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REYNOLDS-NUMBER DEPENDENCE OF STREAMWISE VELOCITY FLUCTUATIONS IN TURBULENT PIPE FLOW

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ABSTRACT

Statistics of the streamwise velocity component in fully-developed pipe flow are examined for Reynolds numbers in the range $5.5 \times 10^4 \leq Re_D \leq 5.7 \times 10^6$. The second moment exhibits two maxima: one in the viscous sublayer is Reynolds-number dependent while the other, near the lower edge of the log region, is also Reynolds-number dependent and follows roughly the peak in Reynolds shear stress. The behaviour of both peaks is consistent with the concept of inactive motion which increases with increasing Reynolds number and decreasing distance from the wall. No simple scaling is apparent, and in particular, so-called "mixed" scaling is no better than wall scaling in the viscous sublayer and is actually worse than wall scaling in the outer region. The second moment is compared with empirical and theoretical scaling laws and some anomalies are apparent. The scaling of spectra using y, R and u_τ is examined. It appears that even at the highest Reynolds number, they exhibit incomplete similarity only: while spectra do collapse with either inner or outer scales for limited ranges of wave number, these ranges do not overlap. Thus similarity may not be described as complete and any apparent k_1^{-1} range does not attract any special significance and does not involve universal constants. It is suggested that this is because of the influence of inactive motion. Spectra also show the presence of very long structures close to the wall.

1. INTRODUCTION

Recent results from the "superpipe" facility at Princeton University (Zagarola and Smits, 1998) have shown that the mean velocity profile outside the viscous sublayer in fully-developed pipe flow exhibits a power-law dependence in the region $60 < y^+ < 500$, and that outside this region, the mean velocity follows a log law provided $R^+ > 9000$. R^+ is the Kármán number based on pipe radius. The power-law dependence of the mean velocity on y^+ expresses the direct influence of viscosity outside the sublayer while the log-law dependence is an expression of a self-similar region in which the mean velocity scales on the wall-friction velocity, u_τ, and the distance from the wall, y, only. The literature abounds with data for near-wall turbulent flow showing that the higher moments do *not* scale simply, and this can be explained by Townsend's (1961) theory concerning "active" and "inactive" motion. See also Bradshaw (1967) and Morrison *et al.* (1992). Of particular importance is the difference in the behaviour of wall-parallel (u, w) and wall-normal (v) velocity components as the wall is approached: the "impermeability constraint", which affects eddies out to a distance from the wall that is of the order of the eddy size is responsible for an increase of the wall-parallel velocities at the expense of the wall-normal velocity. Thus, to a first order, the inactive motion in the wall-parallel components carries no shear stress: by definition, the active motion is the shear-stress bearing motion. Townsend describes inactive motion as a "meandering or swirling" of the large eddies imposed on the near-wall motion. There are also many measurements that show that the active motion does not scale on inner variables either, a particular result being that the "constant stress" region $(-\overline{uv} \approx u_\tau^2)$ does not hold, except in the limit of

very high Reynolds number. These effects may be traced to the direct influence of viscosity outside the sublayer. This is a noteworthy observation since the constant-stress region may be deduced using the same dimensional arguments as those used in a derivation of the log law, but it has yet to be established whether or not the constant stress region appears at the same Reynolds number as the log law. Given these difficulties, it is hardly surprising that simple arguments involving the overlap of scales (so giving rise to self-similarity) may well be inappropriate.

Since publication of Townsend's seminal work, considerable attention has been devoted to the deduction of spectral forms associated with the self-similar nature of "attached wall eddies". Such self-similarity manifests itself at 'high' Reynolds numbers as a range of streamwise wave numbers, k_1, in which the spectrum of the streamwise velocity, $\phi_{11} \propto u_\tau^2 k_1^{-1}$. There are several derivations, the earliest provided by Tchen (1953), reappraised by Hinze (1975), involving the balance between the spectral transfer of energy by the mean shear and that by inertial interactions of the turbulence – a strong interaction or "resonance" condition. Tchen's theory involves several assumptions that are questionable in highly anisotropic wall turbulence. More pragmatically, it should be noted that a prescribed slope over some region of wave number can usually be found in turbulence spectra on log-log axes. A simple theory for pipe flow was proposed by Perry and Abell (1977) and Perry et al. (1986), but it is equally appropriate for boundary layers (Perry and Li, 1990, Marušič and Perry, 1995, Jones et al., 2001). Given the prominence of the theory and its potential usefulness (so much so that its existence at practical Reynolds numbers is often taken for granted – Nikora, 1999), and given the uniqueness of the present results (in terms of the high Reynolds numbers) a careful reappraisal is clearly needed.

Scalings for 'large' scales (in which the direct effects of viscosity may be neglected) contributing to the streamwise velocity component may be scaled using either inner or outer scales. Outer scaling suggests that y is not important and that dimensional analysis therefore yields

$$\frac{\phi_{11}(k_1)}{Ru_\tau^2} = \frac{\phi_{11}(k_1 R)}{u_\tau^2} = g_1(k_1 R), \qquad (1)$$

while, alternatively, inner scaling suggests the exclusion of R as a relevant length scale so that, at higher wave numbers,

$$\frac{\phi_{11}(k_1)}{y u_\tau^2} = \frac{\phi_{11}(k_1 y)}{u_\tau^2} = g_2(k_1 y). \qquad (2)$$

The veracity of these scalings is usually judged b the degree of collapse of the spectra at wave num bers lower than that at which spectral transfer (a high Reynolds numbers, given by the mean diss pation rate) becomes important. In the range ‹ wave numbers $R^{-1} < k_1 < y^{-1}$ over which bot Eq. (1) and Eq. (2) are valid (that is collapse evident with both scalings, as required by asymp totic matching), it then follows that

$$\phi_{11}(k_1) = R u_\tau^2 g_1(k_1 R) = y u_\tau^2 g_2(k_1 y). \qquad (3)$$

Dimensional arguments and direct proportionalit between g_1 and g_2 therefore imply

$$\frac{\phi_{11}(k_1 R)}{u_\tau^2} = \frac{A_1}{k_1 R} = g_1(k_1 R), \qquad (4)$$

and

$$\frac{\phi_{11}(k_1 y)}{u_\tau^2} = \frac{A_1}{k_1 y} = g_2(k_1 y), \qquad (5)$$

where A_1 is a universal constant. Collapse wit both length scales therefore suggests a self-simil structure such that $\phi_{11}(k_1) \propto u_\tau^2 k_1^{-1}$. One coul therefore call this situation "complete similarity" In this situation, the only relevant length scale k_1^{-1} itself, and, owing to the nature of the Fouri transform, a self-similar structure would have t be space-filling in (x, z)-planes parallel to the su face. Now, it is possible that, for example, while and u_τ might form a complete parameter set to d fine the motion in the range of wave numbers ov which collapse is apparent (Eq. (2)), these wa numbers might in fact be too high for collapse be possible using R and u_τ (Eq. (1)). Thus simu taneous collapse is not possible. We shall refer this situation as "incomplete similarity", in whi case the constant A_1 in Eqs. (4) and (5) cannot l universal.

Note that this analysis is predicated on two pri cipal assumptions. The first is that the kinemat viscosity, ν, does not enter the problem. This r quires that $k_1 \ll u_\tau/\nu$. In turn, this requir the Reynolds number to be sufficently high, ‹ equivalently that y is sufficiently large such tl energy-containing scales are not affected direct by viscosity. The second assumption is that ‹ is the correct velocity scale for both the inn and outer regions. In particular, in conformi with Townsend's theory, it supposes that inacti motion arises primarily through the influence attached eddies and that therefore u_τ is the appr priate velocity scale. The analysis does not speci u_τ to be the velocity scale: rather, it specifies th the velocity scale should be the same with both i ner and outer scaling. Note also that this analys

does not apply to the wall-normal velocity component which is blocked at wave numbers $k_1 \sim y^{-1}$.

Below, spectra are presented in premultiplied form on linear-log axes. A linear ordinate enables a closer scrutiny of scalings than that afforded by a logarithmic one. In addition, the use of non-dimensional axes ensures that not only the ordinate, but also the area under the spectra are directly proportional to energy. Thus integration of the spectra yields $\overline{u^2}^+ = \overline{u^2}/u_\tau^2$. Spectra are therefore in the form:

$$\frac{k_1 R \phi_{11}(k_1 R)}{u_\tau^2} = h_1(k_1 R), \qquad (6)$$

for outer scaling, and for inner scaling, in the form:

$$\frac{k_1 y \phi_{11}(k_1 y)}{u_\tau^2} = h_2(k_1 y). \qquad (7)$$

In the context of assessing these scalings for data in the present experiment, it is useful to clarify precisely what the foregoing analysis indicates. Strictly, as long as $\nu/u_\tau \ll y \ll R$ (the Reynolds number is 'high'), Eqs. (4) and (5) should both show a k_1^{-1} range for $R^{-1} \ll k_1 \ll y^{-1}$. However, in order to remove the ambiguity concerning the relative values of y and R, one may fix alternately y in Eq. (4) and then R in Eq. (5). Eq. (6) invites us to retain only R and u_τ as independent variables. Thus while y is fixed, u_τ is varied by changing the pressure drop along the pipe. In practice, this involves a change of Reynolds number (strictly Kármán number) as changes of R are a little more problemmatical. This does not pose a problem as long as the Reynolds number is sufficiently high such that the wave-number range of interest is not directly affected by viscosity. Alternatively, Eq. (7) invites the use of y and u_τ only as independent variables for any fixed R. In this case, y can merely be varied (subject to $\nu/u_\tau \ll y \ll R$) at a fixed Reynolds number, although as long as ν can be neglected, a value of y at *any* Reynolds number might be chosen. For brevity, in what follows we present spectra (obviously using both inner and outer scaling) at different y/R for the lowest and highest Reynolds number. The spectra at fixed y/R for several Reynolds numbers confirm the present conclusions and are presented elsewhere.

2. EXPERIMENTAL PROCEDURE

Details of the pressurised pipe and results from extensive pitot-tube measurements are provided in Zagarola and Smits (1998). Issues regarding the fully-developed nature of the flow, axisymmetry

and temperature control have been dealt with exhaustively by them. Here, velocity measurements are made using standard hot-wire techniques using wires with length-to-diameter ratios, $l/d = 200$, and for $Re_D \geq 3 \times 10^6$, 100. The hot-wire length in wall units, l^+, is 12, 14, 26 at the three lowest Reynolds numbers, respectively, 5.5×10^4, 7.5×10^4 and 1.5×10^5. Convergence of all moments is better than 1%, except for the third moment in the region $10 \leq y^+ \leq 30$. In this range the convergence of the third moment is better than 10% only because here its value is numerically close to zero. Positional accuracy as a fraction of R is better than 0.02%. Hot-wire calibration is achieved using a fourth-order polynomial, the signal being sampled using 12-bit A-D conversion. In order to maximise spatial resolution, the mean velocity is kept as low as possible, the sample rate being set such that the equivalent spatial resolution is slightly better than that set by the wire length. The signal was low-pass filtered at the Nyquist frequency and standard FFT algorithms (Hanning window) are used to calculate the spectra. No curve-fitting is used. $k_1 = 2\pi f/U(y)$. Further issues regarding hot-wire measurements at very high Reynolds numbers are dealt with by Li et al. 2002.
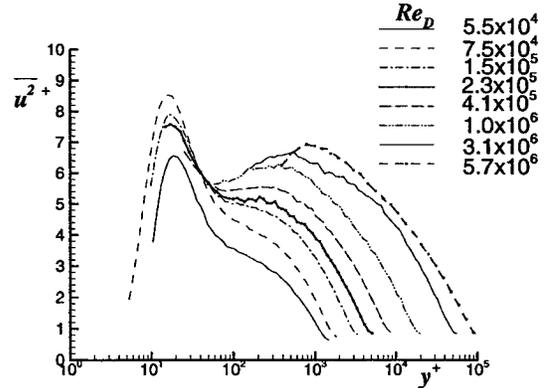

Figure 1: Second moment: wall scaling

3. RESULTS

Fig. 1 shows $\overline{u^2}^+$, which has *two* maxima: the first, prevalent at low Reynolds numbers, is well documented. Using LDA, the data of den Toonder and Nieuwstadt (1997) suggest that $\overline{u^2}^+$ reaches a maximum of about 7.3 that is constant with Reynolds number up to about 2.5×10^4. However, the present data show that this maximum is, in fact, Reynolds-number dependent, increasing with Reynolds number and reaching 8.6 at $Re_D = 7.5 \times 10^4$. At higher Reynolds numbers when $l^+ > 20$, the reduction in this peak with increasing Reynolds number is of course the re-

sult of poorer spatial resolution. Note that any resolution effects even at the lowest Re_D would reduce the maximum below that obtained using LDA. It has also been suggested by Mochizuki and Nieuwstadt (1996) that the position of this peak is also independent of Reynolds number at $y^+ \approx 15$. The present data appear to confirm this, although owing to the effects of probe resolution, no firm conclusions may be drawn. The near-wall peak indicates a principal feature of inactive motion, namely that it increases with Reynolds number. Interestingly, this peak coincides with the expected peak of turbulence energy production.
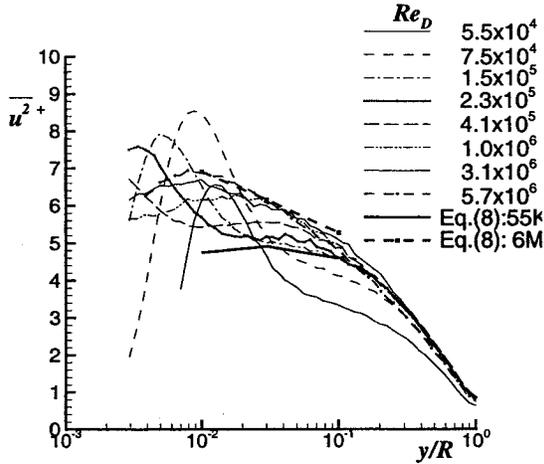

Figure 2: Second moment: outer scaling.

Fig. 2 shows the data of Fig. 1 replotted against y/R. There is a striking collapse in the outer region, $y/R > 0.4$, except at the lowest Reynolds number. There is no collapse in the overlap region, and, as Fig. 1 shows, no collapse anywhere using wall variables, except presumably very close to the wall. Note that the near-wall peak now depends on y/R: this provides a second principal conclusion, namely that inactive motion depends on distance from the wall.

Alternatives choices of velocity scale for the Reynolds stresses, in particular $(U_{cl} - \overline{U})$, are examined by Morrison et al. (2002a,b). Prominent among these is so-called "mixed" scaling (DeGraff and Eaton 2000), which assumes that, for pipe flow, the dissipation rate, $\epsilon \propto U_{cl} u_\tau^2$. Note that in contrast, the local-equilibrium hypothesis suggests $\epsilon \propto u_\tau^3$. A particular problem with the choice of any mean velocity as a velocity scale for the turbulence is that it is frame dependent – the first moment says nothing about the behaviour of the higher moments. Thus the use of $(u_\tau U_{cl})^{1/2}$ has little physical basis. Figs. 3 and 4 show $\overline{u^2}^m, \overline{u^2}$ normalised by $(u_\tau U_{cl})$. Leaving aside the issue of

a corresponding mixed length scale, Fig. 3 shows $\overline{u^2}^m$ vs. y^+, and Fig. 4 shows $\overline{u^2}^m$ vs. y/R. In the case of the former, the collapse is no better than that the wall scaling of Fig. 1, and in the case of the latter, it is demonstrably worse than the outer scaling of Fig. 2.
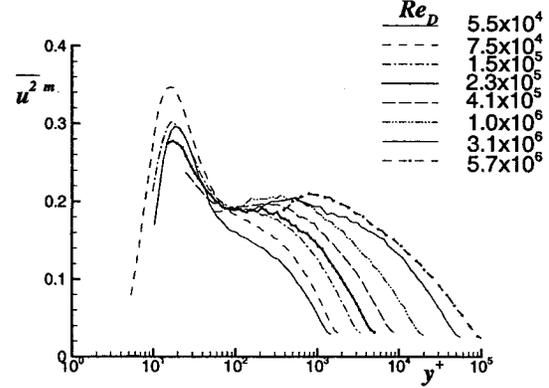

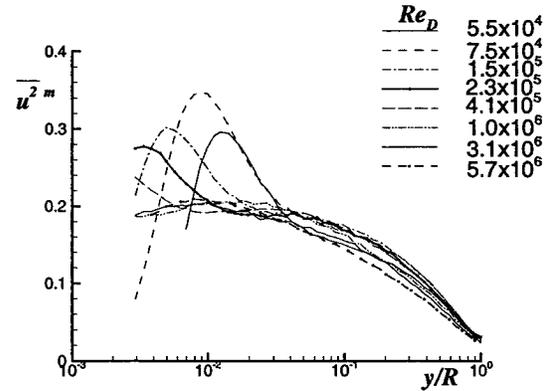Figure 3: Second moment: mixed scaling, y^+ abscissa.

Figure 4: Second moment: mixed scaling, y/R abscissa.

Based on considerations of the self-similar structure of attached wall eddies suggested by Townsend (1976), Perry and Abell (1977) and Perry et al. (1986) have suggested logarithmic functional forms for the normal stresses of the surface-parallel velocities:

$$\overline{u^2}^+ = B_1 - A_1 \ln[\frac{y}{R}] - C(y^+)^{-0.5}. \qquad (8)$$

The log term is obtained by integration of Eq. (4) or (5) for $R^{-1} < k_1 < y^{-1}$. For comparison with the data of Fig. 2, we take the constants suggested by Perry and Abell (1977): $B_1 = 3.53, A_1 = 0.8$ and $C = 9.54$. They are, respectively, 2.67, 0.9 and 6.06 in Perry et al. (1986) but this makes no difference to our conclusions concerning the proposed functional form.

Fig. 2 also shows a comparison with Eq. (8): at $Re_D = 5.7 \times 10^6$, the agreement is quite good,

largely because the viscous deviation term is small. The changes with Reynolds number even at $y/R = 0.1$ derive from the viscous deviation term, which qualitatively predicts the direct influence of viscosity outside the sublayer correctly. At $Re_D = 5.5 \times 10^4$ however, the behaviour at small y/R is incorrect owing to the large inactive contribution. This is one of the two reasons for the change in gradient of the data (and therefore A_1) with Reynolds number. Moreover, for $0.02 < y/R < 0.1$, this change in gradient is not monotonic, first decreasing before increasing. This behaviour is therefore indicative of two effects: one the increase in the inactive contribution with increasing Reynolds number the other the reduction in direct viscous effects emanating from the sublayer as the Reynolds number increases. While the latter is estimated quite well (but only for $Re_D > 10^6$), no account of the former is taken in Eq. (8), which appears therefore to require an additional term, the form of which is strongly dependent on the choice of outer velocity scale.

If a spectral self-similar range exists, such that $\phi_{11}(k_1) \propto k_1^{-1}$ ("complete" similarity), the constant of proportionality (A_1 in Eq. (8)) is universal. However, the evidence of Fig. 2, is that the slope of the data in the vicinity of $y/R \approx 0.1$ (where the viscous deviation is negligible and where a k_1^{-1} range is most likely) is still increasing at the highest Reynolds number. One should also bear in mind that $\overline{u^2}$, as the integral of ϕ_{11}, is less sensitive to Reynolds-number scalings than the integrand itself. It is possible that at even higher Reynolds numbers, the slope of $\overline{u^2}$ may asymptote to a constant value indicative of complete similarity in ϕ_{11}. Re-writing Eq. (8) and omitting the viscous deviation term

$$\overline{u^2}^+ = B_1 - A_1 \ln[y^+] + A_1 \ln[R^+] \qquad (9)$$

shows that the outer peak in Fig. 1 will increase indefinitely with Reynolds number, regardless of considerations of the universality of A_1. One might suppose that, at some stage, the outer peak might become larger than the inner peak in the sublayer. However, this is unlikely as it is realistic to expect the inactive motion near the wall to continue to increase with Reynolds number as long as its source in the outer layer does.

Using inner scaling, Fig. 5 shows $\phi_{11}(k_1y)$ in the form given by Eq. (7) for $Re_D = 5.50 \times 10^4$ over the range in y for which collapse might be expected. Fig. 6 shows equivalent data for $Re_D = 5.7 \times 10^6$ plotted in the same form. In Fig. 5, it is evident that the Reynolds number is simply too low for collapse to be possible. Note that $R^+ = 1500$ only and that the direct effects of viscosity permeate

the whole layer, as evidenced by Fig. 2. At the highest Reynolds number (Fig. 6), there is some collapse for $0.1 < k_1y < 10$ approximately, the range increasing with Reynolds number. However, the collapse is not along a horizontal line, suggesting incomplete similarity.
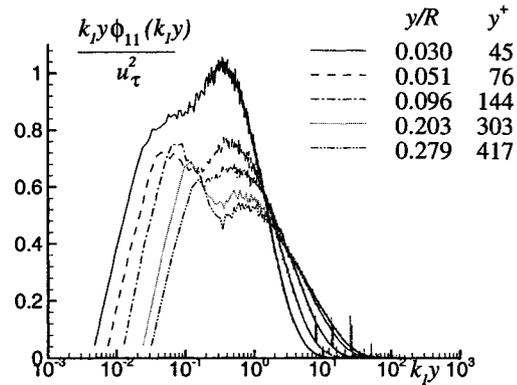

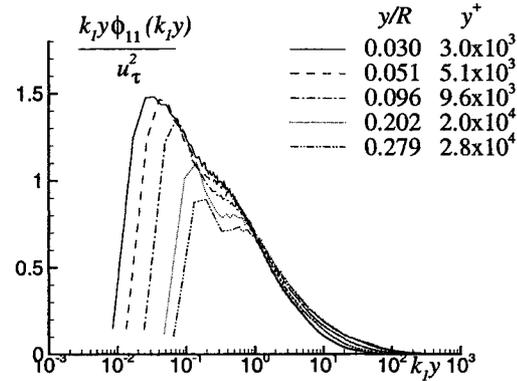Figure 5: Inner scaling, $Re_D = 5.50 \times 10^4, R^+ = 1.50 \times 10^3$.

Figure 6: Inner scaling, $Re_D = 5.7 \times 10^6, R^+ = 10^5$.

Fig. 7 shows the same data as in Fig. 6, but plotted using outer scaling. For $k_1R \sim 1$, there is no significant collapse, although the peaks for $0.033 \le y/R \le 0.107$ lie closer together than the others. Inspection of Fig. 6 in the region of $k_1y \sim 0.1$ shows that the same data ($0.033 \le y/R \le 0.107$) clearly do not collapse using inner scaling. Instead, spectra for $y/R = 0.033, 0.063$ and 0.107 show discrete peaks, appearing in a wave-number sequence determined by y^{-1}, equivalent to the collapse in Fig. 7 occurring at a point, $k_1R \approx 0.75$. Since collapse occurs neither with outer variables nor with inner variables, at best one could expect incomplete similarity only.

As suggested above, an alternative scrutiny of the data may be achieved by using outer scaling at different Reynolds numbers while fixing $y/R = 0.1$. At the two higher Reynolds numbers, there is some

degree of collapse for $k_1 R \approx 0.8$. However, the equivalent data scaled with inner variables (Fig. 6 do not collapse so that, at best, only incomplete similarity is possible. Note also that complete similarity would imply that A_1 takes a universal value, and yet it is clear from all the spectra that this is not the case.

Interestingly, as has been shown by Kim and Adrian (1999) and Jiménez (1998), the spectra show the presence of very long structures near the wall giving rise to a bimodal shape at low Reynolds numbers. Their wavelength increases as y increases, reaching a peak of about $10R$ at $y/R \approx 0.1$ before decreasing at larger y.
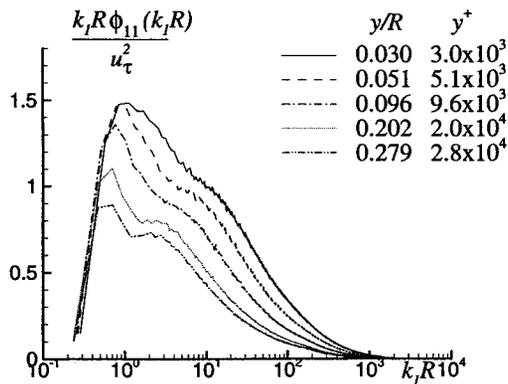

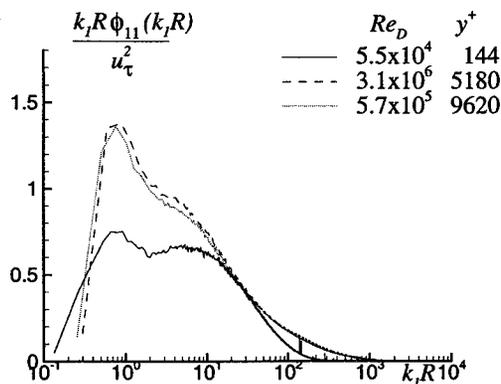Figure 7: Outer scaling, $Re_D = 5.7 \times 10^6$, $R^+ = 10^5$.

Figure 8: Outer scaling, $y/R = 0.1$.

4. DISCUSSION AND CONCLUSIONS

We have illustrated the importance of, firstly, the direct effects of viscosity outside the viscous sublayer at low Reynolds numbers and, secondly, the influence of inactive motion at high Reynolds numbers. The power-law scaling for the mean velocity has been shown by Zagarola and Smits (1998) and this shows how the effect of viscosity contravenes one of the conditions necessary

for the complete similarity embodied in the log law. For the higher moments, it is interesting to note that, as suggested by Fig. 7, the lower limit to the region in which complete similarity of the low-wave-number motion is most likely to exist, $0.033 \leq y/R \leq 0.107$, is equivalent to $y^+ \approx 5000$ at $Re_D = 5.7 \times 10^6$, and that collapse of the spectra is significantly worse at lower Reynolds numbers. Thus it is very unlikely that complete similarity in the form of k_1^{-1} range will be possible below this Reynolds number. Note that an equivalent boundary-layer Reynolds number is $Re_\theta \approx 300,000$! Fig. 2 shows that the direct effects of viscosity on $\overline{u^2}$ are apparent in the outer region for $Re_D < 10^5$.

On balance, it would appear that while collapse of the velocity spectra may be possible with either inner or outer scaling (incomplete similarity), it is unlikely that simultaneous collapse with both in the same wave-number range is possible (complete similarity), at least up to the maximum Reynolds number attained here. Thus spectra here do not exhibit a k_1^{-1} range indicative of self-similar structure, which should be considered as a special case only. The behaviour of $\overline{u^2}$ is consistent with the notions that, (a), inactive motion increases with Reynolds number and that, (b), inactive motion increases as y/R decreases (down to the sublayer). On the basis of (a) and (b) alone, complete similarity as outlined above seems to be unlikely because, while the active motion scales on y and u_τ only (in the limit of infinite Reynolds number) as Townsend proposed, the inactive component always requires three scales, namely y, R, and a velocity scale, in compliance with (a) and (b) above. Whether u_τ is the correct choice of outer velocity scale or not has been questioned and it has been suggested by Zagarola and Smits (1998) that this should be $(U_{cl} - \overline{U})$. This issue will be fully addressed elsewhere (Morrison et al. 2002a,b).

It is possible that a k_1^{-1} range may appear at even higher Reynolds numbers typical of the atmospheric surface layer. Its often-published appearance (see, for instance, Kader and Yaglom, 1991) leads to the obvious question of why this might be so. Questions of interpretation aside, it has been suggested by Hunt and Morrison (2000) that the phenomenon of "shear-sheltering" makes possible a self-similar region which is sheltered from large-scale velocity fluctuations by the effects of strong shear. Thus the influence of inactive motion is mitigated, and can be represented by outer scales alone. However, this suggestion awaits futher investigation.

What is of perhaps more fundamental importance is that the term "inactive" is somewhat

of a misnomer. Westbury and Morrison (1995) have previously noted that the distinction between the large-scale inactive motion and the associated shear-stress-bearing sweeps is not necessarily as clear cut as Townsend's ideas might suggest. The evidence of Fig. 1 is that inactive motion increases $\overline{u^2}^+$ just where the production of turbulence kinetic energy reaches a maximum. Thus the outer eddies are in fact active in terms of producing energy by the shear that they induce. This result underscores the importance of the "top-down" influence at high Reynolds numbers identified by Hunt and Morrison (2000). While the alternative "bottom-up" effect, in which it is supposed that near-wall instabilities drive the momentum flux, may be an adequate description at very low Reynolds numbers, the foregoing suggests that these two effects may be reconciled by recognising that the Reynolds number is a measure of the ratio of one to the other.

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