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LAMINARIZATION MODEL FOR TURBULENT EDDY TRANSPORT IN HIGHLY ACCELERATED NOZZLE TURBULENT BOUNDARY LAYERS

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Page 7, figure 5: The key should be replaced with the following key:

	Skin friction coefficient, C_f
□ Data from ref. 8	--------
— - — Turbulent (modified laminarization model $(y_1^+)_L = 30$)	0.004208
— — — Laminar	.003871

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16. Abstract

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SUMMARY

A laminarization model which consists of a completely laminar sublayer region near the wall and a turbulent wake region is developed for the turbulent eddy transport in accelerated turbulent boundary layers. This laminarization model is used in a differential boundary layer calculation which was applied to nozzle flows. The resulting theoretical velocity profiles are in good agreement with the experimental nozzle data in the convergent region.

INTRODUCTION

The effect of strong flow acceleration on the turbulent boundary layer has often been described as a "laminarization" process (refs. 1 to 5). The idea of laminarization is that the turbulence in the boundary layer flow is believed to be greatly reduced and the boundary layer becomes laminar-like for large flow acceleration. References 2 and 3 suggest that the laminarization process can be described by a greatly increased laminar sublayer region with a significant decrease in the fully turbulent law of the wall region. This laminarization region was expected to be primarily applicable to the low pressure accelerated turbulent boundary layer (refs. 2 and 3).

In the present report, another laminarization model is presented which differs from references 2 and 3 in that a "true" laminar sublayer region (for $y^+ \approx 0$ to 20) is believed to exist for the near wall region, even for the high pressure accelerated boundary layer. This "true" laminar sublayer region is defined as a completely laminar region with negligible Reynolds stresses. As part of this assumed completely laminar region near the wall, the wall generated turbulence region is eliminated by the flow acceleration and only a reduced eddy transport is carried along in the outer part of the boundary layer.

This present laminarization model is used in a similar solution analysis of the differential boundary layer equations for an accelerated turbulent boundary layer (ref. 6). This similar solution analysis is not described or repeated in the present report and the reader is referred to reference 6 for all details and assumptions. The purpose of this study is to show that calculations with a new laminarization model characterized by a "true" laminar sublayer region near the wall gives good agreement with experimental velocity profiles for highly accelerated nozzle flows. Theoretical boundary layer velocity distributions are compared with experimental data from a 30° nozzle (ref. 7) and 10° nozzle (ref. 8). The nozzle velocity data of references 7 and 9 were taken at a subsonic station in the convergent portion of each nozzle operating at high and low stagnation pressures without heat transfer.

SYMBOLS

C_f	skin friction coefficient
M	Mach number
P_0	stagnation pressure
T_0	stagnation temperature
u	velocity parallel to nozzle surface
u^+	velocity parameter, $\dfrac{u}{(\tau_w/\rho_w)^{1/2}}$
y	coordinate normal to nozzle surface
y^+	wall distance parameter, $\dfrac{y\left(\tau_w/\rho_w\right)^{1/2}}{\mu_w/\rho_w}$
δ_i^*	incompressible displacement thickness
ϵ_m	momentum eddy diffusivity
μ	molecular viscosity
ξ	empirical constant (0.018)
ρ	density
τ	shear stress

Subscripts:

e	edge of boundary layer conditions
w	wall conditions

LAMINARIZATION MODEL

The present laminarization model consists of two distinct regions. The region near the wall is assumed to be a completely laminar region until the y^+ (wall distance parameter) approaches 20. Beyond this point a turbulent wake region is assumed and Clauser's approximation (ref. 9) for this region is given by

$$\epsilon_m = \xi u_e \delta_i^* \tag{1}$$

where ξ is an experimental flow constant based on low speed incompressible data and the incompressible displacement thickness δ_i^* is

$$\delta_i^* = \int_0^{y_e} \left(1.0 - \frac{u}{u_e}\right) dy \tag{2}$$

The value of ϵ_m jumps from zero to a constant (see eq. (1)) at $y^+ = 20$.

COMPARISON OF THEORETICAL RESULTS WITH EXPERIMENTAL DATA

The theoretical velocity profiles (from calculations using the laminarization model) are compared with experimental data from a 30° nozzle (ref. 7) and 10° nozzle (ref. 8) at the convergent probing location in each nozzle. The data used in this comparison were obtained at high and low stagnation pressures without heat transfer. All of the tests were conducted with room temperature air ($T_0 \approx 317$ K). Stagnation conditions for the tests are summarized in the following table:

Nozzle	Stagnation pressure, N/cm^2 (psia)	
	High	Low
30° (ref. 7)	207 (300)	31.0 (45)
10° (ref. 8)	103.2 (150)	10.32 (15)

VELOCITY PROFILES

All theoretical velocity profile comparisons with experimental data are made on the basis of the usual u^+ against y^+ velocity profile formulation. The experimental u^+ against y^+ velocity distributions use the skin friction coefficient C_f from the corresponding theoretical calculation. Figure 1 shows a comparison of predicted with measured velocity profiles at the convergent nozzle probing station in the 30° nozzle operating with the short inlet (ref. 7) and the high stagnation pressure, 207.0 newtons per square centimeter absolute (300 psia). The predicted velocity profile (using the laminarization model) is in excellent agreement with the experimental data. In addition, the predicted velocity profile using the eddy diffusivity distribution developed from zero pressure gradient flow (see ref. 6) is readily seen to be considerably below the measured profile (see fig. 1). These comparisons assume that the local similarity calculation method of reference 6 is valid for nozzle flows. The predicted velocity profile for a completely laminar boundary layer is also shown in figure 1 and provides a basis of a known reference for the fully turbulent and laminarized turbulent boundary layer. From the experience obtained by carrying out the numerical calculations with the similarity method, it can be concluded that if the eddy diffusivity is appreciable in the near wall region the predicted velocity profile with fall greatly below the measured profile. In

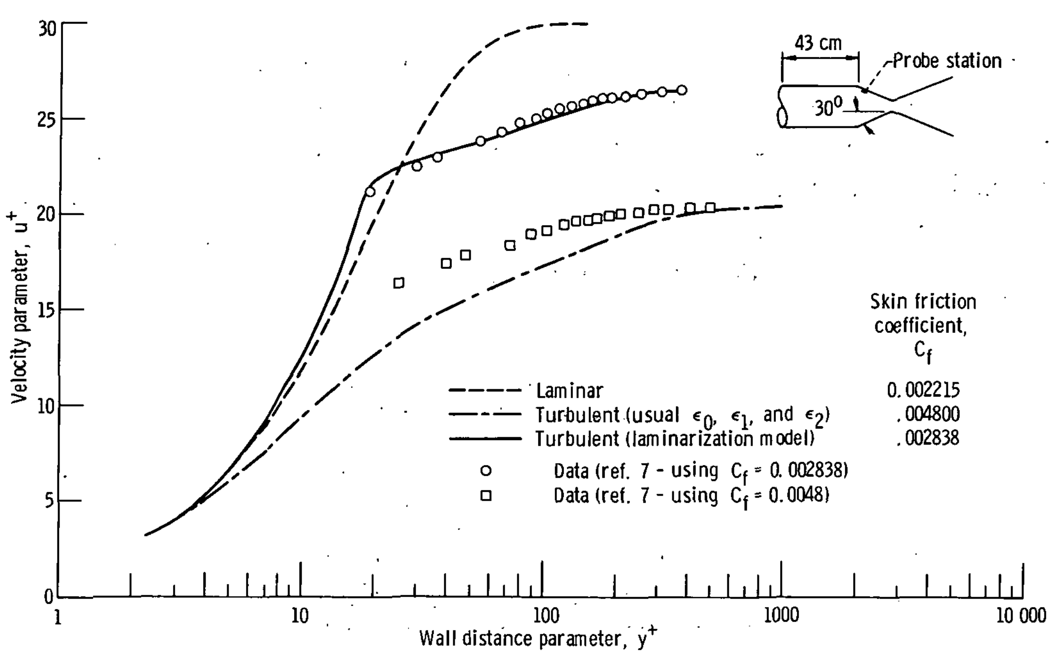

Figure 1. - Comparison of predicted with measured velocity profiles at convergent nozzle probing station (M_e = 0.10) for 30^0 nozzle with short inlet. Cold flow; stagnation temperature, 317 K; stagnation pressure, 207.0 newtons per square centimeter absolute (300 psia).

figure 2 the predicted velocity profile (using the laminarization model) is also in good agreement with the measured data for the 30° nozzle with the long inlet (338 cm). An interesting point to note about this inlet flow is that a fully developed turbulent boundary was evident at the nozzle entrance.

At the low stagnation pressure (31.0 N/cm^2 abs (45 psia)) no experimental velocity profile data is available at the convergent nozzle probing station for the 30° nozzle with the short inlet. However, the theoretical prediction of the velocity profile (using the laminarization model) is of particular interest since it is in such close agreement with

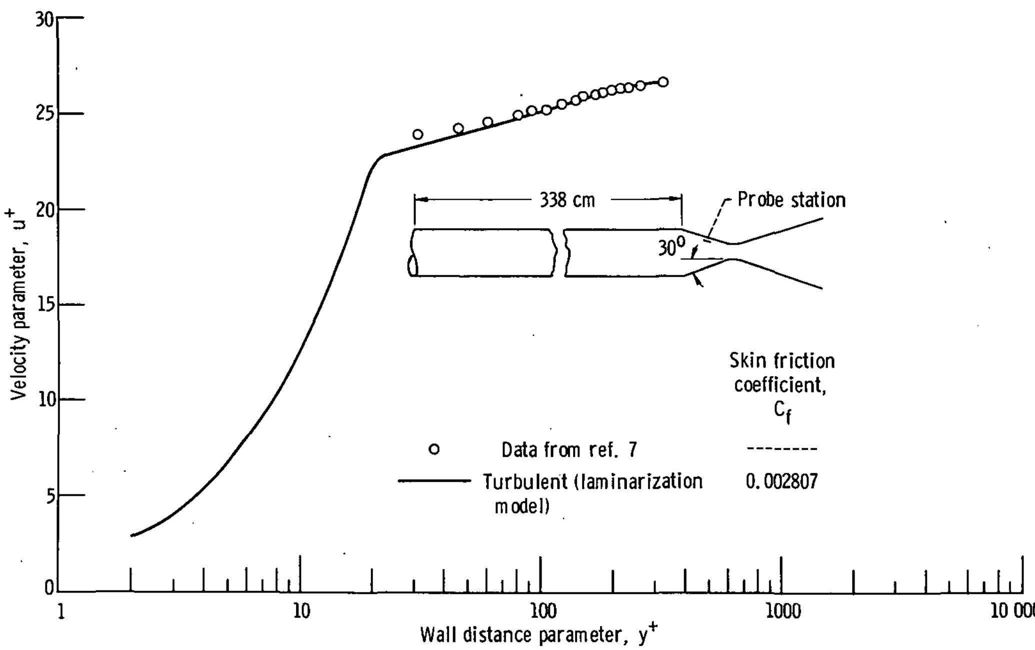

Figure 2. - Comparison of predicted with measured velocity profiles at convergent nozzle probing station (M_e = 0.10) for 30° nozzle with long inlet. Cold flow; stagnation temperature, 317 K; stagnation pressure, 207.0 newtons per square centimeter absolute (300 psia).

the velocity profile calculated for a laminar boundary layer (see fig. 3). As expected the skin friction coefficients tabulated in figure 3 for the turbulent calculation (using the laminarization model) and the laminar calculation are almost identical. The predicted velocity profile (using the laminarization model) at high pressure ($P_0 \approx 207.0$ N/cm^2 abs (300 psia)) is also included in figure 3 in order to demonstrate the large effect that a reduced total stagnation pressure has in laminarizing the turbulent boundary layer. This laminarization effect is believed to result from a greatly increased percentage growth of the "true" laminar sublayer region to the total boundary layer as the stagnation pressure is reduced.

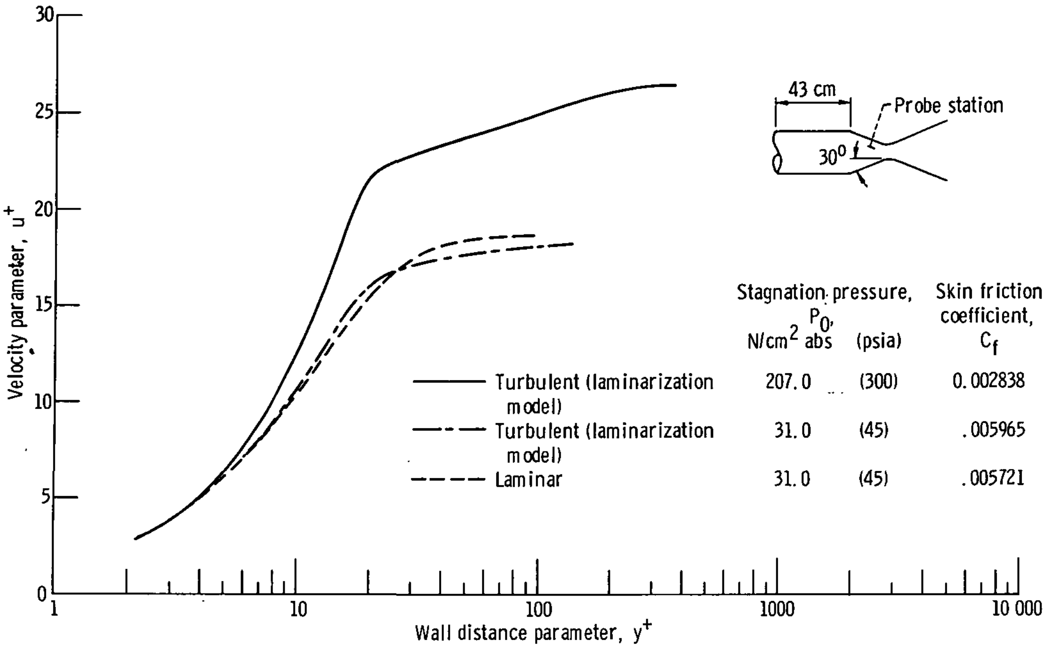

Figure 3. - Effect of total pressure on predicted velocity distribution at convergent nozzle probing station (M_e = 0.10) for the 30° nozzle with short inlet. Stagnation temperature, 317 K.

In figure 4 a comparison of the predicted with measured velocity profiles at the convergent nozzle probing station for the 10° nozzle (ref. 8) is made for the high and low stagnation pressures (103.2 N/cm² abs (150 psia) and 10.32 N/cm² abs (15 psia), respectively). At the high stagnation pressure (103.2 N/cm² abs (150 psia)) the predicted velocity profile from the numerical calculation using the laminarization model is in good agreement with the measured data (see fig. 4). At the low stagnation pressure (10.32 N/cm² abs (15 psia)) figure 4 shows that the numerical calculation (with the laminarization model) predicts a velocity profile which is generally above the experimental velocity data in the laminar sublayer region. An attempt was made to improve this comparison of the theoretical laminarized turbulent boundary layer with experimental data. Changing the extent of the "true" laminar sublayer region from y^+ of 20 to 30 resulted in good agreement of the predicted velocity profile with experimental data (see fig. 5). This necessity for increasing the extent of the laminar sublayer region may be a function of stagnation pressure through a local Reynolds number effect or even a function of flow acceleration.

The present laminarization model is not intended to be a generalized eddy transport model but rather a new description of laminarization which could be extended in scope and application in the future. Further research is required in order to determine the extent of the conditions in which the proposed model is applicable.

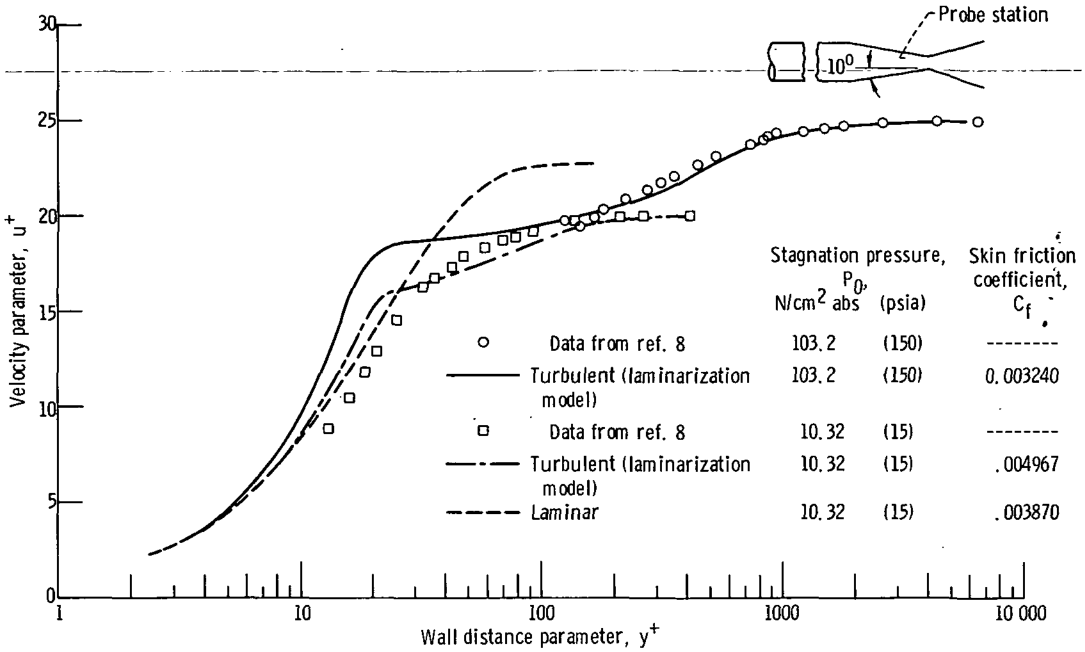

Figure 4. - Comparison of predicted with measured velocity profiles for 10^0 nozzle probing station ($M_e \approx 0.20$). Stagnation temperature, 317 K.

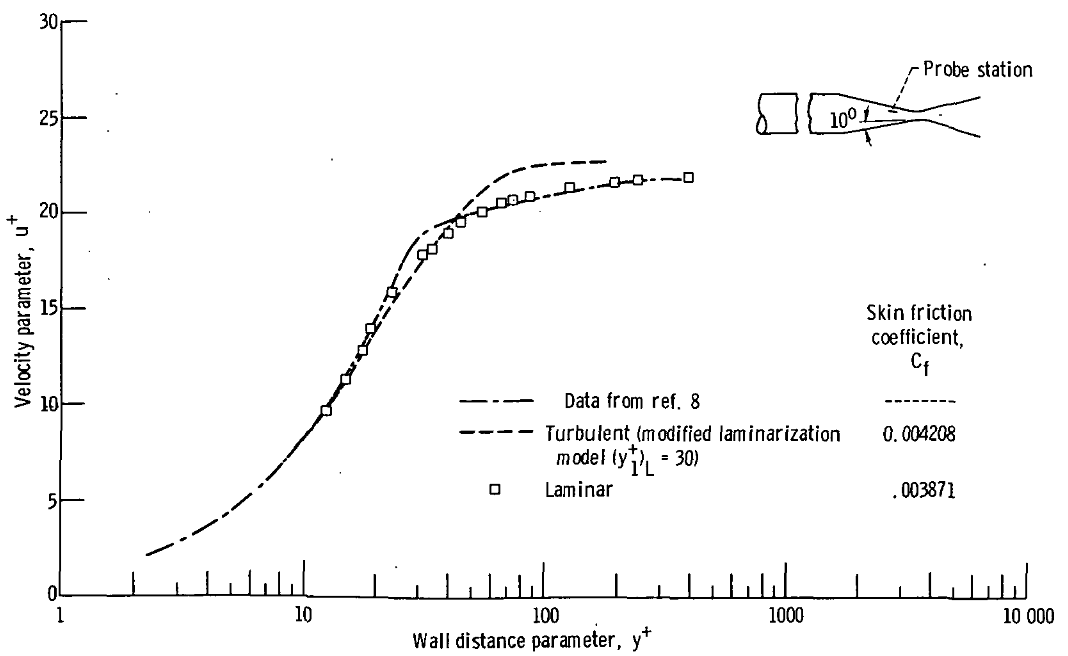

Figure 5. - Comparison of predicted (modified laminarization model $(y_1^+)_L = 30$) with measured velocity profile for 10^0 nozzle probing station ($M_e \approx 0.20$) at low pressure. Stagnation temperature, 317 K. Stagnation pressure, 10.32 newtons per squared centimeter absolute (15 psia).

CONCLUSIONS

The present laminarization model appears to describe the turbulent eddy transport in accelerated turbulent boundary layers for the convergent region of nozzles without heat transfer. This conclusion is a result of a comparison of the theoretical velocity profile (using laminarization model) with experimental data at high and low stagnation pressures. An additional result is that, at low pressures, the velocity profile from a laminar boundary layer calculation is very similar to the velocity profile obtained from the accelerated turbulent boundary layer calculation (using the laminarization model).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 19, 1971,
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