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Effect of Wall Suction on a Turbulent Boundary Layer: Reynolds Number Dependence

O. Oyewola, L. Djenidi and R.A. Antonia

Department of Mechanical Engineering
University of Newcastle, NSW 2308 Australia

Abstract

Single hot wire measurements have been made in a turbulent boundary layer subjected to localised wall suction, applied through a porous strip, at various Reynolds numbers and suction rates. The measurements of the skin friction coefficient (with a Preston tube) not only confirm that pseudo-relaminarization can occur immediately downstream of the strip, but they also show that the Reynolds number/suction rate combination is the main factor controlling it. The mean and rms velocity profiles depart from the corresponding undisturbed profiles for all $R_{\theta o}$ and σ ($R_{\theta o}$ is the Reynolds number based on the momentum thickness of the boundary layer in the absence of suction at the leading edge of the suction strip and σ is the suction rate), the departure being more pronounced at the largest σ and smallest $R_{\theta o}$.

Introduction

The ability to interfere with the turbulence structure of turbulent flows occurring in various engineering applications is of significant importance and benefit. For example, the application of suction to a turbulent boundary layer can lead to delay in flow separation, extension of the region of laminar flow, or a delay in transition ([1]; [4]; [5]; [11]; [12]). Furthermore, from a fundamental viewpoint, the study of the response of a turbulent boundary layer to a perturbation, such as a sudden application of suction provides an opportunity to learn more about the dynamics of the layer [2]. However, most of the past studies have been on the response of the layer to a small amount of suction and the streamwise distance covered is not long enough for the boundary layer to return to a fully turbulent state. For example, [13] studied the effect of wall suction applied through a two-dimensional suction slot. Unfortunately, his measurement extended only to a streamwise distance of $20\delta_o$ (δ_o is the boundary layer thickness at the slot in the absence of suction) downstream of the suction slot. Likewise, the measurements of [9] in a turbulent boundary layer subjected to a wall suction through one or more slots extended only to $5\delta_o$.

The focus of this present study is primarily on studying the influence of the Reynolds number on the response of the boundary layer to the suction. [2] studied the effect of concentrated wall suction, applied through a short porous wall strip, on a low Reynolds number turbulent boundary layer. They showed that, when the suction rate is sufficiently high, pseudo-relaminarization occurred almost immediately downstream of the suction strip. Further downstream, transition occurs followed by a slow return to a fully turbulent state. They also pointed out that while the suction rate is an important factor in the process of relaminarization and subsequent recovery, the Reynolds number should play a non-negligible part in this process. The main objective of the present study, which extends the work of ([2]), is to assess the influence the Reynolds number/suction rate combination has on a turbulent boundary layer. The influence is quantified by measuring the skin friction, mean velocity and longitudinal turbulent intensity profiles at various Reynolds numbers and suction rates, at several x locations downstream of the suction strip.

Mesurements Details

Measurements were made in an open return, suction type wind tunnel driven by an axial flow fan powered by a controllable DC motor. Air enters the working section (Figure 1) via a bell mouth inlet, a honeycomb section, a short settling chamber with fitted screens and a 5:1 two-dimensional contraction. A turbulent boundary layer developed on the floor of the rectangular working section (Figure 1) after it was tripped at the exit from the contraction with a 100 mm roughness strip. Tests showed that the boundary layer was fully developed at the suction strip location. The freestream turbulence level is about 40%. Three values of Reynolds numbers were used ($R_{\theta o}$ = 660, 1100 and 1400; $R_{\theta o}=U_1\theta_o/\nu$, where U_1 is the free stream velocity, θ_o is the

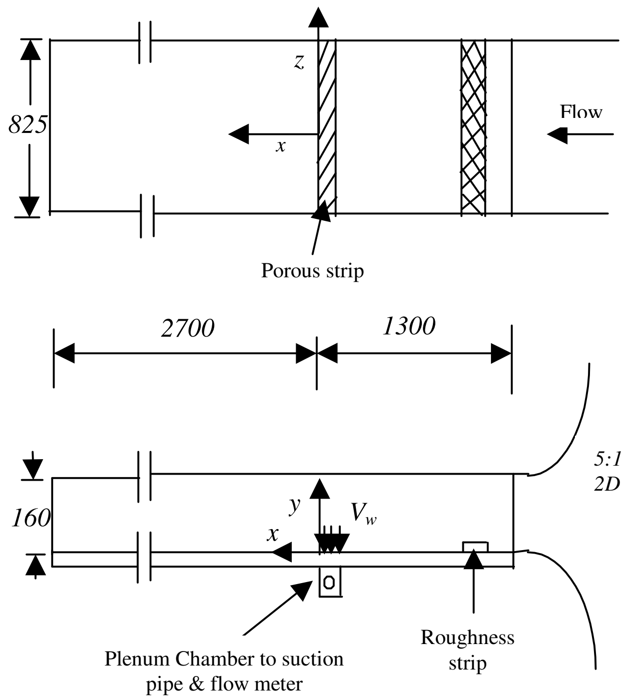

Fig. 1. Experimental Set Up (Dimensions in mm)

momentum thickness at the leading edge of the suction strip when no suction is applied (about 3.2 mm), and ν is the kinematic viscosity of the fluid). The boundary layer thickness at the leading edge of the suction strip when no suction is applied is about 30 mm. A 7.25mm thick porous strip of streamwise length 40mm and made of polytetrafluoroethylene with pore sizes in the range 40-80µm or (0.4-0.9)ν/U_τ (U_τ is the friction velocity) was mounted flush with the test section floor. Allowing for the width of the mounting recess steps, the effective width (=b) of the strip was 35mm. Suction was applied through a plenum chamber underneath the suction strip connected to a suction blower driven by a controllable DC motor. The suction velocity (υ_w) was assumed to be uniform over the porous surface, an assumption partly supported by the (±3% variability of the permeability coefficient of the porous material. Three values of suction rate σ ($=\upsilon_w b/\theta_o U_1$) were used ($\sigma$ = 1.7, 3.3 and 5.5) for each the Reynolds number. Measurements of the skin friction, mean velocity and longitudinal turbulence intensity, with and without suction, were made at several positions downstream of the suction strip. The measurement at $\sigma = 0$ provided a reference for the data when suction was applied. The skin friction was measured with a Preston tube (0.72 mm outer diameter), and a static tube located approximately 35mm above it at the same x position. The Preston tube was calibrated in a fully developed channel flow (for further details see [2] and [3]). The uncertainty in the skin friction measurement was about ±5%. The velocitiy fluctuations in the streamwise direction were measured with a single hot wire. The etched wire (Wollaston, Pt-10% Rh) had a diameter of 5µm, and a length to diameter ratio of about 200. The hot wire was operated by an in house constant temperature circuit at an overheat ratio of 1.5. The analogue output signal of the hot wire was low-pass filtered (1.2kHz-5kHz). The hot wire was calibrated, before and after each y traversed, in the free stream using a Pitot tube connected to a MKS Baratron pressure transducer. The distance between the hot wire and its wall image was measured with a theodolite. The uncertainties of the mean velocity (±1%). and turbulence intensity ±5% were estimated by repeating measurements at several x locations downstream of the strip.

Results and Discussion

The streamwise distributions of C_f/C_{fo} (C_f is the skin friction coefficient of the perturbed layer and C_{fo} is that of the unperturbed layer) for various combinations of the Reynolds number and suction rate are shown in figure 2.

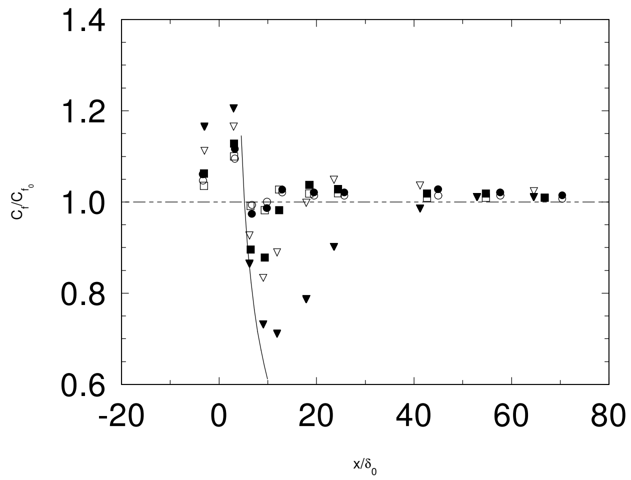

Fig. 2. Streamwise variation of the skin friction coefficient. Open symbols $\sigma = 3.3$; closed symbols, $\sigma = 5.5$. ∇, ▼$R_{\theta o} = 660$; □, ■: 1100; ○, ●: 1400. The line corresponds to the Blasius distribution.

All distributions show almost the same behaviour: C_f/C_{fo} increases upstream of the porous strip, decreases immediately downstream, reaches a minimum, increases again to a local maximum (overshoot), and then relaxes towards a constant value. Note though that this value appears to be larger than 1. This indicates that the perturbed boundary layer does not return to its non-perturbed state at any given value of x after the suction strip. This is clearly seen in the values of R_θ and the shape factors (not shown here): when suction is applied, they do not recover the values of the non-disturbed layer.

Both σ and $R_{\theta o}$ control the streamwise variation of C_f/C_{fo}: as σ increases, the variation amplifies, but weakens as the Reynolds number increases. The pattern of the C_f/C_{fo} variation downstream of the suction strip (decrease – increase – overshoot – recovery) may suggest that the boundary layer reacts in a similar way to suction at different Reynolds numbers. There are, however, marked differences between the distributions at $R_{\theta o} = 660$ and those at $R_{\theta o}$ = 1100 and 1400 for $\sigma = 5.5$: at $R_{\theta o} = 660$ the reduction of C_f/C_{fo} is about 30%, the streamwise recovery distance is $40\delta_o$, compared to about 15-20δ_o for the higher Reynolds number and there is no apparent overshoot. This would reflect structural changes in the boundary layer downstream of the suction strip. It is possible that, in the near-wall region, structures are eradicated or at least significantly weakened for $\sigma = 5.5$ and $R_{\theta o} = 660$ to alter the C_f/C_{fo} distribution pattern. Note that the distributions in the region $0 \le x/\delta_o \le 10$ appear to follow Blasius, indicating that the boundary layer is undergoing a "relaminarization" process downstream of the suction strip. The streamwise location where this process stops, arguably the minimum of C_f/C_{fo}, depends on both the Reynolds number and the suction rate: it decreases with an increase of the ratio $R_{\theta o}/\sigma$. Beyond this point the boundary layer regains turbulent energy and starts its recovery. From a practical point of view, this observation could be used to develop an interesting method of control of the boundary layer by placing successive suction strips at locations where recovery starts (minimum C_f) may be an effective way to achieve relaminarization with less severe suction rates and thus a smaller penalty in terms of total energy input.

Figure 3 show mean velocity profiles for $R_{\theta o}$ = 660 and 1400 and σ = 0, 3.3 and 5.5. (the sign + denotes normalization with ν and U_τ) at x/δ_o = 3.1 and 9.1 downstream the suction strip. Since the Preston tube depends upon the assumption of a universal law, the shift in the log region at $\sigma = 0$ between the two profiles comfirms the inadequacy of the tube for low Reynolds numbers measuements. It is remarkable to observe the collapse of all the data points onto a single line in the region $0 < y^+ < 10$ for all Reynolds numbers and suction rates. This highlights the rather rapid response of the mean velocity in this region to a change in the boundary conditions. This contrasts significantly with the region $y^+ > 10$, where the combined effect of Reynolds number/suction is felt dramatically. The effect of σ on the velocity distributions is similar for both Reynolds numbers. For example, the departure of the perturbed profiles from the undisturbed ones increases with σ. However, the influence of the Reynolds numbers becomes apparent as x increases. As x/δ_o increases, the effect of the suction becomes less pronounced as the Reynolds number increases. Already at $x/\delta_o = 9.1$, the departure of the perturbed profiles at $R_{\theta o} = 1440$ is relatively less important than that for $R_{\theta o} = 660$.

The same observations can be made with respect to the streamwise fluctuation distributions shown in Figure 4. Note that there is no collapse in the region $y^+ < 10$ as, for the mean velocity distributions, implying that the turbulent field responds less quickly than the mean field to a change in boundary condition. The general reduction in the level of u'^+ in the vicinity of the suction strip decreases as the ratio $R_{\theta o}/\sigma$ increases. The reduction is more pronounced at the lower Reynolds number. For instance, the maximum value of u'^+ at $R_{\theta o}$ = 660 and 1400 reduces to 40% and 20%, respectively, when $\sigma = 5.5$. at x/δ_o = 3.1. The reduction in the turbulence intensity is likely to reflect the weakening due to suction, of the active motion. The reason for the overshoot (at $x/\delta_o = 9.1$) is not clear yet.

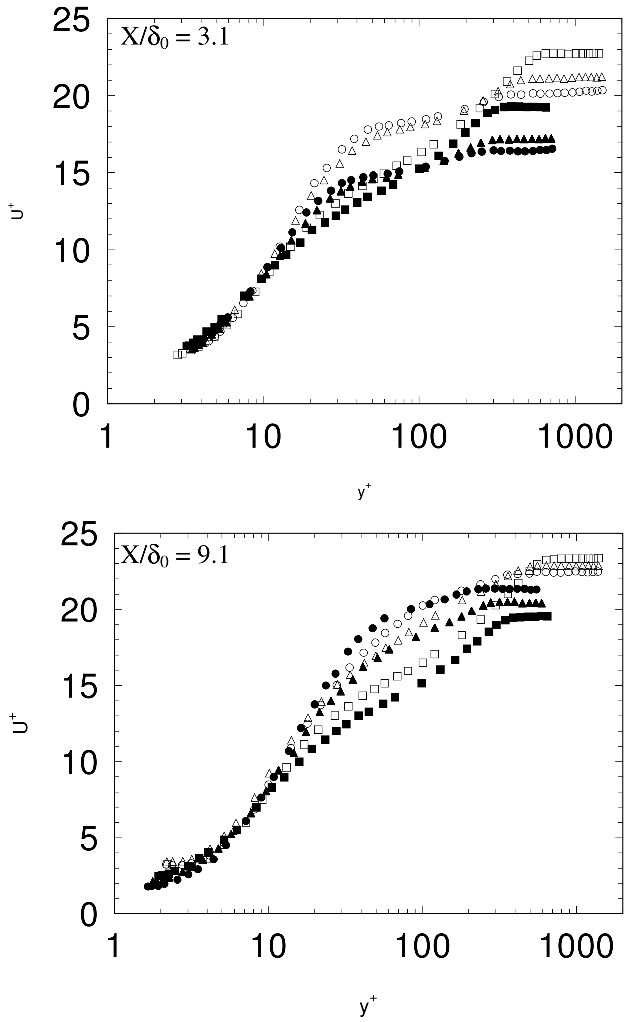

Fig. 3 Mean velocity distributions. Closed symbols $R_{\theta o}$ = 660; open symbols, $R_{\theta o}$ = 1400. □, ■: σ = 0; Δ, ▲: σ = 3.3; ○, ●: σ = 5.5.

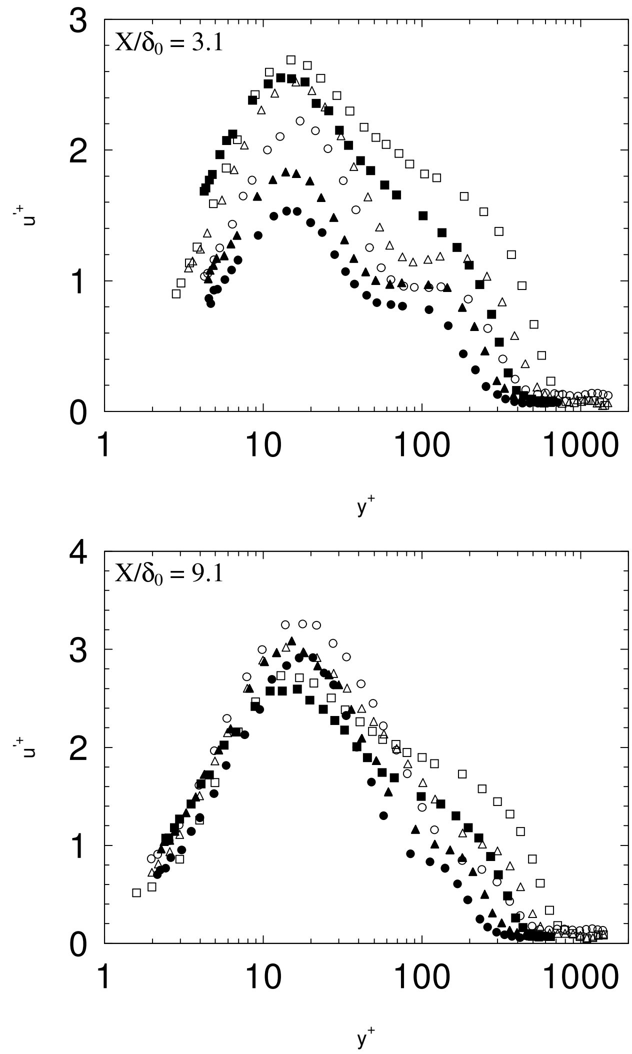

Fig. 4 Streamwise rms distributions. Closed symbols $R_{\theta o}$ = 660; open symbols, $R_{\theta o}$ = 1400. □, ■: σ = 0; Δ, ▲: σ = 3.3; ○, ●: σ = 5.5.

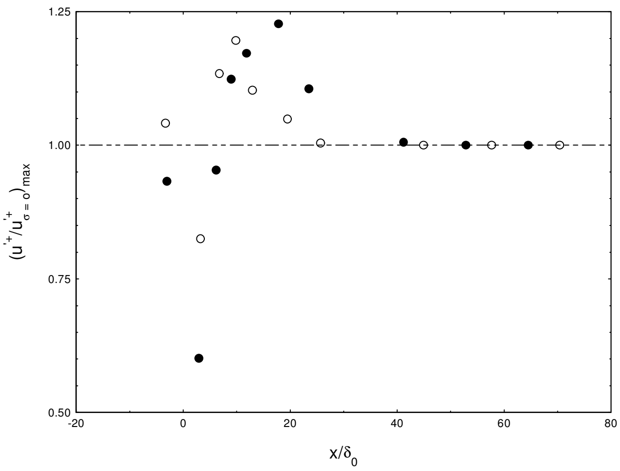

Fig. 5 Streamwise variation of $(u'+)_{max}$. ●, $R_{\theta o}$ = 660; ○, $R_{\theta o}$ = 1400.

Note that because the Reynolds number is reduced when suction is applied, the distributions in the outer region must depart from those at σ = 0 in accordance with the Reynolds number dependency. This was observed in all distributions for all streamwise measurement positions, corroborating the suggestion that the perturbed boundary layer does not return to the undisturbed state.

The influence of the Reynolds number on the effect of suction is clearly evident in Figure 5 showing the streamwise variation of $(u'^{+}/u'^{+}_{\sigma = 0})_{max}$, which is the ratio between the maximum values of u'^{+} with and without suction. Both the magnitude and wavelength of the oscillation reduce as the Reynolds number increases. This behaviour is similar to that of C_f/C_{fo}, and underlines the fast response of the higher Reynolds number boundary layer to suction. Note that the streamwise positions of maximun of $(u'^{+}/u'^{+}_{\sigma = 0})_{max}$ correspond to the positions of minimum C_f/C_{fo}.

The previous results suggest that the boundary layer undergoes some changes when suction is applied, at least in the immediate vicinity of the suction strip. This is confirmed by distributions of the skewness ($S_{u'}$) and flatness ($F_{u'}$) factors of u′ shown in Figure 6. Kline et al. (1967, 1971) identified these quantities in connection with the width of the streak filaments, which are produced close to the wall and contribute significantly to the bursting process. The departure from the non suction case indicates that this process has been altered by suction resulting in changes in the turbulence structure of the layer. The data would indicate that the changes are similar for both Reynolds numbers, but more pronounced for the larger suction rate.

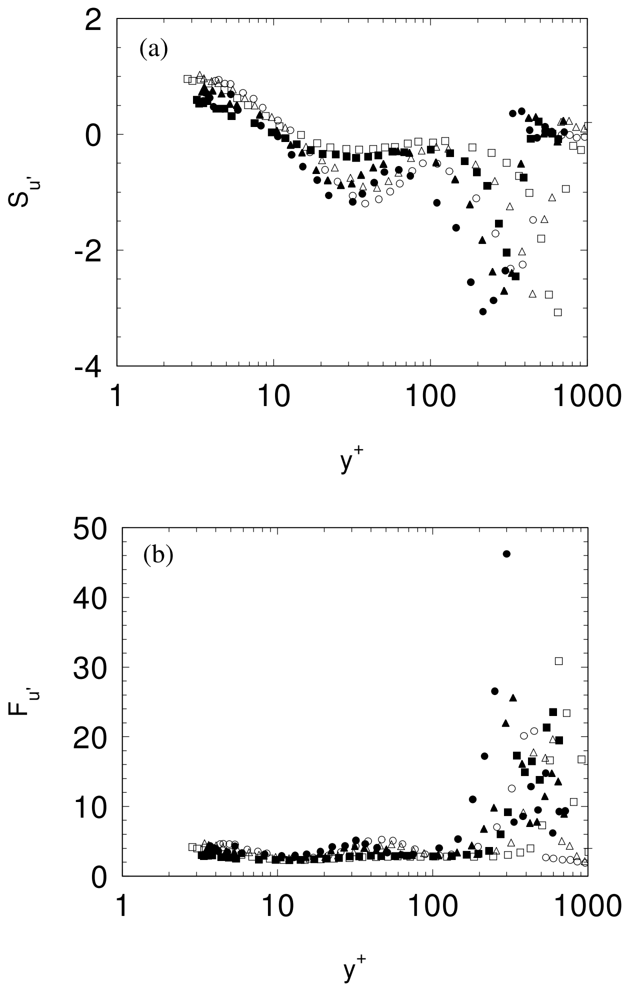

Fig.6 Skewness (a) and Flatness (b) factor distributions. Closed symbols, $R_{\theta o}$ =660; Open symbols, $R_{\theta o}$ =1400. □, ■: σ = 0; Δ, ▲: σ = 3.3; ○, ●: σ = 5.5.

Conclusions

Single hot wire measurements have been made in a turbulent boundary layer subjected to localised wall suction, applied through a short porous strip, at various Reynolds numbers and suction rates.

The results can be summarized as follows:

1. The Reynolds number/suction rate combination play a significant role in relaminarizing the layer.
2. Pseudo-relaminarization occurs downstream of the suction strip for $R_{\theta o}$ = 660 and σ = 3.3, and its streamwise extent increases as σ increases. At $R_{\theta o}$ = 1400, no pseudo-relaminarization is observed even at the largest value of σ (5.5) that was investigated.
3. The streamwise distance required for the boundary layer to become fully developed decreases as the $R_{\theta o}$ increases for all σ.
4. The mean and rms longitudinal velocity profiles depart from the corresponding undisturbed profiles for all $R_{\theta o}$ and σ, the departure being more pronounced at the largest σ and smallest $R_{\theta o}$.
5. $S_{u'}$ and $F_{u'}$ show no significant Reynolds number dependence but reflect changes in turbulence structure.

X-wire measurements of v' and uv are currently made and should be presented at the conference.

Acknowledgments

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