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Decreasing the Side Wall Contamination in Wind Tunnels

To study boundary layers in the transitional Reynolds number regime, the useful spanwise and streamwise extent of wind tunnels is often limited by turbulent fluid emanating from the side walls. Some or all of the turbulent fluid can be removed by sucking fluid out at the corners, as suggested by Amini [1]. It is shown that by optimizing the suction slot width, the side wall contamination can be dramatically decreased without a concomitant three-dimensional distortion of the laminar boundary layer.

Introduction

Operating test facilities in regimes necessary to study boundary layer transition is known to be fraught with problems. Indeed, the operating requirements are so rigid that it was only after years of wind tunnel development and testing that Schubauer and Skramstad [2] were able to identify Tollmien-Schlichting waves in a zero pressure gradient laminar boundary layer. Although present day wind tunnels are much improved, an extreme amount of diligence and care are required to establish appropriate experimental conditions such as smooth test models, low free stream turbulence, etc. However in spite of careful preparations, to study transition the facility must be operated within a Reynolds number regime where small disturbances will be amplified which makes the experimental tasks more difficult.

Usually the test model, such as a flat plate or airfoil, is attached to the side walls or other support mechanism. This almost always distorts the mean flow field and produces a turbulence region which begins at or near the corner and grows downstream. Charters [3] and others have shown that this turbulence encroaches upon the laminar flow field very rapidly downstream; i.e., it spreads typically at a 10 deg angle with respect to the downstream direction. This large growth angle severely limits the useful spanwise extent of the test model. In addition, the pressure fluctuations associated with the turbulence generated from the side walls can contaminate the remaining laminar region causing it to prematurely transition.

Amini [1] apparently was the first to attack this problem by applying suction at the corners to remove the growing turbulent regions. His test model was a 3 m long flat plate 65 cm wide with a turbulent spot generator located 30 cm downstream of the leading edge. Slots between the plate and the sidewalls were used to remove the turbulent fluid. The slots were 2 mm wide near the leading edge and decreased to 1 mm at 1.5 m downstream of the leading edge. A slight overpressure on the working side of the plate was created by a flat at the downstream end of the plate, thus removing the side wall contamination through the slots. Unfortunately, so much fluid was removed that the laminar boundary layer quickly deviated from a two-dimensional one. At 60 cm downstream from the leading edge, the laminar boundary layer displacement thickness, δ^*, at $z = \pm 24$ cm showed a significant departure from that measured along the centerline. Although Amini did notice a significant improvement in the repeatability of the generated turbulent spots, the useful streamwise extent of his model was not increased due to the departure from two-dimensionality. The present research was undertaken to determine if a more optimum distribution of the slot width could be found which would provide a larger usable area on the test model.

Experimental Conditions

The Dryden Wind Tunnel at USC was used for this investigation. This is the same tunnel used by Schubauer and Skramstad [2] and details of the tunnel configuration are found in their investigation. A 1.3 cm thick aluminum plate 550 cm long and 133 cm wide sketched in Fig. 1 was mounted horizontally in the octagonal test section. Note that the usual 10 deg side wall contamination as sketched indicates that much less than half of the plate would have a laminar boundary layer at transitional Reynolds numbers. The coordinate system has it origin on the centerline of the leading edge which had an elliptical nose. A flap having a 63 cm chord was attached to the trailing edge and was set at typically 7 and

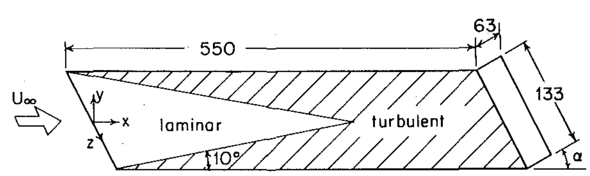

Fig. 1 Sketch of the test model showing the extent of the contaminated turbulent region due to the side wall contamination

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Contributed by the Fluids Engineering Division for publication in the JOURNAL OF FLUIDS ENGINEERING. Manuscript received by the Fluids Engineering Division, November 24, 1982.

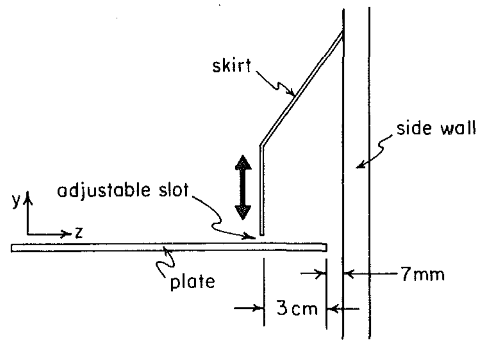

Fig. 2 Sketch of the plate, the side wall, and the adjustable skirt.

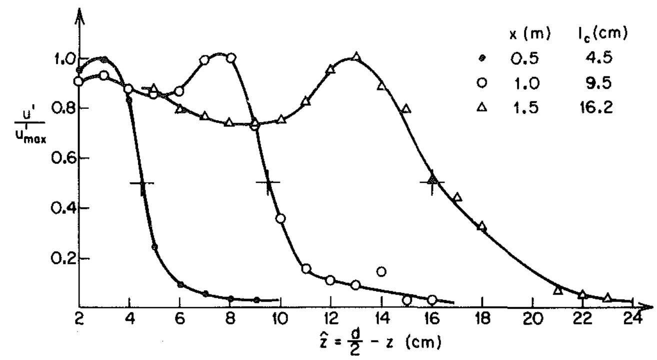

Fig. 3 The measured rms streamwise velocity fluctuations at three positions downstream

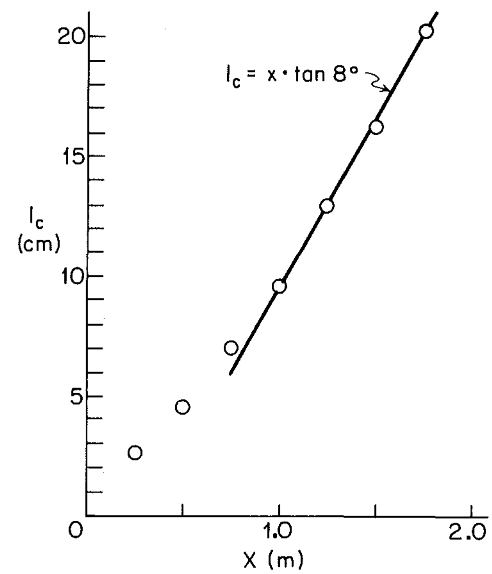

Fig. 4 Typical growth of the contaminated region with $U_\infty = 4.2$m/s and $\alpha = 7$ deg

12 deg ±0.25 deg. A 6 mm × 6 mm mesh screen was positioned in the y-z plane at the end of the plate to insure a higher pressure on the working side. Forty 0.5 mm diameter pressure taps on the plate measured the pressure distribution in the x-z plane. On the working side of the plate, skirts with adjustable slots were mounted along the side walls as sketched in Fig. 2. The skirts could be raised and lowered thus forming slot openings between 0 and 6 mm along the entire length of the plate.

The velocity data were obtained using constant-temperature hot-wire anemometers described by Blackwelder and Kaplan [4]. All data were digitized at typical rates of 1000 samples/s under control of a DEC 11/55 computer and stored on either magnetic disk packs or tapes. Prior to data collection, the hot-wire sensors were always calibrated in the free stream against an MKS Baratron pressure transducer. During a data run, the hotwire was frequently moved to the free stream to determine that no drift had occurred. If errors greater than 3 percent were obtained when compared with the pressure transducer, the data were discarded, a new calibration was obtained and the experiment proceeded. The uncertainty in the mean velocity measurements was approximately 5 percent and the repeatability of the rms velocity values was roughly 8 percent. The position of the hot-wire sensors during calibration and data gathering was determined by a three-dimensional traverse under software control. The accuracy of the traverse movement in the x, y, and z directions were 0.1, 0.025 and 0.05 mm, respectively. Linearization and further data processing were accomplished using FORTRAN programs on the 11/55 computer. Data were displayed graphically on a 4010 Tektronix terminal.

Results

The location of the contamination region is characterized by a virtual origin and an angle depicting its growth rate. These parameters were determined experimentally by finding the spanwise position where the turbulent intensity decreased to half of its maximum value. A traverse in the spanwise direction at a constant elevation of 0.3 cm above the plate was taken at $U_\infty = 4.2$ m/s and the rms streamwise velocity values were recorded as shown in Fig. 3. The rms velocities are normalized with respect to their maximum values and the data are plotted versus $\hat{z} = d/2 - z$ where d is the width of the plate between the skirts. Note that the slope of $u'(z)$ decreases as the streamwise distance increases indicating that the standard deviation of the position of the laminar-turbulent interface increases downstream. At each streamwise location, the boundary of the transverse contamination region, l_c, was defined to be the position at which $u'(l_c) = 0.5u'_{\max}$. A peak in the spanwise distribution was always found nearer the sidewall, i.e., at $\hat{z} < l_c$. This is associated with the large difference in the mean values of the velocity between the laminar and turbulent boundary layers. If the position of the peaks were used to define the interface, the growth angles were the same as defined by l_c above, however, the virtual origins were different.

The resultant locus of the transverse contamination region

Nomenclature

d = width of plate
l_c = spanwise length of contamination
Re = Reynolds number $U_\infty x/\nu$
u' = streamwise velocity fluctuation value
U_∞ = free stream velocity
x = distance downstream of leading edge
y = distance perpendicular to the plate
z = spanwise coordinate
$\hat{z}$ = distance from side wall
α = flap angle
δ^* = displacement thickness
θ = contamination angle
ν = kinematic viscosity

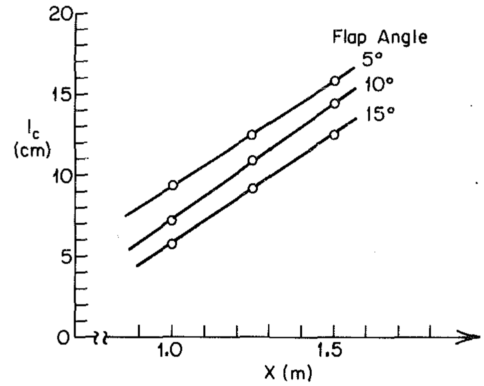

Fig. 5 The effect of the flap angle on the growth of the contaminated region. $U_\infty = 4.2$ m/s.

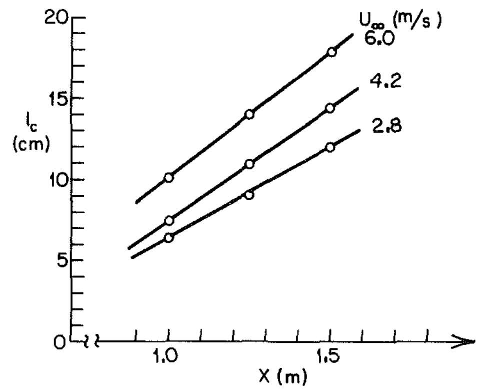

Fig. 6 The effect of the free stream velocity on the growth of the contaminated region. $\alpha = 10$ deg

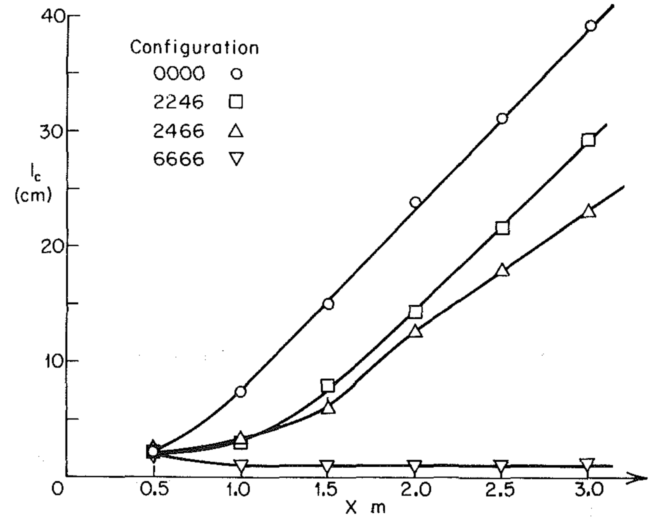

Fig. 7 The variations of the contaminated region as a function of the skirt openings. $U_\infty = 5.0$ m/s, $\alpha = 12$ deg

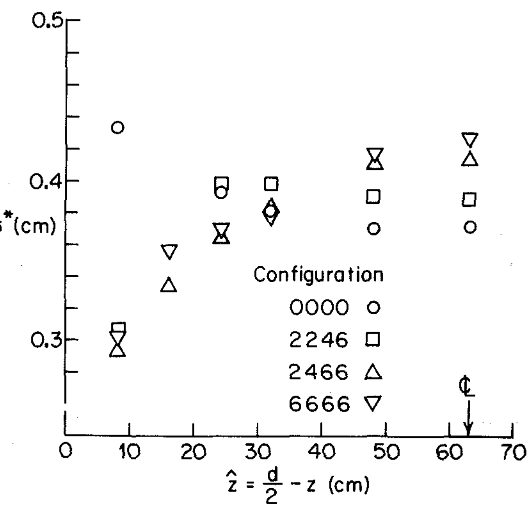

Fig. 8 Variation of the boundary layer displacement thickness for different skirt openings. $U_\infty = 5.0$ m/s, $\alpha = 12$ deg

is shown in Fig. 4 for a free steam velocity of 4.2 m/s and a flap angle of 7 deg. This base line data was obtained with the skirts completely closed. Initially the contamination grows at 5.3 deg but approaches as asymptotic value of 8 deg for $x > 0.8$ meters. Extrapolating the asymptotic value upstream yields a virtual origin at $x = 30$ cm. At this location, the Reynolds number is $U_\infty x/\nu = 85{,}000$; i.e., approximately the Reynolds number at which the flow becomes unstable to Tollmien-Schlichting waves.

The effect of the flap angle and free stream velocity on the side wall contamination are found in Figs. 5 and 6, respectively. Increasing the rear flap angle introduced a more positive pressure difference between the working and back side of the test model. This more favorable pressure difference increased the virtual origin of the contamination but did not affect its growth rate. On the other hand, increasing the free stream velocity alters both parameters. It is interesting to note that the virtual origin is typically located at $U_\infty x/\nu \sim 10^5$ near where the boundary layer first becomes unstable. The contamination angle increases from 6.4 deg to 8.7 deg as the Reynolds number (i.e., U_∞) increases. A similar increase in the asymptotic growth of turbulent spots was reported by Schubauer and Klebanoff [5].

Four different skirt configurations were tested. Each section of the skirts was 91 cm long in the streamwise direction and could be opened independently. The different configurations were denoted by a four digit number: e.g., 2466 indicated the first skirt was opened 2 mm, the second one 4 mm, etc. Beyond the fourth skirt, the remaining ones had the same opened position as the fourth one.

With $\alpha = 12$ deg and all the slots opened 6 mm, no turbulent side wall contamination was observed over the first three meters of the plate as shown in Fig. 7. At more moderate openings, intermediate contamination was found. The asymptotic growth angle was always 7-9 deg and was relatively unchanged with slot widths. However, the greatest improvement is the virtual origin of the contaminated region was moved downstream.

The two-dimensionality of the boundary layers is illustrated in Fig. 8, two meters downstream of the leading edge. With all the slots closed, the displacement thickness increased near the side wall, i.e., as $\hat{z} \rightarrow 0$, due to the turbulent boundary layers there. When all the slots were opened, a Blasius value was obtained on the centerline, but a decrease in δ^* occurs as the side walls were approached because fluid was being removed there, thus thinning the boundary layer. However, for the intermediate slot openings, δ^* only decreased 10 percent at $\hat{z} = 20$ cm at a Reynolds number of $U_\infty x/\nu = 650{,}000$. Thus a large spanwise extent over a meter wide was available for testing with less than a 10 percent deviation of the boundary layer thickness.

Conclusions

By carefully adjusting slots along the edges of a flat plate, the side wall contamination of turbulence could be reduced so that a larger region of laminar boundary layers was available for testing. The spanwise width of the laminar region was essentially doubled. The length also doubled, at least at the lower Reynolds numbers, so that the useful test area was increased by a factor of four. Thus, more comprehensive studies of transitional bounary layers at larger Re_x will be possible with this modification.

Acknowledgements

The authors thank Joe Haritonidis for overseeing the installation and instrumentation of the flat plate and the skirts. The automation of the data gathering was made possible by Dick Kaplan. The keen interest and encouragement of the late John Laufer were much appreciated. The support of the Air Force Office of Scientific Research under Contract F49620-78-C-0060 monitored by Capt. Mike Francis is gratefully acknowledged.

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