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DISCUSSION

E. S. Taylor[2]

The authors are to be commended for adding to our understanding of boundary layer behavior in a favorable pressure gradient, a problem which is becoming increasingly more important as we move toward higher turbine inlet temperatures with the consequent necessity for cooled turbine blades.

In 1956, Senoo[3] reported on work in turbine nozzles. I quote from his conclusions:

"Even when the upstream boundary layer was turbulent, on the end wall the boundary layer near the throat was laminar for the case studied. This is due to the steep favorable pressure gradient." Senoo should certainly be recognized as one of the first to call attention to laminarization.

I should also like to mention Jones and Launder, whose recent publication[4] presumably came too late for inclusion in the paper. Launder's paper is confined to incompressible flow, but shows remarkable success in predicting boundary layer behavior in a favorable pressure gradient. The desirability of applying Launder's analysis to the excellent data of Nash-Webber and Oates is indicated.

P. M. Moretti[5]

The wheel has turned full circle: nine years ago, at Stanford, the groups led by W. M. Kays and S. J. Kline cooperated to deduce friction factors of boundary layers in favorable pressure gradients from measured local Stanton numbers; now we see skin friction measurements being used to predict heat-transfer reduction. This latter seems backwards, since measurements of shear have always been difficult in the presence of pressure gradients; generally, law-of-the-wall assumptions and logarithmic-region measurements have been used in obtaining the pressure-gradient correction for nonthermal wall-shear devices. Only the very recent application of certain refined laser anemometry methods to obtain true velocity profiles within the viscous sublayers has overcome our cautious attitude: it will undoubtedly lead to validation or improvement of other wall-shear devices by permitting a comparison of the wall-shear measurements against velocity profiles measured very close to the wall.

Regarding the argument of the paper, it may be useful to divide the phenomenon of "laminarization" into two parts. The first one has been known for a very long time: when an internal flow is directed through a substantial area reduction, the profile is flattened out (since most of the kinetic energy after the area reduction has just been acquired from the pressure gradient), and the turbulence level appears to be greatly reduced (since the fluctuation velocities are now compared with much greater mean velocities). Hence the boundary layer appears thin and laminar right after it has gone through the region of favorable pressure gradient. This phenomenon has long been utilized by the constructors of wind tunnels and flow loops; it largely accounts for the abnormal shape factors which are used to mark the onset of "reverse transition," although they may merely indicate the presence of a favorable pressure gradient.

The second phenomenon goes beyond this: boundary layers are influenced by favorable pressure gradients in more subtle ways even at the point where the pressure-gradient region has just been entered. There is an exceptional drop in Stanton number and friction factor. There is a reduction in the rate of turbulent bursting in the boundary layer, as reported in reference [11]. There are related changes in turbulence production, and hence further changes in the turbulence distribution and shape factors of the boundary layer downstream.

It is really this second phenomenon which we have difficulty predicting. The authors follow the usual arguments that the pressure gradient, represented by K, might be a governing parameter; and a Reynolds number, such as the momentum thickness Reynolds number, might be another one. Each of them, and a few others, have been used in the past with success—for a limited range of experimental situations in each case. The authors suggest the use of both, and it may well be that this will be satisfactory—for a limited range of flow situations. The question which is still unanswered is whether anything else matters—such as details of the immediately preceding history of the flow as recorded in the precise shape and turbulence distribution in the boundary layer. Without data which include measurements in boundary layers with very different K-factor histories, but identical K-factors and momentum thickness Reynolds number at the point of interest, this question cannot be answered.

Hence we may conclude that the proposed method will work for a certain range of nozzles. We do not know whether it can be extended to more unusual flow situations.

The authors have supplied valuable and meticulous data, particularly in the high momentum thickness Reynolds number range, and have quoted several other experiments. The literature contains heat-transfer-oriented data from W. M. Kays, L. H. Back, R. A. Seban and others (for example, ASME papers 69-HT-10, 53, and 56), which have not been evaluated in this study. Even including these, there are still many inadequately explored areas, and questions such as the effect of a heated wall have not yet been answered in a satisfactory way. Hence the universal procedure for relaminarization prediction still eludes us.

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[2] Professor Emeritus, Massachusetts Institute of Technology, Cambridge, Mass.

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[5] Assistant Professor, School of Mechanical and Aerospace Engineering, Stillwater, Okla. Mem. ASME.

Authors' Closure

The authors would like to thank Professor Taylor for his kind remarks. The pioneering observations of Senoo are referenced in reference [1] of the paper, and the work of Jones and Launder was indeed unavailable prior to submission. We agree that testing of their calculation method against our data would be very useful, although at least one other calculation method giving a good fit to our data has been developed. This was done by Henry McDonald of UARL several years ago.[6]

The authors would like to thank Professor Moretti for his contributing such an extensive discussion, and extend our appreciation for his kind comments concerning the value of the data presented in the paper. We hope our response to his other comments will help to elucidate the intended purpose and scope of the paper.

With regard to the introductory paragraph of Professor Moretti's discussion, the authors are sorry indeed if the impression was given that we felt our skin friction measurements could be utilized to predict heat transfer, but frankly we are at a loss to explain how such an impression was transmitted. The only references to heat transfer in our paper are made in the introduction in referencing Wilson and Popes encountering laminarizing effects in a heat-transfer experiment, and in the final section where our feelings of the qualitative effects of heat transfer on laminarization (not the inverse) are advanced. In addition the conclusion mentions again the restriction of the resuls to the adiabatic case.

The authors can accept Professor Moretti's division of the phenomenon of "laminarization" into the two parts he describes in detail, but disagree with his statement that the first part "largely accounts for the abnormal shape factors, etc." All the effects described by the "first part" involve the primarily kinematic effects of the applied acceleration which have a virtually identical effect on all the boundary layers existing in a given tunnel configuration. It is clear from Fig. 4 of the paper that the shape factor behaves in a very "abnormal fashion" for three of the four cases studied, but in the fourth case (high Reynolds number) no such abnormal behavior occurs, and it is difficult to imagine an explanation of these behaviors without invoking the arguments of "part two" of Professor Moretti's model.

The authors are aware of the influence of the history of the flow and point out our explicit discussion, contained in the paper, of the difficulty of determining precisely what "sustained entry" (in the laminarizing regime) means. As Professor Moretti points out, generally a single parameter has been invoked to predict the onset of laminarization, and we hope that by the use of both R_{δ_2} and K, the applicable range of flow conditions over which the criterion may be applied is considerably extended. The suggested study involving different K factor histories for a given K and R_{δ_2} (and M?) would indeed shed light upon the problem, but one wonders if the student who undertook it would graduate straight into his old age pension!

Finally, we agree that the universal procedure for laminarization prediction still eludes us, but will be patient in our waiting for its appearance.

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