The Influence Of Wall-Porosity Upon The Near-Wall Turbulence Dynamics

M. Uhlmann, A. Pinelli, J. Jiménez and G. Kawahara

School of Aeronautics, Universidad Politécnica de Madrid, Plaza Cardenal Cisneros 3, 28040 Madrid, Spain

Contact e-mail: uhlmann@pik-potsdam.de

1 Introduction

We investigate low-Reynolds number turbulent flow in a plane channel with one impermeable and one porous wall. Both walls satisfy the no-slip condition, but the wall-normal velocity v at the porous surface (for which $y=0$) is proportional (and of the opposite sign) to the pressure fluctuations p' with respect to the local mean at a given streamwise location, viz.

$$v(y=0) = -\beta\, p'(y=0), \text{ where } \qquad p'(x,y,z) = p(x,y,z) - \overline{p}(x) \quad . \tag{1}$$

The wall transpiration is therefore mass-less, i.e. its integral over the wall plane vanishes. This configuration is a model for a passive control device to delay boundary layer separation under adverse pressure gradients. What is required in that case is an *increase* of the local friction coefficient, which eventually results in a lower form factor, and in a more resilient boundary layer. Our purpose here is to clarify the mechanism by which the porosity of the boundary affects the near-wall turbulence statistics.

We have performed a series of direct numerical simulations at a nominal Reynolds number of 190 (based on the channel half-width h and on the friction velocity u_τ of the fully impermeable case), in boxes of size of $8.17h$ and $3.14h$ in streamwise (x) and spanwise (z) directions, respectively, and using a Fourier/-fourth-order B-spline method [1]. The spacing of the collocation points after dealiasing was less than 10×5 wall units in the homogeneous directions; the grid size ranges between $0.4 - 4$ in the wall-normal direction. Several porosity levels β were analyzed, all belonging to a regime where no noteworthy local flow reversal is observed.

2 Results

The results show a 40% increase of skin friction for an *rms* transpiration intensity of $0.17u_\tau$, a substantial increase in overall turbulence intensities, and a decrease

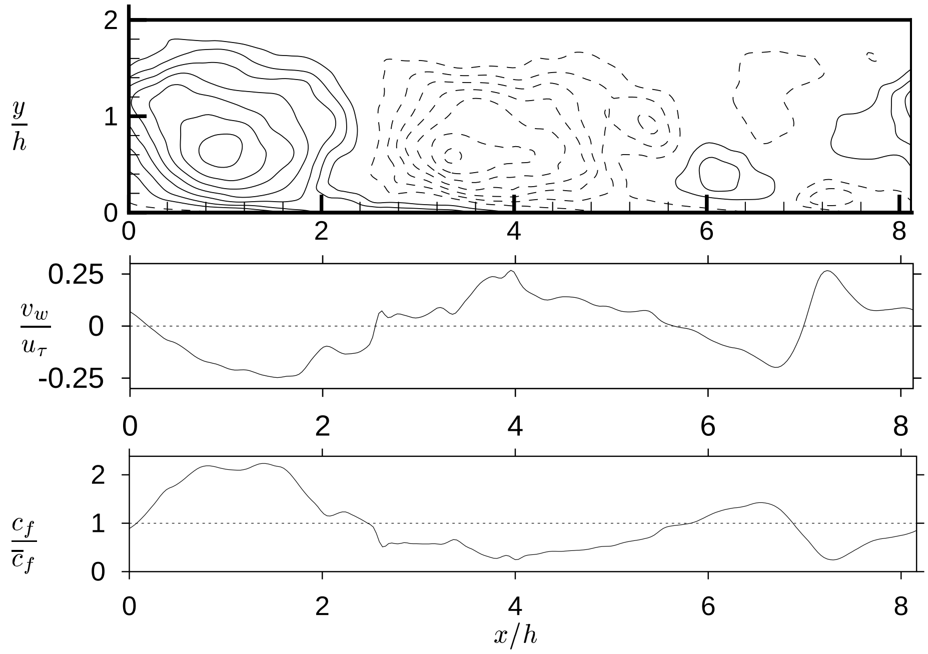

Figure 1: (Top) Instantaneous streamlines of the spanwise-averaged velocity fluctuations, (centre) spanwise-averaged wall-transpiration v_w and (bottom) spanwise-averaged skin friction c_f on the porous, lower wall of the simulated channel flow.

of the shape factor of the mean profile (cf. earlier experimental results in [2]).

Two-point autocorrelations of the velocity components reveal the presence of strong spanwise-coherent structures at large (wall-normal and streamwise) scales, of size $O(h)$. Instantaneous visualizations (figure 1) confirm that this coherent motion is formed by alternating 'roller' vortices which lag slightly with respect to the wall transpiration v_w, and which penetrate far into the core flow. Spatio-temporal correlations show that their streamwise phase velocity is of the order of $12.5\,u_\tau$ which in turn is comparable to the advection speed of the buffer layer structures [3]. The intensity of the rolls is $O(u_\tau)$ and, as a consequence, the buffer zone and the sublayer are alternately accelerated and decelerated, being periodically energized and almost laminarized along spanwise-coherent strips; the instantaneous spanwise-averaged skin friction shows a corresponding cyclic variation along the streamwise direction (figure 1). Locally, skin friction and transpiration exhibit a clear correlation which is shown in figure 2 by means of the histogram of their joint probability density. From the regression of the data it can be deduced that at points of fluid injection ($v_w > 0$) skin friction decreases by an amount that is smaller than the increase at points of equally strong suction. The non-linearity of this correlation leads to the observed increase in

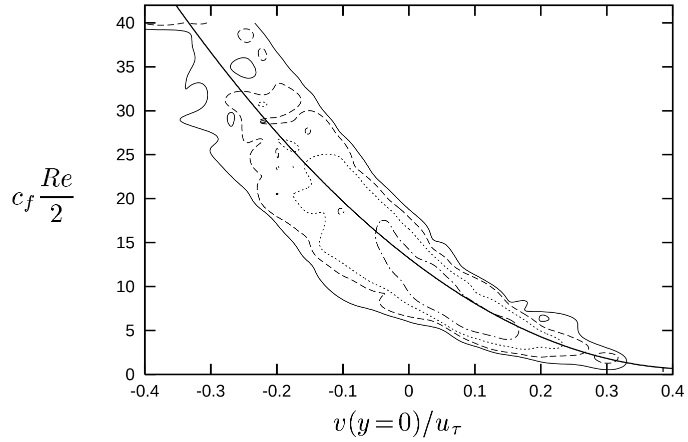

Figure 2: Histogram of the joint probability density function of the spanwise-averaged skin friction c_f and spanwise-averaged wall-transpiration $v(y=0)$. The isolines are: ——— , 10^0; ‑‑‑‑ , $10^{0.5}$; ········ , 10^1; —·— , $10^{1.5}$. The thick solid line is a quadratic regression obtained by a least-squares fit of the data.

overall drag. This situation is consistent with results from cases with spatially uniform suction/blowing (cf. [4] and references therein) and can be shown to hold qualitatively in the laminar regime.

The linear analysis of the mean velocity profile (taking into account 'background turbulence' through an eddy viscosity ansatz) shows that the flow near a porous wall is unstable with respect to two-dimensional eigenfunctions, whose qualitative shape and phase velocity are close to those of the fully non-linear perturbations; the basic mechanism is inviscid and similar to the instability of a plane wake, and is also present in simpler profiles, such as in a confined layer of constant shear near the wall.

We have performed further experiments in which spanwise-coherent wall transpiration, and the resulting rolls, were externally imposed (*active* control) using a simple streamwise sinusoidal distribution. They lead to quantitatively comparable increments in drag (figure 3). Note that, because the large-scale motion is the result of an intrinsic flow instability, active control requires only a net *negative* energy expenditure.

3 Conclusions

The mechanism of turbulence enhancement and drag increase at porous boundaries, with applications to separation control, was shown to be due to large-scale

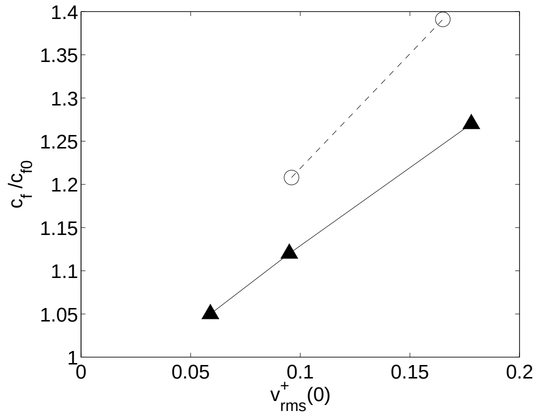

Figure 3: Increase in wall friction as a function of the r.m.s. transpiration velocity at the wall. ∘ , porous wall; ▲ , sinusoidally forced ones.

spanwise-coherent structures possibly arising from an inviscid, two-dimensional instability of the mean profile. Alternatively, active generation of spanwise-coherent, streamwise-sinusoidal, mass-less transpiration can yield a similar effect. In the present strategy there is no need for fine-grained localized flow sensors. Accompanying laboratory experiments are currently being undertaken at LML, Ecole Centrale de Lille, France.

This work was supported in part by the Brite/AeroMems consortium, and by the Spanish CICYT under contract PB95-0159. G.K. received additional support from the Japanese Ministry of Education, Science and Culture.

References

[1] J. Jiménez, A. Pinelli, and M. Uhlmann. Plane channel flow simulation over porous walls. Technical Note ETSIA MF-9809, School of Aeronautics, Universidad Politécnica Madrid, Spain, 1998.

[2] F.S. Collier and J.A. Schetz. Injection into a turbulent boundary layer through porous surfaces with different surface geometries. AIAA paper no. 83-0295, 1983.

[3] J. Jiménez and P. Moin. The minimal flow unit in near-wall turbulence. *J. Fluid Mech.*, 225:213–240, 1991.

[4] Y. Sumitani and N. Kasagi. Direct numerical simulation of turbulent transport with uniform wall injection and suction. *AIAA J.*, 33(7):1220–1228, 1995.