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# SOME EFFECTS OF FREE STREAM TURBULENCE ON BOUNDARY LAYER TRANSITION

J.P. GOSTELOW AND R.M. RAMACHANDRAN

SCHOOL OF MECHANICAL ENGINEERING

NEW SOUTH WALES INSTITUTE OF TECHNOLOGY, BROADWAY, N.S.W. 2007 AUSTRALIA

SUMMARY Serious discrepancies exist between various predictions of transition inception under conditions of high turbulence level and adverse pressure gradient. A description is given of the problem and of a program of work oriented to its resolution. The results presented are limited to the case of zero pressure gradient and show good agreement with established data for the start and end of transition and the intermittency distribution.

## 1 NOTATION

- b diameter of bar
- c blade chord
- L length of transition
- p static pressure
- $R_L$ transition length Reynolds Number, $LU_\infty/\nu$
- $R_x$ length Reynolds Number, $xU_\infty/\nu$
- $R_\theta$ momentum thickness Reynolds Number, $\theta U_\infty/\nu$
- $T_u$ turbulence level
- U velocity in streamwise direction
- $U_\infty$ free stream velocity
- $U^+$ dimensionless velocity, $U/v^*$
- u' streamwise component of fluctuating velocity
- $v^*$ friction velocity, $\sqrt{\tau_w/\rho}$
- x streamwise distance from leading edge
- y normal distance from wall
- $y^+$ dimensionless distance from wall, $yv^*/\nu$
- $\alpha_1$ flow inlet angle
- $\gamma$ intermittency factor
- $\eta$ non-dimensional distance $(x-x_S)/(x_E-x_S)$
- $\theta$ momentum thickness
- $\lambda_\theta$ pressure gradient parameter
- $\nu$ kinematic viscosity
- $\rho$ density
- $\tau_W$ wall shear stress

Subscripts

- E end of transition, S,t start of transition

## 2 INTRODUCTION

The axial flow compressor designer needs blade surface boundary layer calculations in order to predict the loss and stall characteristics. Accurate calculations of displacement thickness are required in the throat region, for setting incidence angles, and at the trailing edge, because the pressure distribution is determined by viscous effects in that region.

For usual operating conditions the behaviour of the suction surface boundary layer determines the above parameters. A good attempt to predict measured boundary layer characteristics on the suction surface of a compressor blade by Seyb (1965) has been reproduced in Fig. 1. Any superficial impression of a satisfactory comparison is misleading; qualitative discrepancies are present which would invalidate the prediction techniques for design purposes. In the operating range between zero and 5° incidence Seyb predicted a laminar separation bubble moving forward from the 50% chord location to about 16% chord. The measurements showed the suppression of this bubble by natural transition moving forward from 63% chord to the 10% chord location. This important qualitative disparity leads to a questioning of the criteria in use for transition and laminar separation.

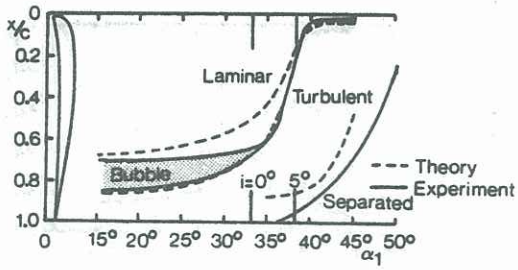


*Figure 1 Comparison between measured boundary layer development and predictions of Seyb.*

The criteria in use for transition and laminar separation by Seyb are based on the use of a plot of the Crabtree (1958) type extended to account for variations in free-stream turbulence level. Crabtree proposed a correlation of available low turbulence level data in the form of $R_{\theta t}$ against $\lambda_\theta$ defined by

$$\lambda_\theta = (\theta^2/\nu)\cdot(dU/dx). \qquad ...(1)$$

$\lambda_\theta$ is purely local criterion making no reference to the history of the flow or its stability. Walker (1968) has argued that $R_{\theta t}$ is dependent on the shape of the pressure distribution and Abu-Ghannam and Shaw (1980) have considered these 'history' effects.

To use correlations of this type one plots the locus of the developing laminar layer in the form of $R_\theta$ as a function of $\lambda_\theta$. Laminar separation would be indicated by $\lambda_\theta$ reaching-0.082 (Thwaites) or -0.09 (Curle and Skan). Assuming this limit is not encountered first then transition is predicted where the locus crosses the Crabtree curve. The approach works well for low turbulence levels; the difficulties occur in extending it to the high turbulence levels encountered in turbomachines. Turbulence levels vary between 2% and 14% in compressors, thus constituting an important independent variable. Cascade tests obtained in low-turbulence wind tunnels or with unstated turbulence levels should be viewed with circumspection.

Figure 2 presents, in an $R_\theta$ - $\lambda_\theta$ plot, the available projections for turbulence effects on the start of transition; the discrepancies are alarming.

Confidence in most results at *zero pressure gradient* is high because of the considerable research on flat plates. Further supporting evidence for zero pressure gradients will be presented in this paper. In the context of the present investigation the zero pressure gradient situation is seen as an essential vehicle for the development of techniques and as a check on the quality of the measurements.

Discrepancies exist in the *favourable pressure gradient* region. These are of concern to turbine designers. The tentative extrapolation of Hall (1968) is now considered to have too steep a slope. The measurements of Blair (1982) and Abu-Ghannam and Shaw (1980) appear to be most reliable and are in reasonable accord with calculations of Van Driest and Blumer (1963). The data of Abu-Ghannam and Shaw are the most comprehensive and fitted curves for these are presented in Fig. 2.

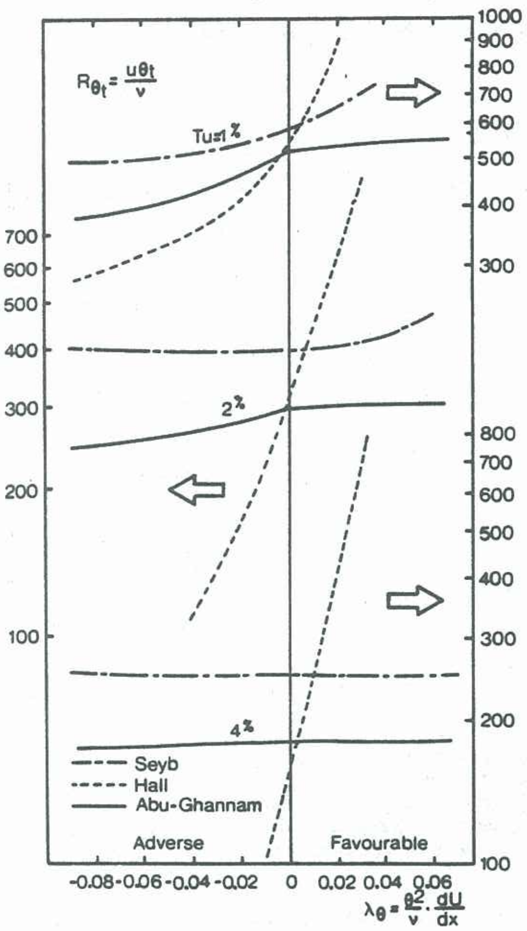


*Figure 2 Transition inception Reynolds Number as a function of turbulence level and pressure gradient parameter.*

The eventual aim of the present investigation is the resolution of the serious discrepancies in the *adverse pressure gradient* region. An important facet of the Seyb correlation is the projection of transition inception curves of constant $R_\theta$ for a range of turbulence levels under adverse pressure gradient conditions. This projection was based on nozzle test data and the heuristic argument that at high turbulence levels transition is more dependent on the inability of damping mechanisms to cope with introduced disturbances than upon the amplification of small perturbations. High turbulence levels would bring about transition regardless of the value of adverse pressure gradient. Hall used the Pretsch stability limit as a basis for his projections. His curves were reasonably compatible with available test data up to turbulence levels of 1.2%. Although their data were comprehensive at lower turbulence levels Abu-Ghannam and Shaw have given little useful information on turbulence levels above 2% under adverse pressure gradients. For these conditions there are still major uncertainties which require clarification.

## 3 A CRITICAL TURBULENCE LEVEL

The crucial question is whether there is a critical turbulence level under adverse pressure gradient conditions. Figure 3, taken from Schlichting and Das (1970), indicates that such a critical level exists. The state of the suction surface boundary layer of a NACA 65 series compressor blade is plotted as a function of turbulence level. These cascade tests by Kiock indicate the existence of a laminar separation bubble at low turbulence levels. As the turbulence level is raised above a critical level of 2.5% the bubble is suppressed and transition moves immediately to the leading edge.

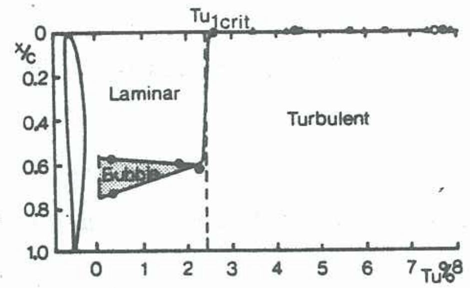


*Figure 3 State of suction surface boundary layer as a function of turbulence level.*

The concept of a critical turbulence level would provide the basis for an explanation of the failure of Seyb's theory to predict the experimental results of Fig. 1 in the incidence range from zero to 5°. The turbulence level for Fig. 1 was 2.6% making the case a sensitive one.

Unpublished work performed at Cambridge University is fully consistent with the concept of a critical turbulence level. The turbulence level was varied up to 4.5% and extensive measurements were made under adverse pressure gradient conditions. The results began to diverge from the Seyb projections at a turbulence level of 2.4%. By 3.2% the results were tending more towards the projections of Hall and at 4.5% this behaviour was firmly established. The techniques used were relatively primitive; no attempt was made to measure intermittency nor to rigorously establish the validity of the results under zero pressure gradient conditions. For this reason the results were not published but regarded as useful preliminary indications of the existence of a critical turbulence level.

The Cambridge results established that the momentum transfer was sensibly independent of pressure gradient at low turbulence levels but decreased with pressure gradient under high turbulence. The relationship between $\lambda_\theta$ and dp/dx was found to depend strongly on turbulence level. At high turbulence levels a variation in dp/dx resulted in virtually no corresponding variation in $\lambda_\theta$.

## 4 THE CURRENT PROGRAM

Following the useful preliminary work a program was established at NSWIT to provide information on transition under conditions of high turbulence level and adverse pressure gradient. The plan is to obtain data for the start of transition at various turbulence levels between 1% and 6%. In this way it is hoped to resolve the discrepancies between the different projections in Fig. 2. As part of this it is considered important to investigate the validity of the critical turbulence level hypothesis and to obtain detailed information on the transfer mechanisms. Whilst the main phase of the work will involve the systematic imposition of adverse pressure gradients for differing turbulence levels initial testing has concentrated on the zero pressure gradient situation. The objective of this first phase is to check the validity of the techniques and to obtain additional information on the start and end of transition and on transitional boundary layers under varying turbulence levels. The following paragraphs describe work already performed with zero pressure gradients.

The experiments were conducted in the 608mm x 608mm octagonal section open circuit tunnel shown in Fig. 4. Air enters through a bellmouth to the octagonal section setting chamber which contains a honeycomb for reduction of swirl and a set of screens for turbulence reduction. A smooth contraction of area ratio 3.88 precedes the test section which has a maximum velocity of 40 m/sec. The free stream turbulence level is usually 0.4%.

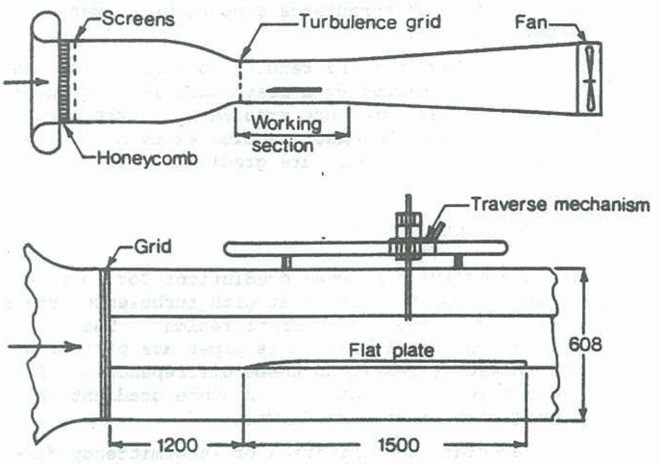


*Figure 4 The wind tunnel and test section.*

Higher turbulence levels required for this study were generated by inserting square array bi-planar grids, constructed from circular steel bars, at the entrance to the test section. Four grids were designed, using Frenkiel's (1948) relation, $u'/U_\infty = 112(x/b)^{-5/7}$, to produce homogeneous turbulence levels in the test section ranging from approximately 1% to 6%.

The boundary layer studies were made on the top surface of a flat aluminium plate of 1500 x 608 x 25mm mounted in the test section. Particular attention was paid to surface finish giving excellent flatness and smoothness. The leading edge was given an elliptical arc form (Davis, 1979) to avoid leading edge separation and was located 1200mm from the test section entrance. Static pressures were measured using centre-line tappings of 0.5mm diameter at 75mm intervals. It was found necessary to impart a negative incidence of ¼° to the plate to avoid laminar separation bubbles; this had an imperceptible effect on the pressure distribution.

A traverse was designed to carry the probe longitudinally over one metre from the leading edge and a lead-screw system was mounted on the carriage for vertical traverse. A dial gauge having a least count of 0.01mm was used for close-interval measurements of vertical movement. High intensity light was focused on the probe tip, the reflection of which on the polished aluminium plate was used for accurate positioning close to the wall.

The reference velocity was set using a pitot tube. Boundary layer traverses were performed using a 1.2 x 0.72mm flat end pitot tube in conjunction with plate static pressures. Transition measurements were performed using a DISA hot wire probe having a 1.2mm platinum-coated wire of 5 micron diameter and a DISA 55M10 C.T.A. system. The preferred method of intermittency determination has been the visual inspection of output signals recorded for the prescribed sampling time on u-v traces having a maximum paper speed of 800 mm/sec.

## 5 RESULTS AND DISCUSSION

The transition regions were identified using hot-wire measurements. The probe was located about one momentum thickness from the plate where the difference between laminar and turbulent profile is large and nearly constant. Turbulent bursts were sensed and the output signal recorded on the u-v chart. A sampling time of approximately 2.4 secs. was used except for grid-III where the signal was recorded for only 1.5 secs. The intermittency factor $\gamma$ was determined by manually measuring the proportion of time for which the boundary layer was turbulent. The transition length was determined with an accuracy of ± 15mm by traversing the probe along the plate. The variation of intermittency in the transition region was measured at different turbulence levels and these results are compared with other observations in Fig. 5.

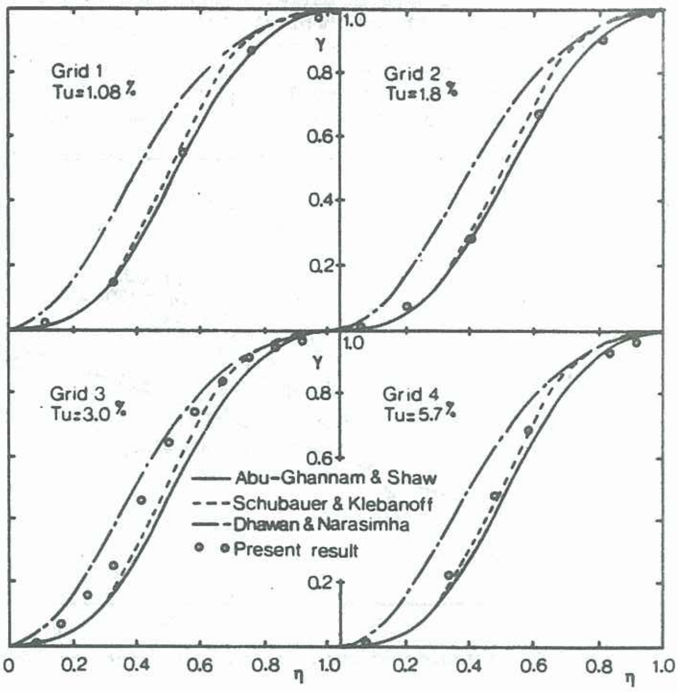


*Figure 5 Variation of intermittency factor in transition region.*

The present results are seen to be in good general agreement with others. The scatter of results for grid-III can be attributed to the relatively short sampling time employed. Abu-Ghannam and Shaw report that the difference between their intermittency curve and previous observations is due to the short sampling time employed by other authors. However accuracy depends not only on the sampling time but also on the accuracy of estimation of transition length. One may easily misjudge the end of transition, due to the presence of very small laminar regions even in fully developed turbulent layers. Uncertainty in locating the end of transition is indicated by the scattered result of Abu-Ghannam and Shaw (Fig. 7).

Boundary layer integral parameters were determined from mean velocity traverses at five locations corresponding to $\gamma = 0$, 0.25, 0.5, 0.75 and 1.0, for each grid turbulence level. These results were plotted on a semi-log graph to compare with the established "law-of-the-wall"

$$U^+ = 2.44 \ln y^+ + 5.0 \qquad \ldots(2)$$

A sample result given in Fig. 6 shows that at $\gamma = 0$, the boundary layer is fully laminar with $U^+ = y^+$ for $y^+ \leq 27$. The velocity profile changes from laminar to a fully turbulent shape as the intermittency factor increases. With an intermittency factor close to one, the velocity profile exhibits a nearly turbulent shape following the law-of-the-wall. For $\gamma = 0.98$ the data have not quite reached the law-of-the-wall line indicating that this location corresponds to the uncertain region at the end of transition.

Reynolds Numbers based on length and momentum thickness for the $\gamma$ values plotted in Fig. 6 were calculated and plotted against turbulence level in Fig. 7. This figure also includes the results from some other sources. These data show the forward movement of transition with increasing turbulence level. The present measurements for the beginning of transition are in good agreement with the theoretical predictions of Van Driest and Blumer and experimental observations of Abu-Ghannam and Shaw, except at very low turbulence level. The deviation at low turbulence level may be due to the effect of leading edge curvature and surface roughness. Blair also obtained good agreement with the predictions of Van Driest and Blumer for onset of transition under zero and favourable pressure gradients. Blair noted that his results were in marked disagreement with the projections of Hall and Gubbings (1972). Only sparse data are available for the end of transition especially at high turbulence levels. The present results are compared with the scattered data of Abu-Ghannam and Shaw and the present result matches the lower band of the scatter.

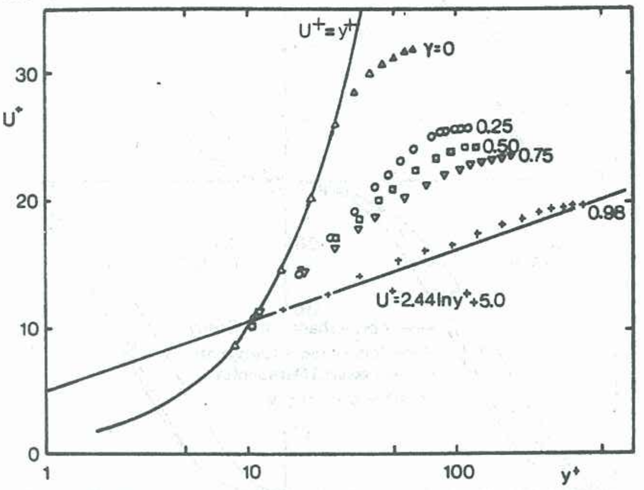


*Figure 6 Variation of semi-log plot with intermittency.*

Dunham (1972) drew on the results of Dhawan and Narasimha to show that the transition length $R_{L\gamma}$ for $0.25 < \gamma < 0.75$ is only 30% of the total transition length. It is of interest to assess the validity of this proportion for higher turbulence levels. Dhawan and Narasimha have defined $R_{L\gamma}$ as a function of Reynolds Number $R_{xs}$ at the start of transition, $R_{L\gamma} = 5R_{xs}^{0.8}$. For total transition length $R_L = 3.36R_{L\gamma}$.

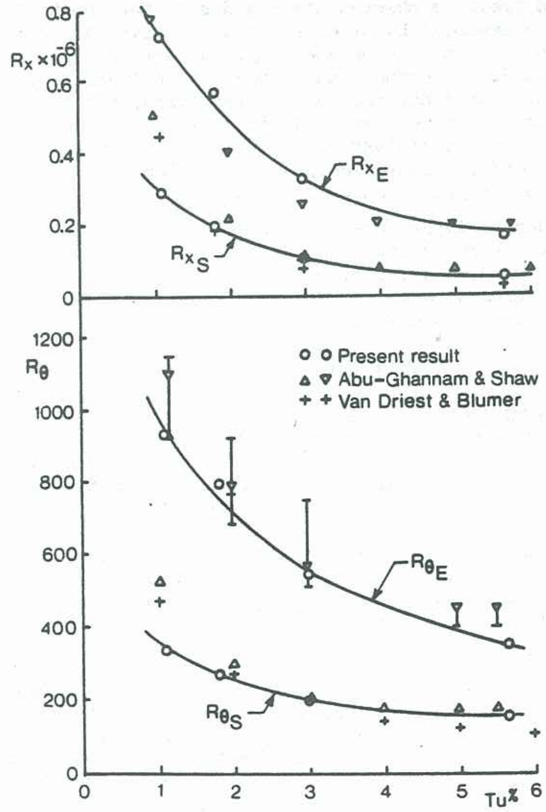


*Figure 7 Effect of turbulence on Reynolds Number at start and end of transition for zero pressure gradients.*

The measured values of $R_{L\gamma}$ were 4% above those of Dhawan and Narasimha for Grid I, 21% above for grid-II and in agreement for grids-III and IV. This is another confirmation of the adequacy of the above relations for high turbulence conditions at zero pressure gradient.

It is considered that the results obtained place the measurement techniques on a reasonable footing under conditions of zero pressure gradient. In the next phase of the work the discrepancies existing in predictions for adverse pressure gradients will be directly addressed.

## 6 CONCLUSIONS

Discrepancies exist between predictions for locating the inception of transition at high turbulence levels in the adverse pressure gradient region. The investigations reported in this paper are part of a program aimed at resolving these discrepancies. From the measurements made at zero pressure gradient the following conclusions are drawn:

1. The accurate determination of intermittency distribution in the transition region depends on the data sampling time and the accuracy of measurement of transition length.

2. Comparison of the present data with the theoretical prediction of Van Driest and Blumer and experimental observations of Abu-Ghannam and Shaw for locating the onset of transition confirms the correlations of those authors.

3. The present result also confirms the adequacy of the correlations by Dhawan and Narasimha and Abu-Ghannam and Shaw for prediction of transition length and end of transition respectively.

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