ABSTRACT

TURBULENCE MEASUREMENTS IN AXISYMMETRIC SUPERSONIC BOUNDARY LAYER FLOW IN ADVERSE PRESSURE GRADIENTS

by
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and

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Measurements have been made of the mean-flow and turbulence properties in adiabatic turbulent boundary layer flows subjected to adverse pressure gradients. In the freestream region upstream of the adverse pressure gradient the Mach Number was 3.86, the unit Reynolds Number 5.3×10^6 per foot. The boundary layer developed on the wall of an axisymmetric nozzle and straight test section. The pressure gradients at the test section wall were induced by contoured centerbodies mounted on the wind tunnel centerline. The flow under study simulated that which might be found in an axially symmetric engine inlet of a supersonic aircraft.

The mean flow measurements were made with a pitot probe and with a normal hot-wire probe used as a resistance thermometer. Normal and yawed hot-wire probes were used with a constant-temperature anemometer

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system to obtain turbulence at several locations in each of two adverse pressure gradients. The turbulence results include total temperature fluctuations, mass flow fluctuations, longitudinal and radial velocity fluctuations and turbulent shear stress and heat transfer.

There have been numerous investigations of the mean flow properties of undisturbed supersonic boundary layers and of supersonic boundary layers in adverse pressure gradients. Only recently, however, have investigators concentrated on obtaining turbulence measurements in supersonic boundary layers in adverse pressure gradients[1-4]. Although there have been some studies detailing the turbulence properties of boundary layers subjected to shock-wave induced pressure gradients, very few turbulence measurements have been made in flows subjected to more gradual pressure increases of the type examined here. Furthermore, very few investigations have been conducted for axisymmetric flows. Some of the difficulties and probable errors associated with performing turbulence measurements in high speed flows will be discussed in the paper.

In the remainder of this abstract results typical of those obtained in this investigation will be described. Figure (1) shows the wall static pressure distributions for the two adverse pressure gradients examined in the study, along with the pressure distribution for a shock wave boundary layer interaction produced by a 9^{o} half-angle cone placed on the centerline of a similar wind tunnel test section. The pressure gradients examined in this study show a gradual initial rise compared to the shock-induced gradient. Only near the end of the pressure rise do the gradients approach or exceed the steepest gradient for the shock interaction.

Figures (2a) and (2b) show the pitot profiles obtained in the two adverse pressure gradient regions. In Figure (3) the pitot pressures and total temperatures as measured in the undisturbed flow are shown. The boundary layer edge based on the total temperature is indicated on the figure. For the undisturbed flow the total temperature boundary layer thickness is seen to agree closely with the boundary layer thickness based on the pitot pressure profile. In Figure (4) the boundary layer thickness based on the total temperature profile through the regions of adverse pressure gradient is shown.

In Figure (5) the normalized longitudinal ($\langle u' \rangle/\bar{U}$) velocity fluctuations in the undisturbed flow are shown.

The figures also show the recently reported results of Rose and Johnson[2] along with the incompressible flow results of Klebanoff[5]. When plotted as a function of y/δ the longitudinal velocity fluctuation from all of the investigators are in good agreement. As shown $\langle u' \rangle/\bar{u}$ increases monotonically from its freestream value to a peak value of almost 10 percent at the measuring stations nearest to the wall. This trend is in constrast to the results of some earlier investigators (see reference 6 for a review of turbulence measurements in compressible flow) which indicate that the normalized longitudinal velocity fluctuations begin to decrease farther from the surface than the results shown on here.

The normalized radial velocity fluctuations ($\langle v' \rangle/u$) are shown in Figure (6) along with results from studies by Rose and Johnson[2] and Mikulla and Horstman[4]. The incompressible results of Klebanoff[5] are also shown. The fluctuations measured on the present study are higher in the outer part of the boundary layer than the other results shown. However, all of these results approach a level of approximately 5 percent at measuring stations nearest to the wall.

In Figures (7) and (8) the longitudinal and radial velocity fluctuations are shown for several stations in the adverse pressure gradient regions. There is a general overall increase in the peak levels of the normalized velocity fluctuations with axial distance into the pressure gradient regions. In the stronger of the two pressure gradients, gradient 2, the longitudinal velocity fluctuation is seen to first increase with x then to decrease. This is in qualitative agreement with the results of Reference 4 which reports measurements through a steep shock induced pressure rise at M = 7.2. The radial fluctuations show an increase in the inner half of the boundary layer for both gradients.

The turbulent shear stress distribution as measured in the undisturbed flow is shown in Figure 9 along with the shear stress distribution obtained by integration of the mean flow equations (Reference 7). The experimental and calculated results are seen to be in good agreement. The data do not show as much of a decrease in the inner part of the boundary layer as has been reported for most other investigations of supersonic flow. The turbulent shear stress measurements made in the adverse pressure gradient regions are shown in Figure 10. The peak levels of the shear increase with axial distance into the adverse pressure gradient regions as has been reported in other studies of adverse pressure gradient flows. Figure 11 shows normalized shear stress distributions for the last measuring station in each of the pressure gradients along with the distributions computed by integration of the mean flow equations. The ratio of wall static pressure to upstream pressure was approximately the same (2.65 and 2.79) for each of these stations. As is apparent, the peak levels of the normalized shear are approximately twice as high as those observed in the upstream flow.

The results obtained in this investigation provide new information about the behavior of the supersonic axisymmetric turbulent boundary layer in an adverse pressure gradient. Good agreement was shown to exist between the normalized turbulent velocity fluctuations as measured here and the results from other recent investigations of compressible boundary layers. In the adverse pressure gradient regions the peak values of the turbulent fluctuations were found to generally increase with axial distance into the pressure gradient, although in the stronger of the two gradients the fluctuations initially increased and then decreased. The turbulent shear stress levels increase substantially with axial distance into the adverse pressure gradient. In both the upstream flow and the region of increased pressure the measured shear stress agrees reasonably well with values computed by integration of the mean flow equations.

REFERENCES

1. Rose, W.C., "The Behavior of a Compressible Turbulent Boundary Layer in a Shock-Wave Induced Adverse Pressure Gradient," Ph.D. hesis, 1972, University of Washington, Seattle, Wa.

2. Rose, W.C. and Johnson, D.A., "Turbulence in a Shock-Wave Induced Boundary Layer Interaction," AIAA Journal, Vol. 13, No. 7, July 1975, pp. 884-889.

3. Walthrup, P.J. and Schetz, J.A., "Supersonic Turbulent Boundary Layer Subjected to Adverse Pressure Gradients," AIAA Journal, Vol. 11, No. 1, Jan. 1973, pp. 50-67.

4. Mikulla, V. and Horstman, C.C., "Turbulence Measurements in Hypersonic Shock-Wave Boundary Layer Flows," AIAA Paper No. 76-162, 1976.

5. Klebnoff, P.S., "Characteristics of Turbulence in a Boundary Layer with Zero Pressure Gradient," Report 1247, 1954, NACA.

6. Sandborn, V.A., "A Review of Turbulence Measurements in Compressible Flow," TMX-62, 337, 1974, NASA.

7. Sun, C.C. and Childs, M.E., "Calculation of Turbulent Shear Stress in Supersonic Boundary Layer Flows," AIAA Journal, Vol. 13, No. 2, Feb. 1976, pp. 224-227.

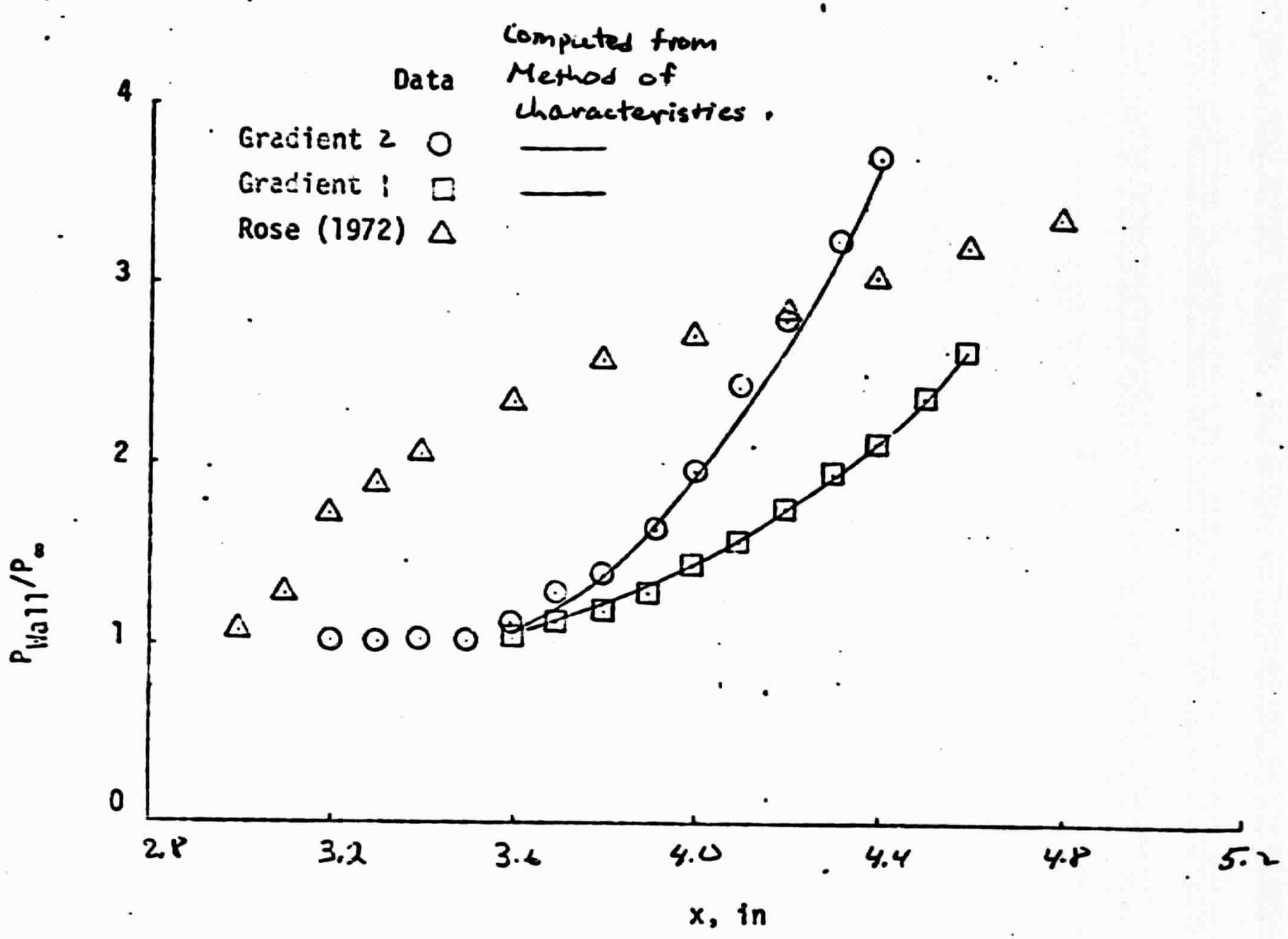


Figure 1. Surface Static Pressures.

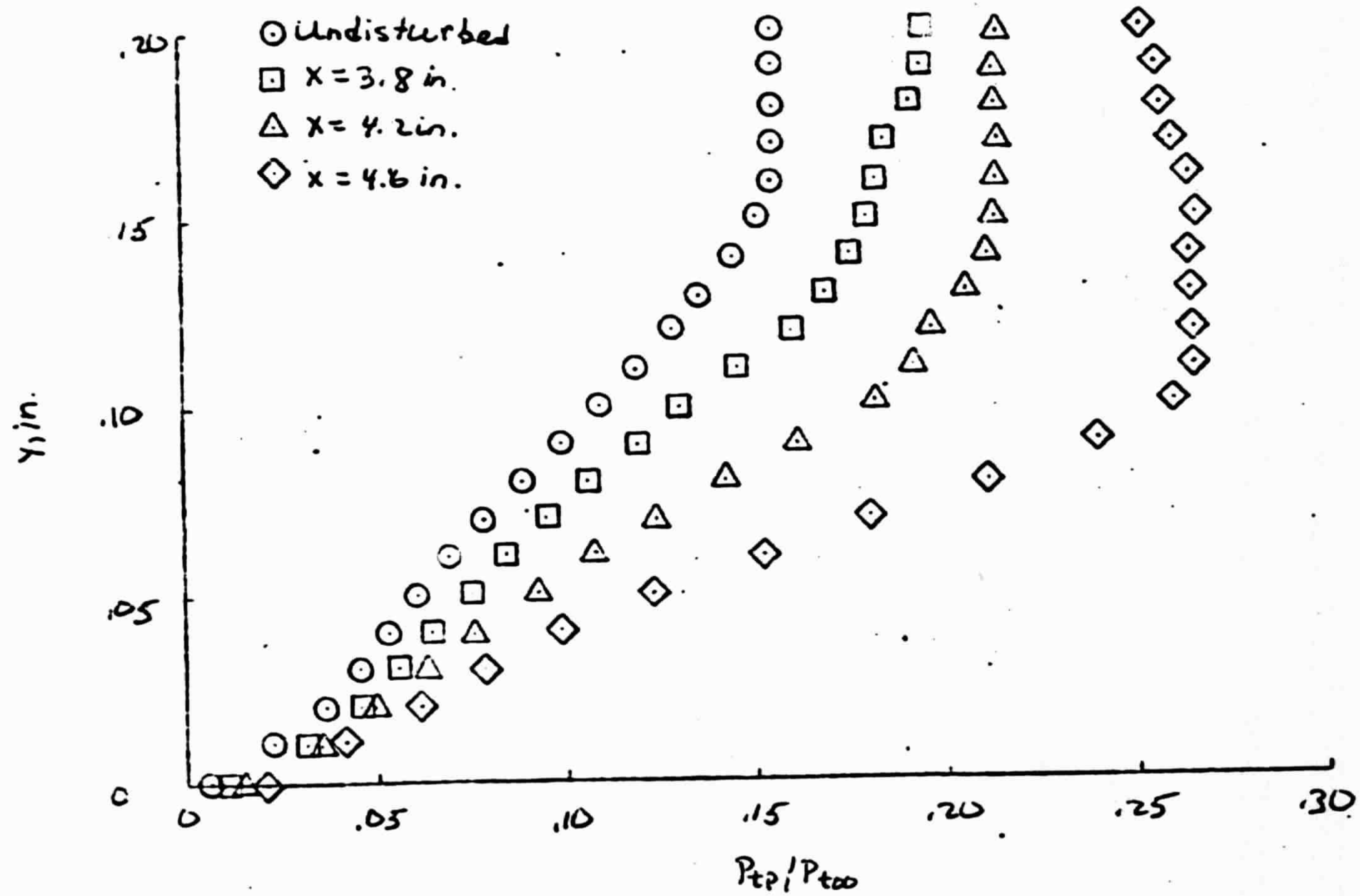


Figure 2a. Pitot Pressures, Gradient 1

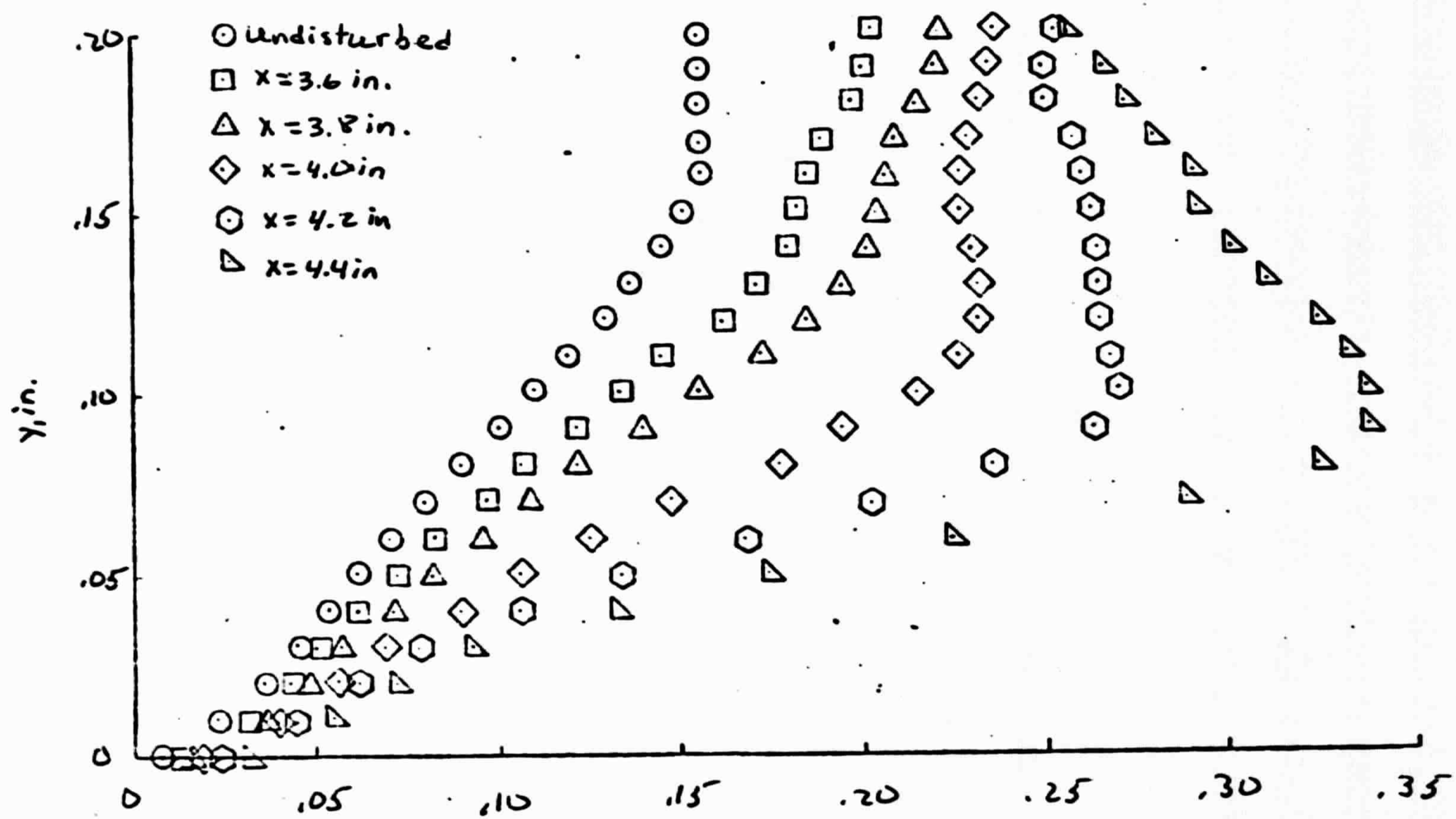


Figure 26. Pitot Pressures, Gradient 2

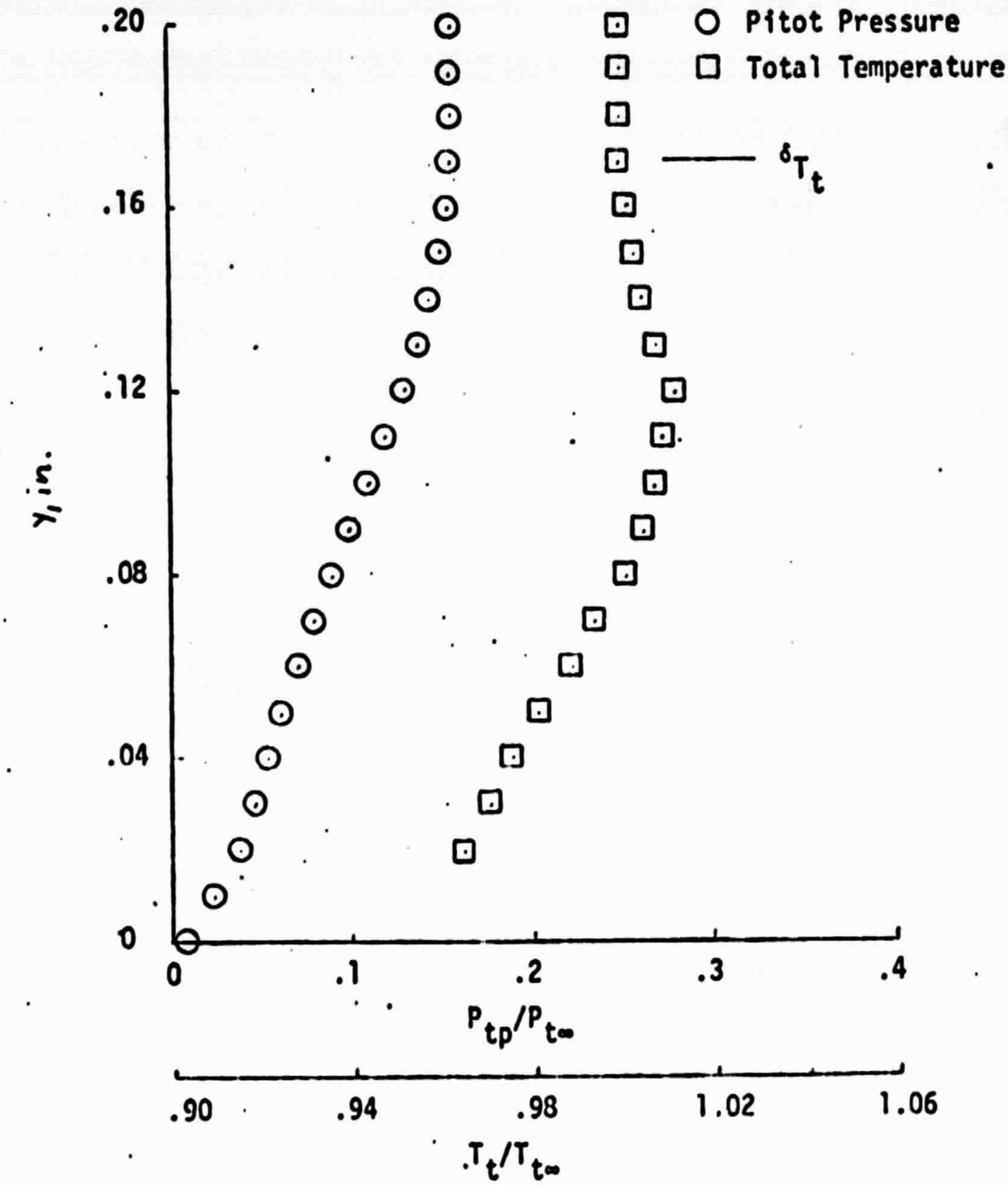


Figure 3 . Undisturbed Flow, Pitot Pressures and Total Temperatures.

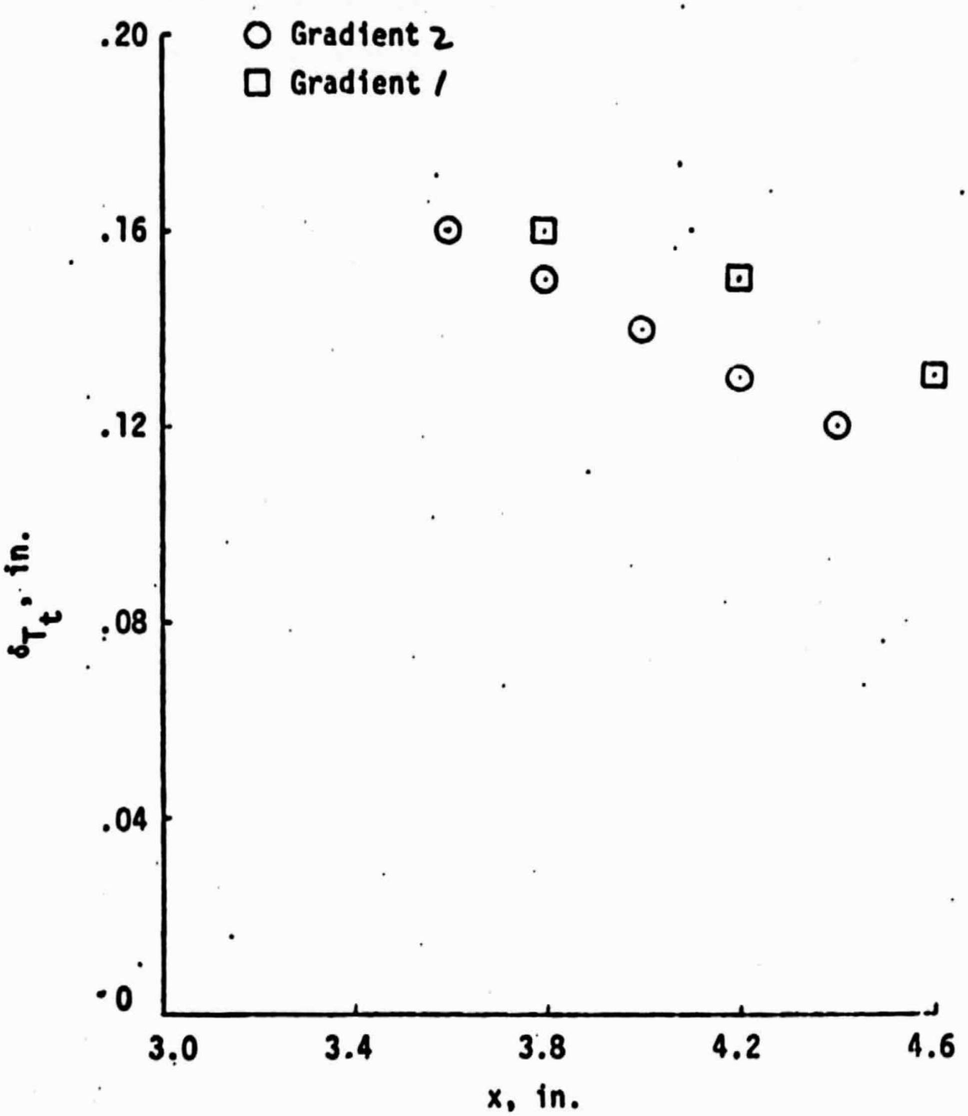


Figure 4. Variation of δ_{T_t} Through Adverse Pressure Gradient Regions.

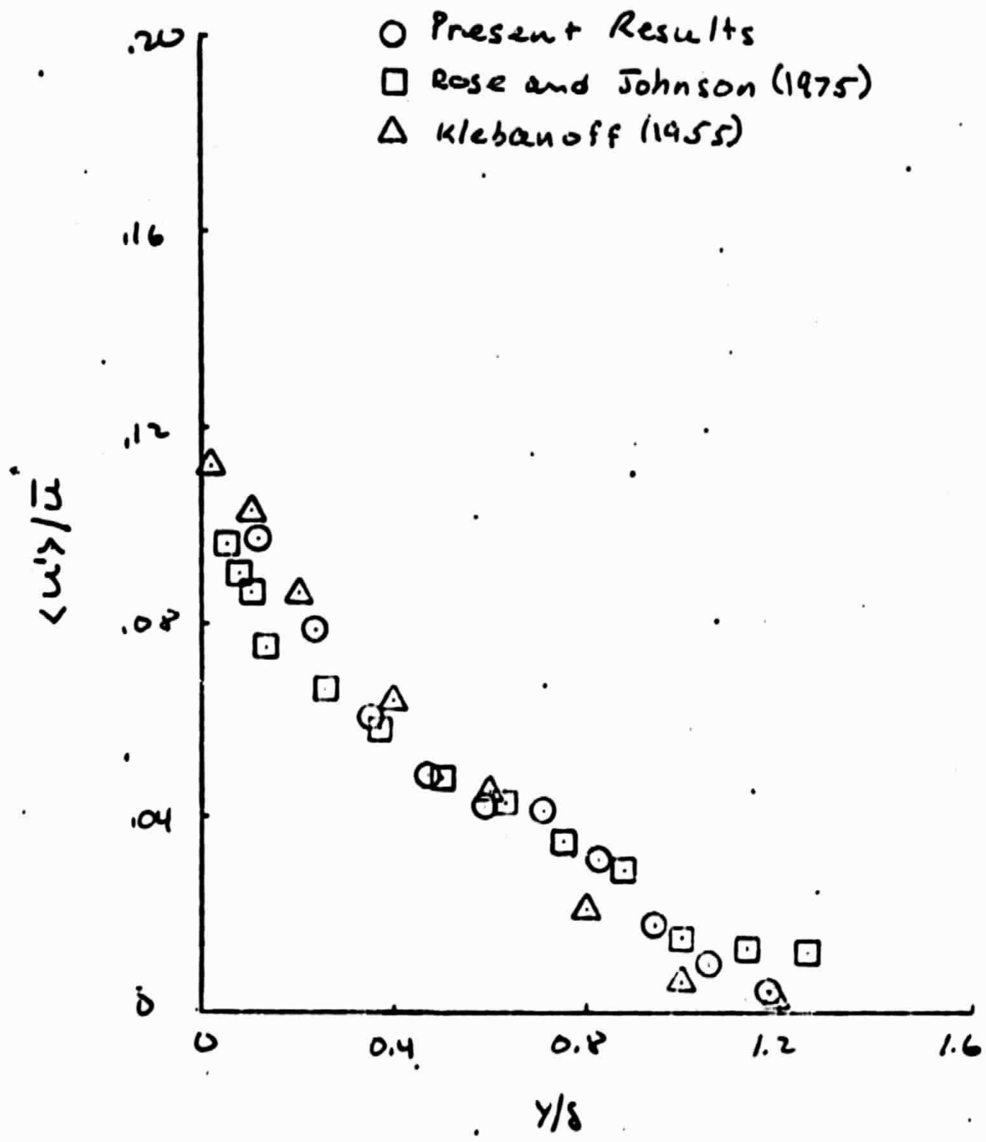


Figure 5. Comparison of Undisturbed Longitudinal Velocity Fluctuations

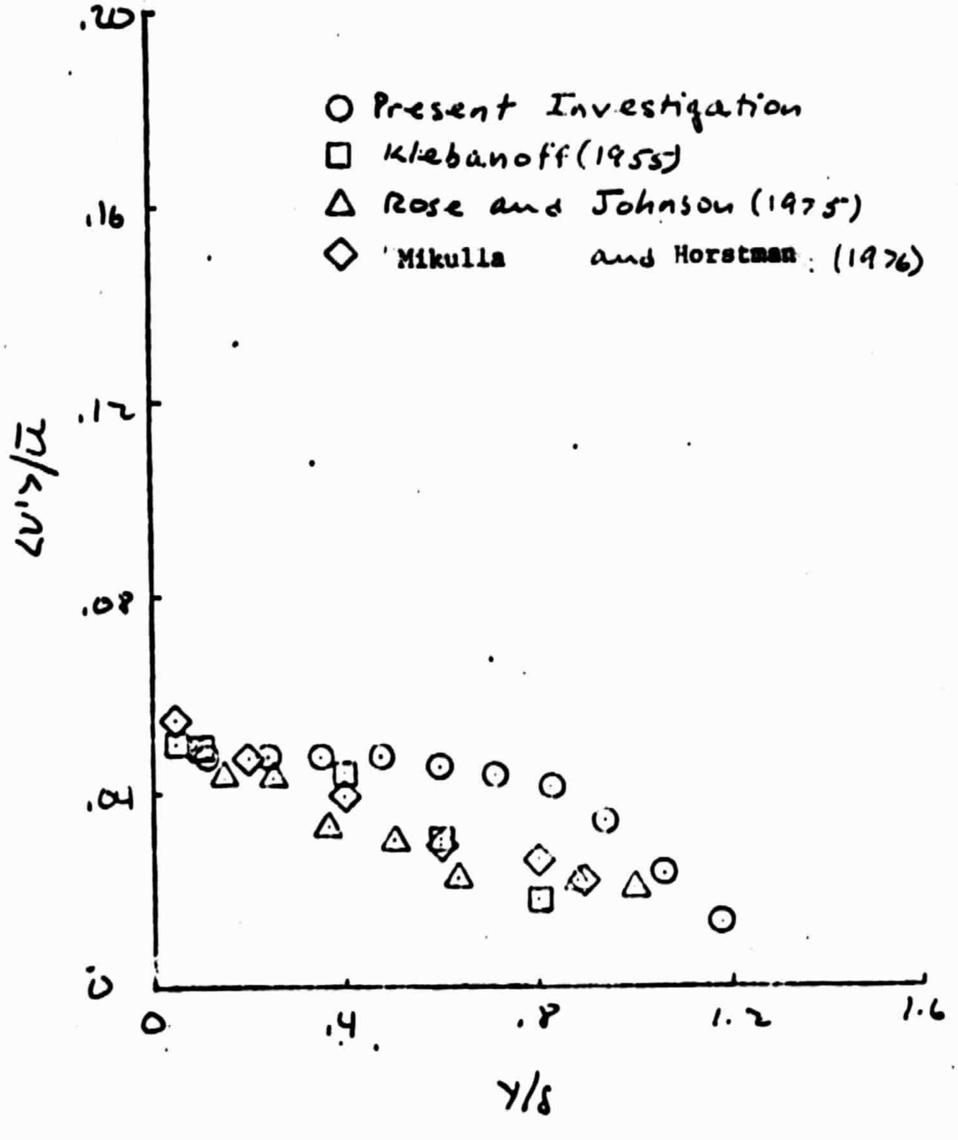


Figure 6. Comparison of Undisturbed Radial Velocity Fluctuations

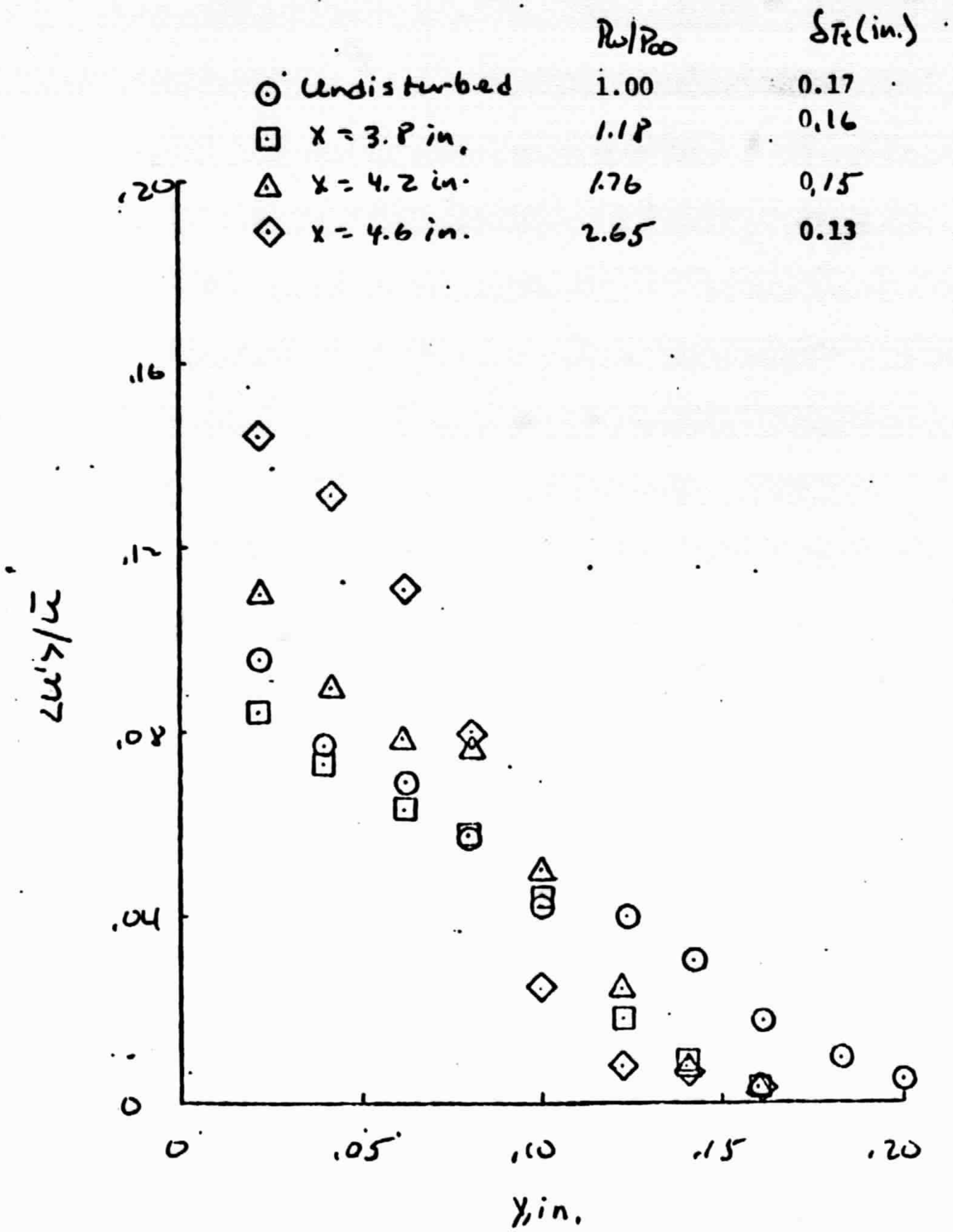


Figure xx. Longitudinal Velocity Fluctuations, Gradient 1

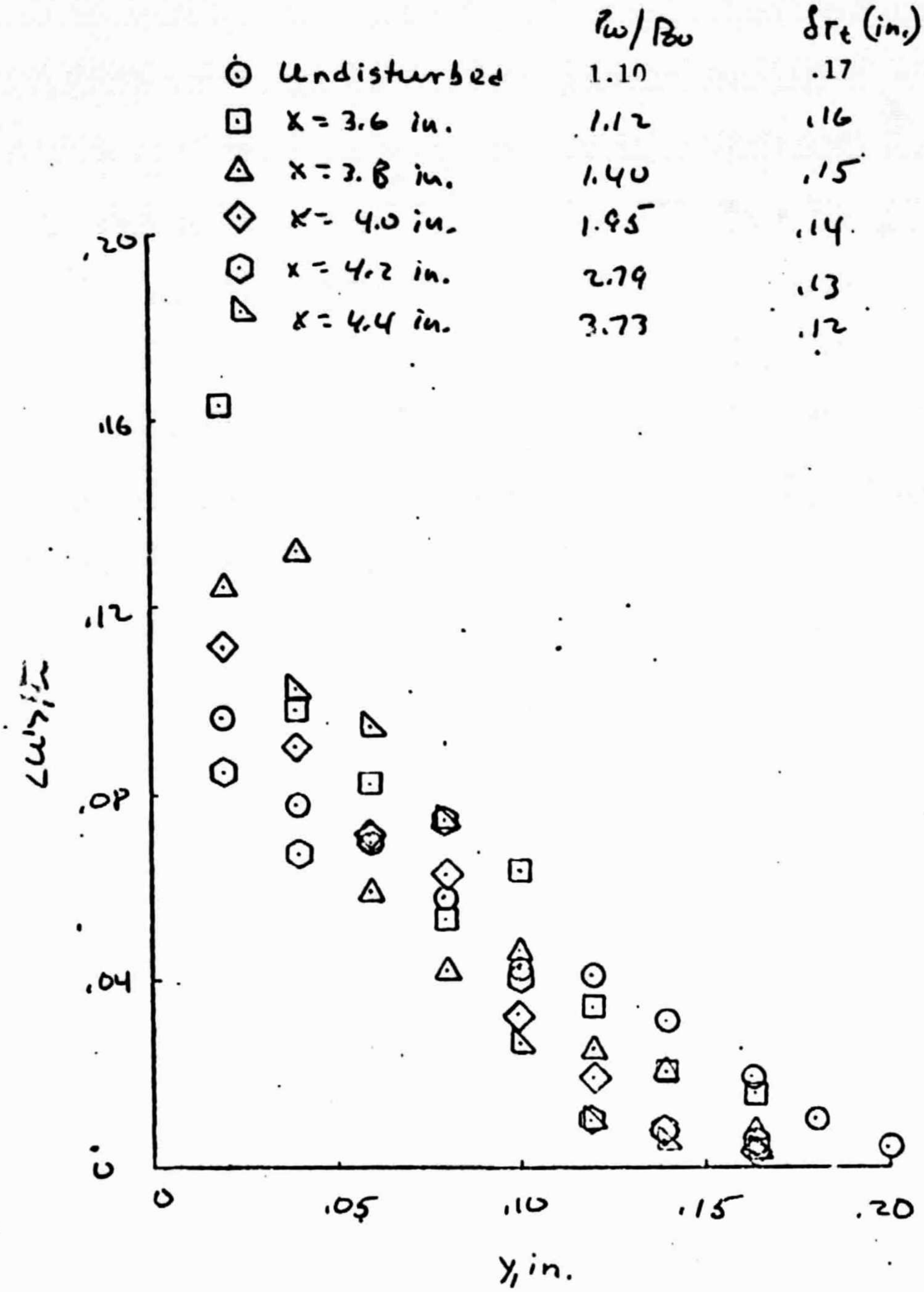


Figure 7b. Longitudinal Velocity Fluctuations, Gradient 2

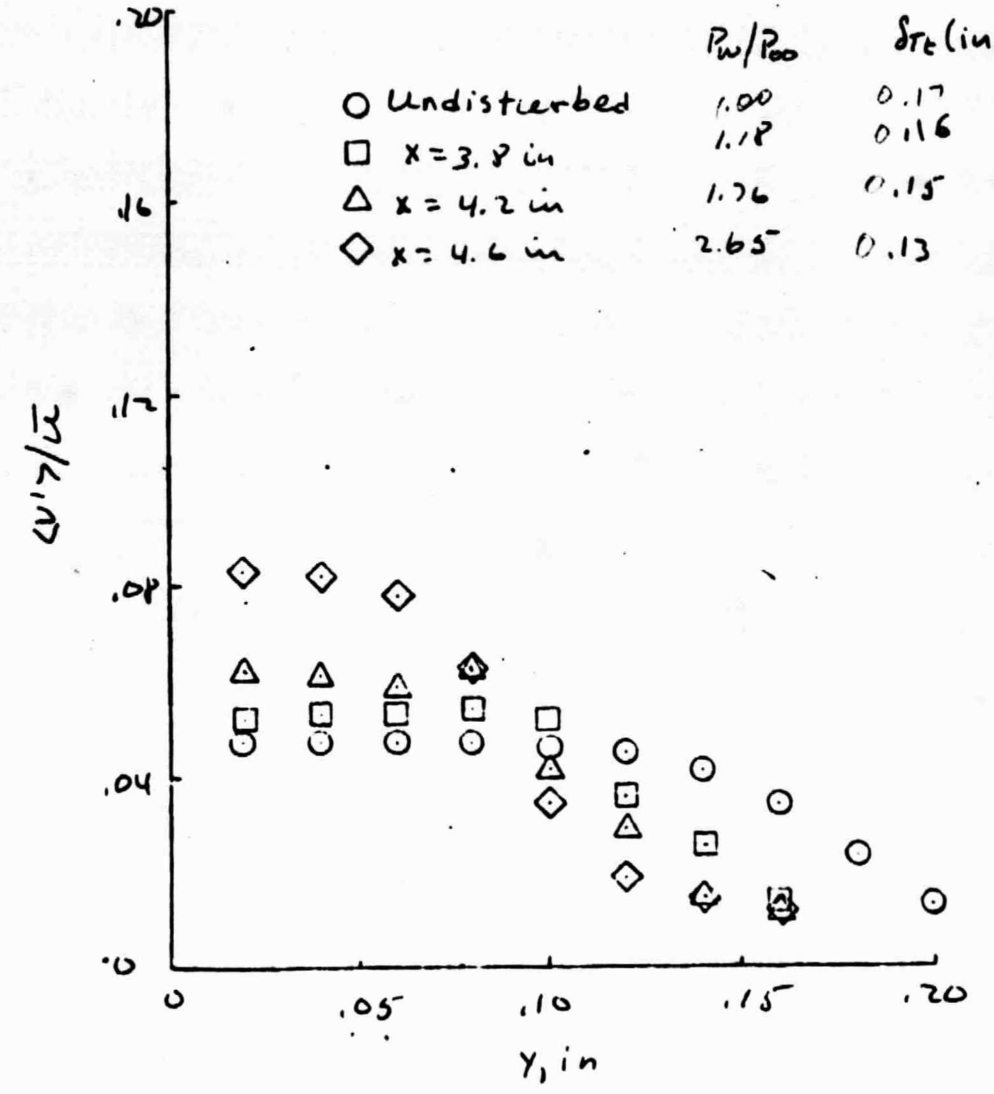


Figure 8a Radial Velocity Fluctuations, Gradient 1

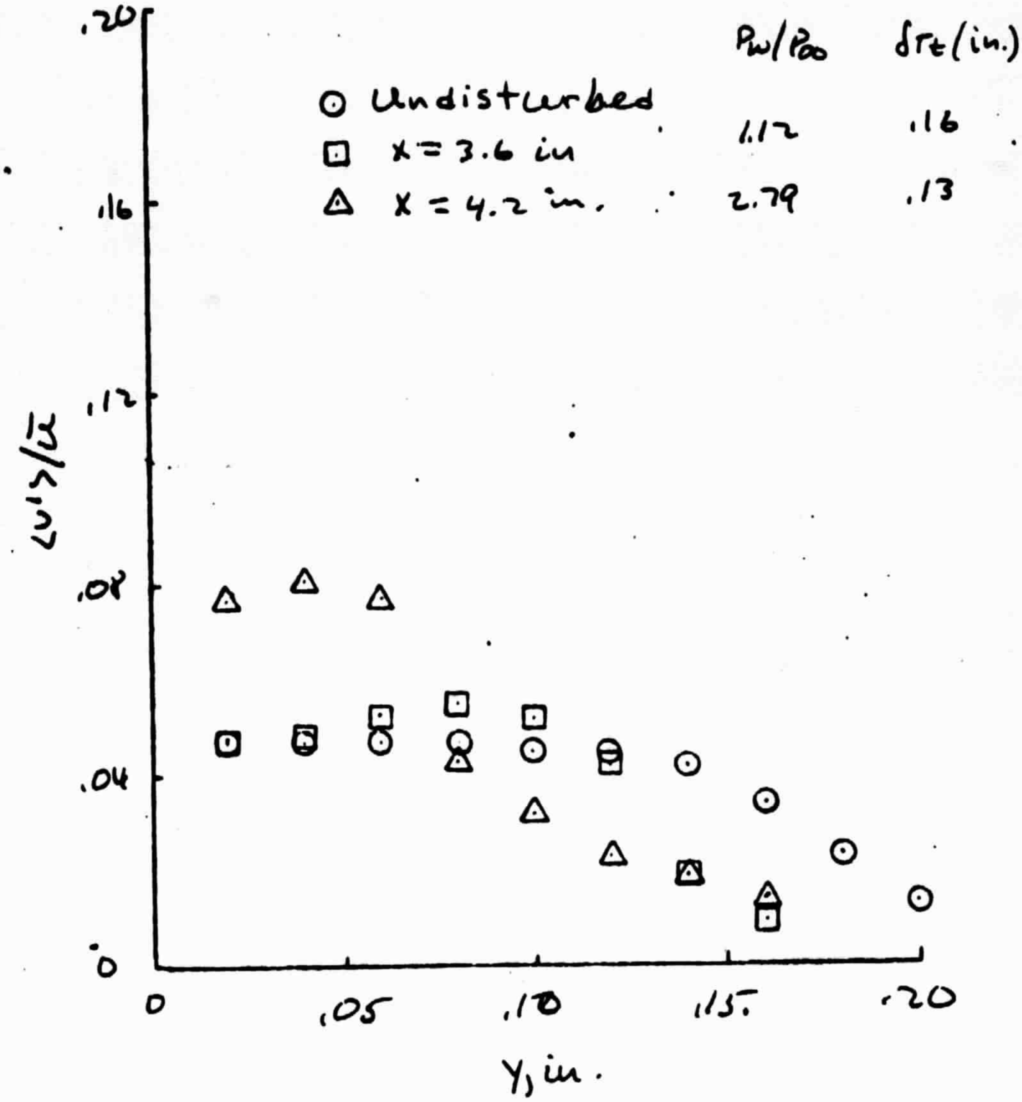


Figure 8b. Radial Velocity Fluctuations, Gradient 2

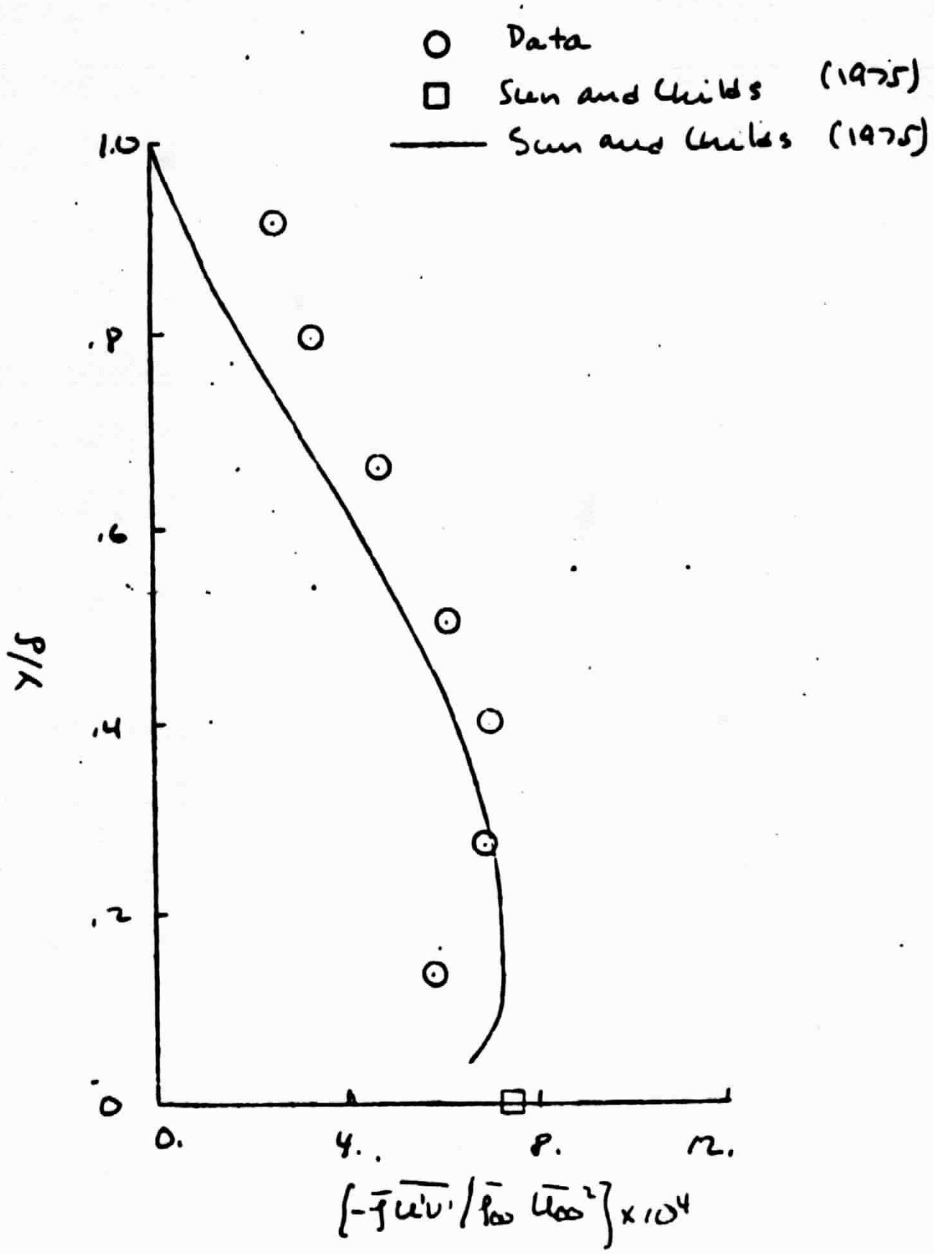


Figure 9. Normalized Turbulent Shear Stress, Undisturbed Flow

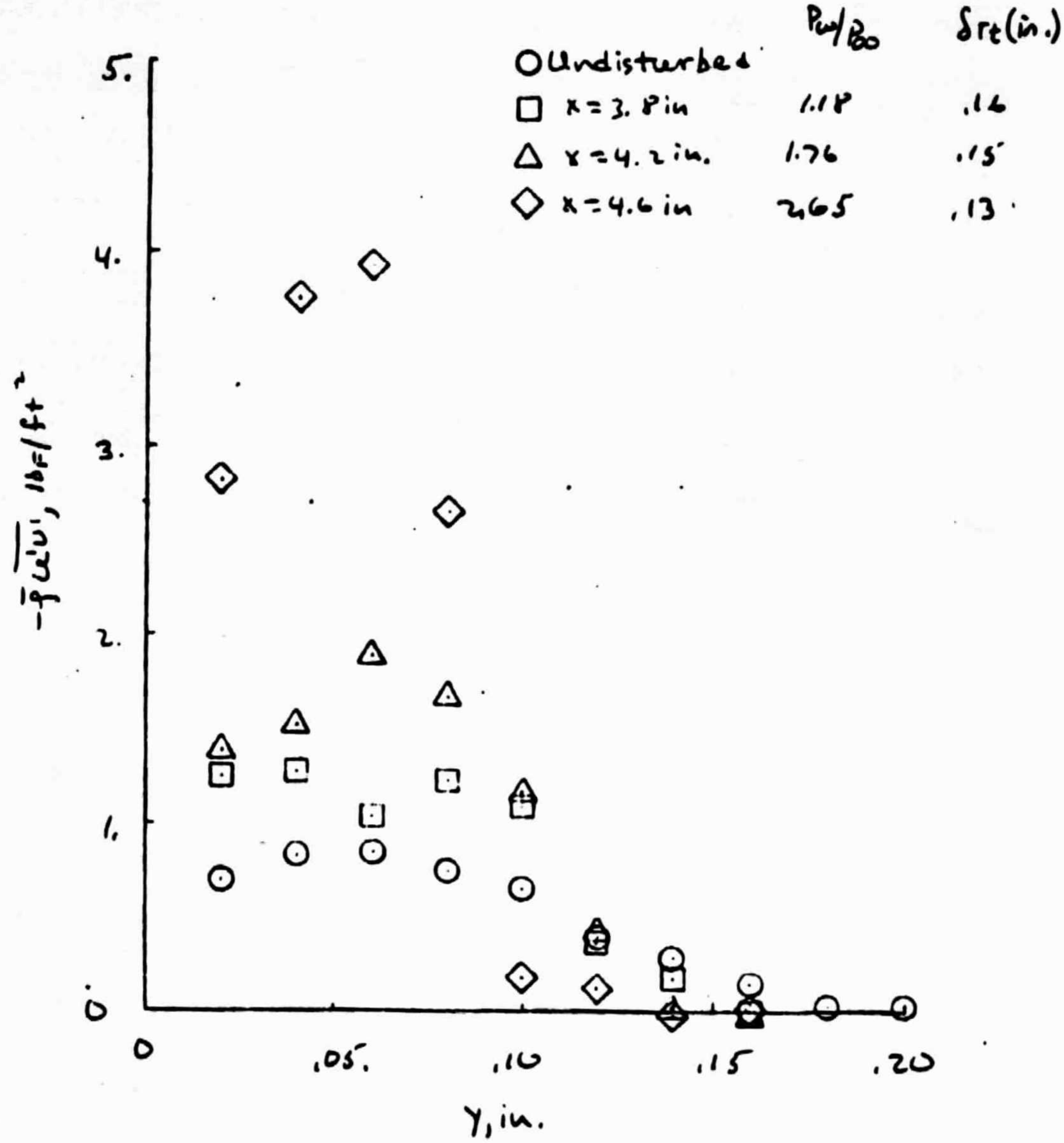


Figure 10a Turbulent Shear Stress, Gradient 1

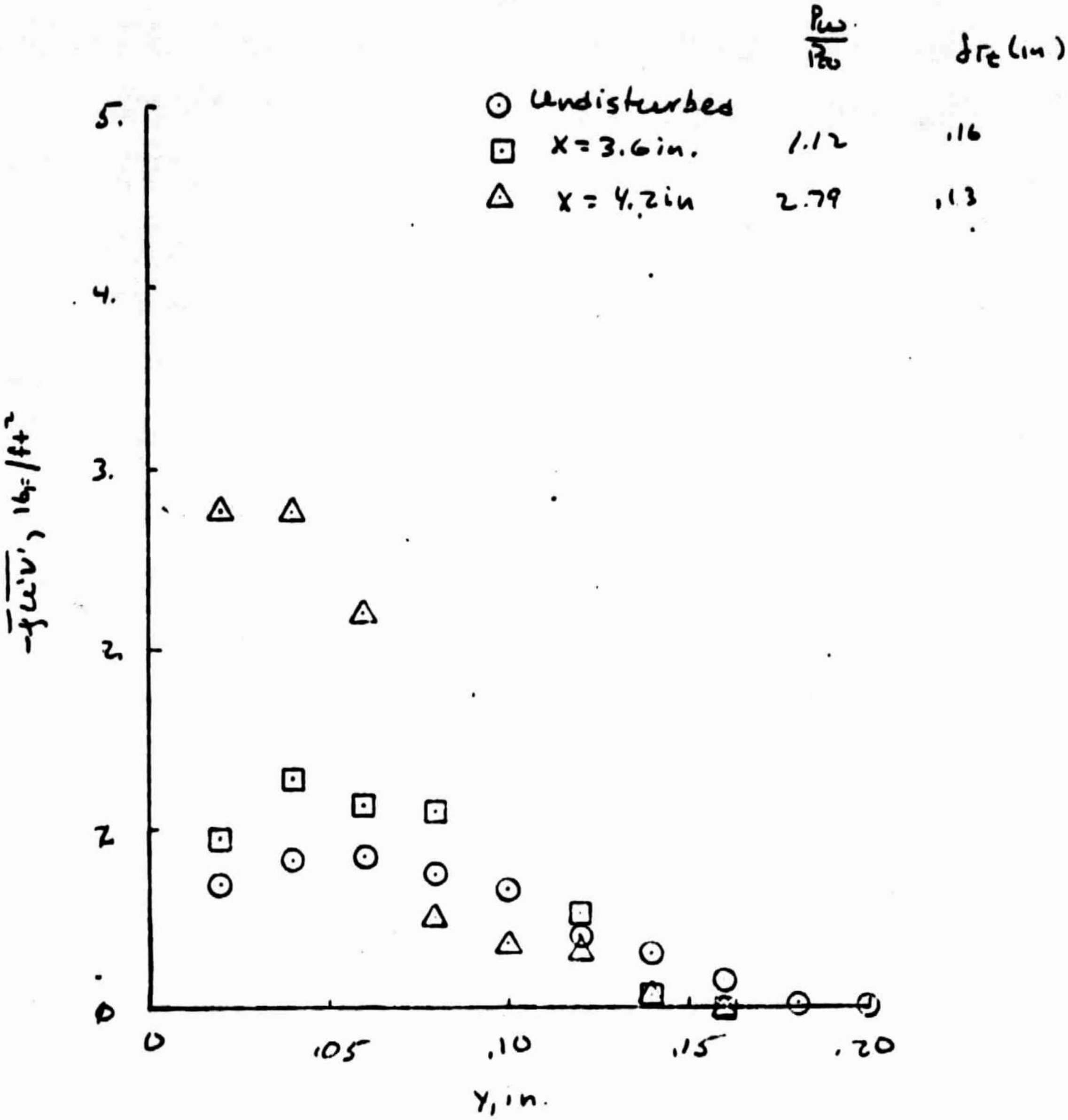
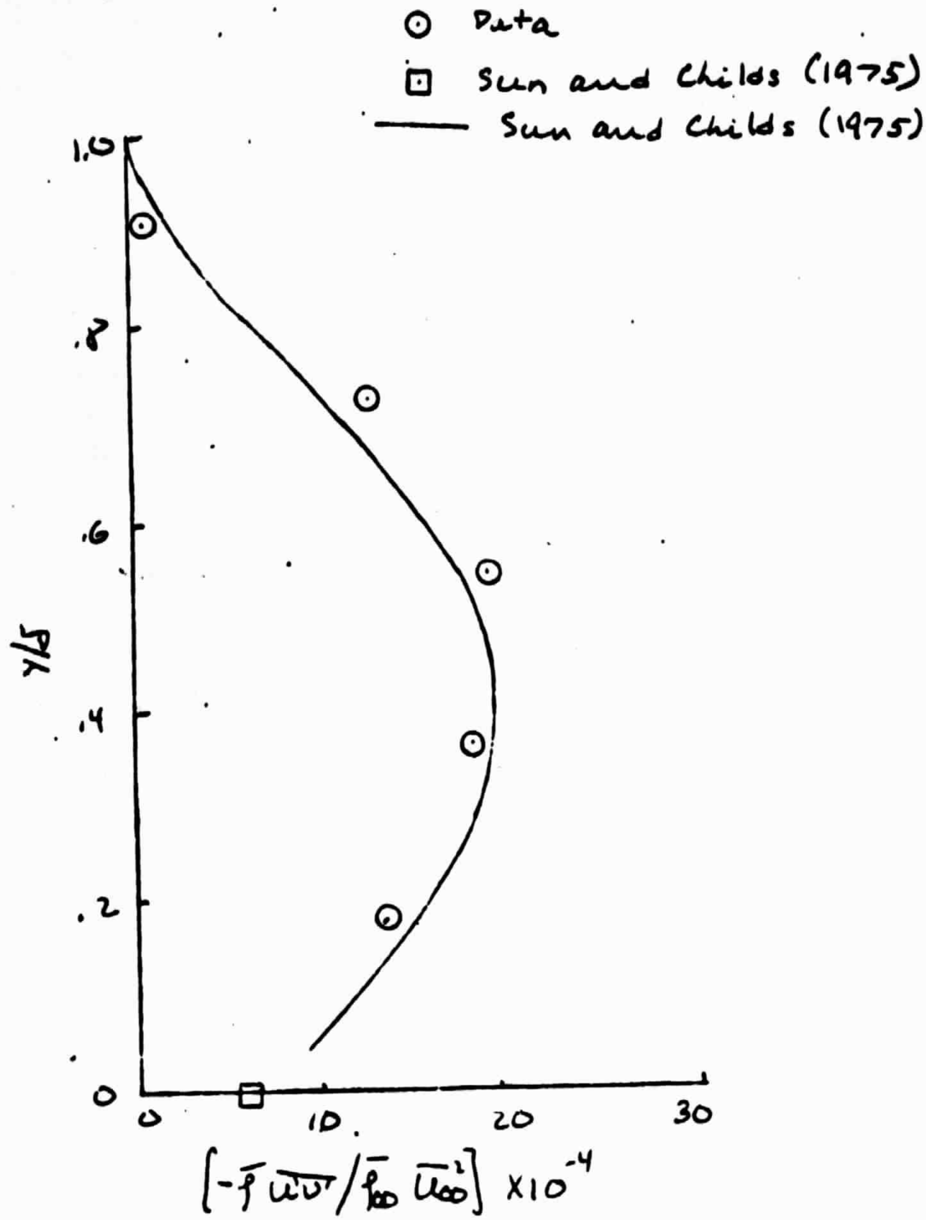
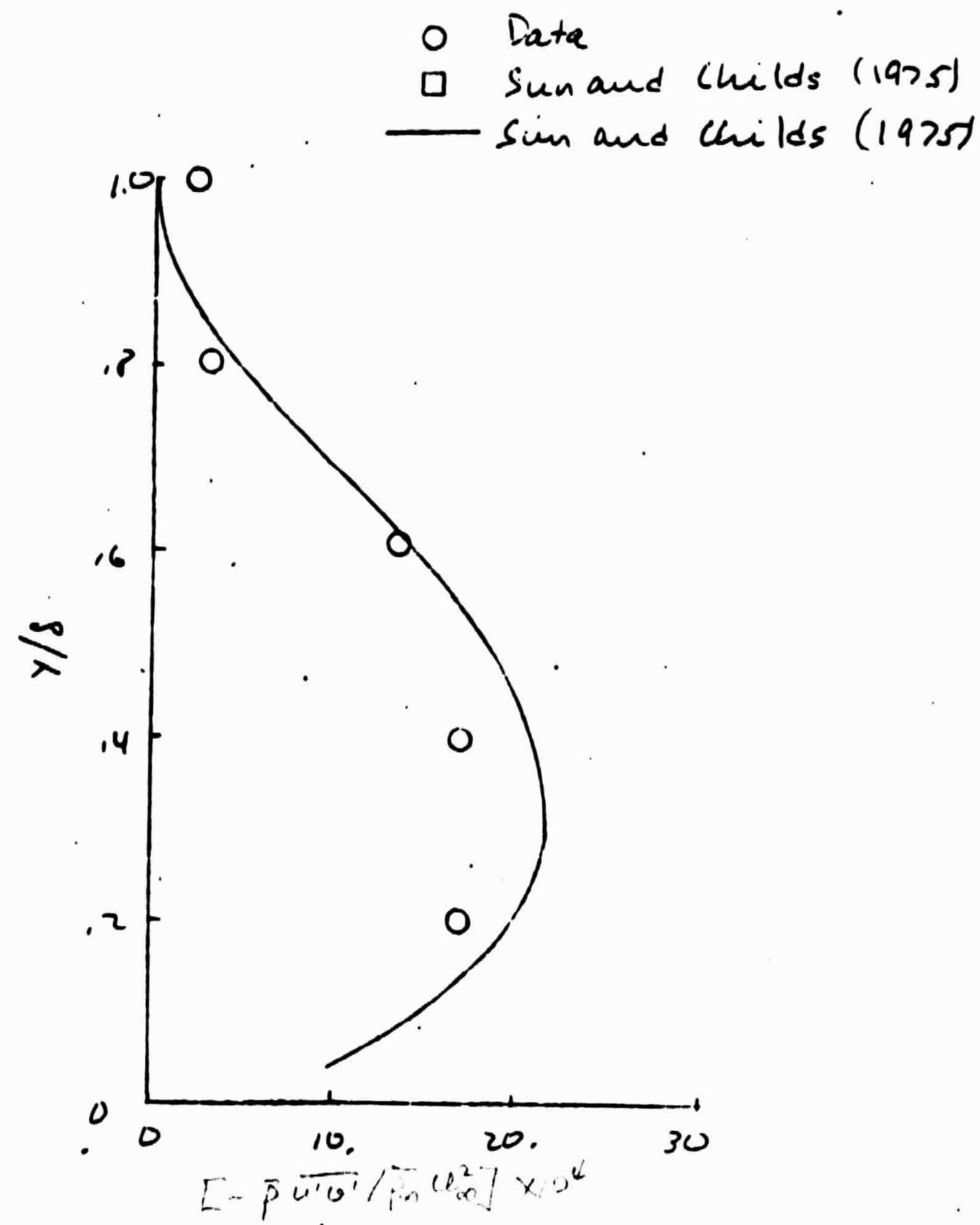


Figure 10b. Turbulent Shear Stress, Gradient 2



(c) X=4.6 in

Figure 11a Concluded



(b) x = 4.2 in

Figure 11b Concluded