ABSTRACT

MEAN AND FLUCTUATING FLOW MEASUREMENTS IN AXISYMMETRIC SUPERSONIC BOUNDARY LAYER FLOW SUBJECTED TO DISTRIBUTED ADVERSE PRESSURE GRADIENTS

by

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Measurements have been made of the mean flow properties and turbulent fluctuations in adiabatic turbulent boundary layer flows subjected to distributed 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. In order to avoid the effects of streamwise surface curvature the adverse 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.

Mean flow measurements made with a pitot probe and a normal hot-wire probe used as a resistance thermometer will be described and compared with

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existing supersonic boundary layer data. Normal hot-wire turbulence results taken at several locations in each of two adverse pressure gradients will be reported and compared with existing data. The turbulence results include total temperature, mass-flow and longitudinal velocity fluctuations and the longitudinal Reynolds stress ($\bar{\rho}\ \overline{u'^2} + 2\bar{u}\ \overline{\rho' u'}$). A constant temperature anemometer system was used during these experiments.

There have been numerous investigations of the mean flow properties of undisturbed supersonic boundary layers and supersonic boundary layers in adverse pressure gradients. Only recently, however, have investigators concentrated on obtaining turbulence measurements in high speed flow[1-5]. Although there have been some studies detailing the turbulence properties of undisturbed boundary layers, very few measurements have been made in flows subjected to adverse pressure gradients. Furthermore, very few investigations have been conducted for axisymmetric flows. To the authors' knowledge no other turbulence data have been reported for axisymmetric distributed adverse pressure gradient boundary layer flows of the type examined in this study. Some of the difficulties and probable errors associated with performing turbulence measurements in high speed flows will be discussed in the paper, as will the data handling procedure and the effect of various mean flow and fluctuating flow quantities on the computed turbulence properties.

In the remainder of this abstract, results typical of those obtained in the investigation will be described. Figure (1) shows the wall static pressure distributions for the two adverse pressure gradients considered in this study, along with a pressure distribution for a shock wave-boundary layer interaction at the wall of a similar test section[1]. The interaction was produced by a 9° half-angle cone placed on the axis of the test section and was strong enough to essentially separate the boundary layer. The gradients for the present study are seen to be quite strong. Indeed, pressure gradient 1 is seen to cause a somewhat steeper overall rise than was observed for the shock-boundary layer interaction. However, the distributed adverse pressure gradients show gradual initial rises, and only near the end of the rises do the gradients approach or exceed the steepest gradient for the shock interaction. Figures (2a) and (2b) show pitot profiles obtained in the two pressure gradient regions. In Figures (3a) and (3b) the pitot pressures and total temperatures for one station in the undisturbed flow and one in the gradient 1 flow (at a location where $P_W/P_\infty = 1.95$) are shown. The boundary layer edge based on the total temperature profile is indicated on the figures. For the upstream station the total temperature boundary layer thickness is seen to agree closely with the boundary layer thickness based on the pitot pressure profile.

One of the difficulties associated with analyzing mean flow or turbulence data in adverse pressure gradients is the determination of the normal static pressure distribution in the boundary layer. The effect of normal pressure gradients on the turbulence measurements has been examined. In Figure (4) the longitudinal Reynolds shear stress is shown for an axial station in adverse pressure gradient 1 where $P_W/P_\infty = 1.95$. The figure shows the turbulence data computed for two normal distributions of the static pressure. In one instance the pressure has been taken as constant across the boundary layer and equal to the wall value. In the other the static pressure as calculated by the method of characteristics (NASA TN-6083) has been used. The difference between the two distributions is seen to be quite small and apparently is associated with differences in mean flow properties which appear in the stress term. The basic normal hot-wire sensing variables, $\overline{T_T'^2}$, $\overline{(\ u)'^2}$ and $\overline{T_T'\ (\rho u)'}$, were found to be virtually identical for the two cases.

Some of the turbulence data for the undisturbed flow are shown in Figures (5a) and (5b). The total temperature fluctuations (see Fig. (5a)) are similar to those reported by Kistler[6] for a Mach 3.56 flow on a wind tunnel wall. The observed longitudinal velocity fluctuations are shown in Fig. (5b). In the inner half of the boundary layer the results from this study agree rather well with data reported by Rose and Johnson[2] for boundary layer flow along the wall of a two-dimensional wind tunnel. In the outer half of the layer the fluctuation level is somewhat higher than has been reported in previous studies. The fluctuations increase at a fairly constant rate as the wall is approached. This trend confirms recent results of other investigators (see Reference 7 for a review of turbulence measurements in compressible flow) which indicate that the velocity fluctuations do not begin to decrease as far from the surface as has been reported previously[1,6].

In Figures (6a) and (6b) the longitudinal velocity fluctuation and the longitudinal Reynolds stress in the undisturbed flow are compared with those observed for pressure gradient 1 at a station where $P_W/P_\infty = 1.95$. Also shown in Figure (6b) are the longitudinal shear stress distributions for an undisturbed flow and for a station where $P_W/P_\infty = 2.05$ in a shock induced adverse pressure gradient region as reported in Reference 1. The results from Reference 1 were obtained in a straight walled test section almost identical to the one used in the present study but the anemometer systems used in the two investigations were different. The freestream Mach Numbers and Unit Reynolds Numbers in the two studies were almost the same. As is shown the distributions for both the velocity fluctuations and the Reynolds stress terms are altered considerably by the pressure gradient, especially in the lower two thirds of the boundary layer. As Figure (6b) shows, the distributions of longitudinal shear stress in the present study and in that of Reference 1 are quite similar at cross sections with approximately equal value of P_w/P_∞.

The results obtained in this investigation provide new information on the behavior of an axisymmetric adiabatic turbulent boundary layer in a supersonic adverse pressure gradient flow. Both mean flow properties and turbulent fluctuations have been measured. The turbulence measurements, which were obtained with a constant temperature anemometer system, are in qualitative agreement with results which have been reported for studies in two-dimensional configurations, and for one earlier known study of axisymmetric adverse pressure gradient flow.

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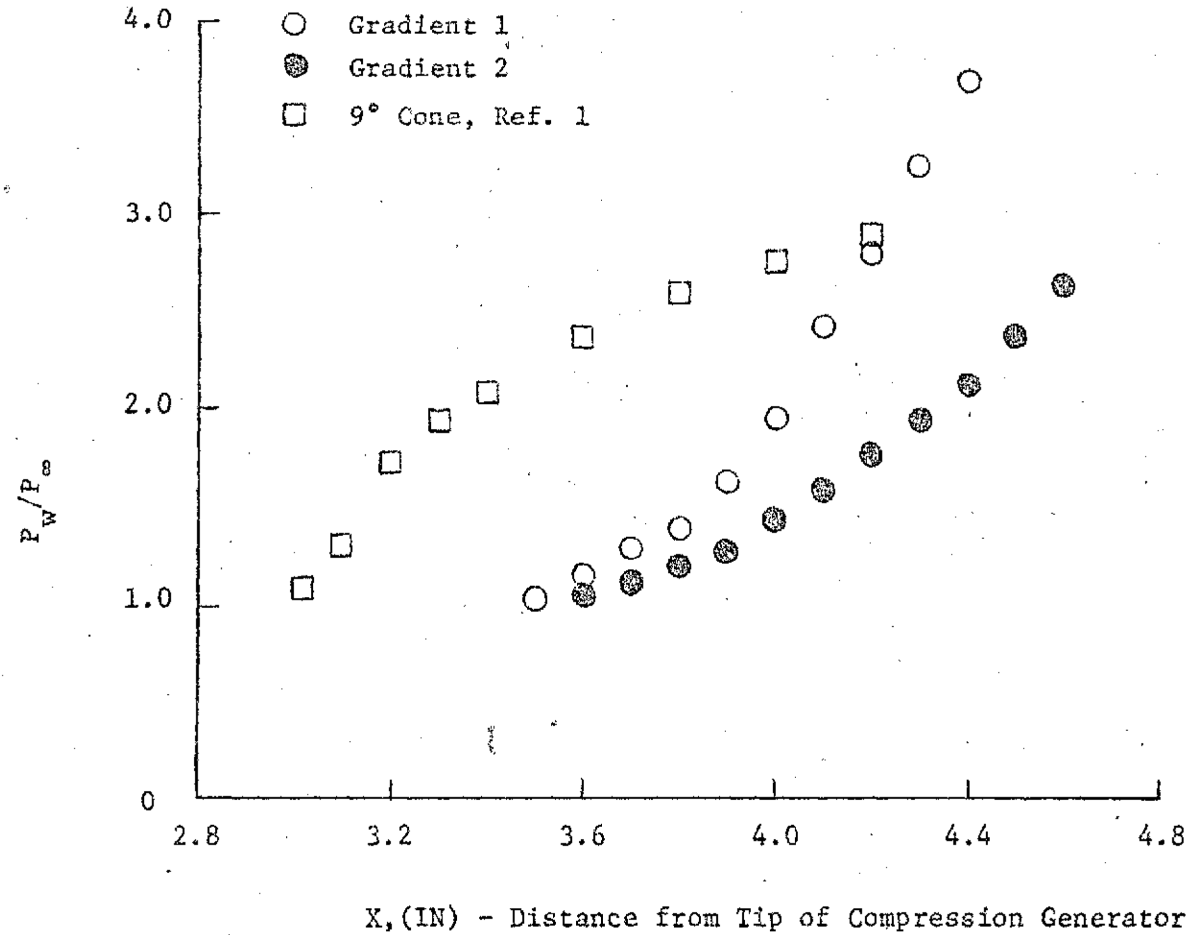

Figure (1): Surface Static Pressure Distributions

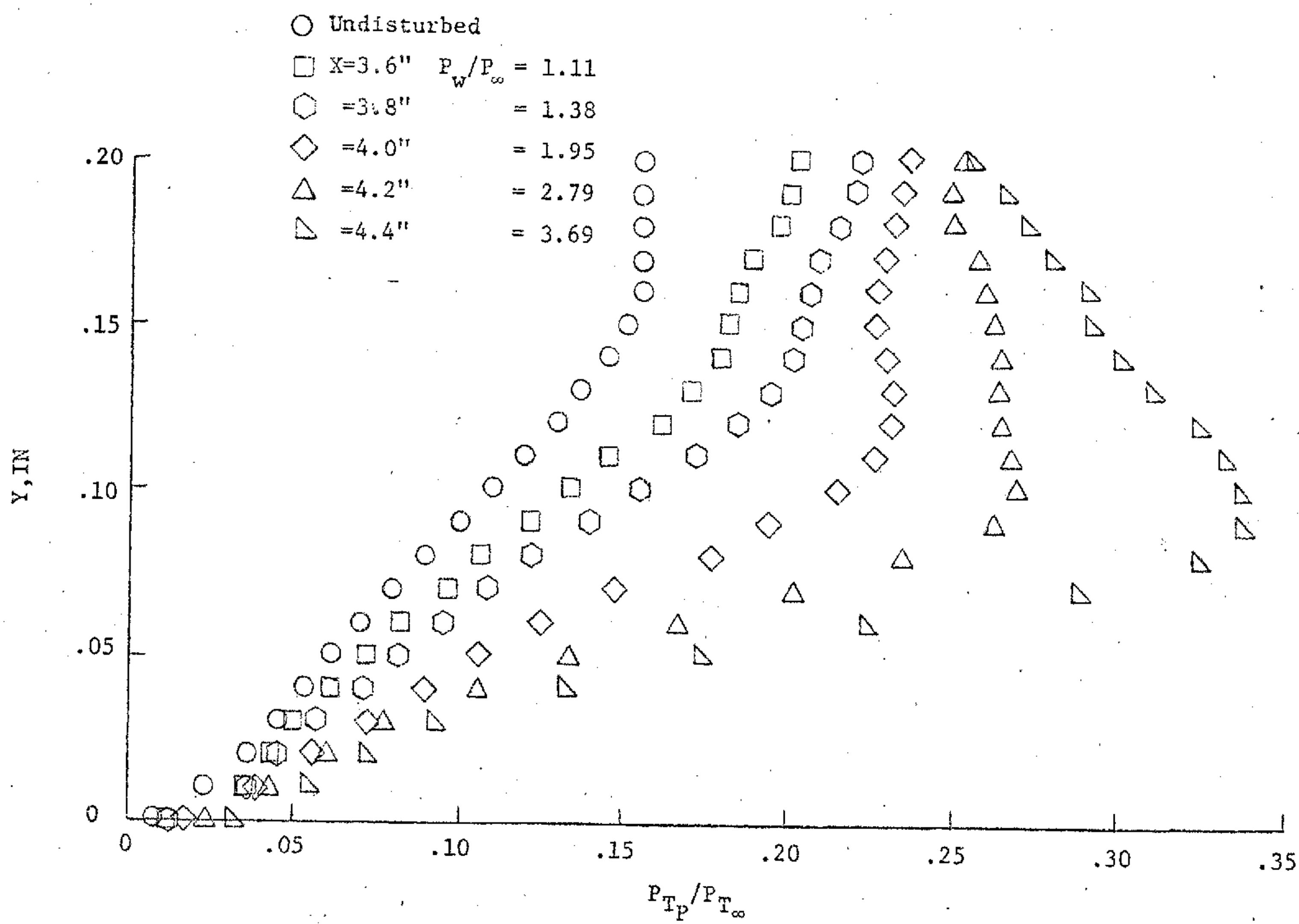

Figure (2a) Pitot Pressures
Gradient 1

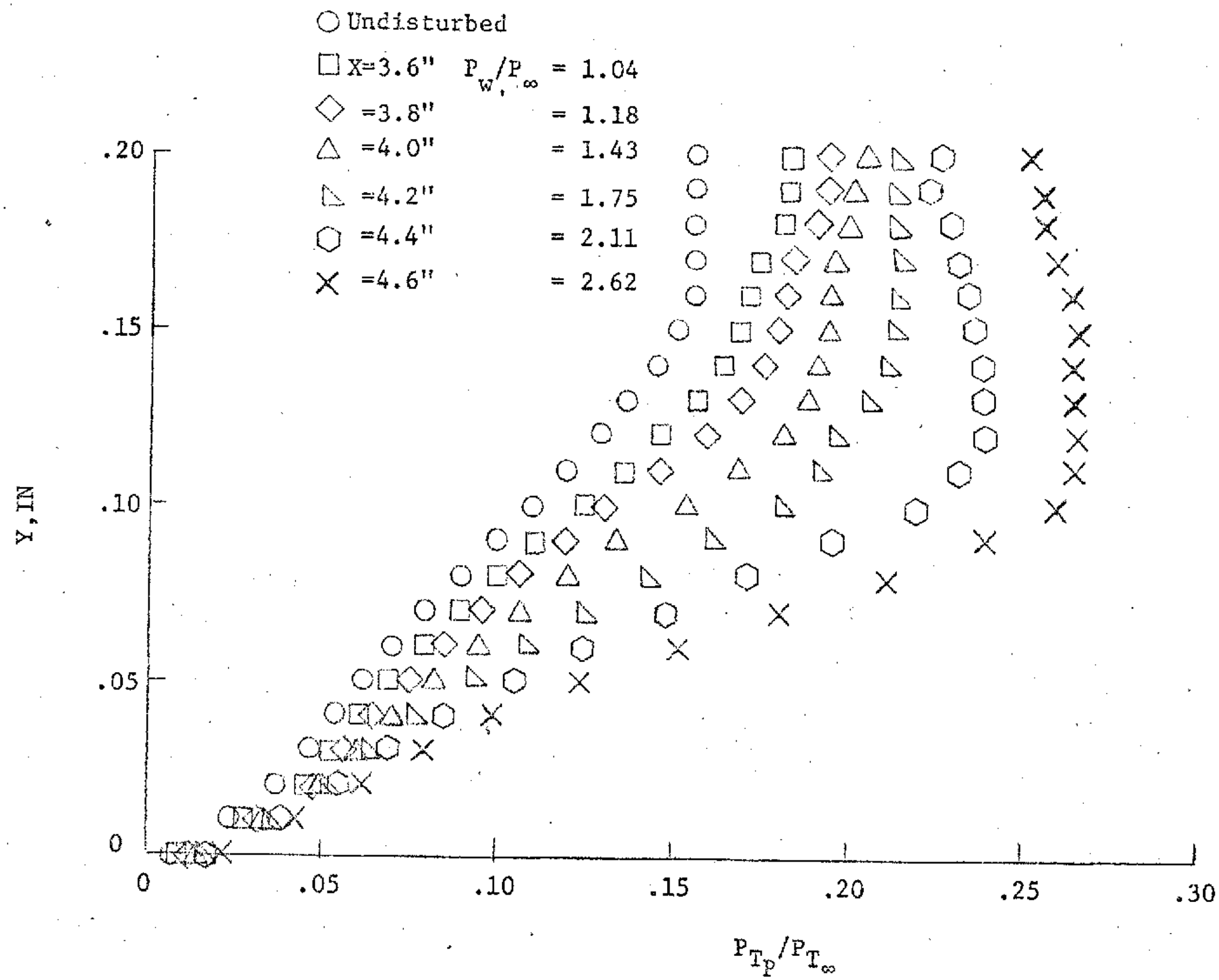

Figure (2b): Pitot Profiles
Gradient 2

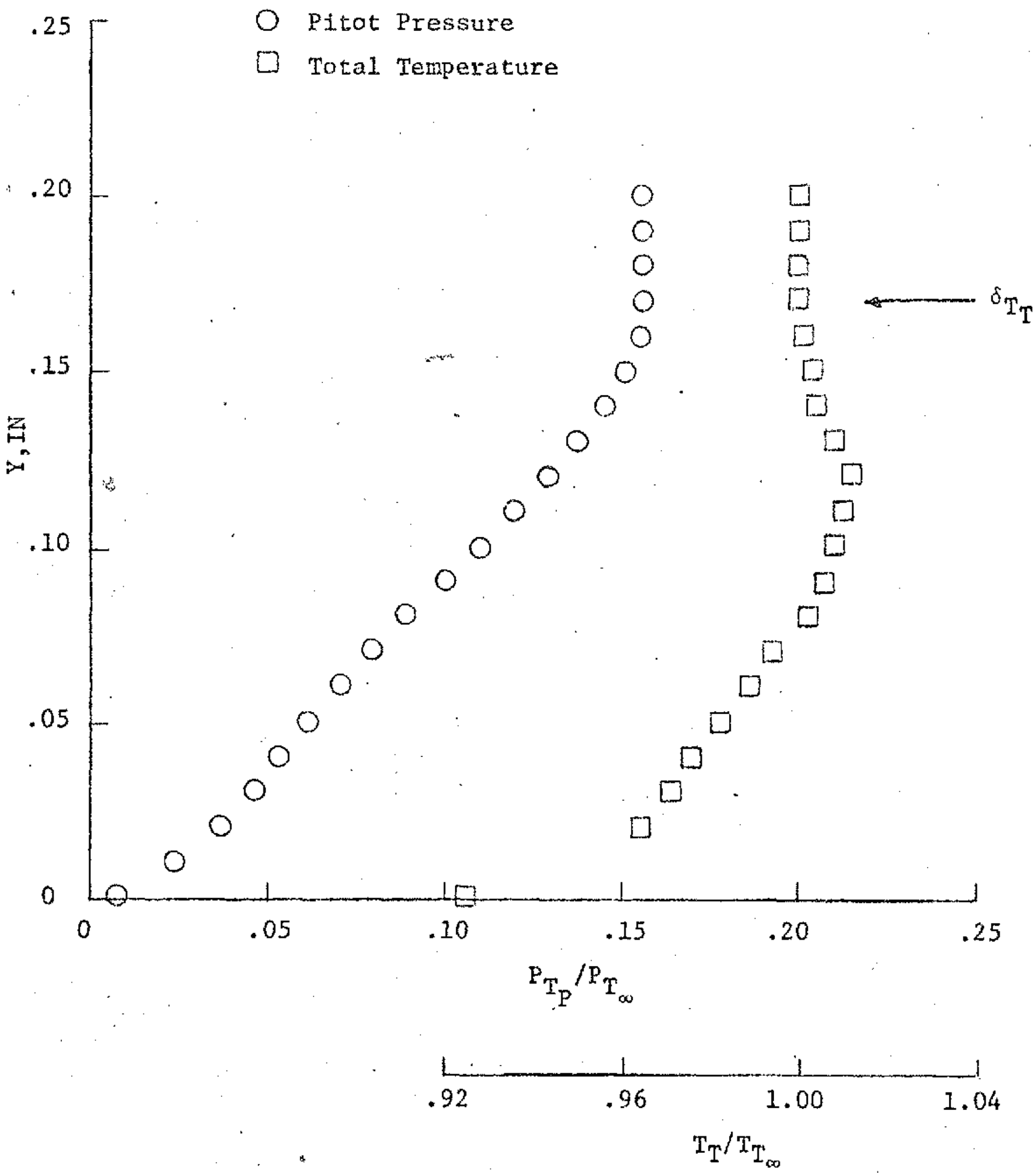

Figure (3a): Pitot Pressures and Total Temperatures
Undisturbed Flow

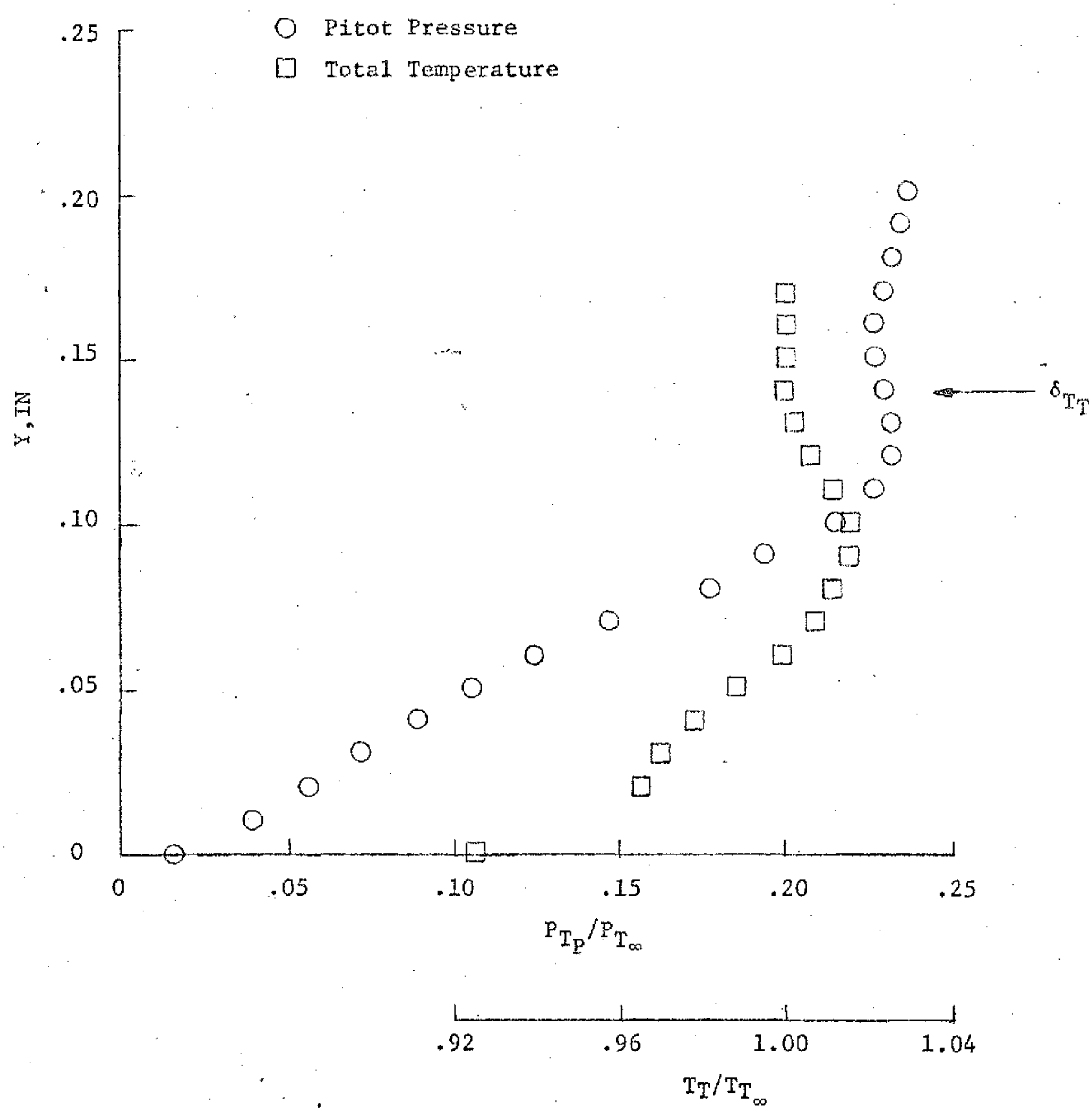

Figure (3b): Pitot Pressures and Total Temperatures
Gradient 1 $P_w/P_\infty = 1.95$
Distance from Tip of Compression Generator = 4.0 IN.

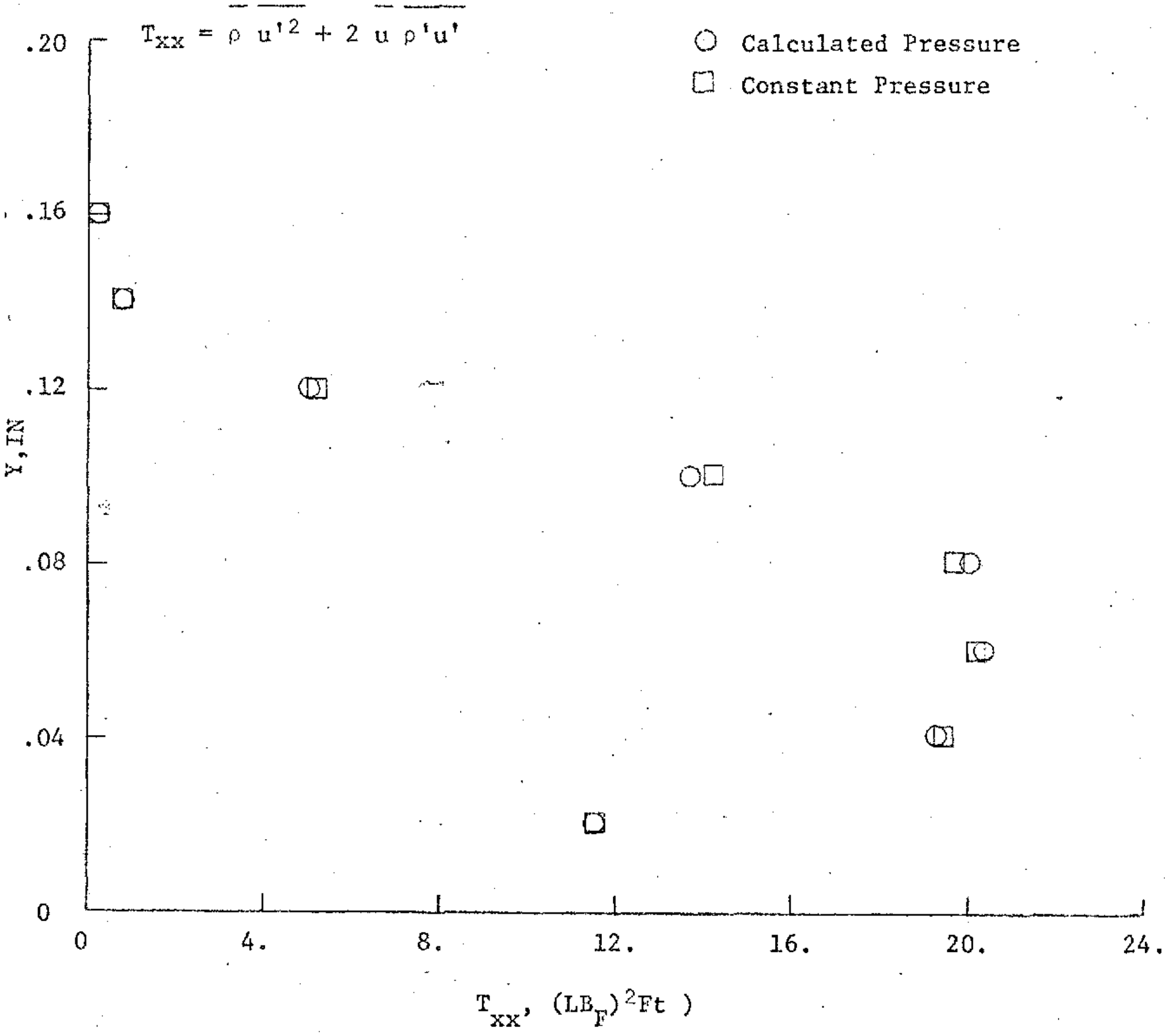

Figure 4: Influence of Boundary Layer Static Pressures on Longitudinal Reynolds Stress

Gradient 1

Distance from Tip of Compression Generator = 4.0 IN.

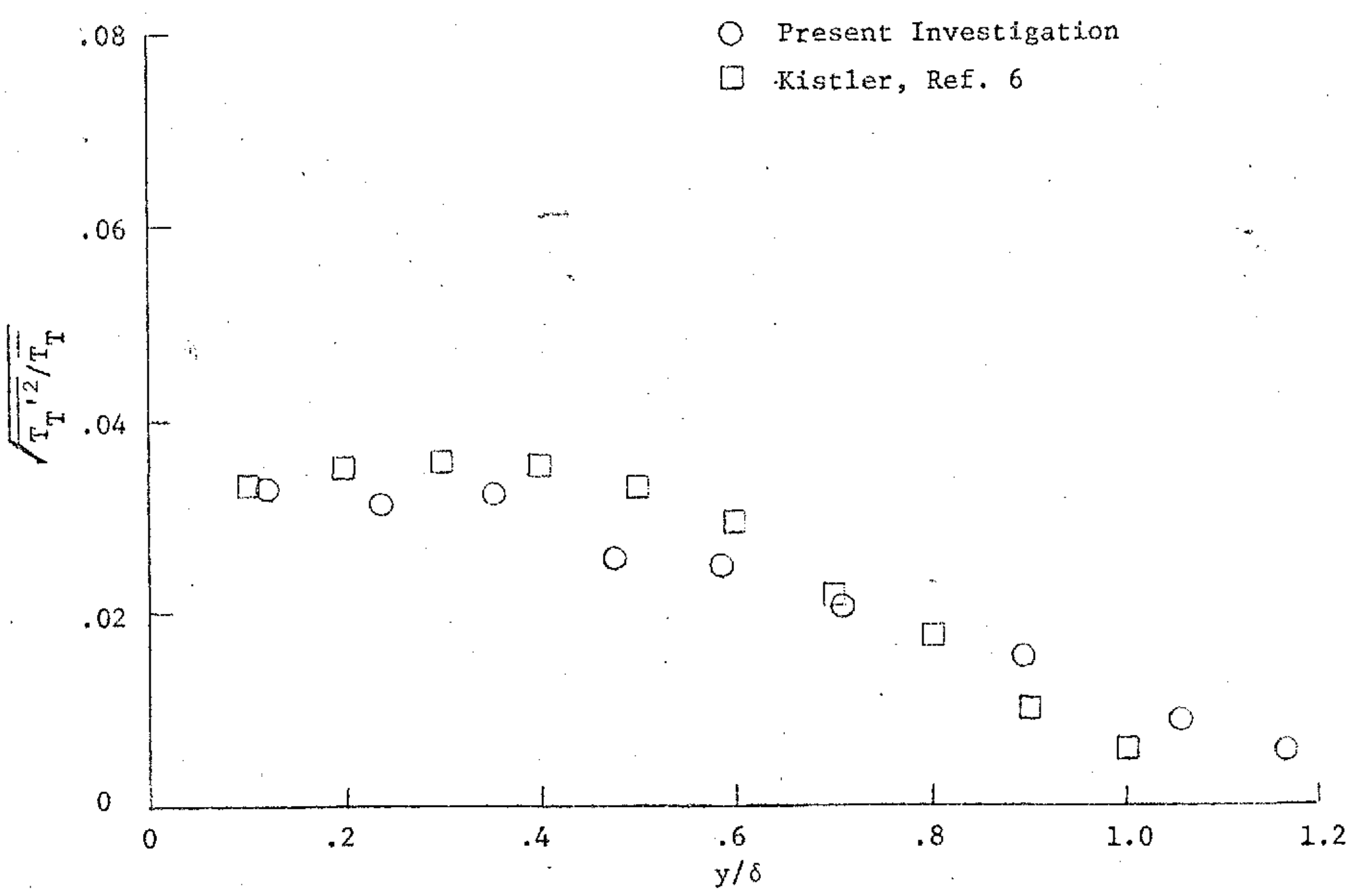

Figure (5a) Total Temperature Fluctuations
Undisturbed Flow

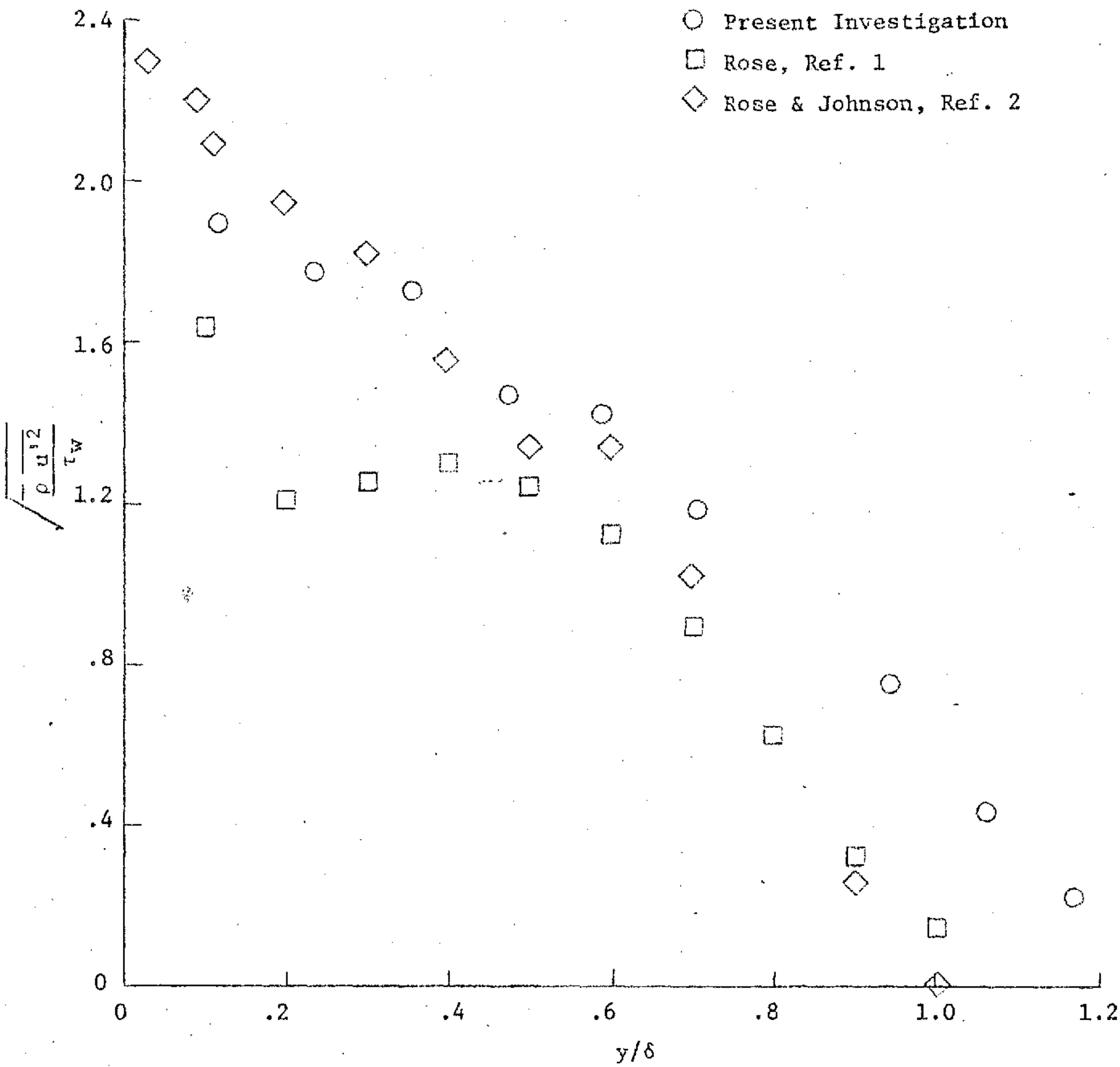

Figure (5b): Longitudinal Velocity Fluctuations
Undisturbed Flow

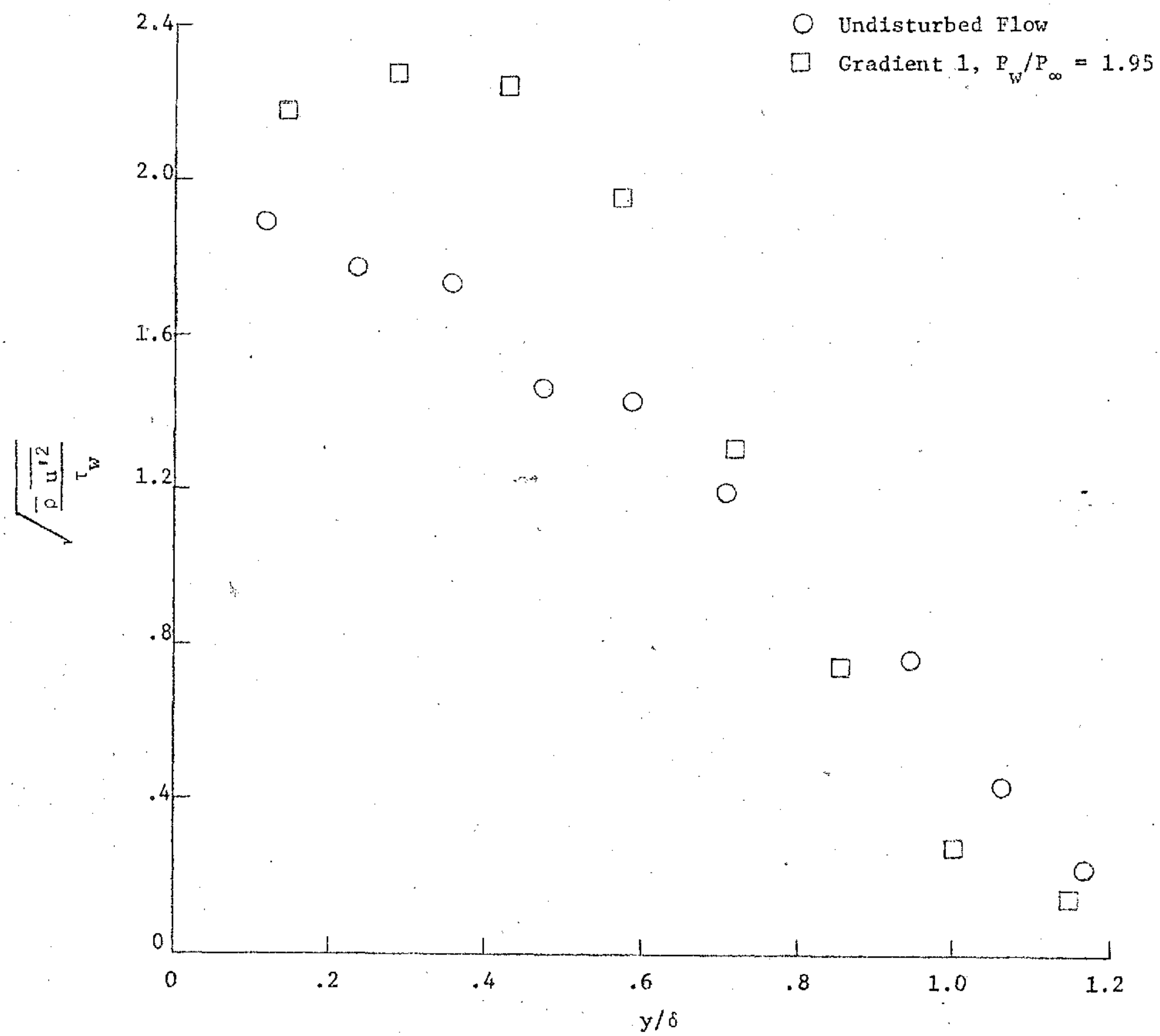

Figure (6a): Longitudinal Velocity Fluctuations

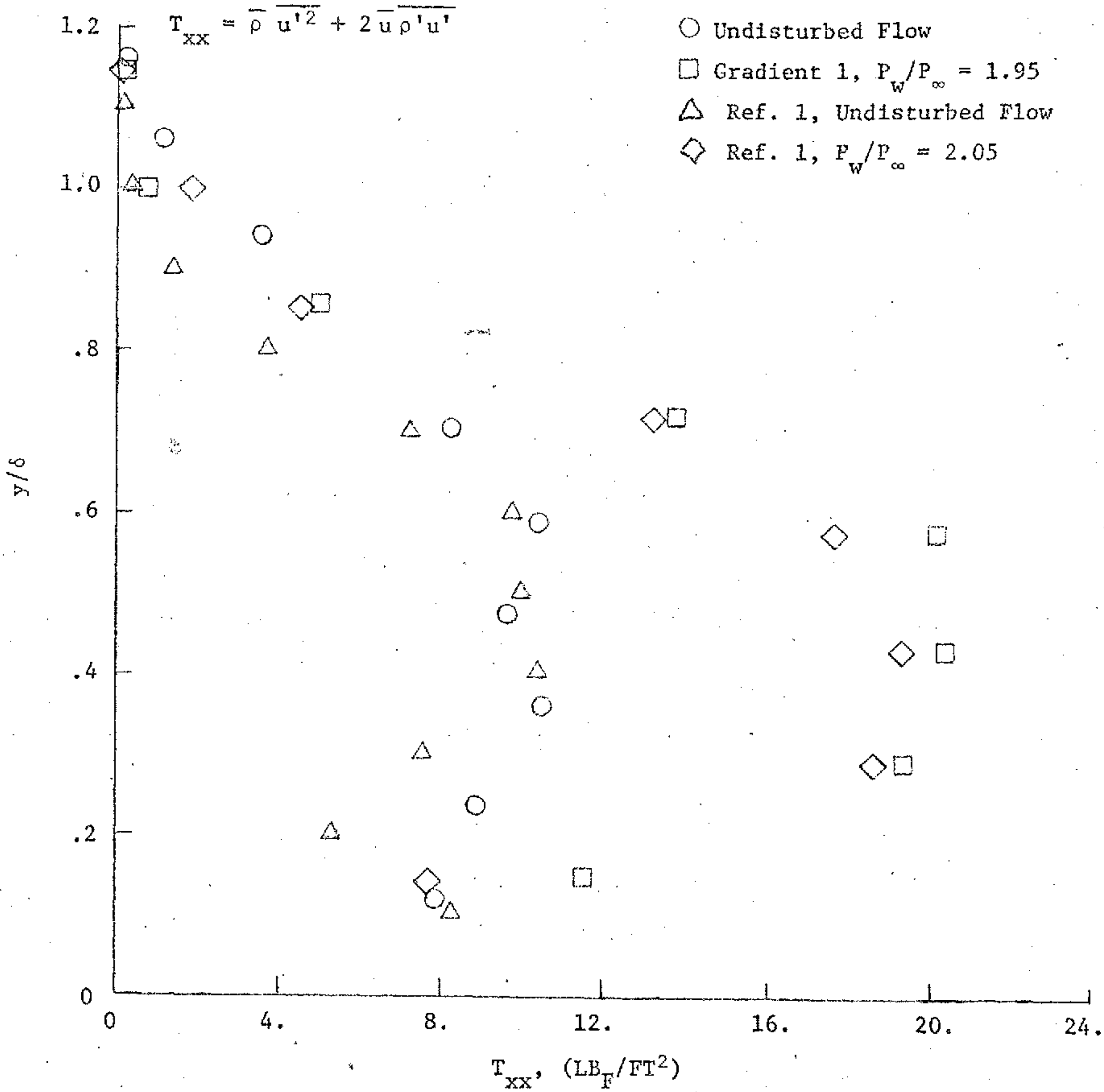

Figure (6b): Longitudinal Reynolds Stress