Discussion

C. C. Lin.[3] The author has provided us with very interesting and useful data regarding the boundary layer over the blades of turbine nozzles. It is interesting that he could correlate the boundary-layer thickness with the distance downstream of the point of minimum pressure. No convincing theoretical justification has yet been advanced for such a correlation, which is very useful, if its general validity can be established. It seems desirable to carry out an analysis based on conventional boundary-layer theory to explain all the phenomena found in the experiments of the author, and, in particular, to explore the extent of the generality of his formula for the boundary-layer thickness.

Charles Shulock.[4] The turbine designer welcomes this investigation into the growth of boundary layer over a turbine nozzle. The optical methods employed herein seem well suited to the study of the phenomenon, since the measuring instruments themselves introduce no disturbance to the flow. In addition, surveys can be extended over the entire passage, rather than being confined to or near the plane of the trailing edges.

However, precautions are still necessary. From Fig. 2 of the paper, it appears that the "optically flat window" forms one side wall of the cascade, and that the boundary layer would be photographed through this window. This side wall, and adjacent sections of the blade profile, would be subjected to boundary-layer growths quite different from that existent over the blade at mid-span. Is this disturbance eliminated by some feature of testing technique, or has it otherwise been shown of limited consequence?

The author correctly associates low shear stresses with a laminar boundary layer, and retarded separation with a turbulent boundary layer. Still undecided, however, is whether the corresponding "skin-friction" drag or "form" drag are the major source of losses in turbine blading. The relative importance of the two types of losses can vary widely with the detail design of each blade passage. In the present investigation, for instance, viscous losses appear prevalent. However, this could be changed by simply varying the passage solidity, or ratio of chord length to blade pitch. Therefore, the range of transition points indicated in Fig. 6 of the paper should be associated not with the nozzle profiles, themselves, but with the particular passage geometry which ensues when these nozzles are assembled into a cascade.

As a matter of interest, a pitch-axial width ratio of 0.72 was obtained by rough scaling Figs. 1 and 2. For comparison, optimum two-dimensional spacing for these same fluid angles, as deduced by O. Zweifel,[5] is at a pitch-width ratio of approximately 1.7.

J. C. Truman.[6] This paper represents a valuable contribution to the literature, both for readers who are interested in boundary-layer behavior, and those interested in interferometric techniques.

The conclusions which are drawn appear to be quite significant and to indicate that further work may be worthwhile. For example, the laminar boundary layer was observed to build up downstream from the minimum pressure point on the suction side, and from the blade-profile inflection point on the pressure side. It should be of value to investigate whether this also holds for blade profiles which differ considerably from the one studied here in respect to chordwise location of these points. Also, the dependence of $\delta/\hat{x}$ on Re_x (using the nomenclature of the author) on the suction side of the blade should be investigated for several different blade profiles. As the author points out, a correlation between these quantities, under proper conditions of dynamical similitude, might be of value as a design criterion.

A comparison of the boundary-layer behavior, as determined from the present study, with that on a blade of the same profile mounted singly, rather than in cascade, also might be of interest. Such a comparison perhaps would not be of immediate value in the design of blades to be mounted in cascade. However, an indication might be gained as to whether the observed departures from the usual concepts of boundary-layer behavior may be in part due to interference effects between blades.

Author's Closure

The author extends his appreciation to Dr. Lin, Mr. Shulock, and Mr. Truman for their interesting and pertinent discussions.

Dr. Lin's comment on the desirability of theoretical justification of the experimental results is indeed appropriate. In addition to contributing to an understanding of the flow phenomena, such an analysis could well serve as an indication of the generality of the results.

In reply to Mr. Shulock's question regarding the effect of side-wall boundary layers on the interferometer data, the interference fringes are displaced in proportion to the integral of the density along the path of any particular light ray passing from one side wall to the other. Since the wall boundary layers in the experimental cascade occupied on the order of from 10 to 20 per cent of the span, the interferometer data measured primarily the two-dimensional flow over the central part of the span. Removal of the side-wall boundary layers would, in the author's estimation, have had no significant effect on the data.

Mr. Shulock is correct in stating that the transition-point range of Fig. 6 should be associated with the blade in the particular cascade in which it was tested, not with the blade alone. Actually, the results presented in the paper have been associated with the distribution of the pressure around the blade and the significant local pressure gradients, for it is the pressure distribution itself, along with whatever turbulence-producing excitation is present, that determines boundary-layer development. The pitch-width ratio is, in turn, a significant factor in the establishment of the pressure distribution. With too large a pitch-width ratio, for example, the pressure distribution necessary for the flow to follow the blade surface would involve excessive adverse pressure gradients, and boundary-layer separation would take place.

The author agrees with Mr. Truman that an investigation to determine the effect of different chordwise positions of the minimum pressure point and profile inflection point on boundary-layer development would be of great value. Until the results of such an investigation are available, in fact, no definite conclusions can be drawn regarding the range of application of the information presented here.

A question is raised regarding the dependence of boundary-layer behavior on the interference of neighboring blades in cascade. As mentioned earlier, the influence of multiple blades in cascade upon the boundary layer on a particular blade is effected by means of the pressure distribution that is established, the boundary layer then being a function of this pressure distribution. The determination of the boundary-layer behavior on a single blade would not seem to have any merit, as here the flow would certainly separate from the suction side long before reaching the trailing edge. The turbulence-producing excitation causing transition might be influenced by the presence and degree of proximity of adjacent blades, but probably to a minor degree.

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[5] "The Spacing of Turbo-Machine Blading, Especially With Large Angular Deflection," by O. Zweifel, *Brown Boveri Review*, vol. 32, December, 1945, pp. 436–444.

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