Experimental Study of Boundary Layer Transition on a Heated Flat Plate

K.H. Sohn and E. Reshotko
Case Western Reserve University
Cleveland, Ohio

and

K.B.M.Q. Zaman
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

A detailed investigation to document momentum and thermal development of boundary layers undergoing natural transition on a heated flat plate was performed. Experimental results of both overall and conditionally sampled characteristics of laminar, transitional and low Reynolds number turbulent boundary layers are presented. Measurements were done in a low-speed, closed-loop wind tunnel with a freestream velocity of 100 ft/s and zero pressure gradient over a range of freestream turbulence intensities from 0.4 to 6 percent. The distributions of skin friction, heat transfer rate and Reynolds shear stress were all consistent with previously published data. Reynolds analogy factors for momentum thickness Reynolds number, $Re_\theta < 2300$ were found to be well predicted by laminar and turbulent correlations which accounted for an unheated starting length and uniform heat flux. A small dependence of turbulent results on the freestream turbulence intensity was observed.

INTRODUCTION

The understanding of boundary layer development under the influence of a highly disturbed freestream is important for many engineering applications. This is especially so for turbine blades of aircraft gas turbine engines. Heat transfer rates from hot gases to cooled turbine blades are largely dependent on whether the boundary layer is laminar, transitional or turbulent. Since boundary layer transition is characterized by a significant increase of skin friction and heat transfer rate, the determination of the transition location on the turbine blade becomes necessary to accurately predict local heat transfer rates and then to properly assess the cooling requirements for the turbine blade (Graham, 1979). On turbine blades, the transition process is extended over appreciable portions of the cooled surface. Heat transfer measurements by Turner (1971) indicated that transitional behavior was observed over about 80 percent of the suction side of a typical turbine blade for a freestream turbulence level of 5.9 percent. The accurate prediction of the transition pattern leads directly to the improvement of engine efficiency and hardware durability. More reliable transition data are required to provide fundamental information for improved modeling and computation of boundary layer transition as it occurs in turbomachinery. This is the motivation of the current work.

Previous studies of the influence of pressure gradient and heat transfer rate as well as freestream disturbances on boundary layer transition were primarily concerned with the mean overall characteristics of intermittent boundary layers. The effects of heat transfer in addition to freestream turbulence level and pressure gradient were considered experimentally by Junkhan and Serovy (1967) on a heated constant temperature wall, by Blair (1982) on a uniformly heated flat plate and by Roed and Wittig (1985) on a cooled isothermal wall. They observed that the effect of heat transfer on boundary layer transition is not significant compared to the corresponding effects of freestream turbulence and pressure gradient. Transition Reynolds number was relatively insensitive to wall heat transfer rate and mild acceleration of the flow. Gaugler (1985) has summarized a number of bypass transition data sets that include the effects of heat transfer, covering a wide range of flow conditions and indicating strong effects of freestream turbulence level and pressure gradient on the location and length of the transition zone. He concluded that the transition length appeared to depend strongly on the freestream parameters within the zone rather than just on the conditions at the start of transition. A general review of transition mechanisms (T-S and bypass modes) and of the prediction and control of transition was presented by Reshotko (1986).

Several other very recent studies of Blair (1988) for mildly accelerating flow, of Kuan and Wang (1988) and Kim, Simon and Kestoras (1989) for flat plate boundary layer flow focused additionally on determination of the separate statistics of the non-turbulent and turbulent parts of the transitional boundary layer using conditional sampling techniques. Results of these studies clearly indicated that the non-turbulent and turbulent parts in the transitional
flow cannot be thought of respectively as Blasius and fully turbulent flows.

The present experimental study was conducted on a uniformly heated flat plate with zero pressure gradient for freestream turbulence intensities ranging from 0.4 to 6 percent. The first part of this experimental program is to document the momentum and thermal mean characteristics of laminar, transitional and low Reynolds number turbulent boundary layers. In addition to mean and rms velocity and temperature profiles, the Reynolds analogy factors are determined for six levels of freestream turbulence. The second part examines correlations of instantaneous velocities and temperature measured simultaneously with a miniature 3-wire probe. Reynolds shear stress and turbulent heat flux are discussed.

EXPERIMENTAL FACILITY

The experiments were performed in a low-speed, closed-circuit wind tunnel located at the NASA Lewis Research Center. This wind tunnel was designed to generate large-scale, two-dimensional, incompressible boundary layers and to study the effects of freestream turbulence, pressure gradient and heat transfer rates on the transitional boundary layer. Upon exiting the blower, the air enters the flow-conditioning plenum chamber, where any flow irregularities introduced by the blower are removed and the freestream turbulence levels are reduced. At the downstream end of the flow-conditioning chamber and upstream of the contraction nozzle, turbulence generating grids could be positioned to set the freestream turbulence in the test section.

The test section of the wind tunnel is rectangular in cross section and measures 27 in. wide, 60 in. long and 6 in. high. At the entrance to the test section, a double bleed scoop assembly is positioned. The large scoop is intended to remove both the boundary layer which develops along the contraction corners. The small scoop, smoothly attached to the test surface, serves as the leading edge of the flat plate, which is a 4:1 ellipse. This arrangement results in a 1.375-in. unheated starting length. This small scoop bleeds off any boundary layer which develops on the large scoop. The heated flat plate is constructed using 12-in. sections of rigid polyurethane foam, 27 in. wide, 2 in. thick, and totaling 56 in. in length. The inconel foil was cemented to the foam to form the test surface. The test surface is uniformly heated using nine strips of 6-in. wide, 24-in. long and 0.001-in. thick inconel foil. The area of the heated surface is 9 ft². The surface temperatures were measured by means of thermocouples spot-welded directly to the back side of the foil through small holes in the rigid foam plate. For more detailed experimental procedure, facility and instrumentation, refer to Sohn and Reshotko (1991).

Two types of probes were used in this experimental work: (1) A commercially available single sensor boundary layer hot-wire probe was used to measure the streamwise component of mean and fluctuating velocity. This probe was also operated in constant current mode to measure the mean temperature in the boundary layer. (2) A miniature 3-wire probe was used to simultaneously measure the instantaneous streamwise and vertical components of velocity and the temperature. This also allowed the determination of correlation quantities like Reynolds shear stress and turbulent heat flux in the boundary layer.

RESULTS

Detailed momentum and thermal boundary layer measurements have been performed on a heated flat plate with zero pressure gradient. The nominal values of the freestream turbulence intensity are 0.4 percent for grid 0, 0.8 percent for grid 0.5, 1.1 percent for grid 1, 2.4 percent for grid 2, 5 percent for grid 3 and 6 percent for grid 4. For grids 0, 0.5, 1 and 2, the turbulence levels are almost constant with streamwise distance, which means that the grid-generated freestream turbulence quickly becomes nearly homogeneous for the relatively moderate levels of freestream turbulence less than 2 percent. However, the freestream turbulence levels for grids 3 and 4 indicate a slow decay with distance downstream due to larger eddies generated by the coarser grids, which means that turbulent cascading is still in progress.

The mean velocity profiles acquired at streamwise locations between X = 5 and 20 in. from the leading edge of the heated flat plate for grid 1 were normalized with wall units, u' and y'. As shown in Fig. 1, the mean velocity profiles are compared to three types of reference curves: (1) u' = y', (2) the Blasius solution with a measured Re for a laminar boundary layer, and (3) the Musker (1979) continuous law-of-the-wall curve for a fully turbulent boundary layer. Excellent agreement of the two upstream profiles with the Blasius curve is observed in profiles taken between X = 5 and 7 in. Note that the data points near the wall of the plate were obtained by u' = y' and the Musker law-of-the-wall curves. Further downstream, the data fell in the region between the Blasius curve and the Musker law-of-the-wall curve. The profiles span nearly the entire range from laminar to turbulent boundary layers. Once the mean velocity profile fell close to the Musker law-of-the-wall curve especially in the log-linear region, it can be said that this might be the location of the end of transition.

The values of uₘ required to construct these plots were obtained from the mean velocity profiles depending on the characteristics of the boundary layers. The laminar values of uₘ were obtained from a laminar theory. The fully turbulent values of uₘ were obtained using the Clauser fit technique, and for the transition cases uₘ was acquired from the momentum integral theory.

The profiles of boundary layer mean temperature plotted in wall units, T' versus y', corresponding to the mean velocity profiles of Fig. 1 with the same conditions, are shown in Fig. 2. Three types of reference curves are also plotted along with the experimental data in these figures. These are: (1) T' = Pr y', (2) the theoretical laminar temperature.
profile obtained by solving the momentum and energy equations simultaneously with proper boundary conditions, including a correction for unheated starting length, and (3) the temperature law-of-the-wall curve for fully turbulent boundary layers suggested by Kays and Crawford (1980) with constant values of $Pr = 0.708$ and $Pr = 0.9$. Due to the finite unheated starting length of $1.375$ in., the profiles of the farthest upstream laminar temperature deviate from the $T^* = Pr y$ curve for almost all $y$ locations. However, the theoretical laminar curve gets closer to the $T^* = Pr y$ curve as $Re_{	heta}$ increases. Note that the values of $u_*$ used to construct these temperature profiles are the same values used to plot the corresponding mean velocity profiles. Excellent agreement of the farthest upstream laminar profiles ($X = 5$, $7$ in.) with the corresponding theoretical laminar curves is observed. One striking feature observed in the transitional boundary layer is that the velocity profiles slightly lag the respective temperature profiles. This velocity lag can be clearly observed by comparing the mean velocity profiles at $X = 15$ in. to the corresponding temperature profiles. Where the temperature profiles are in close agreement with temperature law-of-the-wall curve but the velocity profiles are still developing in the transitional region. This velocity lag is also reflected in the higher values of $Re_{	heta}$ analog factor than $Pr^{-2/3}$. This result is, however, opposite in trend to the observations of Wang et al. (1985) and Kim et al. (1989).

The variation of the experimentally determined skin friction coefficient, $C_f$, with $Re_{	heta}$ is presented in Fig. 3. Negligible effect of freestream turbulence on laminar $C_f$ but increasing values of $C_f$ with freestream turbulence in the turbulent region were observed. One more trend observed in these skin friction profiles is that the laminar boundary layer transition occurs at increasingly lower values of Reynolds number as the freestream turbulence level increases. The values of $C_f$ for laminar and turbulent boundary layers are so different that $C_f$ can be used to determine the transition region. The transition region thus determined is in good agreement with the region obtained from the mean velocity profiles. A plot of Reynolds analogy factor $Pr^{-2/3}$ obtained for the condition of uniform heat flux in the range of $Re_x < 10^6$ ($Re_{	heta} < 2300$) for the six levels of freestream turbulence is shown in Fig. 4. Recall that the Reynolds analogy factor in air for a flat plate with zero pressure gradient and a thermal boundary condition of constant wall temperature is well represented by $Pr^{-2/3}$ for both laminar and turbulent flows. However, the reference curves representing the expected $2St/C_f$ for laminar and turbulent regimes, are quite different from a conventional $Pr^{-2/3}$ curve due to the effects of the thermal boundary condition of uniform wall heat flux and an unheated starting length. Appropriate laminar and turbulent theoretical results suggested by Kays and Crawford (1980) were combined in order to obtain the curves shown. The value $0.332$ comes from the laminar skin friction relation with constant fluid properties and $0.453$ is from the laminar heat transfer relation with a uniform wall heat flux condition, resulting in a ratio of $1.365$. The laminar values of $2St/C_f$ are augmented by $26.5$ percent with $u'$ and $0.453$ is from the laminar heat transfer relation with a uniform wall heat flux condition over the constant wall temperature case, which indicates that the heat transfer rate is very sensitive to the thermal boundary condition in the laminar region. The term in the bracket accounts for the effect of unheated starting length which produces an additional augmentation of $17$ percent at the farthest upstream location ($X = 5$ in.) and diminishes to $5$ percent at the far downstream measurement station ($X = 20$ in.). Consequently, values of $2St/C_f$ as high as $2.0$ can be expected in the laminar region. The turbulent correlation was treated quite similarly to the laminar correlation. For turbulent boundary layers, heat transfer results are much less sensitive to both thermal boundary condition (4.5 percent augmentation due to uniform heat flux) and unheated starting length (1 percent increase at $X = 20$ in.). Thus, the turbulent values are much closer to the well known $Pr^{-2/3}$ value of $1.26$ with $Pr = 0.708$.

The experimentally determined laminar data agree very well with the laminar prediction. Examination of Fig. 4 reveals that the effect of freestream turbulence on $2St/C_f$ in the laminar region is negligible. A progressive decrease of $2St/C_f$ with increase of freestream turbulence level is also observed in the transition region. As known from the variation of skin friction and heat transfer, both $C_f$ and $St$ are much closer to the values obtained from the turbulent correlation. The data for lower freestream turbulence cases (grids 0.5, 1 and $2$), on the other hand, are closer to the values obtained from the turbulent correlation than $Pr^{-2/3}$. A slight increase of $2St/C_f$ with freestream turbulence level in the turbulent region can also be detected.

The streamwise rms velocity fluctuations, $u'$, within the boundary layer were measured at the same time as the mean velocity data were acquired. The profiles of the overall streamwise velocity fluctuations normalized with respect to $U_e$ (streamwise component of turbulence intensities) across the boundary layer are presented in Fig. 5. Recall that the corresponding mean velocity profiles were presented in Fig. 1. The rms velocity profiles at $X = 5$ and $7$ in. are believed to be laminar in the presence of freestream turbulence (pseudo-laminar boundary layer) with a peak value of rms $u'$ occurring at $y/6 = 1.3$, which is quite typical for the laminar boundary layer (Suder et al., 1988; Sond and Reshotko, 1986; Wang et al., 1985).

The peak value of $u'/U_e$ within the boundary layer grows rapidly and the peak moves toward the wall as the flow develops downstream in the transition region. The magnitude of near-wall peak is largest in the transition region. The maximum peak value of $u'/U_e = 0.13$ occurs at $y/6 = 0.5$ in the early stages of transition as shown in the profile at $X = 11$ in.. As the transition proceeds, another peak begins to appear at $y/6 = 2$. While the near-wall peak diminishes, the second peak grows for a while and then decreases before both peaks reach some constant plateau value of $u'/U_e = 0.075$ in the immature stage of the turbulent boundary layer. The decrease in the transitional boundary layer is typical and has been reported by many other researchers (Arnal et al., 1976; Suder et al., 1988; Wang et al., 1988; Kim et al., 1989). This double peak in the overall rms velocity profiles is believed to be due to the velocity jumping quickly between laminar and turbulent levels in the passage of turbulent spots, introducing some artificial overall rms velocity values at that specific location. This kind of velocity behavior can be seen from the direct hot-wire signals measured at
Reynolds number turbulent boundary layers with a large intermittency increases. The turbulent profile has its tile transition process, having the appearance of low creasingly deviate from Blasius curves as the inter-

profiles. However, the non-turbulent profiles in' $X = 9$ in. agree well with the corresponding Blasius overall profiles.

The non-turbulent mean velocity profiles, not from the used for the Blasius profile was the result from the turbulent and turbulent parts. Note that the Re function was equal to one. The overall profiles were acquired during time segments when the indicator function was zero. The turbulent parts were observed to deviate increas-

ingly from the corresponding Blasius shapes, while the turbulent parts were observed to approach the shape of fully turbulent profiles. The conditional sampled mean velocity data obtained during time segments when the indicator was explained in detail in Sohn and Reshotko (1991).

The profiles of intermittency factor $\Gamma(y)$ across the boundary layer at some streamwise locations for grid I are shown in Fig. 6. In these figures the solid curve represents an error function distribution of intermittency factor which is a Gaussian integral curve, for the fully turbulent boundary layer as suggested by Klebanoff (1955). As shown in this figure, the intermittency profiles in the transition region do not decrease monotonically across the boundary layer. Instead, a peak is observed near the wall at $y/\delta = 1$ at relatively low intermittencies ($\Gamma < 0.8$). It can be suspected that the most frequent turbulent activity in the transitional boundary layer is taking place at one displacement thickness away from the wall in the early stages of transition. This near-wall drop-off of $\Gamma$ is in good agreement with a vertical cross-

sectional shape of turbulent spots which exhibits the leading and trailing edge overhangs as observed by Cantwell et al. (1978) and is also consistent with a recent result obtained by Kuan and Wang (1988). The decay of $\Gamma$ toward zero in the outer region is possi-

bly due to the entrainment of the freestream flow into the boundary layer and the peak-top shape of turbu-

lent spots, i.e. the flow passes the turbulent spots less frequently in the region of $y/\delta > 4$.

Plots of conditionally sampled mean velocity profiles normalized with wall units, obtained at the same streamwise locations as the intermittency pro-

files are shown in Fig. 7. Three profiles: non-

turbulent, overall and turbulent parts of intermittency flow are shown in each of these figures along with the Blasius, $u' = y'$ and the Musker curves for reference. The non-turbulent profiles represent the average of velocity data obtained during time segments when the indicator function was zero. The turbulent parts were obtained from the average of instantaneous velocities acquired during time segments when the indicator function was equal to one. The overall profiles were determined from a direct long time average of the digitally recorded data which include both non-

turbulent and turbulent parts. Note that the Re used for the Blasius profile was the result from the non-turbulent mean velocity profiles, not from the overall profiles.

Low-intermittency non-turbulent profiles at $X = 9$ in. agree well with the corresponding Blasius profiles. However, the non-turbulent profiles increas-

ingly deviate from Blasius curves as the inter-

mittency increases. The turbulent profile has its maximum deviation from the log-linear profile early in the transition process, having the appearance of low Reynolds number turbulent boundary layers with a large make region. As the transition proceeds, the devia-

tion from the log-linear region in the turbulent pro-

files is diminished. When $\Gamma = 0.99$, the shape of turbulent profiles looks quite like that of fully tur-

bulent boundary layer.

The distribution of conditionally sampled $C_f$ is shown in Fig. 8. At the beginning of transition, the non-turbulent profile had a Blasius shape but the turbulent parts had quite different shapes from the fully turbulent boundary layer. As $\Gamma$ increased, the non-turbulent parts were observed to deviate increas-

ingly from the corresponding Blasius shapes, while the turbulent parts were observed to approach the shape of fully turbulent profiles. The non-turbulent profiles represent the average of velocity data obtained during time segments when the indicator function was zero. The turbulent parts were observed to deviate increas-

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temperature fluctuations was difficult to achieve with
the temperature bridge. However, due to the heat
transfer equations for a fine wire, the temperature
sensor was operated with the constant current mode
of temperature without solving a series of nonlinear heat
size effects. Therefore, it seemed to be free from severe
probe shear stress data obtained with the present probe con-
figuration, thus, seem to be free from severe probe shear stress.
The Reynolds shear stress profiles in the outer portion
(y/\delta_{99.5} > 0.7) at two streamwise locations of X = 9 and 11 in.
are rather scattered due to the very small rms values of
u' and v'. It can be said that when the intermittency is less
than some threshold value (about 0.5 in this study) the correlation
coefficients are somewhat meaningless because the values of both numerator and
denominator in the correlation coefficient are relatively small. However, with distance downstream,
the correlation coefficient becomes larger and the
locations of the constant plateau values of correlation
coefficient move toward the wall. For profiles at
X = 20 in., when the nominal intermittency factor
is about 0.99 the plateau value of the correlation
coefficient is 0.42 in the range of 0.1 < y/\delta_{99.5} < 0.4 (this is somewhat less than the fully turbulent
correlation coefficient). A correlation coefficient for a fully turbulent boundary layer of between 0.45
and 0.54 was reported by other researchers (Chen and
Blackwelder, 1978; Senda et al., 1980; Blair, 1987). One thing to be mentioned about the data meas-
ured with the 3-wire probe is that large effects of eddy averaging are possibly involved in the data
obtained with the X-shaped sensing wires in the thin
layer of shear flow at the early stages of transition
(1/\theta = 1.35 at X = 9 in. and 1/\theta = 1.01 at
X = 11 in.; 1 is the hot-wire sensor length). Thus,
in order to obtain more accurate data in a thin bound-
ary layer without having significant averaging
effects, the wire should be shorter which would
require a very fine sub-micron diameter wire. This is
not feasible, however. As transition proceeds, the
boundary layer is getting thicker and the effect of
1/\theta is diminished (1/\theta = 0.41 at X = 20 in.). To
confirm that the probe size effect in the thicker
boundary layer is small, the -uv' profile was meas-
ured also at X = 20 in. for grid 3. The Reynolds
shear stress profile for grid 3 agrees well with that of
the fully turbulent boundary layer reported by
others, having a near-wall peak value of -uv'/u_2^2 of
1.0 and monotonically decreasing to zero in the freestream (Sohn and Reshotko, 1988). The Reynolds
shear stress data obtained with the present probe con-
figuration, thus, seem to be free from severe probe size
effects.

In order to directly obtain the instantaneous
temperature without solving a series of nonlinear heat
transfer equations for a fine wire, the temperature
sensor was operated with the constant current
mode, adequate frequency resolution for the
temperature fluctuations was difficult to achieve with
commercially available 5 \mu m diameter wire. Therefore,
a miniature 3-wire probe having a 1 \mu m diameter tem-
perature wire was designed to properly achieve a good
frequency response up to a few kHz. This frequency
limit was considered adequate for the present exper-
iment at low-speed, low-overheat flow with maximum
temperature difference between wall and freestream of
about 15 \degree F.

The distribution of fluctuating temperature nor-
malized with \Delta T (= T_w - T) within the transitional
boundary layer for grid 1 is presented in Fig. 12. In
the early stage of transition at X = 9 in., the rms
t' profile merely shows the monotonic decrease from
the value of 0.065 at \gamma/\delta = 1 to the freestream
certainty level. Due to the vertical X shape of the
3-wire probe, locating the temperature probe closer to
the wall was not possible. No near-wall peak is thus
observed at any streamwise station. As the intermit-
tency increases, a peak which is probably the second
peak, begins to appear at \gamma/\delta = 2. The magnitude of the peak t'/\Delta T, which is about 0.085 at the rela-
tively small flat portion around \gamma/\delta = 2 at
X = 11 in., significantly increases to the maximum
value of 0.11 at X = 13 and 15 in. and then gradually
decreases to the magnitude of 0.075 at X = 20 in. as \gamma approaches unity. A double peak can also be seen
in the profile measured at X = 17.5 in. In addition,
the similarity of the rms temperature profiles in the outer portion (\gamma/\delta > 4) of the boundary layer is also
observed in the latter stages of transition. The trend, especially the vertical location and the maxi-
mum value of second temperature pro-
files is quite similar to that of the corresponding
streamwise rms velocity profiles shown in Fig. 5. Therefore, as far as the rms values are concerned,
the time-averaged data obtained with the miniature 3-wire
probe are acceptable.

Turbulent heat flux, which is a correlation of fluctuating v' and t', was obtained from the digi-
tally recorded instantaneous velocity and temperature
signals. The distribution of turbulent heat flux
normalized with the product of respective rms values
(normalization coefficient) in the transitional boundary
layer is shown in Fig. 13. The values of turbulent
heat flux in the transitional boundary layer are found
to be negative except in the region \gamma/\delta_{99.5} > 0.4
at X = 20 in. The distribution of intermittency factors
(correlation of v' and t') corresponding to these data for grid 1, range from
\gamma = 0.34 to 0.99. The negative correlation indicates that v' and t' are out of phase in these flows.
Since the mean temperature gradient is negative in the
boundary layer, the negative correlation between v' and t' seemingly indicates that the average heat
flux generated by the fluctuating flow is directed
toward the wall. This is a peculiar result not re-
ported in any previous studies.

The above behavior is observed principally in
the transitional boundary layers. The values of the
turbulent heat flux increase, however, as intermit-
tency or Reynolds number increases and finally become
positive at \gamma/\delta_{99.5} = 0.4 when \gamma = 0.99 and
Re\alpha = 1150 (X = 20 in. 61). The value of the cor-
relation coefficient of v't' over the most part of a
fully turbulent boundary layer is measured to be 0.5
by other researchers (0.51 for Chen and Blackwelder
(1978) at Re\alpha = 2900 and 0.55 for Blair (1988) at
Re\alpha = 5400). Obviously, the presently measured small
positive value of this quantity even when \gamma = 0.99
disagrees with these earlier experimental results.

To check if the correlation coefficient would approach
0.5 with increasing Re\alpha, the flow was disturbed by
the coarser grid 3 and measurements were performed at
further downstream locations i.e. at X = 20, 38, and
45 in. The correlation coefficients measured at \( X = 20 \) in. \((Re_\lambda = 2000), X = 38 \) in. \((Re_\lambda = 2800)\) and at \( X = 45 \) in. \((Re_\lambda = 3200)\) for grid 3 are also shown in Fig. 13. The values of correlation coefficient clearly increase as \( Re_\lambda \) increases. However, the profile of the correlation coefficient even at \( X = 45 \) in. exhibit values lower than 0.5 as measured by others. The profile shows a constant plateau value of about 0.4 in the region of \( 0.4 < y^*/\delta_{995} < 0.8 \) and small negative values very close to the wall \( (y^*/\delta_{995} < 0.05) \). The repeatability of this peculiar behavior of \( v'v' \) has been checked additionally with an analog correlator. The validity and consistency between the digital and analog results are reported in Sohn and Roshstko (1991).

Thus the operation of the 3-wire probe and the data reduction schemes seem both to have been properly performed, and so the focus must shift to the 3-wire probe itself. Since the spanwise separation of the velocity and temperature sensors in the present 3-wire probe configuration is relatively large \((S^* = 0.52 mm)\), it is speculated that the correlation of \( v'v' \) and \( t't' \) may be improper. For a fully turbulent boundary layer measured at \( X = 20 \) in. with grid 3 \((U_* = 100 \text{ ft/s}, u'_w = 0.07 \text{ ft/s}), \) the spanwise distance between these sensors in wall units, \( S^* \) is about 46. This value of \( S^* \) is larger than the criterion of 20 suggested by Ligrani and Bradshaw (1987) for resolving proper fine-scale turbulent fluctuations especially in the near-wall region. With the same probe geometry, the only way to reduce the value of \( S^* \) is to lower the freestream speed, which in turn decreases the value of \( u'_w \). Another set of \( v'v' \) data was obtained with a reduced freestream speed of 45 ft/s at the same streamwise location of \( X = 20 \) in. for grid 3, resulting in \( S^* = 22 \). The profiles of correlation coefficient of \( v'v' \) and \( t't' \) across the boundary layer with the two different values of \( S^* \) measured at \( X = 20 \) in. for grid 3 are shown in Fig. 14. Noticeable improvement of \( v'v' \) with the smaller value of \( S^* \) is clearly observed in this figure, even though the shape is different from that of previously reported data for the fully turbulent boundary layer. No distinct constant plateau value around 0.5 is seen and there are still small portions of negative \( v'v' \) very close to the wall.

All possible reasons for the negative correlation of turbulent heat flux in the boundary layer, excessive spanwise separation of the wires of the multiple-wire probe could well be the crucial factor affecting a proper correlation of \( v'v' \) and \( t't' \). To resolve this issue, additional carefully controlled measurements with various values of \( S^* \) as well as using another specially well-designed 3-wire probe are being planned in both transitional and fully turbulent boundary layers.

CONCLUSIONS

A detailed investigation of momentum and thermal boundary layer development focusing on the boundary layer transition moment and in the presence of freestream turbulence and surface heat transfer, was carried out on a heated flat plate with zero pressure gradient as part of an ongoing research program. For each level of freestream turbulence, the time-averaged overall quantities measured with a boundary-layer type single-sensor probe and thermocouples were used to determine the macroscopic momentum and thermal characteristics of laminar, transitional and low Reynolds number turbulent boundary layers. The instantaneous velocities and temperatures were measured simultaneously with a miniature 3-wire probe to determine correlation quantities in transitional boundary layers.

Increasing values of \( \alpha_\lambda \) with increasing levels of freestream turbulence in the turbulent region were observed, but the effect was negligible in the laminar regions. The location of boundary layer transition moved progressively upstream with increasing levels of freestream turbulence. Measured Reynolds analogy factors were found to be well predicted by combining appropriate correlations for the thermal boundary conditions of uniform heat flux and unheated starting length for the respective laminar and turbulent regimes. The Reynolds analogy factors were not sensitive to either thermal boundary condition or unheated starting length in the turbulent region. The boundary layer transition was also observed as a rapid increase of the near-wall peak of \( v'v' \) and \( T'T' \), the occurrence of a second peak at \( y^*/\epsilon = 2 \) due to the switching effect between laminar and turbulent states. This observation is consistent with previous studies. The cross-stream velocity fluctuation \( (\nu') \) indicated that a large degree of anisotropy existed within the transitional boundary layer although isotropy was achieved near the edge of the boundary layer.

The rms fluctuating temperature profiles measured with the 3-wire probe exhibited a similar development as the streamwise rms velocity profiles in transitional boundary layers in terms of magnitude and peak location, showing, for example, double humps at intermediate values of intermittency. The profiles of turbulent heat flux, \( v'T' \) acquired from the digitally recorded instantaneous velocity and temperature signals indicated negative values in certain cases, especially in the intermittent region. Excessive spanwise separation of the wires of the 3-wire probe would well be the crucial factor affecting a proper correlation of \( v'v' \) and \( t't' \). Significant changes in \( v'v' \) were obtained in the intermittent region. Excessive speed and therefore reduced dimensionless separation in wall units \( v'v' \) were more positive and approached the levels observed by others in turbulent boundary layers.

REFERENCES


![Figure 1.—Streamwise mean velocity profile in wall units.](image)
Figure 2.—Mean temperature profiles in wall units.

Figure 3.—Skin friction coefficient dependence on $Re_\theta$ and freestream turbulence.
Figure 4.—Distribution of Reynolds analogy factor.

Figure 5.—Streamwise rms velocity profiles.
Figure 6.—Intermittency profiles across the boundary layer.
Figure 7.—Conditionally sampled mean velocity profiles in wall units.
Figure 8.—Conditionally sampled skin friction coefficient profiles.

Figure 9.—Comparison of streamwise rms velocity profiles measured with single and 3-wire probes.
Figure 10.—Vertical component of rms velocity profiles.

Figure 11.—Correlation coefficient profiles of $u'$ and $v'$. 
Figure 12.—RMS temperature fluctuation profiles.

Figure 13.—Correlation coefficient profiles of $v'$ and $t'$. 
Figure 14.—Correlation coefficient profiles of \( v' \) and \( t' \) with different \( S^+ \).
**Abstract**

A detailed investigation to document momentum and thermal development of boundary layers undergoing natural transition on a heated flat plate was performed. Experimental results of both overall and conditionally sampled characteristics of laminar, transitional and low Reynolds number turbulent with a freestream velocity of 100 f/s and zero pressure gradient over a range of freestream turbulence intensities from 0.4 to 6 percent. The distributions of skin friction, heat transfer rate and Reynolds shear stress were all consistent with previously published data. Reynolds analogy factors for momentum thickness Reynolds number $Re_\theta < 2300$ were found to be well predicted by laminar and turbulent correlations which accounted for an unheated starting length and uniform heat flux. A small dependence of turbulent results on the freestream turbulence intensity was observed.

**Key Words (Suggested by Author(s))**

Transition  
Heat transfer  
Boundary layer  
Flat plate