portion of the blade are due to running of the carbon-black mixture under the force of gravity; the flow velocities there were not large enough to sweep the mixture along in the direction of the flow. The pressure-surface traces show no evidence of flow of the pressure-surface boundary layer toward the end wall. It appears, therefore, that the low-energy fluid which is shown by the total pressure contours to be accumulated in the suction-surface end-wall corner at exit has its origin only in the end-wall and suction-surface boundary layers.

The suction-surface traces show an uninterrupted flow, outside of the end-wall boundary layer, to the region of the trailing edge where there is a discontinuity in the flow. There is evidence that the flow is separated from the blade surface in this region, as has been pointed out previously in considering other data. The spanwise sweep of the lines near the trailing edge again may be due to running of the mixture under the force of gravity, in a separated region.

On the suction surface within $^1/_2$ in. of the blade tip there are two light streaks in the carbon black which stand out quite clearly. These streaks were caused by scouring of the carbon black by relatively high-velocity fluid passing close to the blade surface [note shape and position of the 0.50 contour of Fig. 4(a)]. These streaks describe the path of the end-wall boundary-layer fluid which has rolled up at the suction surface into a vortexlike flow inside the passage, and show the spanwise deflection of the roll-up as it flows to the passage exit. Between the blade end and these streaks is a small region which shows a strong spanwise component of velocity away from the end wall. This flow corresponds to the clockwise rotation (viewed looking upstream) of the boundary-layer roll-up in the end-wall suction-surface corner.

Summary of Results and Conclusions

1 There are strong secondary flows in the end-wall boundary layer of a turbine-nozzle passage which carry low-energy fluid to the suction side of the passage.

2 The low energy of the fluid accumulated in the end-wall suction-surface corner of the nozzle passage at exit is due to frictional dissipation on the end wall and suction surface inside the nozzle passage. The end-wall boundary layer remains thin throughout the passage and is continually being swept to the blade-suction surface by secondary flows. This requires new boundary-layer growth from free-stream fluid. The large shear stresses associated with thin boundary layers may cause high rates of dissipation on the end wall.

3 The secondary flows in the end-wall boundary layer inside the nozzle passage exist independent of the inlet boundary layer and are essentially unchanged even when the inlet boundary layer is completely removed.

4 There is no appreciable difference between the blade-surface pressure distribution at midspan and at the blade end inside the end-wall boundary layer. The blade force does not change, therefore, in the region of the end wall.

5 A roll-up of the end-wall boundary layer into a vortex-like flow was indicated by the total-pressure distribution at cascade exit and by flow traces on the blade surface. The streak on the rear suction surface of the blade observed here and in actual turbines was associated with this flow.

6 For the nozzle profile tested the flow was separated from the suction surface near the trailing edge, except in a region very near the end wall.

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Discussion

Hans Kraft.[8] It is certainly highly welcome to observe that at last fundamental work is being done about the secondary flow in turns. It is an old phenomenon and has been discussed in literature already somewhere around the beginning of the century. Unfortunately, like the weather, it is a complicated and unattractive fluid-flow problem and hence there was more talking about it than doing. For a long time engineers, as contrasted to interested physicists, have tried to do something about it along technical lines. The writer can hardly remember a young engineer entering this field who has not tried to find ways to eliminate or mitigate the secondary flow. The end result was always the same—negative. Only on a recent trip to England the writer found one attempt which claims to have succeeded. However, a check has not yet been made whether the difference in observation has been due to a difference in the adaptability of air to experiment which sometimes seems to exist between the two countries.

The sharply defined streak on the suction side of the nozzle which the author described has been observed in all steam turbines since their very beginning. The author is probably correct when he ascribes this streak to the one-dimensional separation of the fluid from the wall, this separation occurring in a spanwise direction only. It is difficult to change this pattern. Only once has the writer succeeded in doing so. The change resulted from very large fillets (about $^3/_4$ in. radius) around the entrance nose of the blade. The fillets ended before the final large acceleration was started in the nozzle. This had the effect that apparently the spanwise separation was eliminated and that the boundary-layer flow was inclined away from the end walls right up to the center of the span. However, it may be noted here that no beneficial effect could be found as far as performance was concerned.

The writer agrees with the author when he states that the loss created by the secondary flow in a nozzle of large span is probably not too serious in so far as the nozzle itself is concerned. However, in nozzles of normal turbine dimensions and approximately from 2 to 3 in. high, the additional end-wall loss about equals the friction loss around the profile, and in this case is an unwelcome addition.

Furthermore, as the author states, the variation both in angle and velocity magnitude of the issuing velocity vector can well be expected to affect the flow through the rotating part of the turbine rather materially if it can trigger some separation within the moving-bucket passage. Such a trigger action is not entirely impossible, although in view of the comparatively low energy deficiency, it may be somewhat difficult to explain it. It certainly can be said that some action seems to occur in the rotating member of the turbine which as yet cannot be explained fully. If this secondary flow should be the prime culprit, it must be expected that its nonsteady character is primarily to blame. This, of course, does not make the problem any simpler.

It is certainly to be hoped that more work of this nature will be undertaken and published. In view of the difficulty of the

[8] Aerodynamic Engineer, Large Steam Turbine-Generator Department, General Electric Company, Schenectady, N. Y.

undertaking, it cannot be expected that a technically useful explanation of this phenomenon will be furnished quickly. However, if a number of capable experimenters expend some effort along this line the time should come when the effect of the various parameters, especially that of the profile contours, will be understood fully.

While it does not contribute really to the subject matter, the writer would like to discuss the separation, as it is called by the author, which occurs at the exit of the suction surface. The phenomenon is exaggerated here on account of the rather low Reynolds number at which the experiment was run. It seems that this kind of separation comes very close to that discussed by Schmieden around 1940.

The author correctly observes that the air does flow from the pressure to the suction side around the exit edge and joins the suction flow on the suction side. It does that in mid-span as well as near the wall. It does not appear as if this behavior detracts from the efficiency of the nozzle. Rather it seems to be connected with the fact that the wake behind such a nozzle, especially at lower Reynolds numbers, is a Karman street. This can be seen in some of the pictures which have been shown by Faulders in the publications already mentioned.

Yasutoshi Senoo.[9] The investigation of the end-wall boundary layer of a turbine-nozzle cascade was continued after the author left the Institute. In the continued investigation, the end-wall boundary layer was measured directly in the nozzle. Since the author's investigation was mainly based on the flow behavior downstream of the cascade, the writer's experiment may serve to supplement the data for the author's investigation. As a whole, the boundary-layer measurement supports the author's statement, but there are a few results to be added.

[9] Gas Turbine Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.; on leave of absence from Kyushu University, Japan.

1 The end-wall boundary layer was observed to be laminar independently of the inlet boundary layer.

2 The displacement thickness of the end-wall boundary layer was not very different from the prediction based on a two-dimensional laminar boundary-layer theory. The main flow component of the shear stress was also predicted by the two-dimensional boundary-layer theory with a reasonable accuracy. The end-wall boundary layer becomes thin owing to the sweeping effect of the crossflow, but the boundary layer becomes thick because of the converging effect of the side walls (or blades). The writer suspects that in the present case these two effects almost cancel each other; that is, the agreement of the two-dimensional theory prediction is fortuitous.

3 The maximum crossflow velocity and the secondary-flow behavior near the end wall (order of 0.05 in.) are essentially unchanged by the inlet boundary layer, but the behavior outside the thin layer depends upon the inlet boundary layer; i.e., the layer with crossflow is thick if the inlet boundary layer is thick. Since the velocity defect is limited to a thin layer near the end wall, the accumulation of the low stagnation-pressure fluid carried by the crossflow is essentially unchanged by the inlet boundary layer.

4 A two-dimensional laminar boundary-layer calculation shows that the separation of the boundary layer on the suction surface of the blade is completely suppressed by a slight variation of the pressure distribution on the blade surface. As a matter of fact, an experiment showed that an inaccuracy of blade mounting was sufficient to cause the boundary-layer separation. It is expected, however, that the boundary-layer behavior on the blade-suction surface does not affect the end-wall boundary layer.

Author's Closure

In closure, the author wishes to thank Mr. Kraft and Dr. Senoo for adding their greater experience and further work on this problem to the discussion.