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ABSTRACT

Heat transfer experiments have been carried out on a turbulent boundary layer subjected to a strongly accelerated free-stream ($K = 2.5 \times 10^{-6}$), with initial turbulence intensity levels of 0.7 percent, and 3.9 percent. Stanton number, mean temperature and velocity profiles, and turbulence intensity profiles were measured along the accelerated region. The turbulence intensity profiles indicate that at the end of the accelerated region both cases still exhibit the characteristic shapes of fully turbulent layers, though the level of the turbulence is notably reduced. Additionally, the heat transfer data for the two cases are identical within the uncertainty of the experimental data, displaying virtually no effect of the free-stream turbulence intensity. Theoretical predictions obtained by a numerical solution of the boundary layer equations, taking into account the boundary conditions on the turbulent energy corresponding to the two cases, agree well with the results.

ANALYSIS

Introduction

It has been demonstrated by numerous experimenters that when a turbulent boundary layer is subjected to a sufficiently large negative pressure gradient (or free-stream acceleration), a re-transition to a laminar boundary layer will take place[1,2,3]. This phenomenon is accompanied by very substantial reductions in heat transfer, if indeed heat transfer is taking place, and is for this reason of considerable technical significance.

It was originally thought that an abrupt decrease in the Stanton number, when a high acceleration is applied, was evidence of a complete retransition to a laminar boundary layer, and the term "laminarization", coined by Launder[2], has frequently been used in connection with such decreases in Stanton number. More recently it has been demonstrated [3] that even relatively mild accelerations can cause a reduction in Stanton number, and that the degree of reduction increases continuously with the strength of the acceleration. It is thus difficult or impossible to determine from heat transfer data alone whether laminarization is taking place. Examination of mean velocity profiles, and the success of a theoretical model of the accelerated boundary layer, is used by Kays, et al, [3], as evidence that an equilibrium turbulent boundary layer can exist even though Stanton number is decreasing

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virtually as it would were the boundary layer entirely laminar. It appears that acceleration causes a noticeable increase in the thickness of the viscous sublayer (an increase that ultimately will envelop the entire boundary layer at sufficiently strong accelerations), while at the same time the thermal boundary layer penetrates beyond the momentum boundary layer such that it encounters a region of very low or negligible eddy conductivity.

An important question raised by this explanation is whether or not high free-stream turbulence has any substantial effect on the heat transfer performance of a strongly accelerated turbulent boundary layer. Most of the experiments have taken place in wind tunnels where turbulence level is very small, but many of the interesting technical applications (turbine blades, rocket nozzles, for example) involve highly turbulent free-stream environments. For non-accelerated boundary layers it seems that free-stream turbulence is not particularly significant [4], but this may not be the case when the outer part of the boundary layer is providing any substantial part of the overall heat transfer resistance, as it apparently does for prolonged highly accelerated flows.

The objective of this paper is to describe the results of some experiments at relatively high acceleration [$K = 2.5 \times 10^{-6}$, where $K = (\nu/U_\infty^2)(dU_\infty/dx)$] taken first under low turbulence conditions, and then with considerably higher free-stream turbulence artificially induced by a crossed-rod grid. The surface heat transfer measurements were accompanied by mean velocity and temperature traverses, but more importantly by hot-wire traverses of $\sqrt{u'^2}/U_\infty$. Actually, one objective of the hot-wire measurements was to demonstrate that with $K = 2.5 \times 10^{-6}$ the boundary layer is indeed still a turbulent one since, as suggested above, the overall heat transfer behavior is by no means conclusive on this point.

Experimental Apparatus

The experiments were conducted on the Heat and Mass Transfer test rig in the Mechanical Engineering Department at Stanford University. The boundary layer was formed on the lower surface of a rectangular channel having initial cross-section dimensions of six-inches by twenty-inches. The entire channel is eight feet in length. The region of acceleration, extending over a distance of twenty-inches, begins 16 inches downstream of a 1/16" high, 1/4" wide flat boundary layer trip. The height of the upper wall of the duct can be varied to achieve the desired free-stream velocity; in the experiments described here a linear variation of the wall was utilized in order to achieve a constant value of the acceleration parameter K.

In the high free-stream turbulence runs, a crossed-rod grid was placed 13 inches upstream of the trip. The grid consisted of 1/4-inch round wooden dowels formed into a square, interlocked mesh (i.e., all of the dowels were in the same plane) on 1-inch centers.

The lower wall of the eight-foot channel is comprised of 24 segments of 1/4-inch thick sintered bronze, allowing for tests with transpiration when desired. Surface temperature is measured by five thermocouples imbedded in the center six-inch span of each segment. The segments are heated by wires situated in grooves in the bottom surface, spaced such that the top surface of each segment is uniform in temperature to within 0.04°F under all conditions. The heat transfer between the surface and the boundary layer is deduced from an energy balance based on power and temperature measurements in each segment. A detailed description of the apparatus and the data reduction method is contained in [5].

Mean flow velocity profiles were obtained with a flattened pitot probe, while temperature profiles were measured with an iron-constantan thermocouple with the junction flattened. Longitudinal turbulence profiles were taken with a 0.0002-inch constant temperature platinum hot wire and a linearized anemometer system.

Experimental Results

Two experiments were conducted with free-stream turbulence intensities, $\sqrt{\overline{u'^2}}/U_\infty$, of 0.7 percent and 3.9 percent, respectively, at the start of acceleration. The free-stream turbulence intensity decayed to 0.4 percent and 0.9 percent, respectively, in the recovery region. The level of high free-stream turbulence employed is of the same order of magnitude as used by Kestin [4] in his investigation of the effects of free-stream turbulence on a boundary layer subjected to a moderate acceleration. The free-stream energy spectra exhibited in both runs was that of normal turbulence. The grid design was based in part on the work of Uberoi and Wallis [6], in which, 29-inches downstream of a similar grid, the turbulence was found to be homogeneous with $\overline{u'^2} \approx \overline{v'^2}$. Both tests reported here were conducted with a free-stream velocity of about 23 fps.

In Fig. 1 is shown a plot of Stanton number versus local enthalpy thickness Reynolds number for the two cases. The differences in the data sets on Fig. 1 are no greater than the estimated experimental uncertainty. It appears that in the accelerated region, where the abrupt decrease in Stanton number is taking place, there is negligible difference in performance. If anything the high turbulence case yields lower St, which does not seem physically plausible. In the recovery region, where free-stream velocity is again constant, it appears that recovery is slightly more abrupt with high free-stream turbulence, and this would be consistent with the proposed model. Thus the conclusions that one can draw are that initial free-stream turbulence levels as high as 3.9 percent have very little effect on Stanton number for strongly accelerated flows, but this fact in itself is of significance.

Figs. 2 and 3 are plots of traverses of $\sqrt{u'^2}/U_\infty$ taken just before acceleration, and near the end of acceleration, for both the low free-stream turbulence case and the high free-stream turbulence case. Essentially they demonstrate that at this relatively high rate of acceleration the boundary layer is in fact still a turbulent one, but with a lowered turbulence intensity, especially in the wake. The results for the higher free-stream turbulence case are similar to those for low free-stream turbulence, with the differences confined primarily to the wake.

The global characteristics of the boundary layers entering the accelerated region for the two cases are quite different in nature; the test with high free-stream turbulence exhibits a very thick boundary layer with a 52 percent larger momentum thickness. It is not certain whether this effect is a direct result of the high turbulence on the growth of the layer, or whether the grid rod nearest the wall simply introduces a momentum decrement into the developing boundary layer. Nevertheless, the important point is that, in the accelerated regions, the outer layers are affected whereas the inner layers appear to display little, if any, effect of the free-stream turbulence level. In Fig. 4, for example, are shown the velocity profiles, in inner coordinates, at the end of the accelerated region for both cases. The profiles deviate from the accepted law of the wall for a flat plate boundary layer, as is typical of highly accelerated boundary layers, but are quite similar to each other.

Prediction of Experimental Results

Fig. 5 shows the results of theoretical calculations made under the conditions of the experiments, using a combination of a kinetic energy model of turbulence in the outer regions, and the Van Driest mixing-length model near the wall. The calculations were performed by a numerical solution* of the following simultaneous set of equations:

Continuity
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

Momentum
$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U_\infty\frac{dU_\infty}{dx} + \frac{\partial}{\partial y}\left[(\nu + \epsilon_M)\frac{\partial u}{\partial y}\right] \qquad (2)$$

Energy
$$u\frac{\partial t}{\partial x} + v\frac{\partial t}{\partial x} = \frac{\partial}{\partial y}\left[(\alpha + \epsilon_H)\frac{\partial t}{\partial y}\right] \qquad (3)$$

Turbulent Kinetic Energy
$$u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} = \epsilon_m\left(\frac{\partial u}{\partial y}\right)^2 + \frac{\partial}{\partial y}\left[(\nu + \epsilon_q)\frac{\partial q}{\partial y}\right] - D \qquad (4)$$

*The numerical procedure employed is a modification of the Spalding/Patankar procedure [7].

To obtain closure, the following model of the turbulent structure was assumed in the outer region

$$\epsilon_M = 0.22\ \ell_t \sqrt{q} \tag{5}$$

$$D = 0.284\ q^{3/2}/\ell_t \tag{6}$$

$$\epsilon_M/\epsilon_q = 1.70 \tag{7}$$

$$\ell_t = \kappa y\ D_v \tag{8}$$

$$D_v = 1 - \exp(-y^+\sqrt{\tau^+}/A^+) \tag{9}$$

$$\epsilon_H = \epsilon_M/Pr_t \tag{10}$$

$$Pr_t = Pr_t(\epsilon_M/\nu) \tag{11}$$

The relationship for the turbulent Prandtl number as a function of (ϵ_M/ν) is based on the work of Simpson, et al.[8]. In the correlation used here, the values for Pr_t ranged from $1/Pr$ at the wall to 0.86 in the outer layers (this correlation is also presented in [3]). The effects of acceleration on the Van Driest constant, A^+, can be adequately modeled in accelerated flows by the function $A^+(P^+)$ shown on Fig. 6. In the cases under consideration, P^+ is approximately -0.022, and A^+ reaches a maximum of about 65.

In the inner regions, only equations (1) through (3) are utilized, with the additional stipulation that

$$\epsilon_m = \ell_t^{\ 2}\left|\frac{du}{dy}\right| \tag{12}$$

This mixing-length model of the turbulent boundary layer, with a modification in the outer region, has been successfully used to predict experimental results over a wide range of conditions including transpiration and favorable pressure gradients[3]. It was hoped that the addition of the turbulent kinetic energy model, besides providing a potential improvement in the prediction method in general, would in particular permit a prediction of the influence of free-stream turbulence.

The theoretical calculations presented in Fig. 5 are in reasonable agreement with the experimental findings. The deviation between the two theoretical curves is due to the fact that the boundary conditions for the variation of the free-stream velocity, i.e., the precise level and physical location of the imposed acceleration, are slightly different in the two cases. It will be shown next that, were the imposed experimental conditions identical, the theoretical model would predict nearly identical curves for the two cases.

A question naturally arises concerning the effect of still higher initial levels of free-stream turbulence under these same conditions of acceleration. To investigate the theoretical aspects of this point, three predictions were made utilizing the experimental boundary conditions and mean-flow starting profiles of the 3.9 percent case.

The results are shown in Fig. 7 for initial free-stream turbulence levels of 0.7 percent, 3.9 percent, and 10 percent. The curves for the lower two intensities are indistinguishable on the plot, whereas the higher turbulence level clearly decreases the effect of acceleration on St, and significantly increases St in the recovery region. Eventually, all three predictions converge on the accepted correlation for the flat-plate turbulent boundary layer.

Prior to acceleration, the free-stream turbulence for the 10 percent case is on the order of the self-generated turbulence within the boundary layer. It is not unreasonable that the heat transfer should be affected under these conditions. An experimental hydrodynamic study by Kline, et al. [9] for a constant velocity turbulent flow substantiates the notion that a free-stream turbulence level of this magnitude has significant effects on the characteristics of the boundary layer. In the accelerated zone and thereafter, however, it is believed that the influence of the high turbulence is manifested through a different mechanism. As the thermal layer grows outside of the momentum layer, the higher free-stream turbulence acts to increase the apparent conductivity in this laminar-like outer region, resulting in higher Stanton numbers.

Conclusions

The following are the conclusions that may be drawn from this work:

(a) For the acceleration parameter, K, as high as 2.5×10^{-6} the boundary layer is still a turbulent one, despite the fact that when heat transfer is taking place the Stanton number decreases very markedly;

(b) The decrease in Stanton number observed during strong acceleration is independent of initial free-stream turbulence levels up to at least 4 percent;

(c) Theoretical calculations for an initial free-stream turbulence level of 10 percent suggest that if initial free-stream turbulence is of the same order of magnitude as the self-generated turbulence within the boundary layer, a substantial increase in Stanton number will be obtained throughout the accelerated region.

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NOMENCLATURE

Symbol	Description
A^+	Van Driest constant (defined by Eq. 9)
C_f	Surface shear stress coefficient $(= \tau_w/(\frac{1}{2}\rho_\infty U_\infty{}^2))$
D	Dissipation term in the turbulent kinetic-energy equation (defined by Eq. 6)
D_v	Van Driest damping factor (defined by Eq. 9)
K	Acceleration parameter $(= \nu \frac{dU_\infty}{dx}/U_\infty{}^2)$
ℓ_t	Length scale (defined by Eq. 8)
P^+	Acceleration parameter $(= -K/(C_f/2)^{3/2})$
Pr	Prandtl number $(= \nu/\alpha)$
Pr_t	Turbulent Prandtl number $(= \epsilon_M/\epsilon_H)$
Re_H	Enthalpy thickness Reynolds number $(= U_\infty \Delta_2/\nu)$
q	Turbulent kinetic energy $(= \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}))$
t	Temperature
u,v	Mean velocity components in streamwise and normal directions
u^+	Normalized streamwise velocity $(= u/U_\tau)$
U_τ	Shear velocity $(= \sqrt{\tau_w/\rho})$
U_∞	Free-stream velocity in streamwise direction
u',v',w'	Fluctuating velocity components in streamwise, normal, and transverse directions
x	Denotes streamwise direction
y	Denotes normal direction
y^+	Inner region normal coordinate $(= yu_\tau/\nu)$
α	Molecular thermal diffusivity

Symbol	Description
ϵ	Eddy diffusivity
Δ_2	Enthalpy thickness $\left(= \int_0^\infty \frac{u}{U_\infty} \left(\frac{t - t_\infty}{t_w - t_\infty}\right) dy\right)$
κ	Von Karman constant (≈ 0.44)
ν	Kinematic viscosity
ρ	Density
τ	Shear stress

Subscripts

H	Denotes heat
∞	Denotes free-stream
M	Denotes momentum
w	Denotes wall
q	Denotes turbulent kinetic energy

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FIGURES

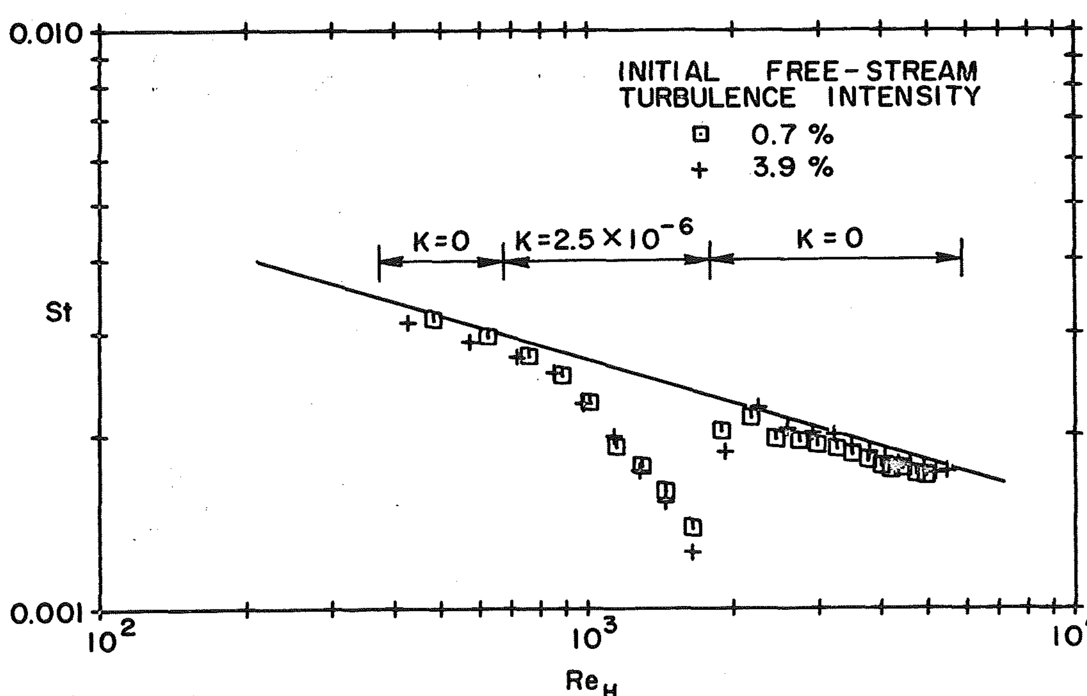

Fig. 1. Experimental heat transfer for low and high initial free-stream turbulence intensities in a strongly accelerated flow.
——— Typical correlation for constant U_∞,
$St = 0.0128\ Re_H^{-1/4} Pr^{-1/2}$.

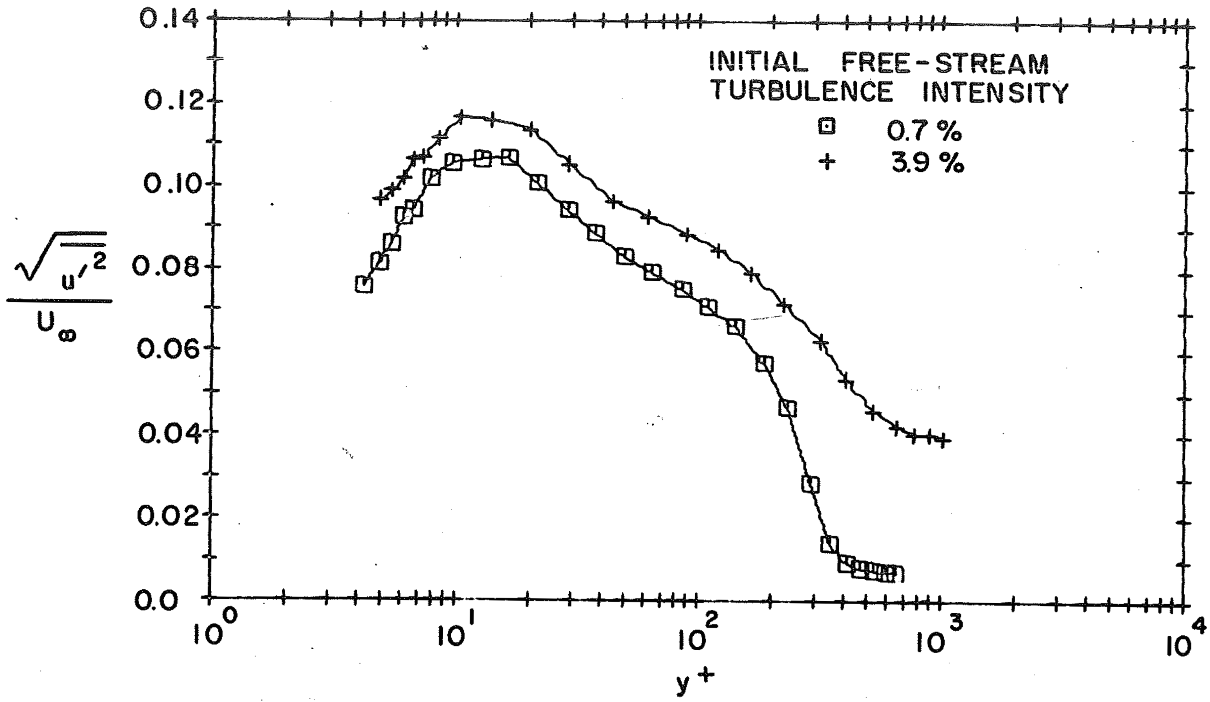

Fig. 2. Experimental turbulence intensity profiles in the constant U_∞ region prior to acceleration. $Re_H \approx 600$.

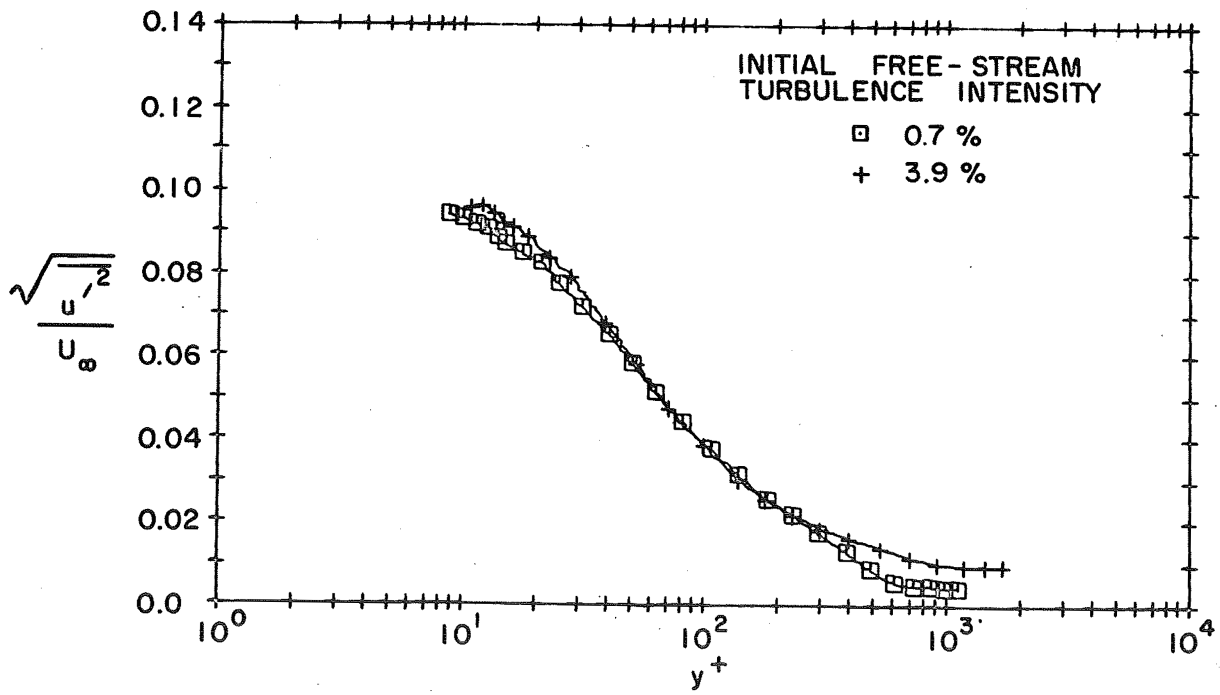

Fig. 3. Experimental turbulence intensity profiles near the end of the accelerated region. $Re_H \approx 1430$.

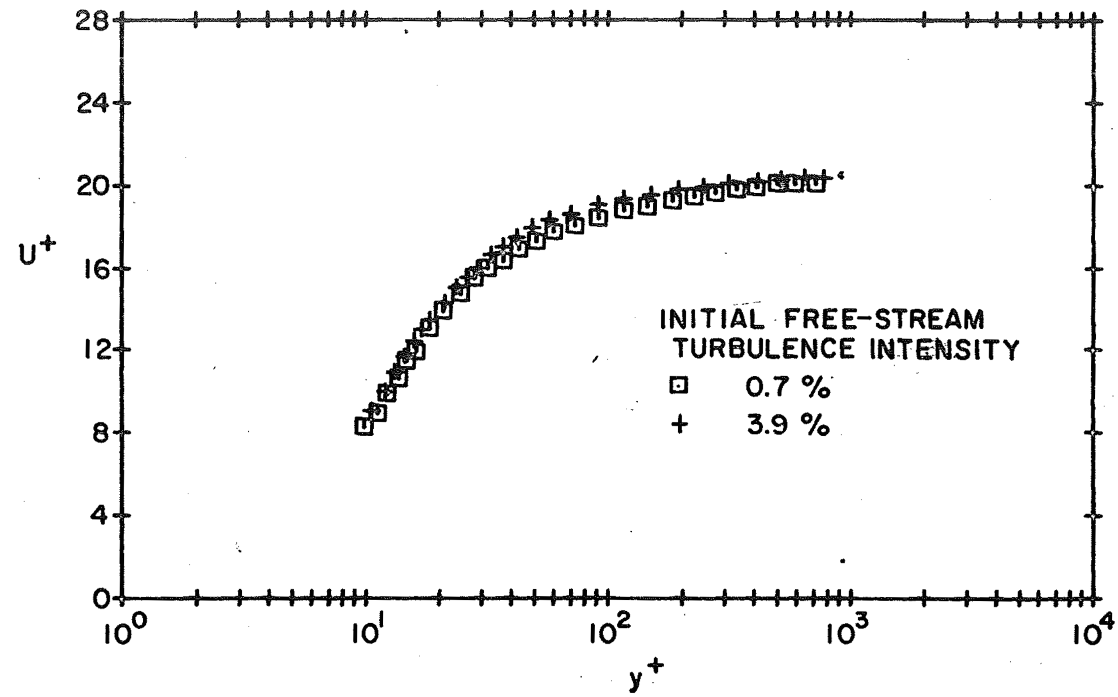

Fig. 4. Experimental velocity profiles near the end of the accelerated region. $Re_H \approx 1430$.

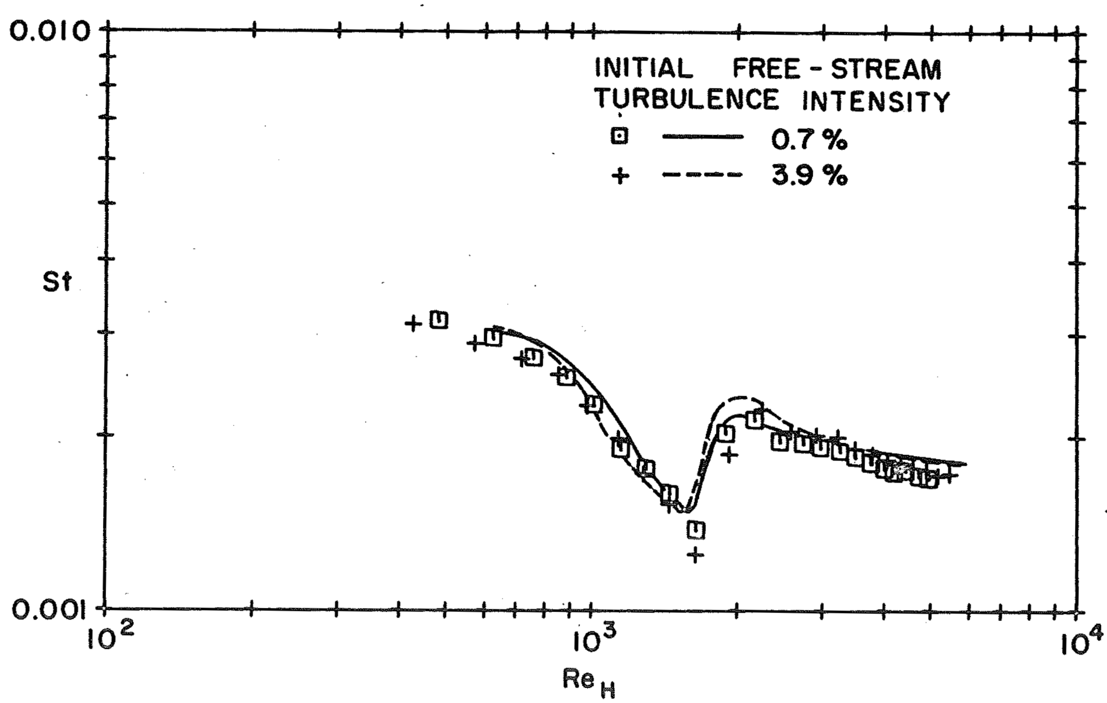

Fig. 5. Comparison of predicted and experimental heat transfer results.

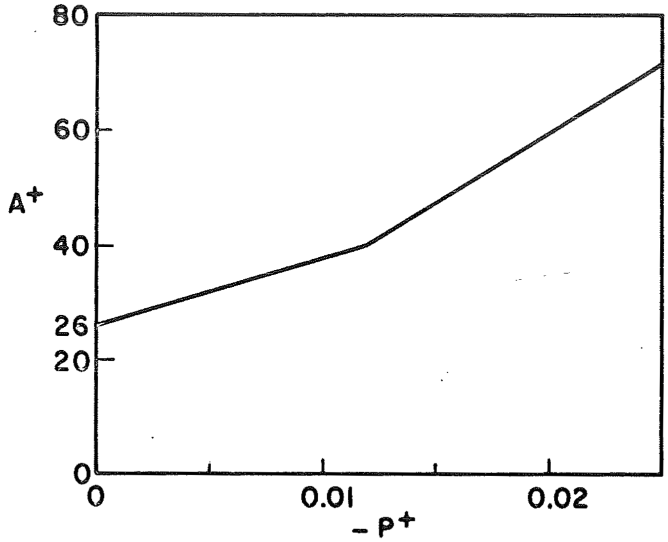

Fig. 6. Correlation for the Van Driest constant in accelerated flows.

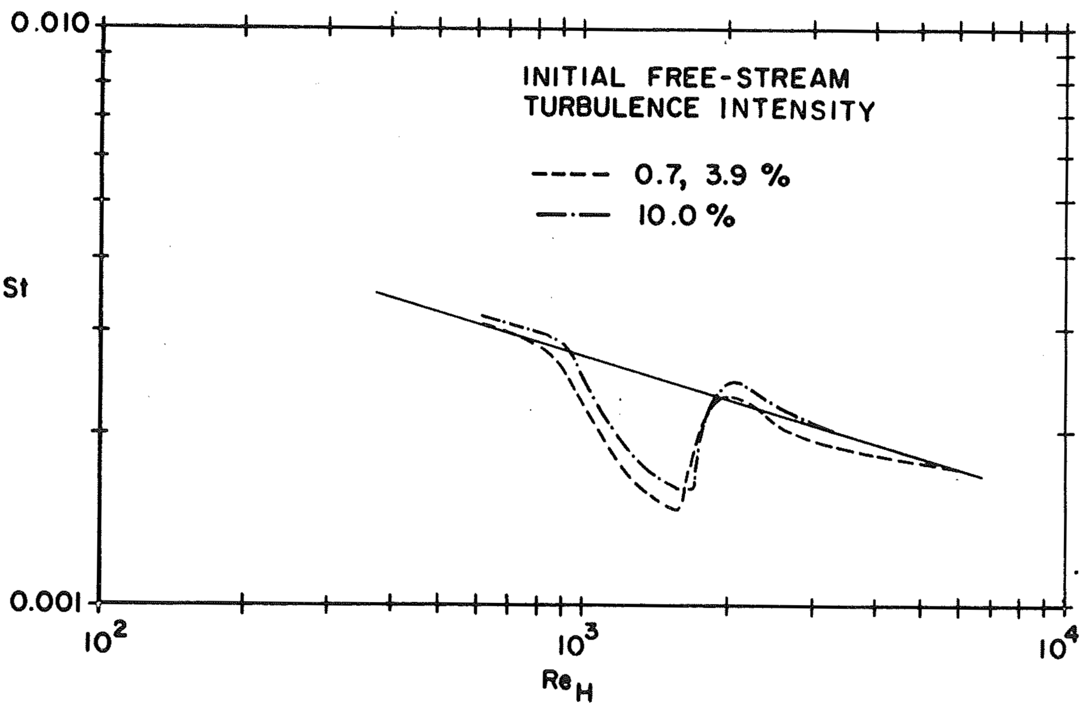

Fig. 7. Effect of initial free-stream turbulence level on the predicted heat transfer performance. ——— Typical correlation for constant U_∞, $St = 0.0128\ Re_H^{-1/4} Pr^{-1/2}$.