DISCUSSION

F. M. White[7]

The authors are to be congratulated for developing a truly simple analysis for diffuser separation prediction. Perhaps the greatest achievement is merely to show that it can be done, whereas workers in the field have apparently agreed almost unanimously that diffusers cannot be analyzed by ordinary boundary layer theory. In this respect the authors are rather like bumblebees, who fly effortlessly in spite of the fact that standard aerodynamic theory forbids them to do so. Thus I applaud their achievement without reservation; but as long as a critical discussion is called for, I would venture to criticize some of the details.

In essence, the authors have demonstrated beyond contradiction that ordinary boundary layer theory can predict diffuser separation accurately if coupled with an accurate displacement thickness computation to model the true pressure gradients. Apparently this was not known to be true. The authors have weakened their analysis by choosing a Kármán-type integral theory which has no definitive separation criterion. This flaw in the theory forced them to manipulate their computed results until an ad hoc separation criterion could be found, namely, their equation (7). I personally believe that equation (7) is strictly a *rough* criterion and should not be awarded any generality. It simply expresses the fact that the separation shape factor is "higher" if the freestream pressure gradient is "lower," which is exactly the case under high inlet blockage conditions. In fact, when plotted parametrically, the data in Fig. 3 reveal a *family* of lines for each diffuser angle 2ϕ, not the single line expressed by equation (7). For example, equation (7) would overpredict the separation length significantly for diffuser angles less than $2\phi = 6°$. Fig. 6(*c*) gives us hope for generality by demonstrating a good prediction for a 10° cone, but this occurs at $B_s = 0.3$ where equation (7) should work best for a divergence of ten degrees. Fig. 4 proves to *me* that the exact distribution of adverse pressure gradient is very important to accurate separation prediction. Equation (7) serves only as a rough upper bound. There is also a small but significant inlet Reynolds number effect which is not treated by equation (7). All of this ad hoc correlation of separation shape factors could be avoided by using an integral theory which directly predicts separation at $C_f = 0$; I know this statement to be true because I have duplicated the authors' computations with such an alternate approach.

For the moment, since reference [18] is not yet available, we must take the authors' word for it that their calculations are not dependent upon any artifacts or peculiarities in their new method. However, I disagree with their statement below Fig. 2 that the boundary layer method must be combined iteratively with the continuity relation (1) to find the true axial distribution of freestream velocity. This procedure can be avoided by first *differentiating* equation (1) before combining it with the boundary layer method, in which case the velocity distribution $U(x)$ becomes one of the unknowns and no iteration is required. That leads me to a question: were the authors' calculations confined to equation (1), or were end-wall corrections such as equation (15) used in the calculations? Are such end-wall corrections significant?

Finally, I was very impressed by the authors' predictions of the pressure distribution downstream of separation, equations (12), (13). What can we say about the future? Presently the authors' approach is essentially confined to the beginning of separation, near the *a-a* and $C_p{}^*$ lines. Can such relations as equations (12), (13) be used to extend the method into other regions such as the fully-developed bistable or jet-flow regimes? Or must we instead resort to fully elliptic numerical modeling to handle such complicated flow regimes?

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The authors present an interesting "separation-limit relation," equation (7), that is claimed to be the highest value of H for which the flow remains attached. This value of H is specified as the "limit of conventional boundary layer calculation," and the flow beyond this point is calculated assuming that it is similar to that in a free jet and by using an approximate momentum analysis. A stability analysis for a detaching flow is also presented, and the interaction between the boundary layers and the irrotational core clearly pointed out.

Although the basic concepts used in this paper appear sound, several questions arise. The "separation-limit relation," equation (7), is a calculated quantity only and has not been verified by any experimental data. The authors obtain this "correlation" by the following process, each step of which could profit from further explanation.

1 They postulate that diffusers that operate on the Cp^* line are "critical geometries for separation" and that this "line can be used as a reasonable limit of applicability of conventional boundary layer calculation."

2 For several diffusers that fall on the Cp^* line, they *calculate* the exit values of the blockage B and shape factor H. This gives the relation between H_s and B_s, equation (7).

3 Finally, they assume that for a diffuser that is *not* operating at the Cp^* line, the relation given by equation (7) locates the "separation point."

The authors also maintain that for external flows the location of the "separation point" is given by $H_s = 1.8$. This is true only for a very restricted class of flows and does not work in general. An examination of the measured data for separating flows that were presented in the 1968 Stanford Conference [22] will verify this assertion. Further justification that the separation point does not occur at a unique value of the shape factor H can be

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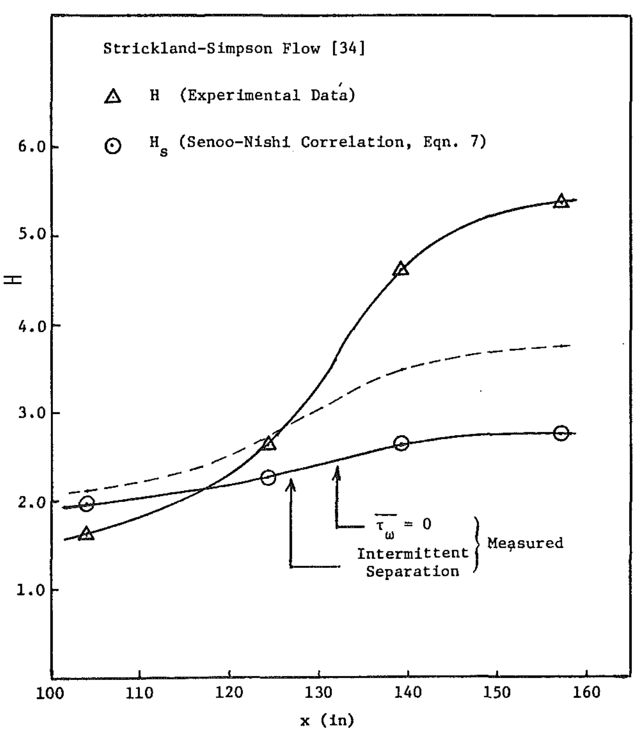

Fig. 11 Comparison of the correlation, equation (7), with the measurement of Strickland, et al. [34]. The dashed line is added by the authors as the correlation line H_s assuming asymmetry of the flow passage.

found in the paper by Cebeci, et al. [10].

In footnote 4 of the present paper, it is claimed that several calculation methods presented at the '68 Conference [1] "correctly predicted experimental distribution of boundary layer" for flows #3200 and #3800. This statement is not correct for *any* separating flows near the zone of detachment. An examination of the attempts to predict the 3800 flow, as well as *all* other separating boundary layers, shows that the typical error in prediction of H and δ^* in the separating zone is 40 to 50 percent. This is a result of *a priori* prescription of the pressure gradient, without taking the free-stream interaction explicitly into account.

It is well known [31, 32] that the classical boundary layer calculation method, where the pressure gradient is imposed upon a separating flow, does not produce reasonable predictions in the region near flow detachment. The pressure gradient for detaching flows is the result of strong mutual interaction between the boundary layer and the potential core, and both must be simultaneously calculated. For details see Ghose and Kline [33].

To illustrate the questions raised in the previous paragraphs, we have plotted the data of Strickland and Simpson [34], Fig. 11. The measured values of H and the "stall-limit relation," equation (7), are both plotted. The crossover point locates the "stall-limit" at $x = 117$ in. (2972 mm). The data indicate intermittent separation at $x = 127$ in. (3226 mm) and time-averaged zero wall shear at $x = 132$ in. (3353 mm); both of these are well downstream of that given by equation (7). Thus, instead of falling beyond the $\tau_\omega = 0$, as it should to qualify as a "stall-limit," the Senoo-Nishi equation predicts separation well upstream. We further note that the line of first stall occurs at $H = 2.9$ instead of the value of 1.8 used by Senoo and Nishi. The discrepancies between these data and the items postulated by the authors need clarification.

A last comment needs to be made regarding the use of the term "separation," which has been used in this paper in three entirely different contexts. It is used to indicate

1. boundary layer separation, i.e., flow detachment,
2. separated diffusers operating above the Cp^* line,
3. diffusers operating with local H_s and B_s values that are greater than those given by equation (7).

Since stall can involve a spectrum of shapes, as noted by the second discusser in [13], these are different phenomena and need not even occur at the same conditions. The use of the same word for all these items is therefore ambiguous and potentially misleading.

To summarize, we reiterate our belief that the proposed procedure can be a useful tool for rapid calculation of zeroth order quantities in stalled diffusers, provided the questions raised in this discussion can be satisfactorily resolved.

Additional References

31 Bower, W. W., "An Analytical Procedure for the Calculation of Attached and Separated Subsonic Diffuser Flows," AIAA Paper 74-1173, 1974.

32 Gerhart, P. M., "On Prediction of Separated Boundary Layers with Pressure Distribution Specified," *AIAA J.*, Sept. 1974, pp. 1278–1279.

33 Ghose, S., and Kline, S. J., "Prediction of Transitory Stall in Two-Dimensional Diffusers," Rept. MD-36, Thermosciences Div., Mechanical Engrg. Dept., Stanford University, Dec. 1976.

34 Strickland, J. H., and Simpson, R. L., "The Separating Turbulent Boundary Layer: An Experimental Study of an Airfoil Type Flow," T.R. WT-2, Thermal and Fluid Sciences Center, S.M.U., Aug. 1973.

Authors' Closure

The authors are grateful to Professor Kline and Mr. Ghose, as well as Professor White for their comments which help to clarify the involved problems. First of all, the authors want to make it clear that separation which they are concerned with is not a local, three-dimensional, time dependent separation but a global one which directly deteriorates the pressure recovery of diffuser. That is, they want to make a tool which is useful to design a diffuser of maximum pressure recovery. In this paper a local, three-dimensional time dependent separation is named "stall" to distinguish it from a global "separation."

It is well known that this kind of separation in diffusers is controlled by "something" in addition to the boundary layer itself and the freestream pressure-gradient. Usually the "something" is assumed as diffuser geometries such as the divergence angle, the length ratio and the area ratio. In this paper the authors propose that the "something" is the local blocakge factor of boundary layer at the section of separation.

Separation-limit relation equation (7) is certainly a calculated quantity, but equation (7) is supported by experimental data as shown in Fig. 4 and Fig. 6. Additionally Fig. 12 deduced from [12] is presented here. In the two pictures of Fig. 12 the circles with an arrow indicate the corresponding points. The top picture shows that the circle is the separation point, while in the bottom picture the circle is just on the line of equation (7).

$H = 1.8$ is not always the separation limit of boundary layer for external flow. It is just like the transition-Reynolds number of 2,320. In some cases, a pipe flow can be laminar at as high as $Re = 10{,}000$. Similarly, in cases of decelerating flow, a turbulent boundary layer is susceptible to stall and separation at $H = 1.8$, but the stall limit of H can be higher if the disturbance is very weak and the separation limit of H can be even higher if there are stabilizing structures such as adjacent vanes or walls as mentioned in this paper. Most of the experimental data presented in the Stanford Conference and others were secured in

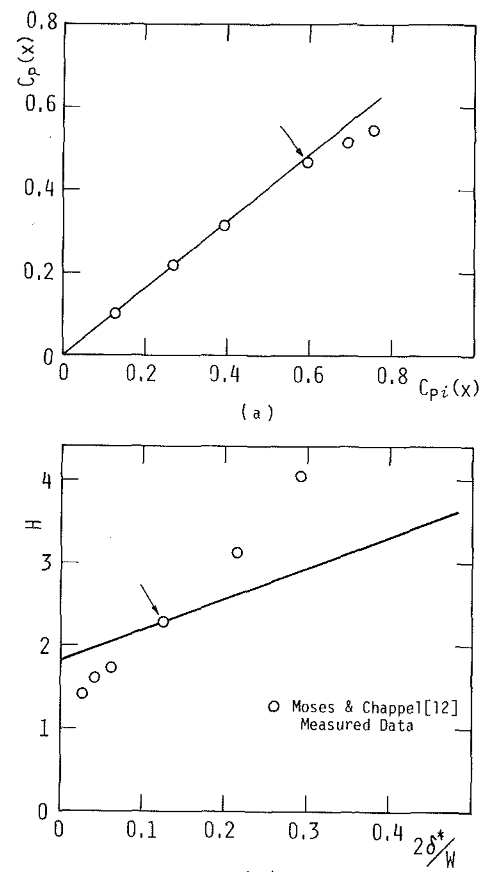

Fig. 12 Comparison of the prediction with experiment on 11.3 deg two-dimensional asymmetric diffuser [12]

test sections with opposite walls which were not far away, and they are not the data of truly external flow. One possible reason that the critical shape factor for separation was not consistent for those experiments is a difference of blockage factors which have been disregarded among them. Anyway, this paper is concerned with internal flow, and the separation criterion of external flow is not the main point of this paper.

Prediction of the boundary-layer shape factor is less accurate near a separation point although the predicted momentum thickness is fairly accurate. That is, if H is predicted larger than the true value, the displacement thickness and the blockage factor B are also large; consequently, the velocity of the core flow is larger and the calculated adverse pressure gradient is less steep. As a result, the calculated development of the boundary layer is not so fast. In addition, according to equation (7) the larger the blockage B is, the larger the H_s is, and the predicted separation point is shifted further downstream. Due to these two factors, even if the predicted shape factor is somewhat inaccurate, the influences of inaccuracy on the predicted location of the separation point and on the predicted pressure at the separation point are considerably reduced. Furthermore, the pressure gradient is usually moderate near a separation point, and the predicted pressure-recovery coefficient of a diffuser varies only a little depending upon prediction methods. On the other hand, according to experimental data, the pressure-recovery coefficients of a group of diffusers with a similar geometry are not always identical to each other. They vary a little from one apparatus to another apparatus. Therefore, prediction cannot be perfect for all diffusers with separating flow.

The authors doubt if the flow passage of Strickland and Simpson is symmetric, because the title of the paper is "An Experimental Study on an Airfoil Type Flow." If the flow passage is not symmetric, $2\,\delta^*/W$ should be used instead of the local blockage factor as mentioned in the present paper, where W is the distance between the blade surface and the opposite wall. Reference [34] is not available to the authors, and the correct distribution of H_s with respect to x is not known. If the discussers calculated the blockage factor as $B = \delta^*/W$ disregarding the thin boundary layer along the wall of wind tunnel, the blockage factor should be doubled. Under the above assumption, the authors estimated δ^*/W from the discussers' H_s-line in Fig. 11 and the correct distribution of H_s was calculated based on $B = 2\,\delta^*/W$. The results are drawn as the dashed line in Fig. 11. The crossover point of the dashed line and the line of experimental data are located at $x = 126$ in (3200 mm), which is almost identical to the measured intermittent separation point.

If separation occurs in a wide angle diffuser, the curvature of the streamline near the separation point is large and the mutual interaction between the boundary layer and the potential core is significant. However, in cases of moderate divergence-angle diffusers where flow separates but a reasonably high pressure-recovery coefficient is observed, such as $2\phi = 14 \sim 16$ deg, the curvature of the free-streamline near the separation point is not large due to the thick boundary layer displacement thickness near the separation point and the small wedge angle of the separated zone. Therefore, the influence of the boundary layer or the separated layer on the potential core is not significant other than the displacement effect, and the present method is sufficiently accurate as the first order approximation.

Professor White mentions that separation can be predicted at $C_f = 0$ by using an integral theory. Does he challenge the idea [13] that separation of diffusers cannot be predicted by boundary layer theory alone? In a wide angle diffuser, flow does not separate if splitter vanes are inserted. Although the freestream pressure-gradient should be little affected by removal of the vanes, the flow separates as soon as the splitter vanes are removed. How can such phenomenon be explained by boundary layer theory alone?

He might have misunderstood equation (7). The blockage factor in the equation is not the inlet blockage factor but the one at the separation point. Therefore, a larger blockage factor in equation (7) does not necessarily mean a lower freestream pressure-gradient.

Professor White comments that in Fig. 3 the calculated points deviate from the separation limit line equation (7). Of course, the $C_p{}^*$-line is a line representing a group of scattered points and it should be a band with a finite width. That is, the truly representative $C_p{}^*$-line may be a little higher than the one in Fig. 2. If the $C_p{}^*$-line is shifted a little upward so that it passes many of the marks in Fig. 2, then the calculated points for the 8 deg diffuser in Fig. 3 approach the separation-limit line equation (7). In the case of a 6 deg diffuser, the boundary layer parameters do not exceed equation (7) before the boundary layers fill up the diffuser, while it is well known that flow seldom separates in diffusers whose divergence angle is less than 6 deg.

Although equation (7) itself is not a function of Reynolds number, the boundary layer along the wall is influenced by the inlet Reynolds number. Therefore, flow separation is affected by the inlet Reynolds number. In all calculations in this paper, the end-wall boundary layers were included by considering the respective aspect ratio in the original papers. The results show that the end-wall effect is not significant for most cases.

The continuity equation and the boundary layer equations may be solved simultaneously. In that way one may work on his own equations rather than on well established boundary layer calculation methods. It is a matter of preference.

The calculation method of separated flow is derived for the cases beyond the $C_p{}^*$-line, and it should not be used for the cases between the a-a line and $C_p{}^*$-line in Fig. 2 where diffusers have good pressure recovery. Of course, these equations (12), (13) can be used for separated jet flow regimes, providing that the curvature of the free-streamline is not large. However, it should be noted that the pressure gradient in the separated region is inversely proportional to the displacement thickness of the separated region. That is, in cases of wide angle diffusers, pressure rise is expected only near the separation point.