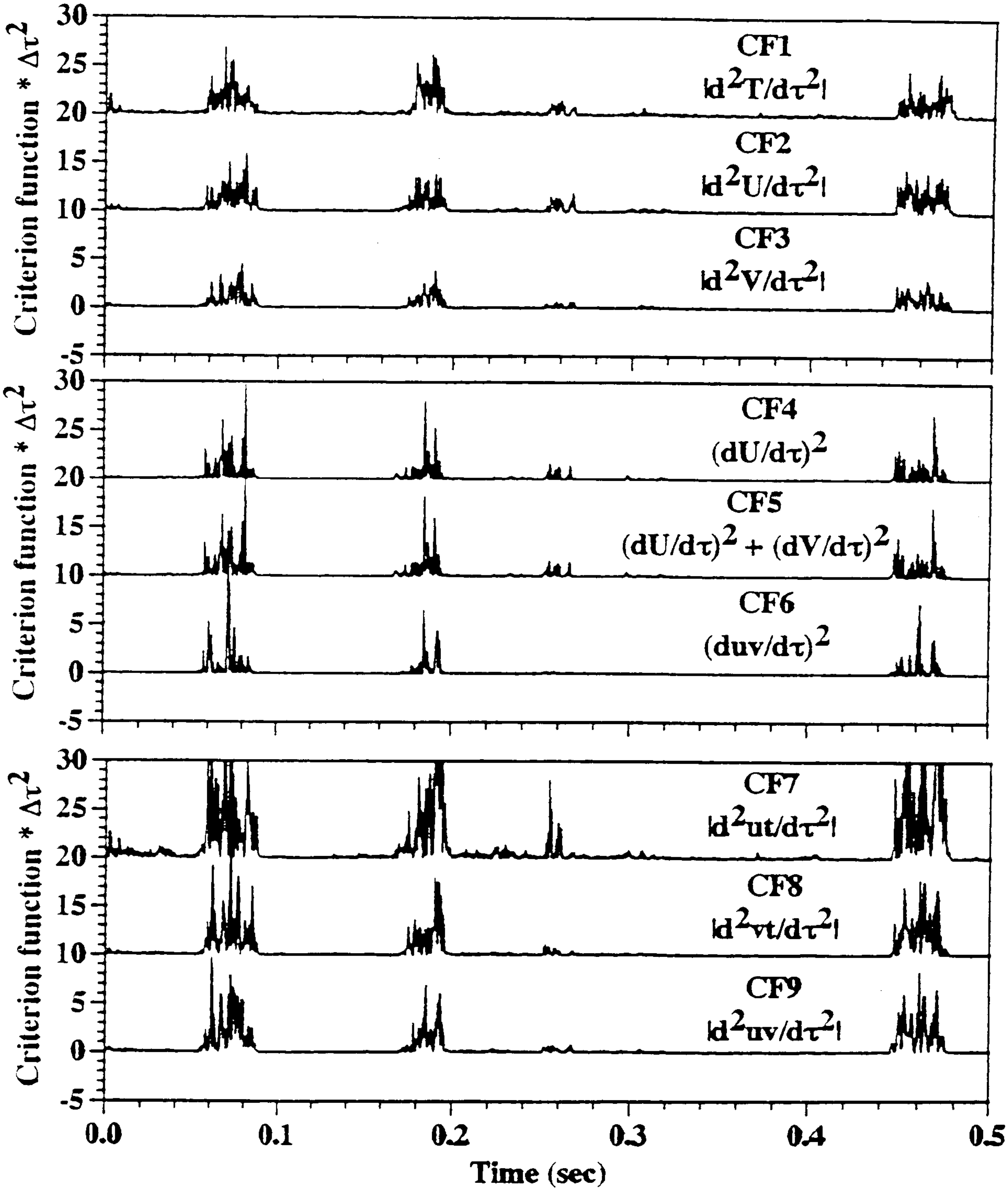


Figure 4.29 Ratio of gradient of Reynolds streamwise heat flux to gradient of Reynolds cross-stream heat flux for the baseline case.

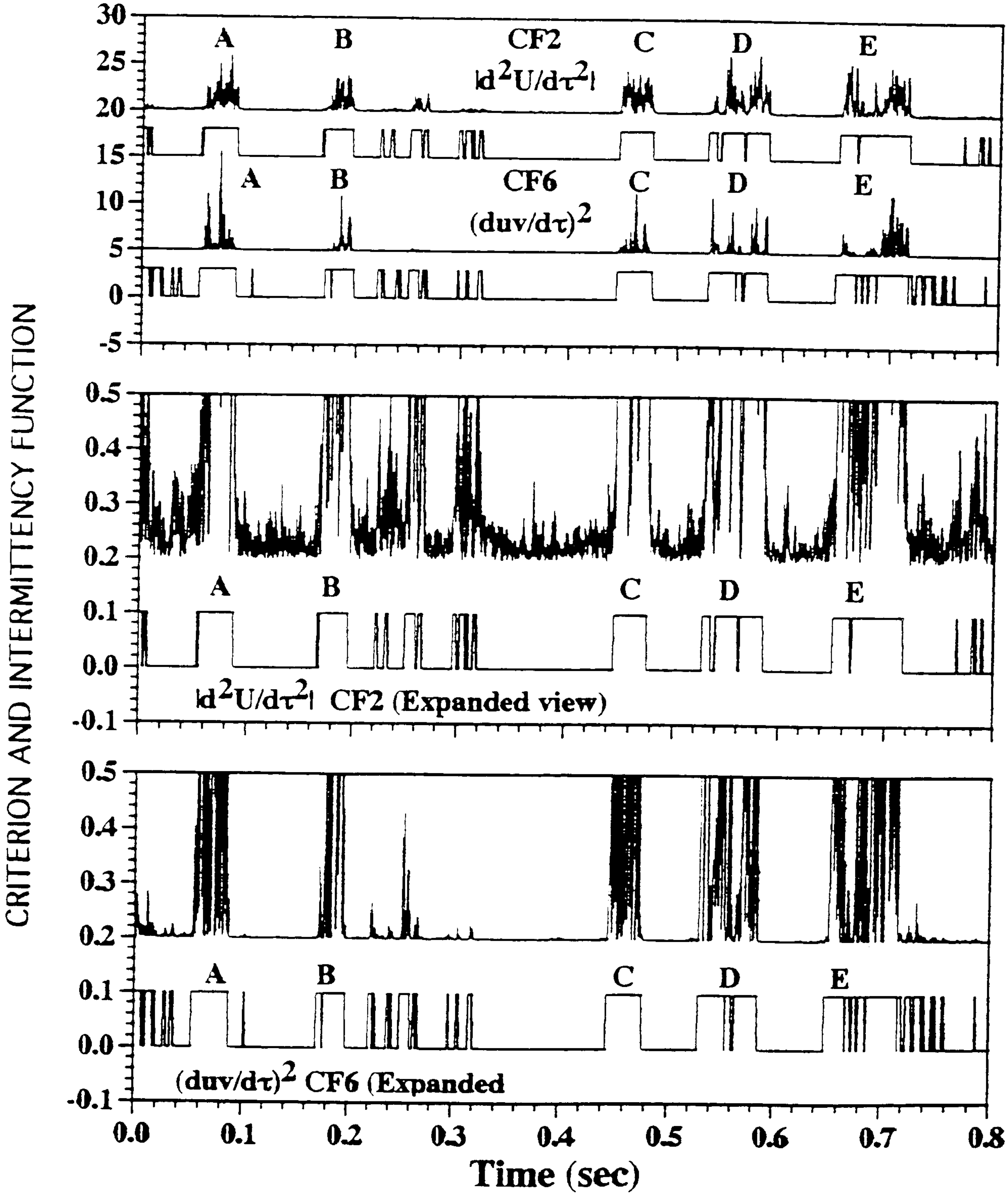
CORRESPONDING CRITERION FUNCTIONS FOR $\Gamma = 0.5$, $y/\delta^* = 1.1$ (BASELINE CASE)



FACTORS FOR DETERMINING WHICH CRITERION FUNCTION IS "BEST"

- SHARPNESS IN DEMARCATION BETWEEN TURBULENT AND NON-TURBULENT PORTIONS OF THE FLOW
- SMALL VARIATION OF THRESHOLD VALUE THROUGHOUT TRANSITION REGION
- LOW UNCERTAINTY IN DETERMINING THRESHOLD VALUE
- LOW SENSITIVITY OF RESULTED INTERMITTENCY TO UNCERTAINTY IN CHOOSING THRESHOLD

COMPARISON OF TWO CRITERION FUNCTIONS AND CORRESPONDING INTERMITTENCY FUNCTIONS FOR $\Gamma = 0.5$, $y/\delta^* = 1.1$ (baseline case)



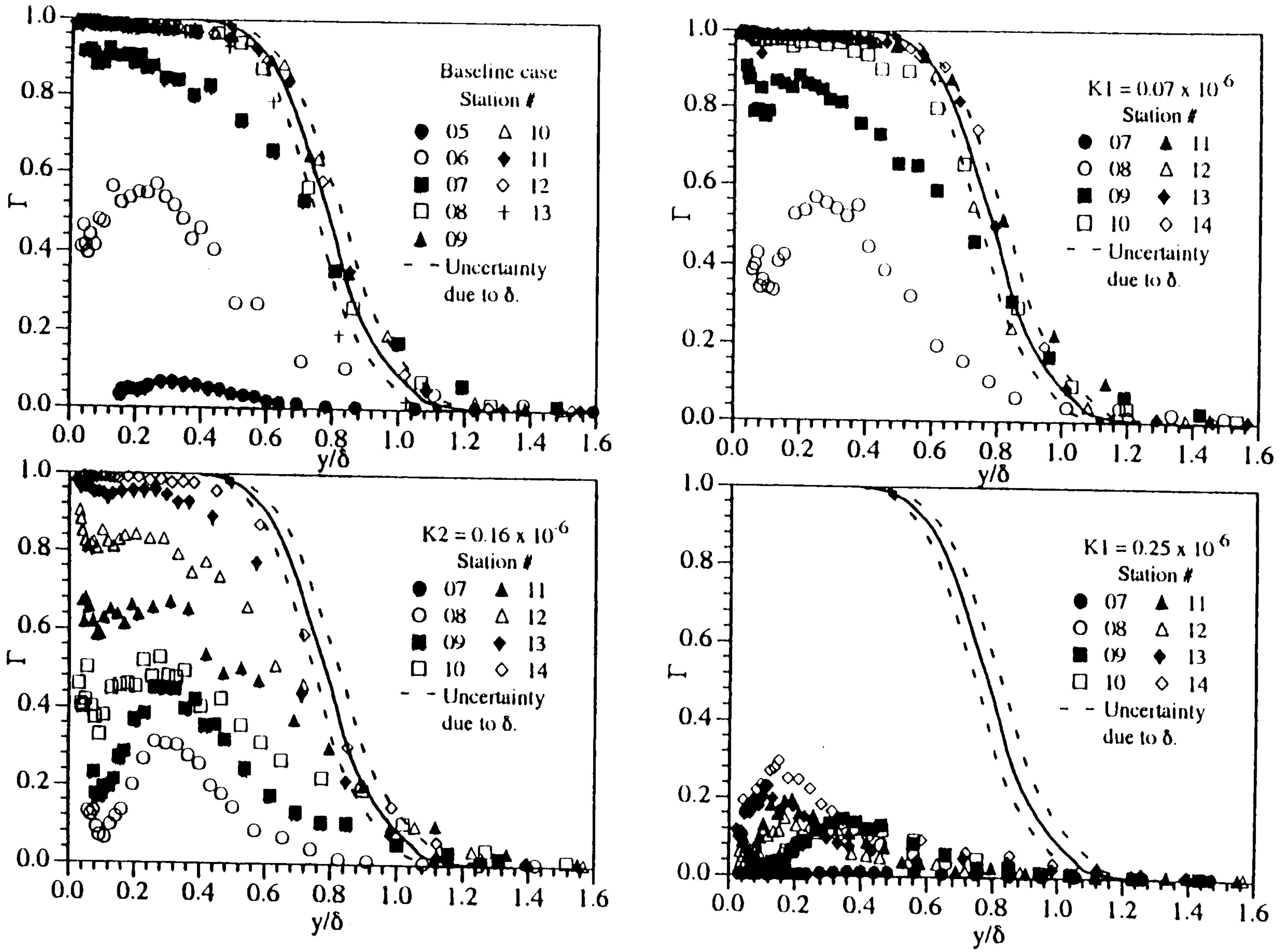
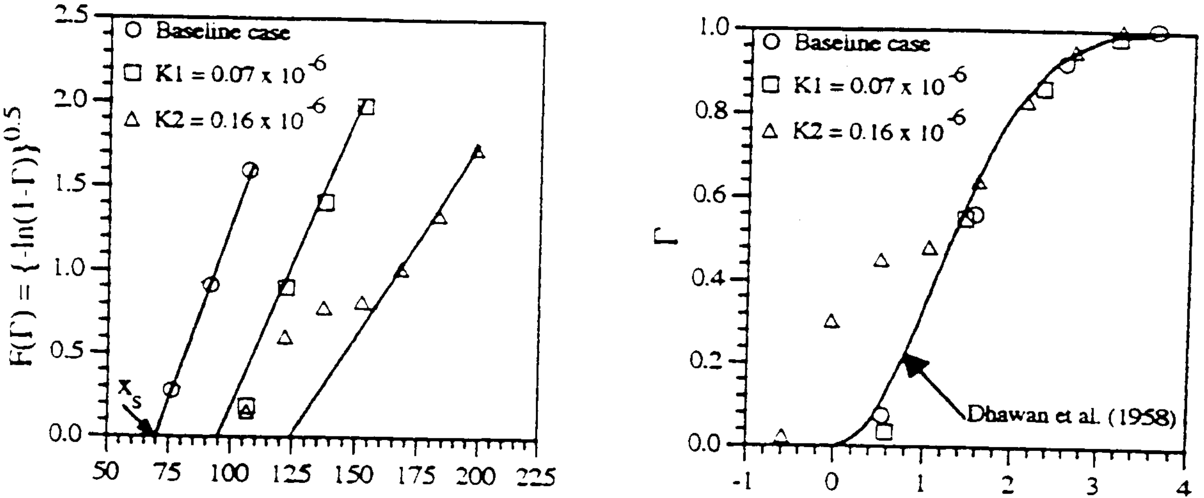
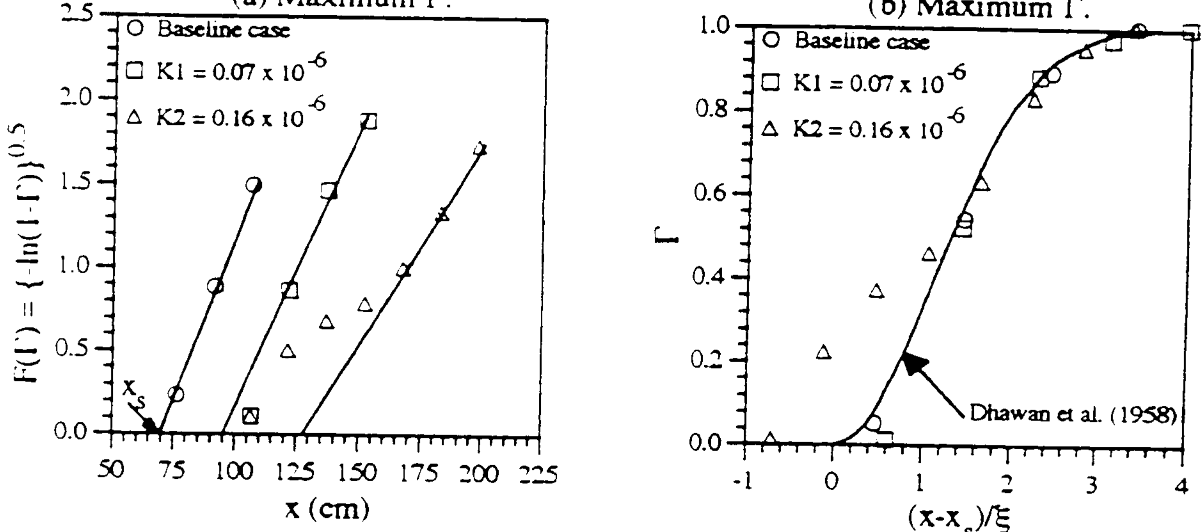


Figure 6.12 Intermittency distribution through boundary layer using $(duv/d\tau)^2$.



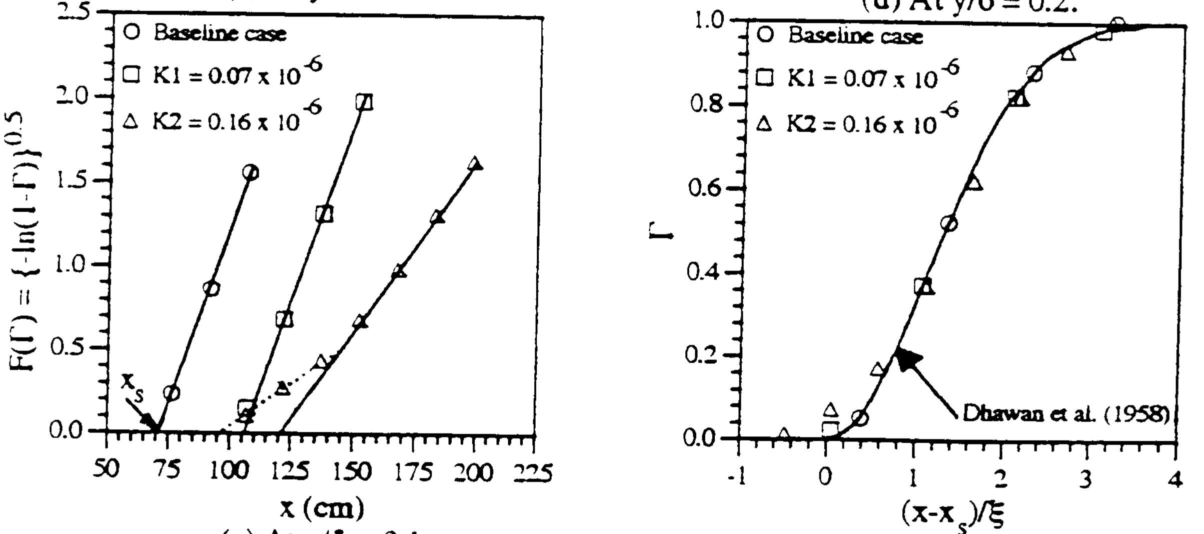
(a) Maximum Γ.

(b) Maximum Γ.



(c) At $y/\delta = 0.2$.

(d) At $y/\delta = 0.2$.



(e) At $y/\delta = 0.1$.

(f) At $y/\delta = 0.1$.

Figure 6.13 Determination of x_s and corresponding representative near-wall intermittency in Γ versus x coordinates using the value of Γ at different y/δ locations as the representative intermittency.

DETERMINATION OF NEAR-WALL INTERMITTENCY

- THREE LOCATION CONSIDERED FOR REPRESENTATIVE NEAR-WALL INTERMITTENCY
  - (1) LOCATION OF INTERMITTENCY PEAK $(y/\delta \approx 0.3)$
  - (2) VALUE AT $y/\delta = 0.2$ (MOST COMMONLY USED)
  - (3) LOCAL MINIMUM VALUE NEAR THE WALL $(y/\delta \approx 0.1)$
- BOTH (1) AND (2) RESULT IN TOO LARGE A DEVIATION FROM UNIVERSAL DISTRIBUTION
- USING (3) MATCHES UNIVERSAL DISTRIBUTIONS AND IS CONSIDERED APPROPRIATE FOR NEAR-WALL INTERMITTENCY VALUE

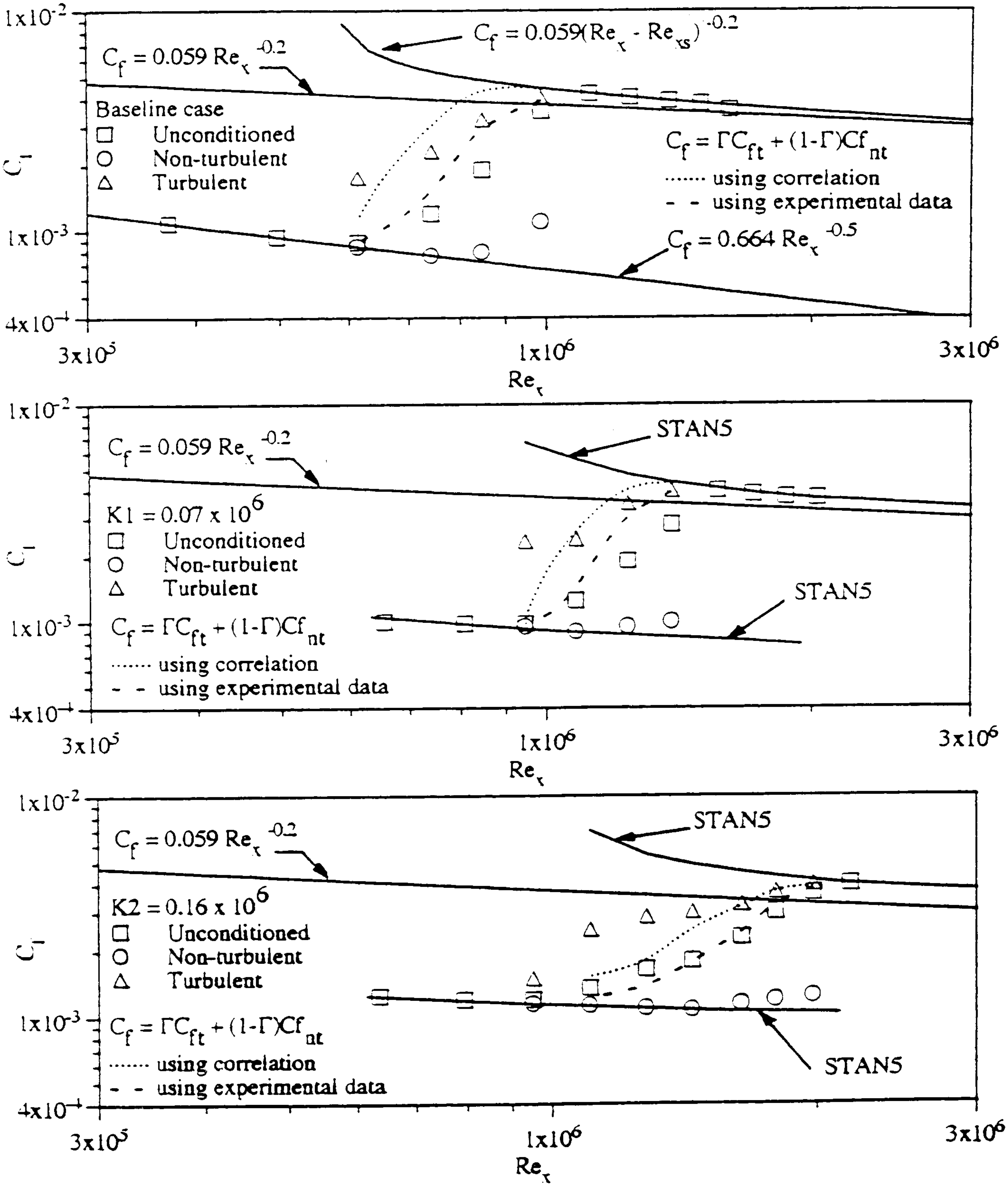


Figure 7.1 Conditionally sampled skin friction coefficient.

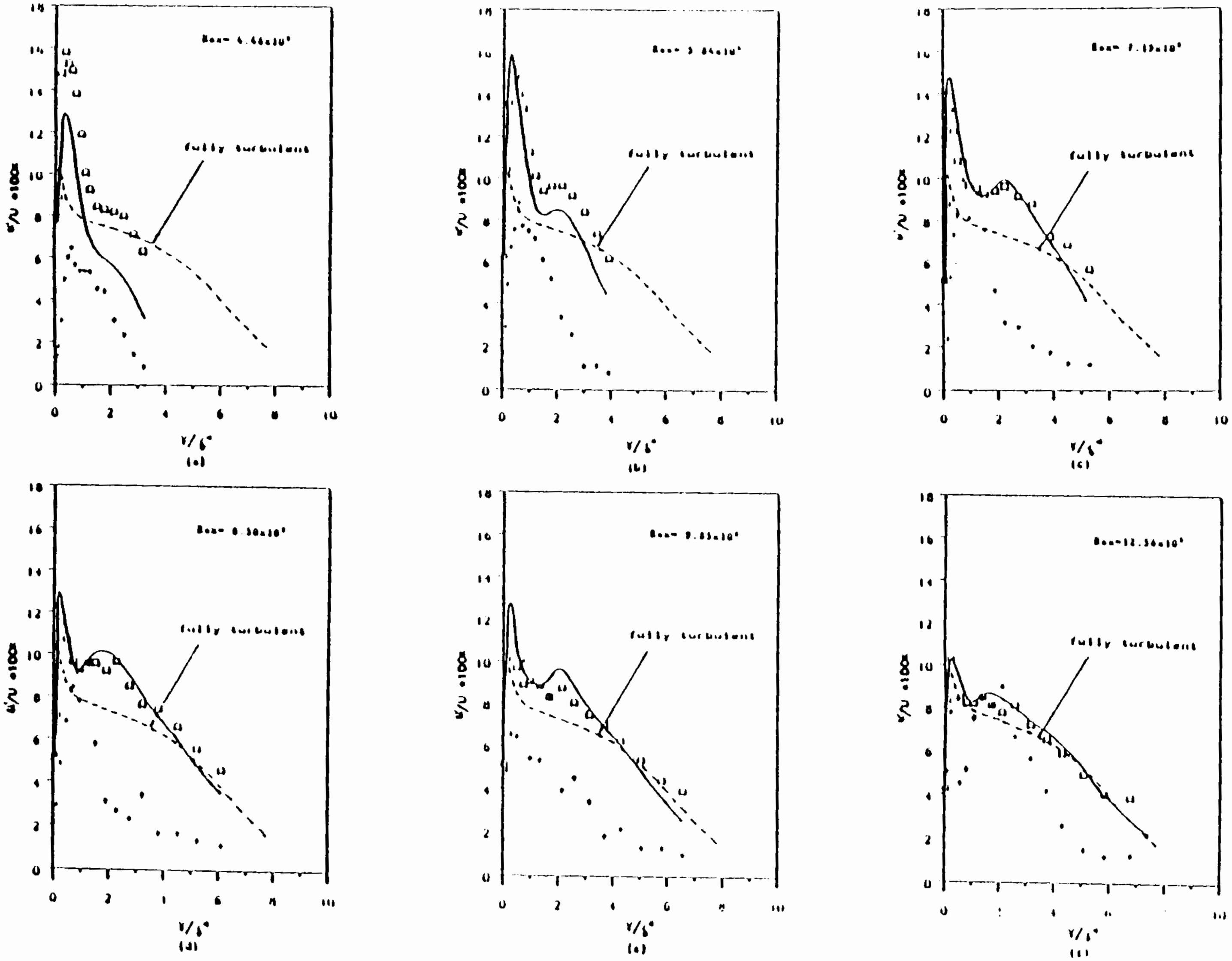


Figure 3.25. Conditionally Sampled Result of Reynolds Normal Stress Distribution (—— - total part; ☐ - turbulent part; * - non-turbulent part)

PUBLICATIONS

"Combined Effects of Elevated Free-Stream Turbulence and Streamwise Acceleration on Flow and Thermal Structures in Transitional Boundary Layers," Zhou, D., and Wang, T., to be presented at the 1993 National Heat Transfer Conference at Atlanta, Georgia. ASME HTD-Vol. 242, PP. 41~52.

"Effects of Elevated Free-Stream Turbulence on Flow and Thermal Structures in Transitional Boundary Layers," Zhou, D., and Wang, T., presented at the 1993 ASME International Gas Turbine and Aeroengine Congress and Exposition, Cincinnati, Ohio. ASME paper 93-GT-66.

"Effects of Different Criterion Functions on Intermittency in Heated Transitional Boundary Layers with and without Streamwise Accelerations," Keller, F.J., and Wang, T., presented at the 1993 ASME International Gas Turbine and Aeroengine Congress and Exposition, Cincinnati, Ohio. ASME paper 93-GT-67.

"Experimental Investigation of Reynolds Shear Stresses and Heat Fluxes in a Transitional Boundary Layer," Wang, T., Keller, F.J., and Zhou, D., ASME HTD-Vol. 226, Fundamental and Applied Heat Transfer Research for Gas Turbine Engine, pp. 61-70, 1992.

"Laminar Boundary Layer Flow and Heat Transfer with Favorable Pressure Gradient at Constant K Values," Zhou, D., and Wang T., presented at the 1992 ASME International Gas Turbine and Aeroengine Congress and Exposition. ASME paper 92-GT-246.

Keller, F.J., 1993, "Flow and Thermal Structures in Heated Transitional Boundary Layers with and without Streamwise Acceleration," Ph.D. Dissertation, Dept. of Mech. Engr., Clemson University, Clemson, SC.

Kuan, C.L., 1987, "An Experimental Investigation of Intermittent Behavior in the Transitional Boundary Layer," M.S Thesis, Dept. of Mech. Engr., Clemson University, Clemson, SC.

Kuan, C.L and Wang, T., 1990, "Investigation of Intermittent Behavior of Transitional Boundary Layer Using a Conditional Averaging Technique," *Experimental Thermal and Fluid Science*, Vol. 3, pp.157-170.