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BOUNDARY LAYER CHARACTERISTICS OF QUASI-TRANSPIRATION COOLED SURFACES

by

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SUMMARY

Injection of cool fluid into the boundary layer over the surface of a turbine blade permits operation at elevated turbine inlet temperatures thus leading to improved specific fuel consumption and specific thrust.

This paper describes an experiment wherein the detailed boundary layer characteristics were measured by crossed, hot-wire anemometers over four surfaces with discrete jet mass injection.

The integral parameters δ^*, θ and C_f are shown to be primarily functions of the rate of mass injection and rather insensitive to hole spacing/hole diameter ratio. The calculated values of C_f correlate well with a "Modified Law of the Wall". The mean velocity profiles are shown to be in good agreement with a discrete jet-boundary layer interaction theory.

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Introduction

A number of theories have been advanced to correlate data in boundary layers with blowing, e.g., a three-layer model for tangential slot injection (1) and an additive term to the "Wall-Wake" formulation for continuous transpiration (2). This experiment and theory attack the problem of injection of cooling fluid through a large number of small discrete jets.

It has been shown in previous studies, e.g. (3), that the heat transfer effectiveness of a surface with discrete mass injection depends on both the rate of mass injection and the hole spacing/diameter ratio. The effectiveness increases with decreasing hole spacing/diameter ratio and for a given hole spacing/diameter ratio, passes through a maximum as the rate of injection is increased (Figure 1).

The problem in general is that of maximizing the heat transfer effectiveness and minimizing the aerodynamic losses. The purpose of this experiment was to isolate the discrete jet-boundary layer interaction such that the fluid dynamical phenomena could be studied, viz., the effects on the boundary layer characteristics induced by varying the hole spacing/diameter ratio and rate of mass injection.

Experiment

The experimental study was conducted in the Detroit Diesel Allison Subsonic Tunnel which has a 0.3 m X 0.3 m X 1.5 m long test section, flexible upper and lower sidewalls, upper Mach No. of 0.8 and a remotely controlled, three-axis probe traversing system.

The experimental model was a flat aluminum plate 0.3 m span, 2 cm thick, 1.5 m long with an anodized surface finish of approximately 0.1 micron. The leading edge was undercut to 20 degrees and the leading 2.5 cm of the upper plate surface was covered with a No. 3½ grit sandpaper boundary layer trip. The model was constructed such that flat plate sections containing various blowing geometries could be inserted with the jets located 0.44 m downstream of the leading edge.

Four injection geometries at four blowing ratios were studied. The injection geometries were:

LSR (Large single row of holes)

0.254 cm dia. on 1.27 cm centers, 21 holes, located 0.44 m downstream of the leading edge

SSR (Small single row of holes)

0.180 cm dia. on 0.66 cm centers, 42 holes, located 0.44 m downstream of the leading edge

LMR (Large multiple rows of holes)

0.112 cm dia. on 1.27 cm centers, 5 staggered rows, 105 holes, first row located 0.44 m, last row located 0.49 m downstream of leading edge

SMR (Small multiple rows of holes)

0.079 cm dia. on 0.66 cm centers, 5 staggered rows, 210 holes, first and last rows located as LMR

All holes were drilled at 30 degrees to the surface.

The imposed rates of mass injection or blowing ratio (VR) were 0.0, 0.5, 1.0, 1.5, 2.0;

where, $VR = \dfrac{\text{Area averaged jet velocity}}{\text{Free-stream velocity}}$.

All four injection geometries have the same total jet cross-sectional area. Thus, for a given blowing ratio, the same mass flux at the same area averaged velocity was introduced into the boundary layer. Any differences noted in the boundary layer characteristics at a given blowing ratio are thus only a function of the hole spacing/diameter ratio.

The test conditions were maintained at a free-stream velocity of 45.7 m/sec, free-stream total temperature of 300°K, test section static pressure of 10^5 n/m^2 and zero free-stream pressure gradient. The injected air passes through a regulator, orifices calibrated against a standard rotameter, a series of filters and an electrical heater which increases the temperature to the free-stream temperature.

The experimental measurements were made with a DISA miniature crossed, hot wire probe and consist of profiles of U, V, $\overline{u^2}$, $\overline{v^2}$ and $\overline{uv}$ normal to the plate surface at six stations downstream of the injection region. The stations were at 5 cm increments, beginning at 7 cm from the single row or last multiple row centerline.

The probe position was externally controlled by a 3-axis manipulator to the nearest 25 microns. The hot wire probe was calibrated for each experiment against a pitot-static probe indicating on a micromanometer and a total temperature probe. The total temperature was monitored continuously so that the hot wire measurements could be corrected for ambient temperature drift. The wire angles with respect to the free-stream direction and the position of the center of the volume of resolution of the hot wire probe with respect to the plate surface were measured with a telescope with cross hairs on a vernier with a least count of 25 microns and an inclinometer with an angular least count of one minute.

The crossed hot wire signals were linearized, summed, differenced and correlated by DISA analog modules. The parameters U, V, $\overline{u^2}$, $\overline{v^2}$, $\overline{uv}$ and T were logged on punched paper tape and subsequently processed on a Hewlett-Packard computer. The data was converted from measured voltages to physical dimensions, corrected for ambient temperature drift and tangential cooling of the hot wires (4, 5), smoothed in the x and y directions by a bi-directional smoothing routine and the integral properties of the injected boundary layer were calculated.

Discussion

The most striking features of the boundary layer profile data are the variations of $\overline{u^2}$, $\overline{v^2}$ and $\overline{uv}$ at blowing ratios greater than unity, c.f. Figure 2.

1) Maxima occur in $\overline{v^2}$ and $\overline{uv}$ at the same point in the boundary layer,

2) $\overline{uv}$ changes sign implying a positive correlation between the u and v fluctuations, and

3) $\overline{uv}$ does not go to zero at the point where $\partial U/\partial y$ equals zero as required by the conventional "eddy viscosity" formulation.

In general, skin friction measurements are made indirectly, e.g., by Preston tubes whose calibration is based on the "Universal Law of the Wall". The "Universal Law of the Wall" is premised on the existence of an "equilibrium" boundary layer wherein the production and dissipation of turbulent kinetic energy are nearly equal and predominant over the advection and diffusion and further, that the shear stress is constant in the "wall" region. As evidenced by the data of this experiment, there are large shear stress gradients in the "wall" region. Thus, the "Universal Law of the Wall" would not be expected to hold in these cases and indirect measurement of the wall shear stress would yield doubtful results (6).

A "Modified Law of the Wall" has been developed by Townsend (7) and extended by McDonald (8) wherein the effects of a constant shear stress gradient in the "wall" region are considered.

"Universal Law of the Wall" where: $U^+ = \dfrac{U}{U_\tau}$, $\tau_w = \rho U_\tau^2 = C_f\, \rho\, \dfrac{U_\infty^2}{2}$

$$U^+ = \frac{1}{\kappa} \ln y^+ + C; \qquad \begin{array}{l}\kappa = 0.41\\ C = 5.45\end{array} \qquad y^+ = \frac{yU_\tau}{\nu}, \quad \nu = \frac{\mu}{\rho}$$

"Modified Law of the Wall"

$$U^+ = \frac{A^{1/2}}{\kappa} \ln \left| \frac{4A}{\alpha} \left\{ \frac{(\alpha y^+ + A)^{1/2} - A^{1/2}}{(\alpha y^+ + A)^{1/2} + A^{1/2}} \right\} \right| + \frac{2}{\kappa} \left[(\alpha y^+ + A)^{1/2} - A^{1/2} \right] + B^+$$

$$A = \frac{\tau_o}{\tau_w}, \quad \alpha = \frac{\partial \tau}{\partial y} \left(\frac{\nu}{\rho U_\tau^3} \right), \quad B^+ \simeq \text{con.} = 5.0 \text{ (in this experiment)}, \quad \tau = \mu \frac{\partial U}{\partial y} - \rho \overline{uv}$$

The effects of variation in A on the function U^+ vs. y^+ are shown in Figure 3. The effect of varying α in the range 10^{-4} to 10^{-3}, the range of this experiment, produces an insignificant change in U^+ vs. y^+.

Optimizing the fit of the measured mean velocity data to the "Modified Law of the Wall", utilizing the experimental values of "wall region" shear stress gradient, $\partial\tau/\partial y$, and "extrapolated" wall shear stress, τ_o, (Figure 2) yields the "true" wall shear stress, τ_w. The corresponding skin friction coefficient, C_f, is an increasing function of blowing rate and not significantly affected by hole spacing/diameter ratio (Figure 4).

A nominally independent check on the values of C_f obtained by this method can be made from the integral momentum equation. Assuming that the injected mass flow imposes a favorable pressure gradient over the "wall" region, as evidenced by the shear stress gradient, good agreement is obtained (Figure 4).

A significant portion of the displacement thickness, δ^*, and the momentum thickness, θ, is contained in the integral between the wall and the first measured data point. In this analysis, it is assumed that $U^+ = y^+$ for $y^+ < 10$ and the "Modified Law of the Wall" holds from $y^+ \geq 10$ to the first data point closest to the wall. The measured data are used for the remainder of the integral. Both the displacement thickness and the momentum thickness, within the experimental accuracy, appear to be rather insensitive to hole spacing/diameter ratio and are strong decreasing functions of blowing ratio (Figures 5 and 6).

A theoretical model for the boundary layer development, based on the discrete jet-boundary layer interaction, was formulated concurrently with this experiment (9). This model is based on the cross-stream averaged continuity, momentum and energy equations which account for the momentum and energy which the jets impart to the surrounding fluid, the influence of the jets on the turbulent structure of the boundary layer and the entrainment by the jets. The correlation of this theory with the single row of jets data gave excellent agreement downstream of the jet mixing region (Figure 7).

Conclusions

The displacement thickness, momentum thickness and skin friction coefficient appear to be relatively insensitive to changes in hole spacing/diameter over the range investigated in this experiment (3.7, 5.0, 8.4, 11.3), but are strong functions of the rate of mass injection. The injected air appears to impose a favorable pressure gradient in a thin layer of about 0.2 the boundary layer thickness. Good agreement is obtained between predicted and experimental mean velocity profiles utilizing the recently developed discrete jet-boundary layer interaction theory.

Acknowledgments

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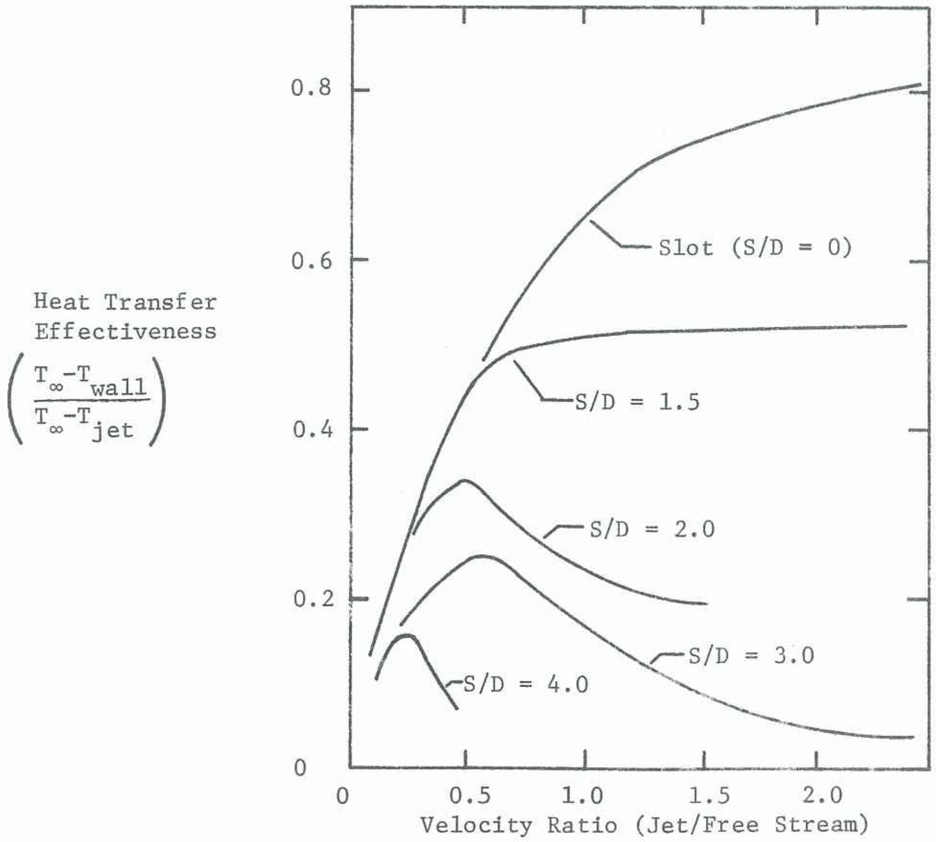

FIGURE 1. Effect of Rate of Mass Injection and Hole Spacing/Diameter Ratio (S/D) on Heat Transfer Effectiveness for a Single Row of Jets

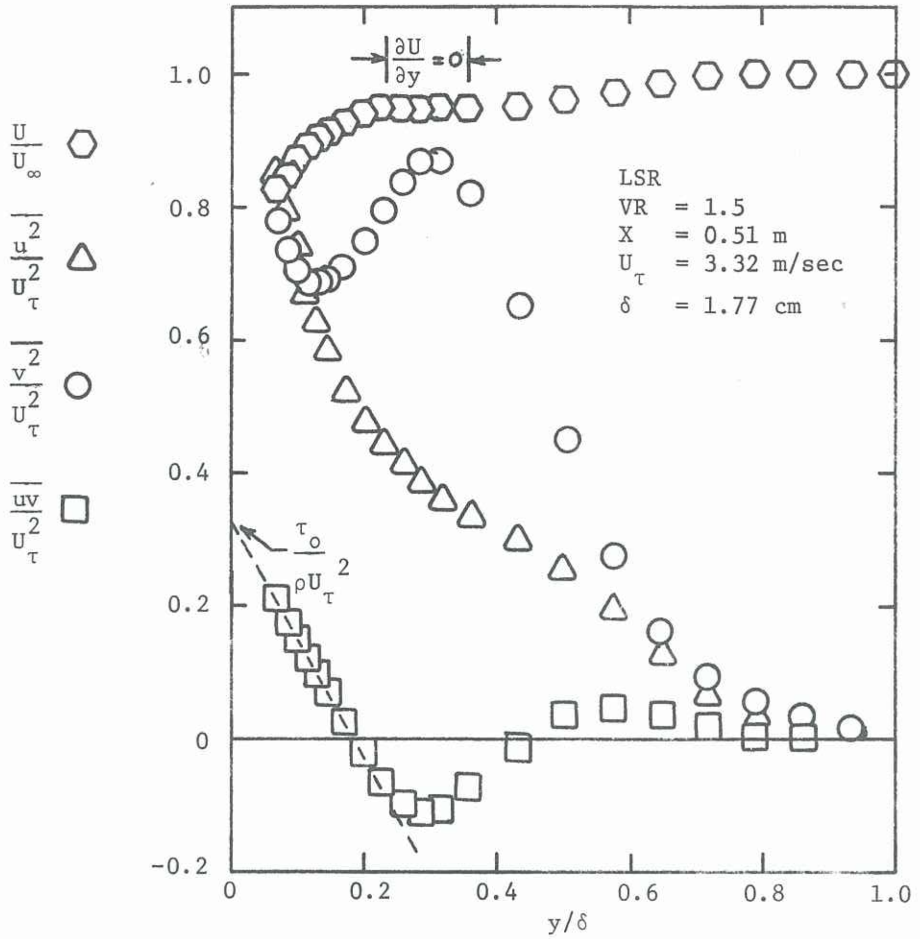

FIGURE 2. Typical Boundary Layer Profile with Shear Stress Gradient

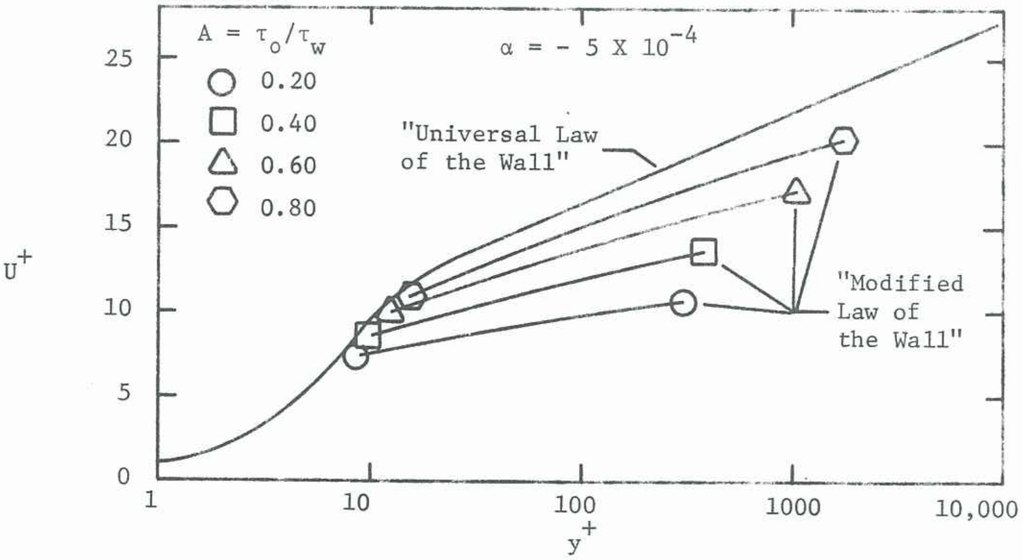

FIGURE 3. Comparison of the "Universal Law of the Wall" with the "Modified Law of the Wall" for Accelerating Flow

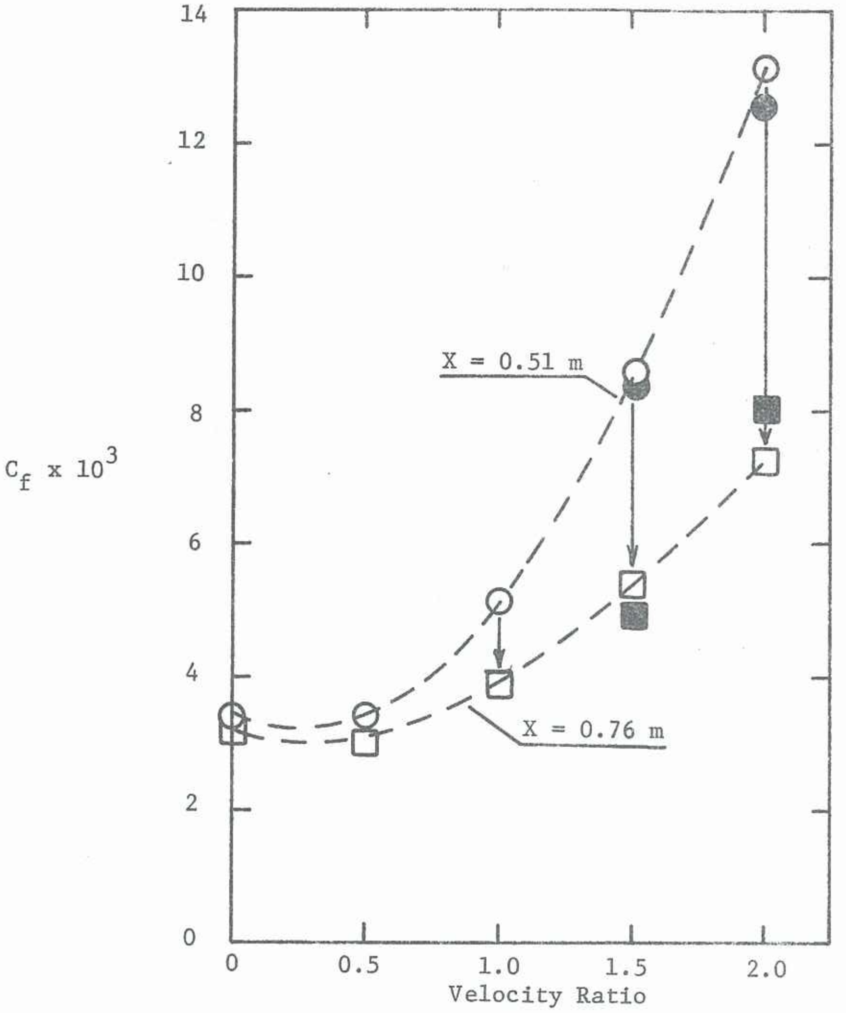

FIGURE 4. Dashed Lines are the Estimated Bounds of Skin Friction Coefficient Utilizing the "Modified Law of the Wall", Closed Symbols are a Comparison with the Integral Momentum Equation

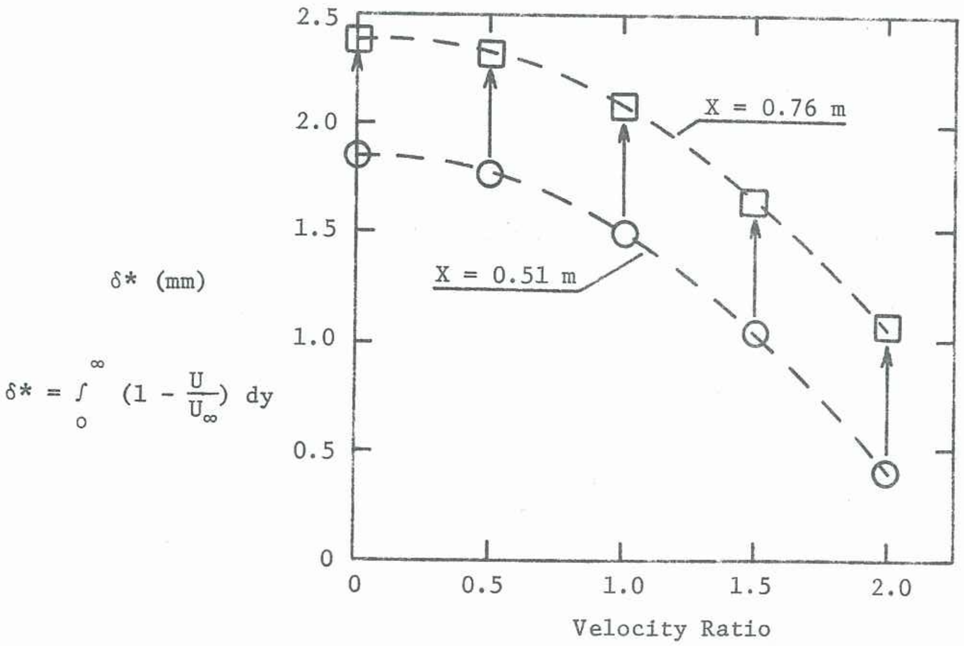

FIGURE 5. Dashed Lines are the Estimated Bounds on Displacement Thickness

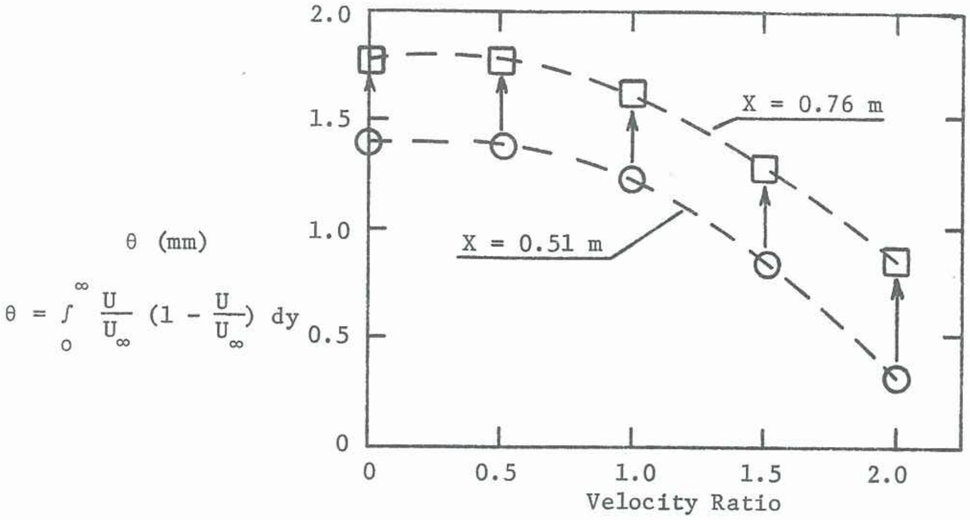

FIGURE 6. Dashed Lines are the Estimated Bounds on Momentum Thickness

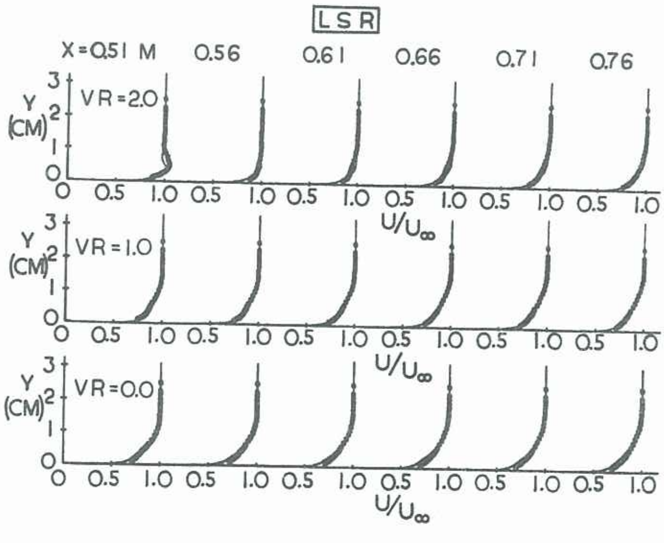

FIGURE 7. Comparison between Predicted Mean Velocity Profiles (Ref. 9) and Experimental Data