Effects of free stream turbulence on the distribution of heat transfer around turbine blade sections

W. J. Priddy* and F. J. Bayley†

Local convective heat transfer coefficients to a number of modern gas turbine blade sections have been measured under a wide range of mainstream conditions, from notionally steady flows to highly perturbed turbulent flows. The paper discusses the results and, through a detailed analysis of the pertinent boundary layer flow parameters and their relation to the observed experimental results, tests criteria for the occurrence of transition from laminar to turbulent boundary layers, a factor which all the data from this work confirm as critical in predicting the quantitative effects of mainstream turbulence on heat transfer rates. Artificially induced mainstream turbulence, which is endemic in the flows in a real turbine, enhances significantly the heat transfer rates, especially to the leading edge regions and on the pressure surface, particularly when the acceleration is tending to suppress transition. The results presented here confirm existing criteria for laminarisation and the applicability of some of those available for predicting laminar-turbulent transition. The observations also demonstrate how surface geometry can influence the stability of the flows, and the uncertainties which remain in assessing the effect of Goertler vortices and their role in the convective heat transfer process

Keywords: *turbomachinery, turbine blades, heat transfer, vortices*

Currently, the designer of turbine blade cooling systems is ill-equipped to predict precisely the distribution of heat transfer around turbine blades. This is so despite the substantial research effort in the field in recent years and the concomitant wealth of literature on the subject which now exits.

Ignorance of the details of the flows within the harsh environment of the turbine has meant that theoretical studies, and experimental simulations of the flows and heat transfer within representative test sections, have not reproduced all the characteristics of the real engine which determine the convective heat transfer to operating blades. In particular, the mainstream flow in a turbine is highly unsteady and turbulent, and it is well known that turbulence can augment the convection process significantly. There is doubt, however, about which parameters define quantitatively the turbulent and unsteady flow, and about how to reproduce them in order to determine which are the most critical in effecting the true convective heat transfer rate to a blade surface. Certainly, the amplitude or intensity of the turbulent velocity fluctuations is recognized as a principal parameter, but the effects of several other quantities, such as scale and frequency, are less well understood. Theoretically, Ishigaki[1] has shown that an increase in the frequency of a harmonic perturbation, as well as amplitude, can raise the level of heat transfer through a laminar boundary layer. This could be important in the turbine, where the blades are subjected to a periodic unsteadiness as they pass in relative motion through the wakes shed from the upstream rows[2], and where they can exhibit large areas of laminar boundary layer flow at the Reynolds numbers at which they operate.

In a continuing programme of research at Sussex University, turbulence and wake passing unsteadiness have been simulated upstream of a stationary cascade of blades using a novel form of turbulence generator. In the early stages of the work[3] the turbulence intensity or amplitude of velocity fluctuation, the frequency spectrum, and turbulence scale and power were systematically varied to observe their separate influences on the heat transfer to a modern rotor blade section. An effect of the wake passing frequency, in particular, was apparent in addition to the expected effect of intensity or amplitude of velocity fluctuation. These effects, however, were observed at levels of unsteadiness and turbulence much higher than would be expected in the turbine upstream of the blades, and frequencies somewhat lower than those associated with the passing rates of rotating blade rows. Consequently, to concentrate on the effect of intensity and frequency of perturbation in particular, the turbulence generator was modified and tests were performed with perturbations to the flow more appropriate to perceived engine conditions[4,5]. These tests, discussed here, have shown less clearly defined frequency effects. Also presented are further heat transfer results from cascades placed downstream of conventional turbulence generating grids used to produce an alternative structure of turbulent flow.

This study, of the effects of turbulence and un-

* Technical Engineer, Rolls Royce and Associates, Derby, UK; formerly Research Fellow in Mechanical Engineering, University of Sussex
† Department of Mechanical Engineering, University of Sussex, Falmer, Brighton, Sussex BN1 9QT, UK
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steadiness on turbine blade heat transfer, has emphasised the need for a much greater understanding of the basic boundary layer before it will be possible to predict the heat transfer distribution over a blade surface accurately. Therefore, more recently the research programme has concentrated on understanding the development of the boundary layer over turbine blades. The findings of an analysis performed for seven different blade profiles in steady flow are reported, with especial attention given to the problem of boundary layer transition. The different regimes of the boundary layer, laminar or turbulent, as is well known, will respond differently to free stream turbulence, as indeed our measurements of heat transfer rates confirm, and prediction of transition is thus crucially important. Yet, surprisingly, despite numerous papers on the subject, the process of transition to turbulent boundary layer flow on turbine blade surfaces is not fully understood and there are no established criteria available for its prediction. In this paper several criteria proposed for the onset of boundary layer instability and transition are tested against the experimental observations. As a result, understanding of the mechanisms of transition on the highly curved convex suction and concave pressure surfaces of turbine blades is extended and some criteria confirmed.

Turbulent flow heat transfer

Heat transfer measurement

Two separate procedures for measuring the distribution of convective heat transfer coefficient around a blade section have been developed and used at Sussex in the Thermo-Fluid Mechanics Research Centre. The first method, and still necessary for testing metal blade sections at representative temperatures, involves the measurement of blade surface temperature at a number of stations. Numerical solution of the Laplacian conduction equations with internal boundary conditions set by the cooling arrangements then yields the distribution of heat transfer coefficients around the blade surface. This technique was developed, and fully described, by Turner[6].

The second technique uses the blade section reproduced as a shell in a low conductivity metal-plastic composite material: measurement of the inner and outer shell surface temperatures gives a direct measurement of the local rates of heat transfer. This technique is much less demanding of computer time than the first and is convenient for rapid testing of blade sections over a wide range of varying conditions, as required in the present programme. Data obtained by the two methods from a representative blade section are critically compared, and the 'shell' technique described more fully elsewhere[7].

Turbulence generation

Various means have been employed to subject a number of different blade sections to turbulent flows of 4–32% turbulence intensity, above the unperturbed stream level of 0.5%. To yield a nominal turbulence intensity of 17%, a 16 mm pitch mesh of 5 mm wide steel strips has been placed 90 mm upstream of the leading edge of the instrumented blade. This was measured with hot-filament anemometry in the absence of the cascade of blades, and is a value believed representative of the turbine. Lower levels of 4% and 8% nominal turbulence intensity, and more typical of the majority of the research reported elsewhere, have been achieved using a perforated plate placed at distances of 240 mm and 90 mm respectively from the blades. The plate consisted of staggered rows of 9.5 mm diameter holes spaced at 11 mm pitch between holes.

A less conventional procedure for generating mainstream turbulence has been developed at Sussex with the object of separately varying the characteristic frequencies and amplitude of the velocity fluctuations. The device developed, in essence, comprises a circular cylinder of equispaced bars, a so called 'squirrel cage'. The cylinder of circular bars or rods rotates about an axis

Notation

A_1, A_2	Cascade inlet and throat areas respectively
a	Start of concavity
c	Diameter of leading edge
G_θ	Goertler number, $(Re_\theta(\theta/r)^{1/2})$
h	Local heat transfer coefficient
I	Cumulative amplification factor, $=\int_a^x \beta\,dx$
k	Thermal conductivity
K	Acceleration parameter, $(\nu/U^2)\cdot(dU/dx)$
le	Leading edge
$\dot{m}$	Mass flow rate through cascade tunnel
M	Mach number
N	Rotational speed
Nu	Nusselt number
Nu_D	Nusselt number at stagnation point, $(hD/k(T_0))$
Nu_x	Local Nusselt number, (hx/k)
Pr	Prandtl number
r	Radius of surface curvature
R	Recovery factor
Re_2	Exit Reynolds number based on chord, $(\dot{m}c/A_2\mu(T_2))$
Re_D	Reynolds number based on leading edge diameter, $(\dot{m}D/A_1\mu(T_0))$
Re_x	Local Reynolds number (Ux/ν)
Re_θ	Momentum thickness Reynolds number, $(U\theta/\nu)$
Tu	Turbulence intensity, $((\overline{u'^2})^{1/2}/U)$
T_0	Gas total temperature
T_2	Cascade exit temperature
U	Streamline velocity
u'	Streamwise velocity fluctuation
V_2	Cascade exit velocity, $(\dot{m}/A_2\rho_2)$
x	Surface distance from blade leading edge
β	Disturbance amplification factor
λ	Wavelength of Taylor-Goertler vortices
λ_x	Pohlhausen pressure gradient parameter, $(\theta^2/\nu)\cdot(dU/dx)$
θ	Boundary layer momentum thickness
μ	Dynamic viscosity
ρ_2	Gas density at cascade exit
ν	Kinematic viscosity
∞	Subscript for approach flow condition

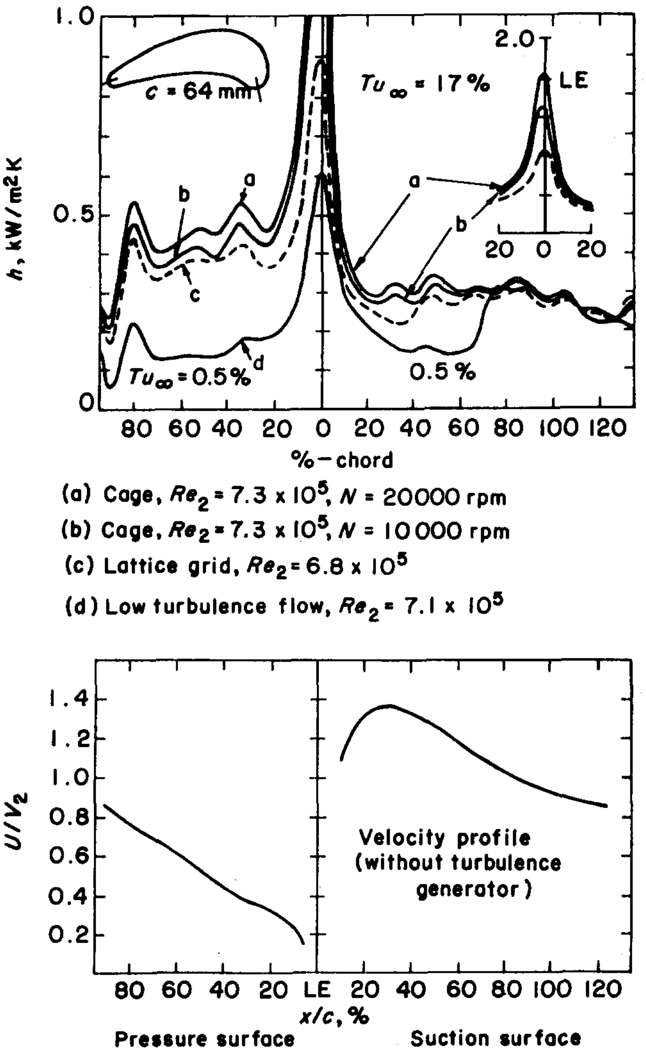

Fig 1 Effect of turbulence on local heat transfer coefficients measured on a rotor blade

parallel to the blade span ahead of the cascade. This was thought to produce more closely the conditions in a turbine in which the perturbations are due, partly at least, to passing blade wakes. The turbulence intensity is controlled by the diameter and spacing of the bars of the cage, and its distance from the blade cascade, and the blade or bar passing frequency, up to 10 kHz here, by the rotational speed and the number of bars. The results presented here are from tests using a single cage consisting of thirty bars, 2.4 mm in diameter and pitched 6.1 mm apart. The operating characteristics of the squirrel cage turbulence generator[3–5,7] show that a dominant bar passing frequency in the power spectrum and the turbulence intensity (up to 32% in the current programme) can be varied independently of each other and of the flow rate.

Results

Figs 1 and 2 show some typical results obtained by the procedures described in this section of the paper and the velocity profiles corresponding to the blade sections shown. Local heat transfer coefficients around a rotor blade section are given in Fig 1, where the two upper curves correspond to tests with the squirrel cage. The cage was placed 32 mm ahead of the blade leading edge resulting in the nominal turbulence level of 17%, and was driven at 10 000 and 20 000 r/min to yield respective characteristic bar passing frequencies in hertz of half these values. The third heat transfer curve corresponds to a test downstream of the conventional mesh grid, and the fourth, the lowest, was obtained in unperturbed flow. Fig 2 shows local heat transfer coefficients taken from a nozzle guide vane section which was exposed to steady flow and then to streams perturbed by each of the conventional turbulence grids in turn.

Both sets of heat transfer curves were obtained from shell models of the respective blade section, and both testify to the very significant effect of the turbulence on the pressure and leading edge surfaces in particular. On the pressure surface of the rotor blade profile of Fig 1, for example, the nominal intensity level of 17% has resulted in a trebling, almost, of the heat transfer above that for steady flow.

Unfortunately, the squirrel cage turbulence generator distorts the time mean flow field in the cross-section plane (normal to blade span) to a degree dependent upon its rotational speed. It is, therefore, not possible to discern the clear frequency effect observed at higher intensities from these results since the observed influence of cage speed on heat transfer could be attributable to slight changes in velocity profile. Any effect of frequency at these lower intensities is certainly small, a fact compounded by the observation[4,5] of a weak characteristic frequency spike corresponding to bar passing rate relative to the remainder of the power spectrum at 17% turbulence intensity. Indeed, the bar passing influence has only appeared clearly significant[3] in the turbulence spectra for rms intensities of well above 20%. This would

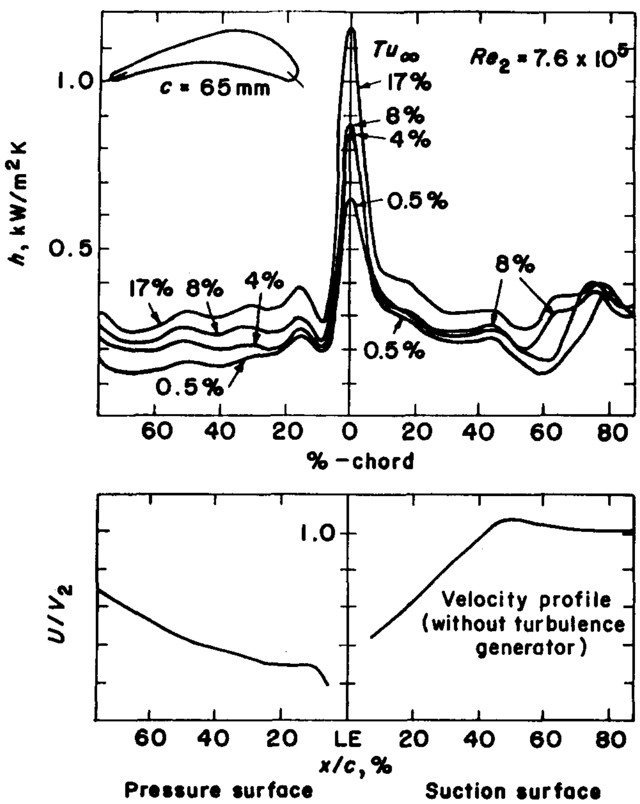

Fig 2 Effect of turbulence on local heat transfer coefficients measured on a nozzle guide vane

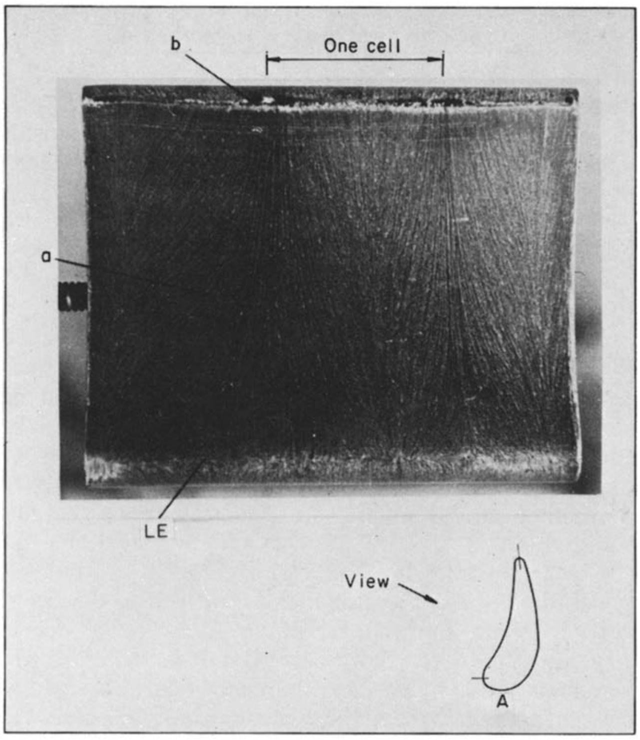

Fig 3 Flow visualisation on the pressure surface of rotor blade A using paint downstream of the lattice turbulence grid: (a) 3-dimensional flow consequences of the lattice producing the 17% turbulence level; (b) trailing edge separation; $Re_2 = 7.2 \times 10^5$

suggest that, at fluctuation levels believed representative of the engine, (10 to 20%), the squirrel cage produces predominantly what is usually regarded as 'turbulence' in the flow over the blade, rather than unsteadiness associated with passing wakes.

Despite the distortion to the approach flow induced by the cage, flow visualisation by the surface oil technique[8] has shown the same basic streamline flow pattern as observed in steady flow over the blade surface, that is, substantially two-dimensional flow with the usual secondary end-wall effects. The same cannot be said of the lattice when placed for turbulence intensities as high as 17%. Close to this grid, the wakes downstream of its coarser elements apparently induce a three-dimensional streamline flow within the blade passages, as may be seen in Fig 3. This shows the patternproduced by the surface oil technique on the pressure side of the rotor blade section of Fig 1. A mixture of vacuum pump oil and Titanium dioxide powder (2 ml oil to 1 gram powder approximately) was brushed onto the surface of a replica blade section painted black. The white pigment within the surface oil film is sheared in the direction of flow to form a pattern of streaks. In Fig 3, the pattern is indicative of a cellular structure of vortices through the blade channel. The reason for the differences between the leading edge peak heat transfer rates in Fig 1 at the different conditions, therefore, cannot be clearly explained. They may be due to differences in the basic streamline flow field as well as in structure of turbulence and frequency of unsteadiness upstream of the blade. Nevertheless, over the remainder of the rotor blade section the similarity of the turbulent flow heat transfer curves is noteworthy, as is that of the shapes of the guide vane distributions in Fig 2 for the different turbulence grids. This observation suggests that the primary convecting flow around a blade is determined largely by its profile geometry, irrespective of the flow structure in the approach stream to the cascade.

The nature of the heat transfer curves produced from the present experimental programme suggests that the large response to mainstream turbulence on the pressure side and at the leading edge is that of a basically laminar boundary layer. On the suction surface, a sharp transition has generally occurred in the low turbulence, unperturbed stream, as demonstrated at sixty per cent chord in both Figs 1 and 2 for those particular aerofoil sections. Further downstream of this transition all the heat transfer data have shown virtually no response to turbulence in the free-stream. Flow visualisation by the technique already described has confirmed that the sharp transition on the suction surface of the rotor blade of Fig 1 in steady flow is certainly associated with a separation bubble, as discussed below. In the high level turbulence produced by the squirrel cage, these flow visualisation experiments have further confirmed that this boundary layer separation is avoided, so that transition must have advanced towards the leading edge; most of the boundary layer along the suction surface, therefore, becomes turbulent in the presence of the cage. Transitional behaviour has been evident from the heat transfer distributions of the rotor blade of Fig 1 on its pressure surface also, in low turbulence flow but only at the highest flow rates achievable through the cascade tunnel. This observation is discussed later. The squirrel cage turbulence generator restricted the flow rate to below the highest steady flow levels and, unlike the suction surface, the enhancement of heat transfer to the pressure surface, as on the leading edge, continued to increase with the turbulence level even up to the highest nominal intensity achieved of 32%[4].

Over the forward convex suction region of the nozzle guide vane, where the free-stream flow accelerates (Fig 2), all the heat transfer curves exhibit laminar-like behaviour, apparently ahead of a transition, but show little response to mainstream turbulence. The 17% turbulence curve is an exception, but this level of turbulence is associated with the coarse lattice grid and, therefore, with the uncertainties about the three-dimensional streamline flow it produces as discussed above. This is compared to the significant response, already noted, of the concave pressure surface and of the stagnation region at the leading edge, where the free-stream flows at the boundary layer edge are also subject to acceleration. Such a variation in the response of these distinct regions of the aerofoil surface shows that the nature of the local streamline flow field relative to the wall is an important factor in determining the interaction of the boundary layer with external turbulence. Certainly, streamline curvature is widely known to influence the boundary layer, rendering it more unstable on a concave wall and less unstable on a convex wall.

There is evidence[9–17] to suggest that Taylor-Goertler vortices could influence the boundary layer on pressure surfaces of turbine blades and that a similar type of instability exists in the leading edge stagnation region. Indeed, the cellular vortex pattern (Fig 3) observed in the flow visualisation experiments and induced by the periodicity due to the wakes shed from the lattice described above could be a large scale form of the roll-cell condition predicted by Sutera *et al*[12,13]. Their prediction is for a two-dimensional stagnation flow subjected to a spanwise sinusoidal periodicity in the approaching stream. In this experimental programme, pitot traverses and laser doppler anemometry showed 30% peak to peak variations in velocity 90 mm downstream of the lattice turbulence grid. The two flows are similar in that velocity decreases towards the concave side of the primary streamlines. Kestin and Wood[16] have argued that the effect of free-stream turbulence on heat transfer to the stagnation region is indirect, in that it merely intensifies the action of the already present roll-cell mechanism. Clearly, the basic behaviour of the boundary layer and its immediate free-stream flow, in all regions of the aerofoil surface, must be established before the interaction with mainstream turbulence can be understood.

A further important factor to be considered in the interpretation of these results is the development of the free-stream turbulence around the aerofoil. An experimental study of this aspect has been made during the current research programme but is beyond the scope of this paper. Any amplification or decay of the velocity fluctuations could affect the enhancement of heat transfer locally, and such effects would clearly need to be incorporated into the predictions of the blade designer.

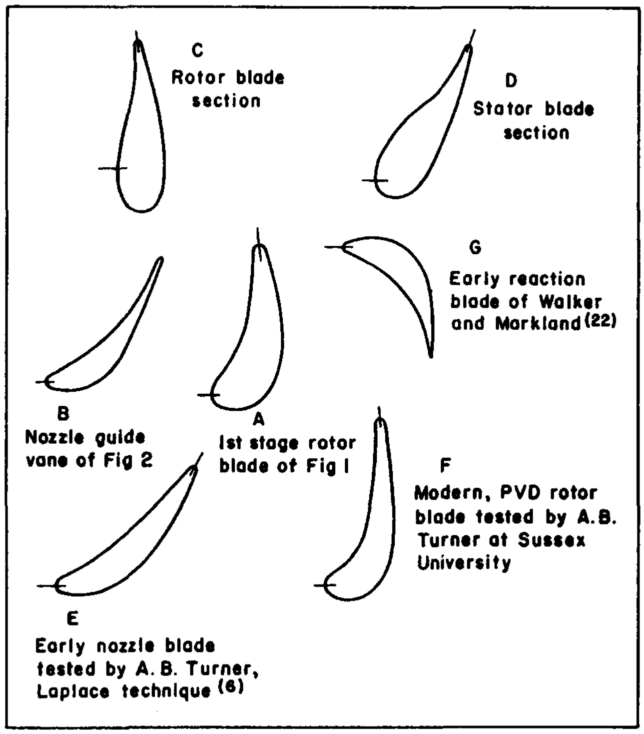

Fig 4 Aerofoil sections examined

Boundary layer analysis

The analysis of turbulent flow heat transfer given above clearly demonstrates the importance of the location of boundary layer transition in determining the effect of mainstream turbulence on heat transfer. In some laminar regions the enhancement due to turbulence was significant, whereas downstream of transition there was virtually no effect. Furthermore, the location of transition could vary with the turbulence level, causing enhancement compared to the low turbulence stream by extending the turbulent portion of the boundary layer.

Prediction of transition is, of course, crucial in determining the heat transfer coefficient distribution around turbine blades, whether or not these are subjected to mainstream turbulence. Yet there appear to be no established criteria in the huge amount of literature on the topic of transition which enable the designer to make reliable prediction of its occurrence on turbine blade surfaces. Additionally, it was apparent from the heat transfer measurements presented above that the response of the boundary layer to freestream turbulence is dependent upon the nature of the streamline flow field at the blade surface locally. Taylor-Goertler vortices are widely recognized as a possible influence on the concave pressure surface. This instability, however, has not received sufficient attention to establish if and when vortices occur on turbine blades or to predict heat transfer and transition in their presence. In view of their importance, the cascade experiments performed during the course of this research programme have given the opportunity for some of the theories and empirical correlations relating to transition and Taylor-Goertler instability to be tested against a large amount of experimental flow and heat transfer data. Six different blade profiles have been tested at Sussex (Fig 4), five of them by the thin-shell technique. As a first step, the heat transfer coefficients of all these profiles measured in unperturbed flow have been examined, along with their surface pressure data, to analyse boundary layer behaviour. Some specific examples follow to summarise the analysis so far.

The necessary free-stream velocity profiles from which the calculations proceed have been derived from pressure-tapped aerofoils assuming one-dimensional isentropic flow. Examples are the velocity profiles for the rotor and stator blades shown in Fig 1 and 2 respectively. A full description of the technique to measure surface pressure is given elsewhere[5]. Basically, tappings of 0.5 mm diameter were employed, with approximately ten equispaced orifices each side of the aerofoil, placed in the central one third region of its span.

As a beginning, the heat transfer coefficients were compared with the simplest flat plate predictions for laminar and turbulent boundary layers, and at the geometric leading edge, with Lin's correlation[18] for the forward stagnation point of a circular cylinder. Such comparisons clarify which regions of the boundary layer are basically laminar and which are turbulent. Fig 5 is an example showing the analysis for blade A tested by the thin-shell technique.

For this figure the experimental heat transfer coefficient at the leading edge has been corrected to allow for the first order term containing the second derivative of temperature and the error inherent in the one-dimensional thin-shell assumption. This error can become significant at the leading edge. Estimates[5] have shown the thin-wall assumption to result in an underestimate of the leading edge heat transfer by as much as 8%. The agreement between theory and thin-shell wall measurement at the geometric leading edge is good considering that the stagnation of the flow impinging on the asymmetric aerofoil section does not strictly coincide with this point.

The experimental heat transfer coefficients in Fig 5 have been defined according to an adiabatic wall temperature based on the theoretical recovery factor for a

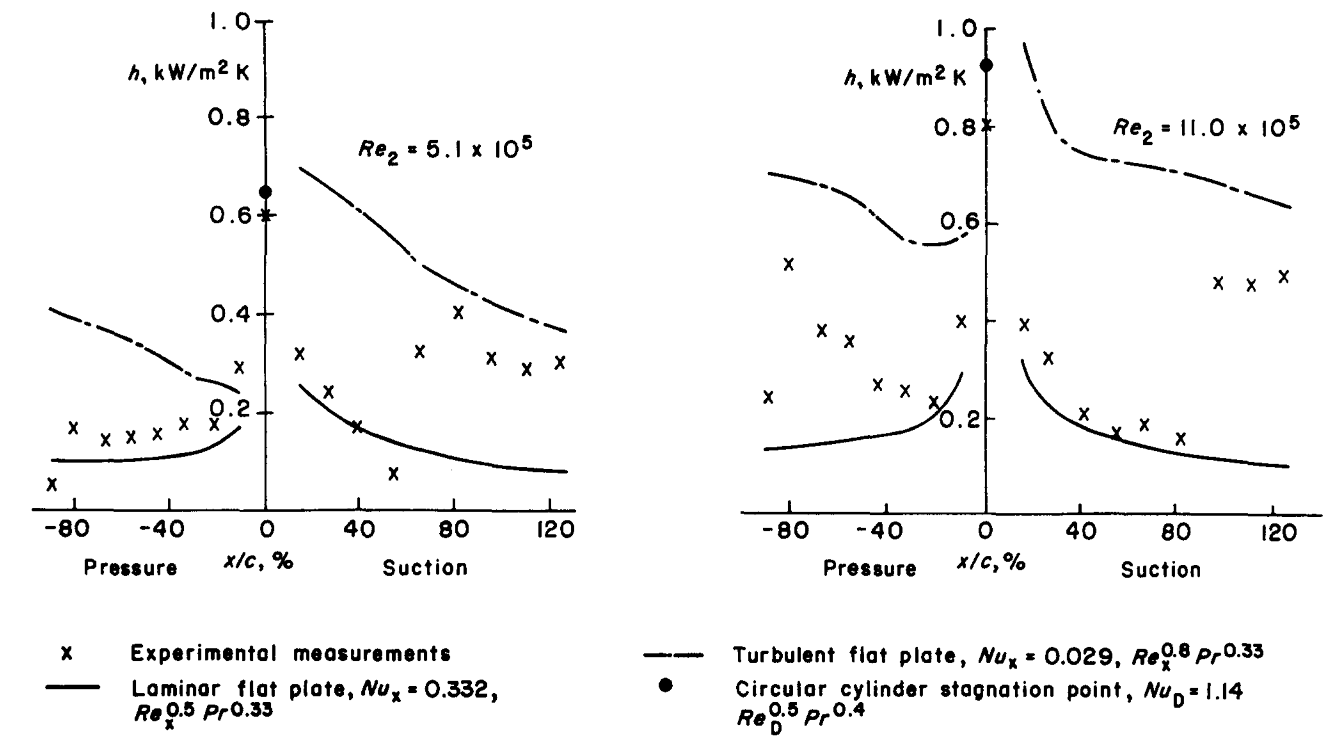

Fig 5 Local heat transfer coefficients in low turbulence flow

laminar boundary layer on a flat plate ($R = 0.84$). Also, the local Nusselt and Reynolds numbers in the theoretical equations were evaluated using the gas properties at a local film temperature defined by Eckert (see page 241 of Ref 19, equation 7–2). Measured surface temperature and velocity profiles were employed to calculate the film temperature in this way.

Generally, on the pressure surfaces of the aerofoils examined, the whole of the boundary layer has, in most cases, appeared laminar but the corresponding flat plate prediction has underestimated the heat transfer by 30–50% under these conditions. In contrast, a sharp transition has been observed in all cases on the suction surface, but in the laminar region upstream; agreement with theory was generally better than for the pressure surface (Fig 5). Further comparisons for some of the other blades are given elsewhere[6,20]. In a few instances, at the highest Reynolds numbers tested, much of the boundary layer on the pressure surface has appeared to be in a transitional state.

Further examples of these observations are now compared separately for the suction surface and the pressure surface with some available criteria for boundary layer instability. Throughout the analysis, the momentum thickness has been determined from the velocity profile data using the well known equation of Thwaites[21] for laminar boundary layers.

Suction surface

Fig 6 shows graphs of heat transfer coefficient, the Pohlhausen pressure gradient parameter, and momentum thickness Reynolds number versus surface distance as measured from the geometric leading edge and expressed as a percentage of the true or plan chord. The curves correspond to an early nozzle blade (blade E) and to a rotor blade, section C, modelled as a thin shell. The sharp rise in heat transfer in each case is located in the region of

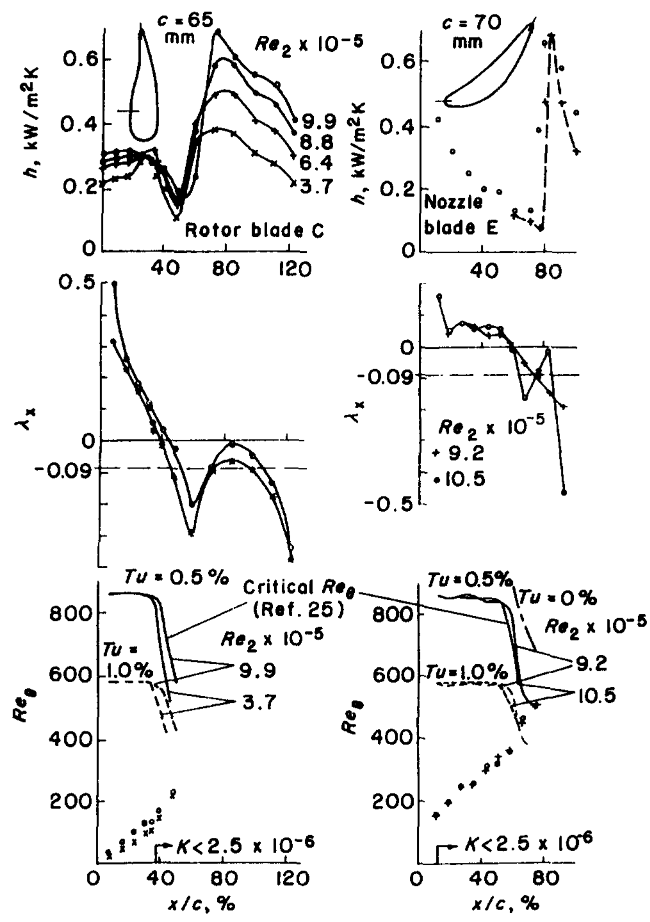

Fig 6 Transition analysis: suction surface

adverse pressure gradient (λ_x negative) and is preceded by a dip in heat transfer.

This behaviour has been observed on the suction surfaces of all the blade sections tested and was reported much earlier by Walker and Markland[22] who attributed it to separation of the laminar boundary layer on their blade. According to Dunham[23], an accepted criterion for incipient separation is that the pressure gradient parameter, λ_x, should fall below -0.09; the analytical basis of this criterion is given in Ref 24. Nearly all the Sussex data comply closely with this criterion independently of flow rate, as exemplified in Fig 6.

Thus, it is concluded that separation of the laminar boundary layer is responsible for the sudden rise in heat transfer observed on the suction surfaces. The localised dip in heat transfer is, by Reynolds analogy, accompanying the skin friction tending to zero at the separation. The rise in heat transfer caused by, so called, 'natural' transition is usually more gradual, the development into a fully turbulent boundary layer occupying a finite region along the surface.

Momentum thickness Reynolds number, Re_θ, in Fig 6 is compared with the correlation of Abu-Ghannam and Shaw[25] for natural transition. Their analysis, which combined the results of their own extensive experimental programme with much of the best earlier work, led to a comprehensive correlation applicable over a wide range of flow conditions, making good many of the deficiencies of earlier proposals. The judgement that Abu-Ghannam and Shaw's correlation for the onset of natural transition was the most effective currently available has been subsequently confirmed by the experimental results of Blair[27]. The critical momentum thickness Reynolds number for the onset of transition according to the prediction is sensitive to free-stream turbulence intensity up to a level of 5%. However, with the observed level of less than 1% in the free-stream locally to the suction surface in the low turbulence unperturbed flow, Fig 6 suggests that natural transition might be expected to commence close to the observed separation. In the vicinity of transition in Fig 6, Re_θ is approaching the critical curves which drop rapidly on reversal of the pressure gradient as represented by λ_x. These plots are typical of all the blade sections examined. From this, it might not be unreasonable to expect a short separation 'bubble'.

In fact, this has been confirmed directly by the flow visualisation technique, described above, for the sections to which it has been applied (blades A and D). Fig 7 shows the pattern produced on the suction surface of rotor blade A in low turbulence flow, using a similar paint mixture as was used to produce Fig 3. These photographs show a separation 'bubble line' across the span, except near the end-walls, which has shifted rearward with increase of flow rate. The tendency is for paint to agglomerate at separation, where the shear flows at the surface converge from opposite directions, from upstream, and from downstream under the recirculation zone. At reattachment the surface shear flows diverge, thus scouring the paint locally. The success of the technique depends on a number of factors, but in particular on the local rate of shear and the paint mixture used. In the upper part of Fig 7, for low flow rate, slightly too much paint has been used and has accumulated towards the trailing edge in the time for which it was exposed to the flow. Below, for the higher flow rate, an increase in consistency of the paint to allow for the increased shear rates has been overdone, and the pigment has not run so readily. Too little oil has been applied to the surface of the blade and has dried within the exposure time to leave a less clearly defined pattern of the flow. Nevertheless, in both photographs the bubble transition, and indeed the secondary end-wall phenomena, are clearly identifiable.

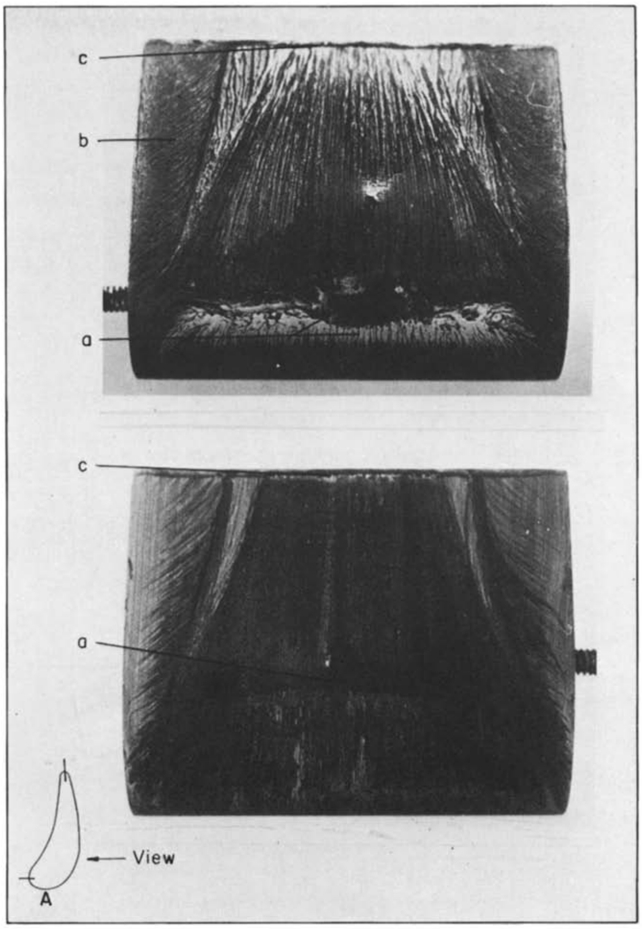

Fig 7 Flow visualisation on the suction surface of rotor blade A using paint in steady flow. Top: $Re_2 = 4.3 \times 10^5$; *(a) the agglomerated spanwise band of pigment and immediate scouring downstream indicate bubble transition*[8]; *Bottom:* $Re_2 = 11.0 \times 10^5$; *the separation band has shifted rearward. The pattern is less clearly defined but the results are highly sensitive to the paint mixture, flow rate, local surface shear, etc. The salient features include the secondary wall effects (b) and trailing edge separation (c)*

Suction side heat transfer coefficients for blade A in the undisturbed mainstream are shown in Fig 8. These clearly show the shift of transition at the higher flow rates confirmed by the flow visualisation experiment and may be compared with the observations on blade D. Such a shift of the bubble transition has only been observed when the free-stream flow becomes supersonic locally, as indicated by the lowest plots in Fig 8 of Mach number. It is suggested that a shock boundary layer interaction is then responsible for the separation, through the rapid recompression to subsonic flows. (The location of transition in Fig 8 coincides with a decreasing Mach number of unity at high flow rate.) Recent measurements of the surface velocity by laser Doppler anemometry would appear to support this view. They also suggest that the indirect surface-pressure derived velocities are less reliable on the suction surface, particularly in the vicinity of the diffusing stream in transonic flow. The estimate of

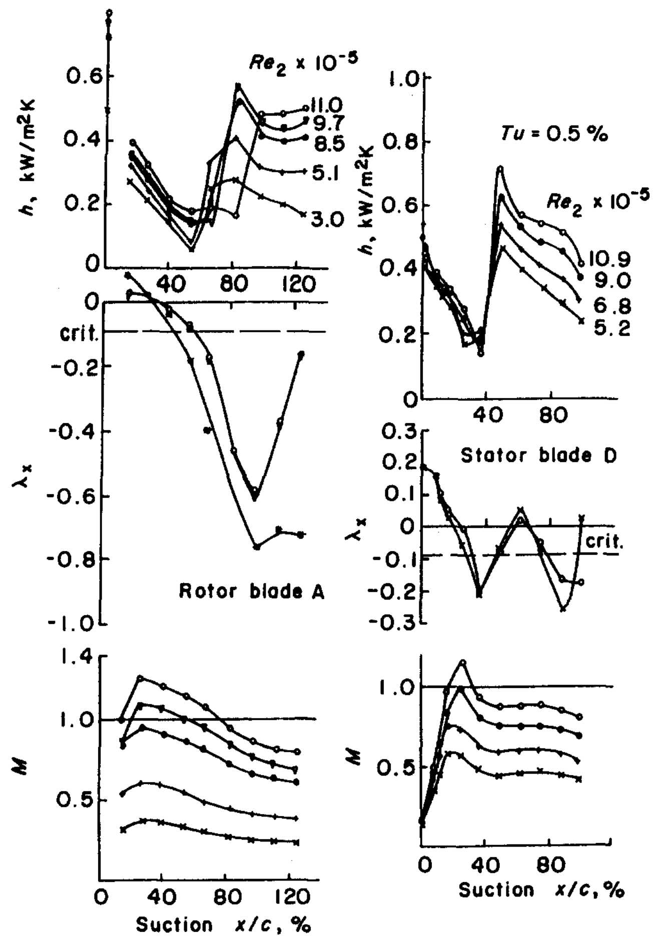

Fig 8 Transition analysis: suction surfaces

velocity gradient is especially prone to error, which perhaps explains why the shift of transition in Fig 8 is not so well accounted for by the parameter λ_x, derived from surface pressure measurements.

Certainly, then, in low turbulence free-stream flow, the sudden rise of local heat transfer coefficient observed on all the suction surfaces examined is attributable to separation of the laminar boundary layer. The results confirm that this is predicted by the correlation $\lambda_x = -0.09$ and suggest that when the flow becomes trasonic, the velocity profile alters, and this effect of the adverse pressure gradient can occur at a location determined by a recompression shock.

The correlation for natural transition of Abu-Ghannam and Shaw[25] is not inconsistent with the experimental observations on the convex surface of a blade. For the wide range of aerofoil sections examined for low turbulence free-stream flow, the correlation does not conflict with the observation of an abrupt transition due to separation rather than a more gradual 'natural' transition of the boundary layer. Under tubulent mainstream conditions, the flow visualisation experments have shown that bubble transition on blade A of Fig 1 is avoided at the high turbulence levels produced by the squirrel cage (as discussed earlier). This would occur through the advancement of natural transition sufficiently far upstream that the resulting turbulence boundary layer could overcome the retarding effect of the adverse pressure gradient. The Abu-Ghannam and Shaw correlation is entirely consistent with this interpretation. It predicts a decrease of the critical momentum thickness Reynolds number with turbulence intensity, to an asymptotic value of approxinately 160 for free-stream turbulence intensity as low as 5%. The momentum thickness Reynolds number reaches this value at about 20% chord on the suction surface of blade A for the flow rate of Figure 1. However, transition apparently did not advance so significantly on the suction surface of the guide vane of Fig 2 due to free-stream turbulence. Flow visualisation has not been applied to this particular aerofoil to make a direct observation. However, the extent of the forward region of the surface over which the flow accelerates is greater than for blade A. It may be that the stabilising influence on the boundary layer which such acceleration can impose (discussed in the next section for the pressure surface) has delayed the onset of natural transition on the guide vane.

Pressure surface

Figs 9 and 10 show the boundary layer parameters relevant to the nature of the flows on the concave pressure surface. As for the convex suction surfaces of Fig 6, the observed heat transfer rates for the three blades analysed here are shown in the upper diagram. From these, it is clear that under some conditions a large proportion of the boundary layer appears to have been in a transitional state. In Fig 9, for example, it is difficult to distinguish the precise location at which transition commences on the pressure surface of the rotor blade section at the highest

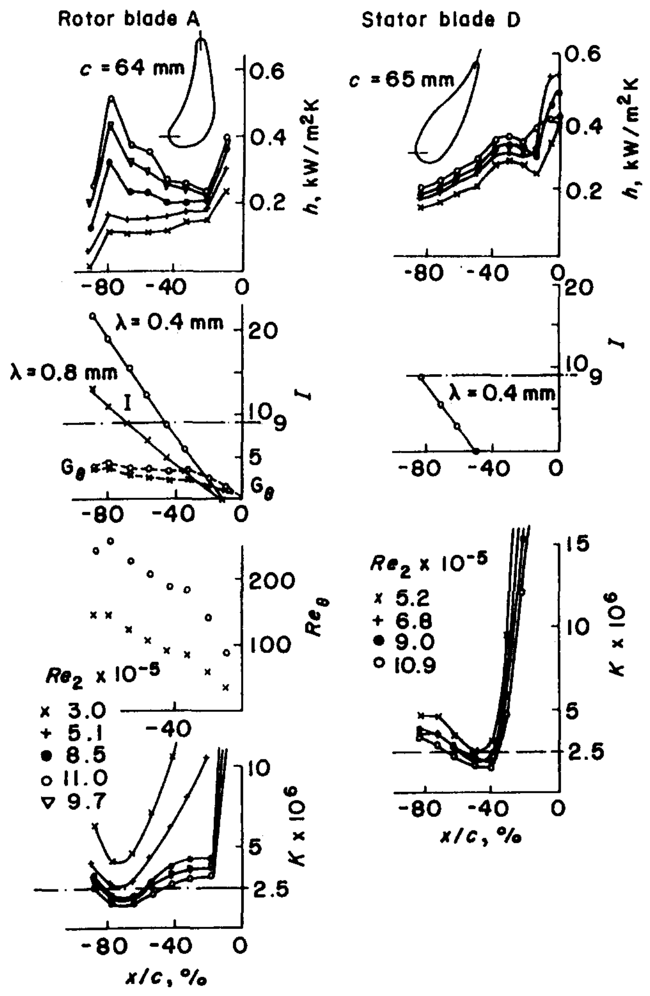

Fig 9 Pressure surface analysis

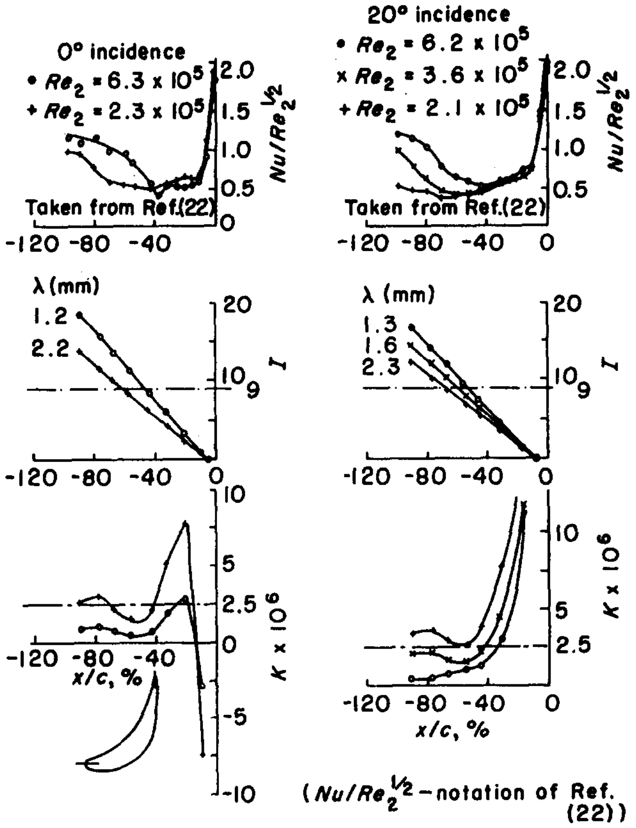

Fig 10 Pressure surface analysis: reaction blade of Walker and Markland

flow rate, but at forty-four per cent chord there is a significant rise in heat transfer. The estimated momentum thickness Rynolds number at this point is 180. According to the correlation of Abu-Ghannam and Shaw[25], the critical value of this parameter for the onset of natural transition depends on turbulence intensity locally in the free-stream. Measurements using a laser Doppler anemometer, already referred to in the analysis for the suction surface, have shown that the turbulence intensity locally along the pressure surface of blade A is, in fact, certainly no more than one per cent at the boundary layer edge, when the flow is unpertured. For such a turbulence level the predicted critical momentum thickness Reynolds number[25] is approximately 600, in a favourable pressure gradient. This is well above the estimated boundary layer growth (Re_θ in Fig 9) along the whole blade section. Thus, the empirical correlation of Abu-Ghannam and Shaw[25] based on flat plate experiments clearly cannot account for the observed rise in heat transfer at high Reynolds number. As might be expected, the boundary layer on the concave pressure surface of the blade section A is apparently more unstable than on a flat surface under otherwise similar conditions. The growth of Re_θ in Fig 9 is typical of all the aerofoil sections of Fig 4 which have been examined for similar exit Reynolds numbers. To cause transition, according to Abu-Ghannam and Shaw[25], such growth would require a local free-stream turbulence level of above three per cent. Assuming that the level which has been measured around blade A is typical, the above conclusions concerning the sometimes transitional pressure surface boundary layer are general.

Concerning the destabilising influence of surface concavity on the pressure surface boundary layer, it is possible that Taylor-Goertler vortices mentioned earlier might account for the observed heat transfer behaviour. However, there appears to be little information, or predictions, which can be compared against the experimental results. Theoretical analyses have usually derived a neutral stability condition of the boundary layer, in terms of the Goertler number and wavelength, downstream of which Goertler vortices start to grow†. Transition to a turbulent boundary layer has been associated with the growth and eventual breakdown of the vortices. Only two empirically based criteria for transition due to Goertler vorticity seem to have been suggested. One approach has been to correlate the Goertler number with the onset of transition. According to experimental data available, Smith[29] showed this criterion to be entirely inconsistent with observation, the Goertler number at transition varying tenfold. He suggested a criterion based on the growth of the vortices calculated according to his theoretical stability analysis. This assumed a weak perturbation to the basic streamline flow, the convention method of linearisation, but permitted variation of curvature, free-stream velocity, and boundary layer thickness with surface distance, as can be the case on a turbine blade. From a limited number of test cases in which transition has been observed on concave walls in wind tunnels of low turbulence level ($<0.2\%$ typically), Smith showed the criterion $I=\int\beta\,dx\simeq 9$ to be a much better indicator of transition than the Goertler number. Here, I is the comulative amplification factor and β the disturbance amplification factor of the vortices according to Smith's analysis. This empirical criterion has been applied to all six blade sections tested at Sussex and to the aerofoil of Walker and Markland[22]. The heat transfer measurements of this additional aerofoil generally exhibit transitional behaviour over much of the pressure surface. The surface pressure data were also conveniently available[22], so that the results of Walker and Markland have provided a useful test case in support of this analysis. Smith imposed a system of Goertler vortices on the laminar boundary layer theoretically to produce a stability chart; a series of curves in the Goertler number-wave number plane representing the local growth rate of Goertler instability. According to the chart, all disturbances of continuously variable wavelength are possible, but the most susceptible wavelength, corresponding to the minimum of the neutral curve, ensues when the Goertler number, G_θ, reaches the value 0.32. For all the blades (Fig 4) this critical value is exceeded at the very start of concavity downstream of the leading edge for the full range of conditions tested. The growth of vortices along the pressure surface of each blade section has been evaluated using Smith's chart, assuming that a single wavelength, the one undergoing maximum amplification, predominates and commences at the start of surface concavity. As Smith suggested, the cumulative amplification factor of this vortex has been traced in order to locate transition by integrating the disturbance amplification factor, β, corresponding to the minima of the stability curves. The minima do not strictly coincide with a single size of vortex, but the integral I is sufficiently insensitive to wavelength in the region of values undergoing maximum amplification that it could be determined from the Goertler number and a line intersecting the

† A review of the literature on Goertler vortices is given in Ref 28

minima of the stability curves. Figs 10 and 11 give cumulative amplification factor for blades A, D and G and show the approximate wavelength of predominant vortices expected to occur according to Smith's analysis; for blade A, the local Goertler number is also included.

From Figs 9 and 10 there would appear to be a level of consistency between the experimental observations and Smith's semi-empirical criterion. The mathematical analysis behind the criterion is not sound, however. Recently, Hall[30,31] has presented a more rigorous mathematical solution to the Goertler vortex problem in which the partial differential equations governing the linear stability of the flow are solved numerically. A principal result of this analysis is that the concept of a unique neutral curve is not tenable in the Goertler vortex problem. The position of neutral stability is found to depend on how and where the boundary layer is perturbed. According to Hall[30], ordinary differential approximations to the full partial differential equations governing the flow, such as used by Smith[29], do not describe adequately the decay of the vortex at the edge of the boundary layer. Any linear solution to the Goertler problem presumably departs from physical reality as the vortices grow and eventually break down to produce turbulence within the boundary layer. The mechanisms by which this breakdown takes place are complex and are not currently understood. The possible co-existence of Tollmien-Schlichting waves cannot be overlooked, as is apparent from Hahn and Cox's visual study[9]. Other factors are the finite extent of the blade span, and the influence of free-stream turbulence, even at low levels such as considered here when the flow is not perturbed by turbulence grids. The first of these parameters presumably influences the wavelength and spatial growth of the vortices, while turbulence in the free-stream could affect the initial perturbation on the boundary layer and then the subsequent strength and break-down of the vortices downstream. This is an area of fluid dynamics which clearly needs a great deal of further research effort. In the meantime it is not possible to assess how much Smith's empirical criterion departs from physical reality and, thus, assess its utility as an indicator of transition in spite of its noteworthy agreement with Figs 9 and 10.

The final parameter which has been considered in connection with transition and which is plotted in Figs 9 and 10 is the acceleration parameter, K. Severe acceleration of the free-stream flow is known to have a stabilising influence on a boundary layer. For turbulent boundary layers, the well known Launder's criterion[32] is that laminarisation effects start to become significant when K exceeds 2×10^{-6}. Such effects were confirmed by the experiments of Kearney *et al*[33], although they reported that complete relaminarisation of the turbulent boundary layer did not occur at their tests for K up to 2.5×10^{-6}. At the higher acceleration levels of $K>3.5\times10^{-6}$, Moretti and Kays[34] concluded that turbulence generation is apparently completely inhibited within the boundary layer, which becomes effectively laminar. Thus, for a laminar boundary layer, it has long been suggested that in an accelerating free-stream of $K>2.5\times10^{-6}$, approximately, transition to a turbulent boundary layer will not take place. The acceleration parameter is compared with this critical level for the pressure surface in Figs 9 and 10. Certainly, above the relaminarisation value the local heat transfer coefficients are suppressed. As the Reynolds number increases, the acceleration parameter decreases. Correspondingly, the heat transfer distributions of blades A and G exhibit transitional behaviour as K approaches the critical level and then drops below it.

The heat transfer results for the stator blade, D, in Fig 9 do not suggest transitional behaviour despite the acceleration parameter apparently falling below the relaminarisation level at the highest Reynolds number. It will be noticed in this case that surface concavity commences relatively late down-chord, towards the trailing edge. These observations further support the conclusion that the transitional flow, where apparent on the pressure surfaces of the other blade sections examined, is due to the boundary layer instability introduced by surface concavity. Otherwise, the experimental results seem to be generally in line with the relaminarisation criterion. Of the remaining aerofoils shown in Fig 4, not included in Figs 9 and 10, most are subject to an acceleration always above the relaminarisation level on the pressure surface, for the range of conditions tested, and transition has not been observed.

The significant effect of mainstream turbulence on heat transfer to the pressure surface has been discussed earlier. The turbulence generators used for the experiments in this research programme restricted the maximum flow rate and hence the Reynolds number such that the acceleration parameter has been generally above the relaminarisation level along the pressure surface under turbulent flow conditions. Thus, rather than minimising the level of heat transfer to the blade, by inhibiting the development of the turbulent boundary layer, the result of severe acceleration appears to be maintenance of a boundary layer highly sensitive to disturbances in the mainstream. The measurements on the pressure surfaces of the blade sections tested at Sussex University have demonstrated heat transfer rates increasing with turbulence intensity. At intensities believed to be representative of the engine, the experiments have yielded heat transfer coefficients comparable with, and in some cases even greater than, those predicted by the flat plate equation for a turbulent boundary layer. Clearly, it would not be enough for the blade designer just to ensure that the acceleration parameter is above the relaminarisation level in order to minimise blade temperatures in the operating turbine.

Conclusions

Using different techniques of perturbing the mainstream flow through cascades of blades of varying sections, this work has confirmed earlier conclusions showing the significant effects of mainstream turbulence levels upon the rates of convective heat transfer to blade surfaces, especially in the leading edge regions and on the pressure surfaces. The use of the squirrel-cage turbulence generator to simulate the frequency effects in mainstream flow perturbations which arise from passing upstream blade rows has not, in this work, indicated conclusively a separable effect of frequency. Such an effect, which was observed earlier[3] with intensities of fluctuation in excess of 20%, is not clearly evident at the lower intensities which appear to typify engine conditions and on which the present work has concentrated. At intensities of 8–17% the squirrel cage produces, like the grids also used in this programme, the unstructured and random perturbations usually regarded as turbulence. The present work has also demonstrated the need for turbulence-generating devices to be placed sufficiently far upstream for the wakes to have merged before the flow reaches the blades; otherwise the flow will be so modified as to vitiate any conclusions to be drawn concerning the effects of the perturbations themselves, and this makes for some difficulty in achieving intensities in the ranges believed to represent engine conditions using conventional stationary grids.

Comparisons of the heat transfer results from behind the different turbulence generators used in this work suggest that, downstream of the leading edge, profile geometry is an overriding factor in determining the primary convecting flow (ie flow in the boundary layer and just outside) around a blade section, irrespective of the flow structure in the approach stream. On the convex, suction surfaces transition to turbulence in the boundary layers on most of the blades tested followed reattachment of a separation bubble, the existence of which was shown by the heat transfer measurements to be adequately predicted by the position on the surface where the Pohlhausen pressure gradient parameter, λ_x, attained the often observed critical value of -0.09. The existence of shock-induced separation was predictable from the velocity distributions in their effects upon the observed rates of heat transfer, which were also entirely consistent with the criteria for 'natural' transition[25].

On the pressure surfaces, a sometimes transitional heat transfer behaviour in low turbulence flows could not be accounted for by the natural transition criterion[25], which is derived from flat plate measurements. It seems clear that surface curvature affects boundary layer stability. A semi-empirical procedure for predicting the onset of transition based on the growth of Goertler vortices[29] displays some consistency with the experimental observations, but doubts which have been cast upon the physical validity of the theoretical model must leave the procedure uncertain. The very limited amount of information on the behaviour of Goertler vortices under the conditions of turbine blade pressure surfaces makes this an area which is in urgent need of further theoretical and experimental investigation.

The results from all of the blade surfaces examined in the present work closely comply with the now well established criteria for predicting suppression of transition to turbulence or of relaminarisation of an already turbulent boundary layer. Such conditions frequently obtain in modern, heavily-loaded turbine blades, with consequential advantageous effects in terms of the heat transfer rate in an unperturbed flow. It may thus appear paradoxical to observe that these same conditions make the heat transfer rates more susceptible to flow perturbations, as is demonstrated by the results presented in this paper.

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BOOK REVIEW

Heat Conduction

U. Grigull and H. Sandner

Fundamental concepts of conduction, initial and boundary conditions are introduced briefly in chapter 1. Thermal conductivity of metals, liquids, gases and laminated bodies is considered in chapter 2. This chapter is well written and quite informative. Chapter 3 covers one-dimensional, steady conduction through slabs, cylinders, spheres and simple fins, with several interesting examples of application of the theory.

One-dimensional conduction through slabs, cylinders and spheres containing uniformly distributed heat sources is summarized very briefly in chapter 4. An example of the application of the theory to a cylindrical nuclear fuel element is given. It is not clear why the authors placed this material in a separate chapter of only two pages.

Chapter 5 discusses multidimensional steady conduction and the various analytical tools available for such problems. The analytical tools are limited to Kirchhoff's transformation, conformal mapping, and the method of fictitious heat sources and sinks. Experimental analogue methods, graphical methods and the relaxation method are discussed briefly. This chapter introduces the concept of thermal resistance and conduction shape factor and ends with a summary of shape factors applied to several two-dimensional configurations. The authors have not discussed other analytical methods such as separation of variables and Fourier sine or cosine transforms which are very useful in several coordinate systems.

Chapter 6 is the longest and best written section. The authors discuss the application of several analytical methods such as the Boltzmann and Laplace transformations, separation of variables, Duhamel's theorem to transient one-dimensional conduction in slabs, cylinders, spheres and semi-infinite bodies. Analogue and finite-difference methods are applied to simple examples. The chapter ends with periodic temperature variation in an isotropic, semi-infinite body.

Chapters 7, 8 and 9 cover instantaneous and continuous point and line sources as well as moving sources. These chapter are well written and give the reader a clear picture of the underlying physical concepts. Other conduction texts should include the topics covered in these chapters.

A brief summary of the applications of the one-dimensional transient solutions to multi-dimensional conduction within several bodies is presented in chapter 10. Chapter 11 has a brief description of conduction with phase change in a semi-infinite body, and several good examples with industrial applications

The appendices contain units, universal constants of physics, dimensionless groups in heat and mass transfer, thermophysical properties of selected solids, liquids and gases, and short tables of Gauss's error function, exponential integral and modified Bessel functions.

Overall this introductory test is well written, covers a wide range of topics and should be included in a list of reference texts on conduction. Professor Kestin's translation of the original German text is excellent and the Series Editors are to be congratulated for bringing it to the attention of the English speaking heat transfer community.

M. M. Yovanovich
University of Waterloo,
Ontario,
Canada

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