Rough-Wall Boundary Layers

Jonathan F. Morrison
Department of Aeronautics, Imperial College
London SW7 2AZ

j.morrison@imperial.ac.uk

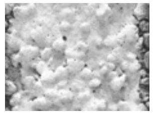
FLOW-NORDITA Spring School on TURBULENT BOUNDARY LAYERS

KTH Royal Institute of Technology Stockholm, Sweden
April 6-9, 2010

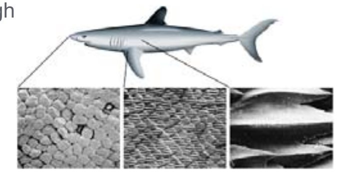
Outline

1. Historical perspective and current motivation
2. Fundamentals: the log law as a ‘map’ – self-similarity
3. Definition of scales, distinction between internal flows (pipes, channels) and external flows (boundary layers) – what are the differences?
4. Roughness definition – why this is complicated
5. The Moody chart for pipe flow
6. Townsend “outer similarity”
7. Boundary layer roughness: the atmospheric surface layer
8. Effects of very large roughness – limits to classical definitions
9. Outlook: what are the outstanding issues?

1. History and motivation




- Types of roughness: sand, grass, pitted turbine blade, barnacles, vegetation, tree canopy, urban roughness, mountain range
- Pipe flows: the Moody chart - pipe transmission losses
- Drag reduction: airline industry uses ~1.5 M barrels of oil per annum, but ocean shipping uses 2.1 M barrels
- A meteorological perspective: atmospheric surface layer is fully rough



2. Fundamentals

1. Contrasting types of roughness: importance of the roughness distribution
2. The log law as a ‘map’ – self-similarity
3. Coles’ profile: changes to accommodate roughness - Hama’s roughness function
4. Hydraulically smooth, transitional and full roughness
5. Meteorological definitions

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Definitions

- Historically, definitions arise from early work on pipe flow
- Fully developed flow - very useful because surface friction simply related to pressure drop
- Define coefficient of resistance, λ: $\tau_w = \frac{1}{8}\lambda\rho\overline{U}^2$
- Define friction factor, f: $\tau_w = \frac{1}{2}f\rho\overline{U}^2$
- Compare with skin-friction coefficient (external geometries) $C_f = \frac{\tau_w}{\frac{1}{2}\rho U_e^2}$
- Use h (channel half-height), pipe radius R and boundary layer thickness δ interchangeably; similarly U_{cl} and U_e

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \qquad \overline{U} = \int_0^h U dy$$

	τ_w
Pipe	$-\frac{R}{2}\frac{dp}{dx}$
2D duct, height $2h$	$-h\frac{dp}{dx}$
Square-sectioned duct, $2h$x$2h$	$-\frac{h}{2}\frac{dp}{dx}$

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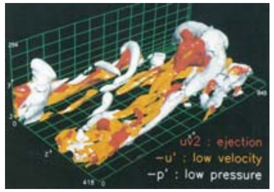
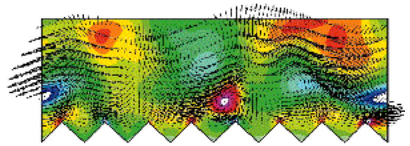
A physical description

- Friction drag increases once wall is no longer hydro-dynamically smooth
- For "small" roughness, the effects may be scaled by the increase in wall-friction velocity, $u_\tau = \sqrt{\tau_w/\rho}$ alone.
- The viscous sublayer is replaced by the roughness sublayer, $y \le 10k$
- Near the roughness elements, there is an increase in dissipation (over that for an equivalent smooth surface) which is not matched by an increase in production
- Riblets impede near-wall cycle of energy production but without increase in form drag of roughness elements

Robinson 1991





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Basic properties

$$\lambda = 8\left(\frac{u_\tau}{\overline{U}}\right)^2 = 4\left(\frac{U_{cl}}{\overline{U}}\right)^2 C_f = 4f$$

- Fluid response depends on a large number of parameters

$$\frac{U}{u_\tau} = f\left(y^+, k^+, h^+, \text{ geometrical properties}\right)$$

- The "roughness sublayer", $y \le 10k$: can we expect roughness effects to be confined within it?
- Larger roughness elements exert a disproportionately large effect - pressure drop across a particular element goes as k^2, that is, when roughness is large, form drag dominates and wall shear-stress variation with velocity is quadratic
- "Shielding" of smaller roughness elements by larger ones
- Hence, for the sake of argument, identify k as the maximum roughness height in a distribution.

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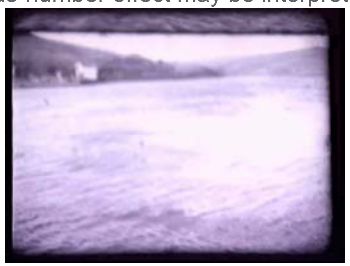
A physical description - inner-outer interaction

- If the direct effects of roughness do not extend beyond the roughness sublayer (no interaction), the "local equilibrium" approximation ("production = dissipation") can be expected to hold
- Roughness may be viewed as a form of "bottom-up" inner-outer interaction (IoI): for large roughness, $k/R \to 1$ and even when $k^+ \sim R^+ \to \infty$ inner (k) - outer (R) scale separation is not possible and the IoI can be expected to be large.
- A high-Reynolds-number effect may be interpreted as a "top-down" interaction:



Scorer
(Hunt & Morrison 2000)

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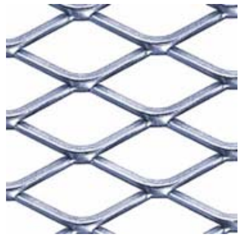
Types of roughness


Heavy industrial abrasive


Expanded metal mesh


Lacquered MDF

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Similarity

- The near-wall mean velocity profile depends on:

$$U = f_i(\tau_w, \rho, \nu, y, k, \text{ roughness properties})$$

$$\frac{U}{u_\tau} \cong f_i(y^+, k^+)$$

- In the outer layer, for the velocity deficit we have:

$$U_{cl} - U = f_o(\tau_w, \rho, y, h)$$

$$\frac{U_{cl} - U}{u_\tau} = f_o\left(\frac{y}{h}, \frac{u_\tau}{U_{cl}}, \beta\right) \cong f_o\left(\frac{y}{h}\right)$$

$$\beta = \frac{\delta^*}{\tau_w}\frac{dp}{dx}$$

- The shear stresses will behave in a similar fashion - hence:

$$-\frac{\overline{uv}}{u_\tau^2} = g_i(y^+, k^+) \quad \text{and} \quad -\frac{\overline{uv}}{u_\tau^2} \cong g_i\left(\frac{y}{h}, \frac{u_\tau}{U_{cl}}, \beta\right)$$

- Note that in the outer layer, both the velocity deficit and the stresses are taken to be independent of the surface roughness - “Townsend outer-layer similarity” - thus the affect of the roughness appears through an increase in skin friction alone.

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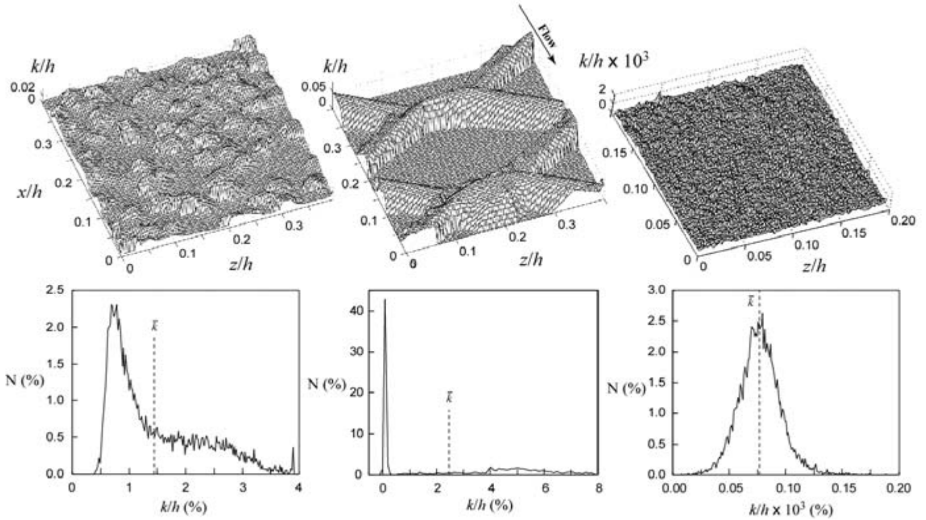
Roughness definition: laser profilometer



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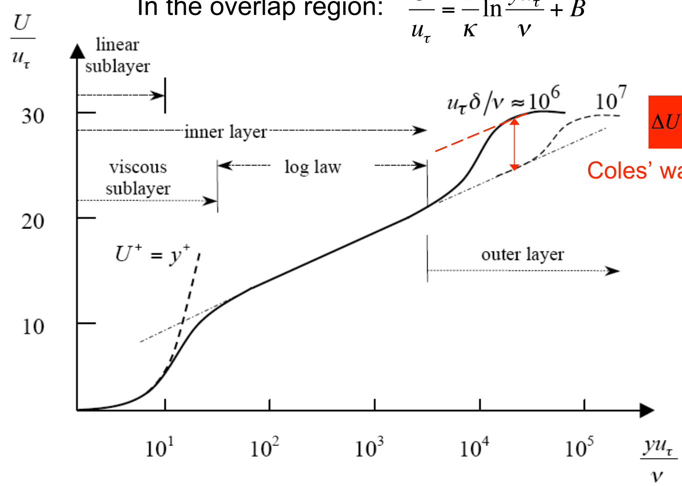
Self-similarity: the log law on a smooth surface

In the overlap region: $\frac{U}{u_\tau} = \frac{1}{\kappa}\ln\frac{yu_\tau}{\nu} + B$



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Complete or self-similarity

- The log law is self-similar: this means that it is specified completely by a single velocity scale, u_τ and a single length scale, y, and κ can be taken to be a universal constant
- Self-similarity implies that the constant in the log argument may be freely chosen - a consequence of simultaneous overlap
- Therefore as long as there is a sufficient separation of scales, the log law may be written for outer variables

$$U_{cl}^+ - U^+ = -\frac{1}{\kappa}\ln\left(\frac{y}{h}\right) + B^*$$

- By extension, it may also be written for a rough surface in the form

$$U^+ = \frac{1}{\kappa}\ln\left(\frac{y}{k}\right) + B_2$$

- A sufficient separation of scales $\frac{\nu}{u_\tau} << k << h$ also implies that both B^* and $B_2 \rightarrow$ constants

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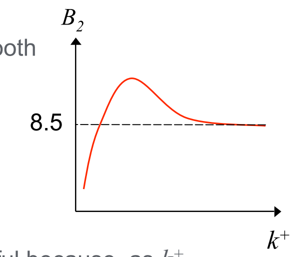
Transitionally rough and fully rough



- For $k^+ < 5$, expect surface to be hydraulically smooth
- For convenience, drop d and write

$$\frac{U}{u_\tau} = \frac{1}{\kappa}\ln\frac{yu_\tau}{\nu} + B_1(k^+)$$
$$= \frac{1}{\kappa}\ln\frac{y}{k} + B_2(k^+)$$

- B_1 and B_2 are roughness functions: B_2 more useful because, as k^+ increases, log law requires scale separation $y >> k$ and Reynolds number effects absorbed into a single term
- Hence for $k^+ >\sim 70,\ B_2 \rightarrow 8.5$: "fully rough"
- and for $5 \sim< k^+ \sim< 70,\ B_2 \rightarrow f(k^+)$: "transitionally rough"

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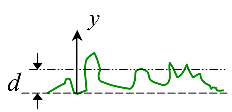
Describing roughness effects



- Reynolds number is 'high' - so assume log law is valid

$$\frac{U}{u_\tau} = \frac{1}{\kappa}\ln\frac{(y-d)u_\tau}{\nu} + B - \frac{\Delta U_R}{u_\tau}$$

- y origin arbitrary but measured from bottom of roughness
- $d\ (<k)$ is zero-plane displacement, representing height at which momentum is extracted
- $\Delta U_R^+ = \frac{\Delta U_R}{u_\tau}$ is the velocity shift relative to the log law for a smooth surface - the Hama roughness function
- For a smooth surface, expect d and $\Delta U_R^+ \rightarrow 0$: "hydraulically smooth". But how do they change with k?

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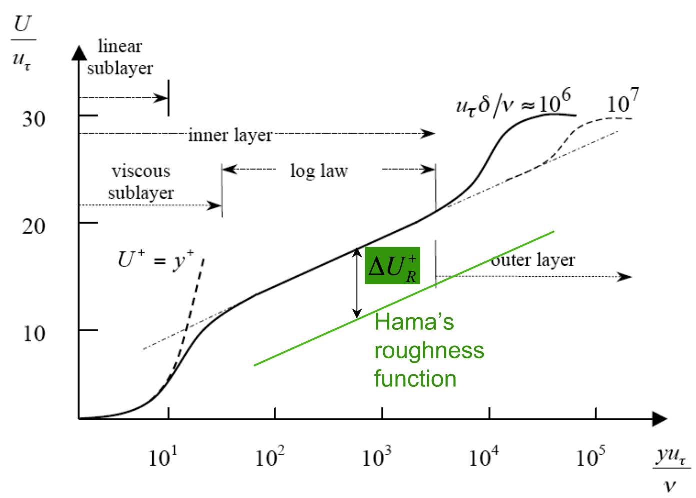
The log law - fully rough surface



For a fully rough surface..

- Meteorological definitions of the log law $U^+ = \frac{1}{\kappa}\ln\left(\frac{y-d}{y_0}\right)$
- Where y_0 is the roughness length (of the order 0.1k) and is geometry-specific
- The velocity shift may be written: $\Delta U_R^+ = \frac{1}{\kappa}\ln\left(k^+\right) + B + \frac{1}{\kappa}\ln\left(\frac{y_0}{k}\right)$
- In what follows, it will be important to distinguish Hama's roughness function ΔU_R^+ from Coles' wake function $\Delta U^+ \approx \frac{2\Pi}{\kappa}$

Prandtl and Nikuradse

- In smooth pipes, a friction factor relationship may be obtained by assuming self- (complete) similarity of the mean velocity profile and integrating the log law:

$$\frac{1}{\sqrt{\lambda}} = 2.0\log\left(\mathrm{Re}\sqrt{\lambda}\right) - 0.8$$

- This is Prandtl's universal law of friction for smooth pipes
- It has recently been revised (McKeon *et al*. 2005) for $31\mathrm{x}10^4 \le \mathrm{Re}_D \le 18\mathrm{x}10^6$
- Prandtl's law may be expressed as $\frac{1}{\sqrt{\lambda}} = 2\log\left(\frac{\mathrm{Re}\sqrt{\lambda}}{2.51}\right)$
- In the fully-rough regime, Nikuradse showed that

$$\frac{1}{\sqrt{\lambda}} = 2\log\left(\frac{3.71D}{k_s}\right)$$

i.e. the friction factor is determined fully by the relative roughness. Nikuradse used sand-grain roughness, of height k_s.

3. Pipe flow

1. Prandtl's universal law for friction in smooth pipes
2. Nikuradse's sand-grain roughness
3. Colebrook's roughness function
4. The Moody chart
5. Recent developments
6. Roughness characterisation

Sand-grain roughness

- In a famous set of experiments, Nikuradse measured the pressure drop in a rough-walled pipe using close-packed sand of uniform size - so-called "sand-grain roughness", k_s
- These data can be used to define an "equivalent sand-grain roughness" by comparing the friction factor for a surface of arbitrary roughness (in the fully-rough regime) to that for Nikuradse's sand-grain roughness
- Unfortunately, sand-grain roughness is of a specialised form - "mono-disperse" and close-packed: naturally occurring roughness is "poly-disperse" (a wide distribution) with spaces
- "Nikuradse's fully-rough results on the same unrealistic uniform-sand surface simply define a useful common currency roughness size - like paper money, valueless in itself but normally acceptable as a medium of exchange" (Bradshaw 2000).

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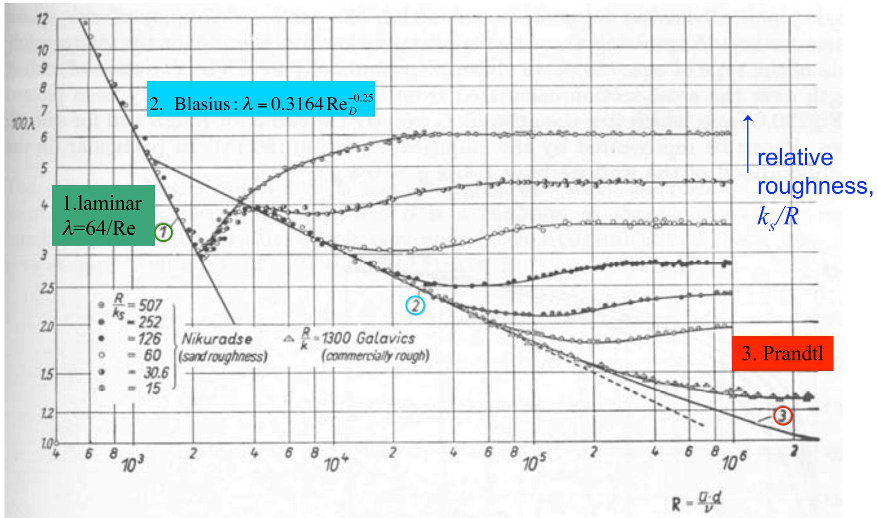
Nikuradse's results for sand-grain roughness



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The Colebrook roughness function

- Colebrook also devised a "transitional" roughness function by

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{k_s}{3.71D} + \frac{2.51}{Re\sqrt{\lambda}}\right)$$

- At small relative roughness, k_s/D, it asymptotes to Prandtl's law. Similarly the function represents the fully-rough regime as $Re \Rightarrow \infty$.
- However, there is little theoretical justification for its form (equivalent to taking the harmonic mean of the separate log arguments for smooth and fully rough functions)
- Colebrook also rewrote the function in the form

$$2\log\left(\frac{3.71D}{k_s}\right) - \frac{1}{\sqrt{\lambda}} = 2\log\left(\frac{3.29}{k_s^+} + 1\right)$$

- This makes the choice of independent variable clearer, but…

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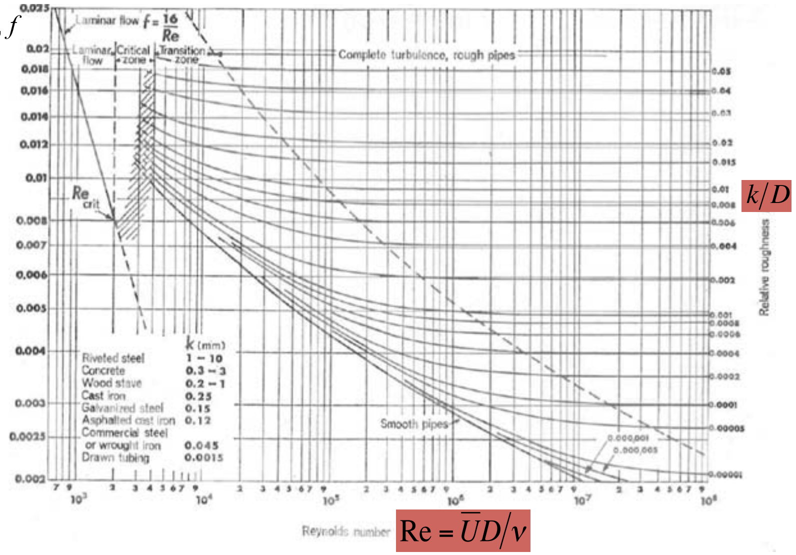
The Moody Chart

Friction factor, f

$$\lambda = 4f$$



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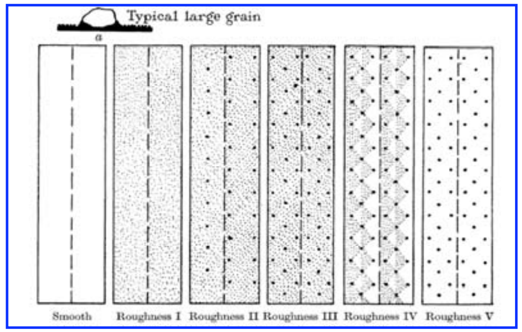
Major Colebrook

- Colebrook & White (1937) and Colebrook (1939) measured λ for five different types of roughness which were much more representative.
- In particular, very large roughness grains were used on only about 2% of the area
- Hence "shielding" of the small grains by the larger ones.



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Colebrook roughness details

	Description of surface	λ (fully rough)	k_s mm	k_s/k
I.	Uniform sand 0.35 mm diam. $(=k)$ in 2 inch pipe	0.0369	0.48	1.36
II.	Uniform sand with large 3.5 mm grains on 2.5% area	0.0425	0.73	–
III.	Uniform sand with large 3.5 mm grains on 5% area	0.047	0.93	–
IV.	48% area smooth, 47% area uniformly covered with fine grains, 5% area large grains	0.041	0.66	–
V.	95% area smooth, 5% area large grains	0.034	0.38	0.11

Equivalent sand-grain roughness

$$\lambda = \left[2\log\frac{3.71}{k_s}\right]^{-2}$$

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Colebrook's roughness function

$$2\log\left(\frac{3.71D}{k_s}\right) - \frac{1}{\sqrt{\lambda}} = 2\log\left(\frac{3.29}{k_s^+}+1\right)$$

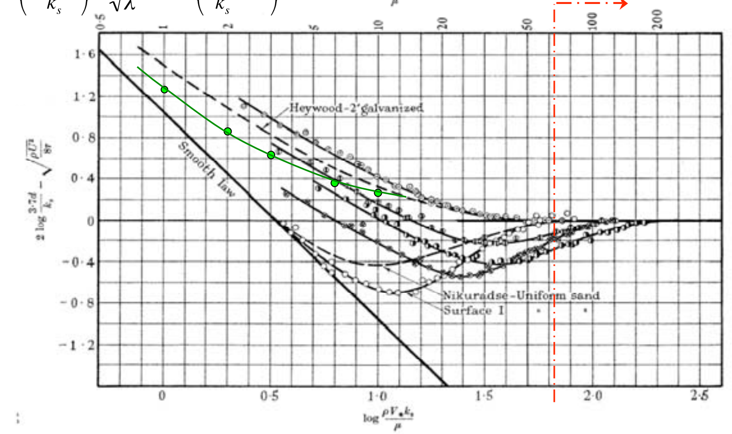

Fig. 10—Deviations from "rough" law as function of $\frac{\rho V_* k_s}{\mu}$, where k_s is equivalent grain size. The surfaces I to V are described in fig. 5 and in Table I. ○ surface I; ⊗ surface II; ◑ surface III; ⦶ surface IV; ⊛ surface V.

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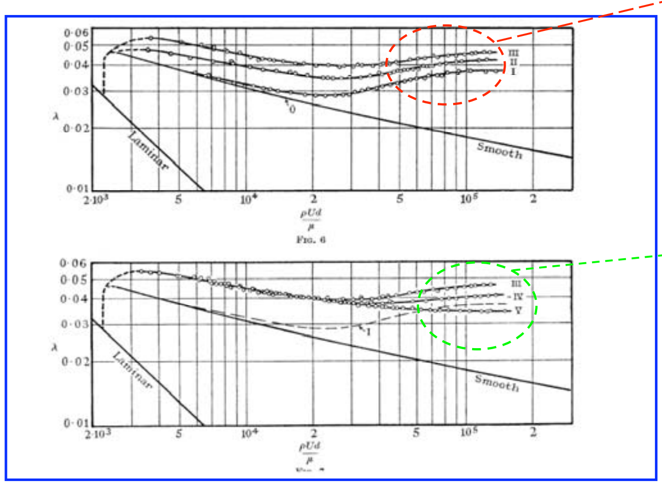
Colebrook's data are not inflexional…

…unlike Nikuradse's!



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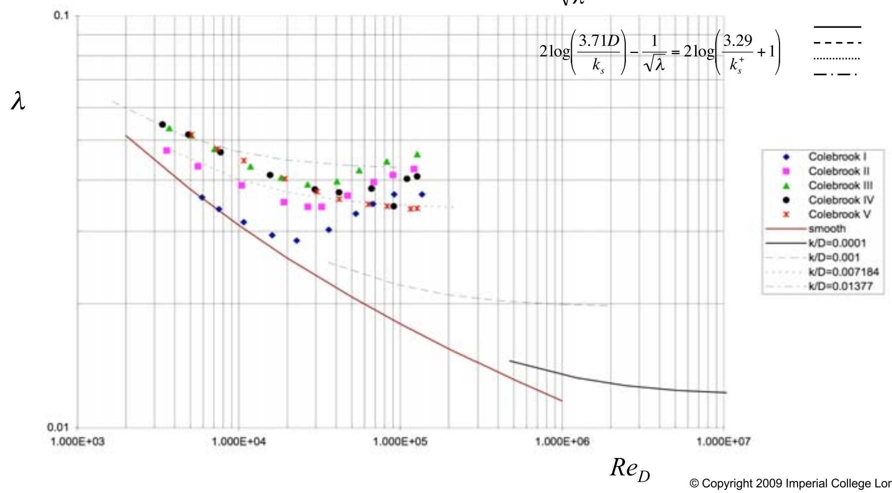
Moody chart with Colebrook's data

$$\frac{1}{\sqrt{\lambda}} = 2.0\log\left(\mathrm{Re}\sqrt{\lambda}\right) - 0.8$$

$$2\log\left(\frac{3.71D}{k_s}\right) - \frac{1}{\sqrt{\lambda}} = 2\log\left(\frac{3.29}{k_s^+}+1\right)$$

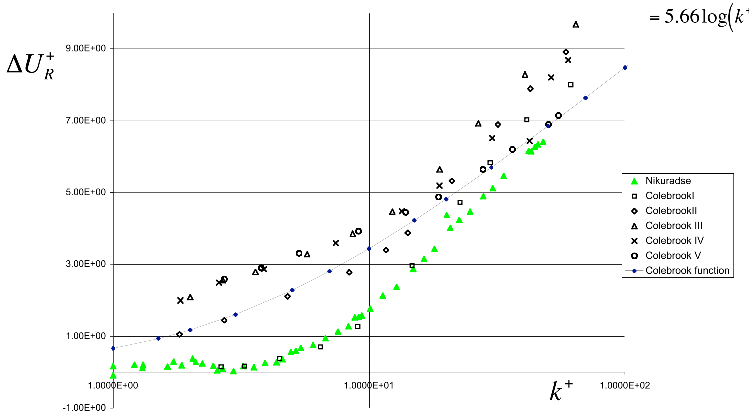


Hama's roughness function for Colebrook's data

- Hama's roughness function formulated using Colebrook function:

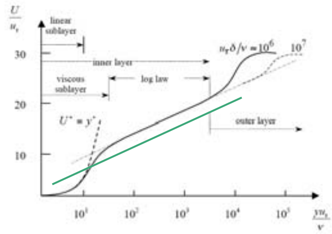
$$\Delta U_R^+ = \left(\frac{8}{\lambda}\right)^{\frac{1}{2}}\Bigg|_{smooth} - \left(\frac{8}{\lambda}\right)^{\frac{1}{2}}\Bigg|_{rough} = B - B_2 + \ln k^+$$

$$= 5.66\log\left(k^+ + 3.3\right) - 2.92$$



Difficulties with the Colebrook function

- Colebrook's transitional roughness function does not follow his own data
- These differences are also clear when plotting the data as Hama's roughness function, ΔU_R^+, which avoids ill-conditioned behaviour of the roughness function at small relative roughness
- ΔU_R^+ is also a good measure of changes to the sublayer by extrapolation of the log law
- The analysis for its part-justification is somewhat simplistic and rests primarily on taking the harmonic mean of the smooth and fully roughness function arguments

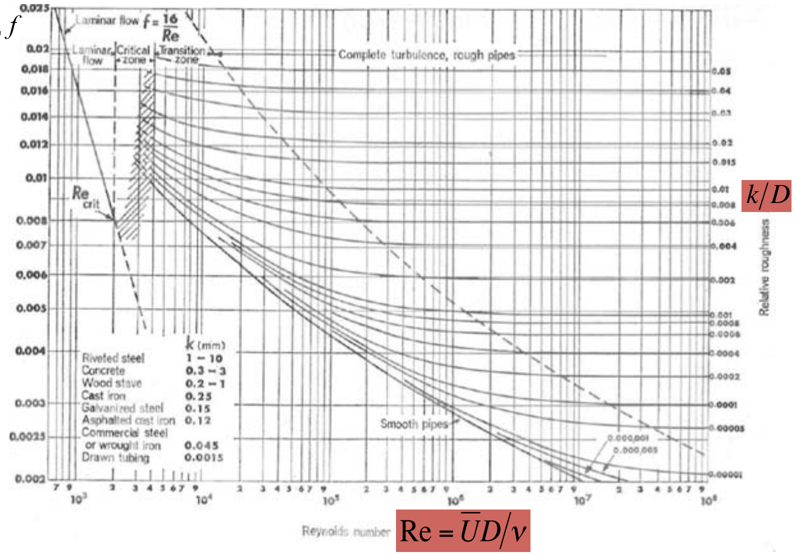


"It is regretted that Professor (now Major) Colebrook, who has been serving in the British Army since 1939, was unable to submit a discussion". Lewis Moody (1944) in discussion of the paper presenting his chart.

The Moody Chart

Friction factor, f

$$\lambda = 4f$$



Recent developments

- Shockling, Allen & Smits (2006)

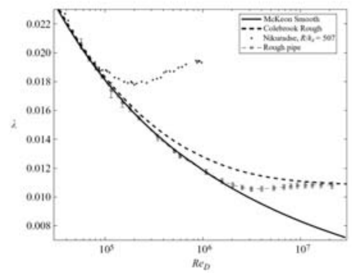


FIGURE 6. Friction factor λ for the present surface, compared with the rough-all relations of Colebrook (1939) for the same k_s, the smooth-wall relation of McKeon *et al.* (2005) (equation (2.4)), and the results for the smallest sandgrain roughness used by Nikuradse (1933).

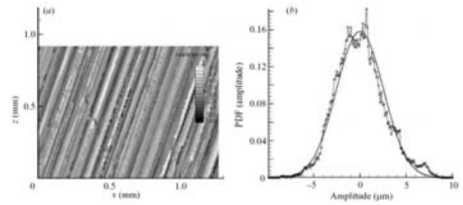


FIGURE 3. (*a*) Two-dimensional surface plot of the new rough pipe. Area shown is about 0.8 mm × 1.2 mm, and the amplitudes are in μm. (*b*) Probability density function of surface elevation.

Honed pipe flow
k/D=1/17,000, Gaussian

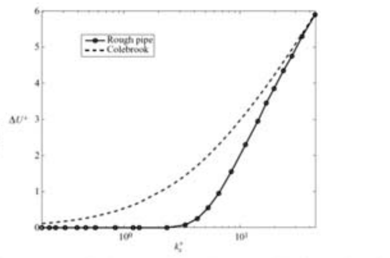


FIGURE 13. Hama roughness function. - - - -, Colebrook roughness function equation (3.1), with $k_s = 7.4 \times 10^{-6}$ m; ——, ΔU^+ determined using McKeon's *et al.*'s (2004) constants.

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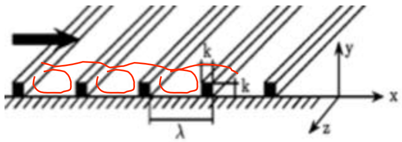
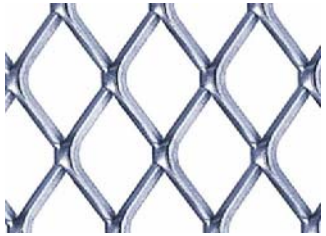
Roughness characterisation

- Difficulties with Moody chart stem from the Colebrook transitional roughness function
- Equivalent sand-grain roughness not very useful – effects of a distribution of roughness sizes, orientation, spacing, shielding are all absorbed into a single variable, k_s, and effects of a distribution of roughness sizes subsumed into a fully-rough equivalent
- So far we have focused on so-called k-type roughness.
- 2D spanwise ribs - d-type roughness - shows atypical behaviour
- We consider a "2.5D" mesh later – very different to "3D" roughness





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4. Effects of very large roughness

- Do the details of the roughness leave their imprint on the flow?
- Does self-similarity of the mean velocity profile persist?
- Does Townsend outer-layer similarity persist?
- What aspects of turbulence structure are common to both rough and smooth surfaces?

- Jiménez suggests that k/h < 2.5% "before similarity laws can be expected"..

- If so, is this limit dependent on other roughness details?
- Is it the same for both internal and external flows?
- So what happens for k/h > 4% ?
- It is likely that self-similarity is a stronger requirement than Townsend outer-layer similarity

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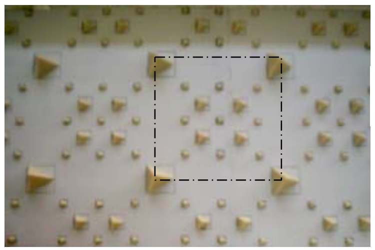
Roughness characterisation

- Fractals? A single dimension that provides a true measure of surface topology
- Non-integer fractal dimension, $N = \dfrac{\log N(l)}{\log l}$
- Or use Euclidean (integer) dimension and exploit similarity, so lengthscale = $\sqrt{\text{area}}$ or $\sqrt[3]{\text{vol}}$
- But still have to contend with variable Re_k for standing vortex pair (≈ 25) or 'shedding' (≈ 50)



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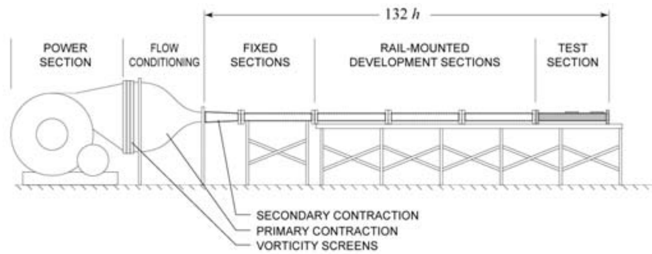
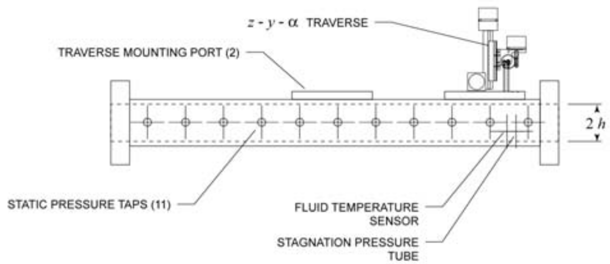
Channel flow facility





h = 50.8 mm

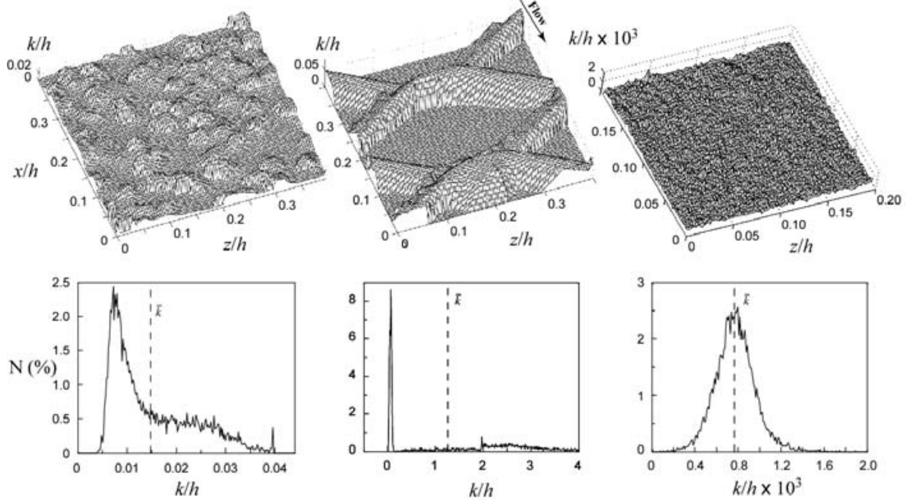
x/h ~ 132

U_o ~ 30 m/s

Re_τ = 5,700 - 7,700

W/h = 15

Surface topologies



Experimental parameters

Surface	U_{cl}	$\overline{U}$	Re_τ	$Re_h \times 10^{-4}$	$k u_\tau/\nu$
Grit	24.7	21.0	4780	7.28	186
Grit	26.7	22.8	5130	7.78	200
Grit	28.6	24.4	5540	8.43	216
Mesh	21.1	17.3	5230	6.12	410
Mesh	23.2	18.8	5830	6.77	458
Mesh	25.0	20.5	6270	7.38	493
Smooth	41.9	31.5	4480	12.4	–

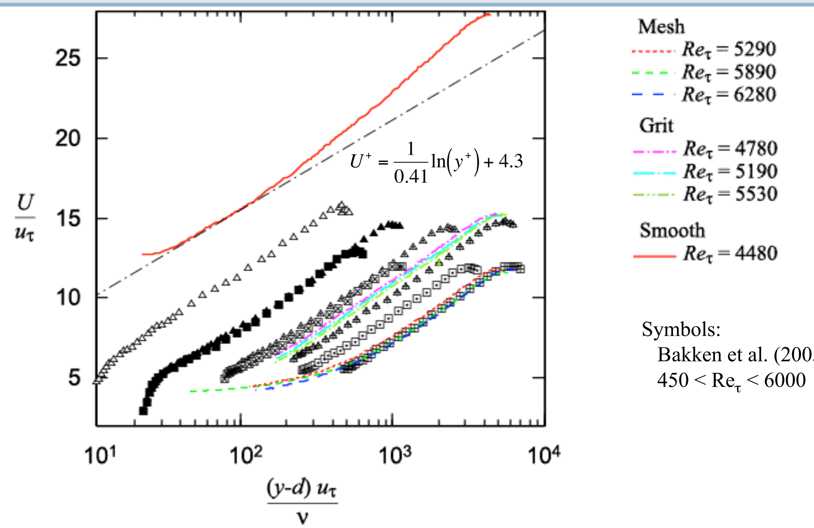
k_{max}

$$\mathrm{Re}_\tau = \frac{u_\tau h}{\nu} \qquad \mathrm{Re}_h = \frac{U_{cl} h}{\nu} \qquad \overline{U} = \frac{1}{h}\int_0^h U(y)\,dy$$

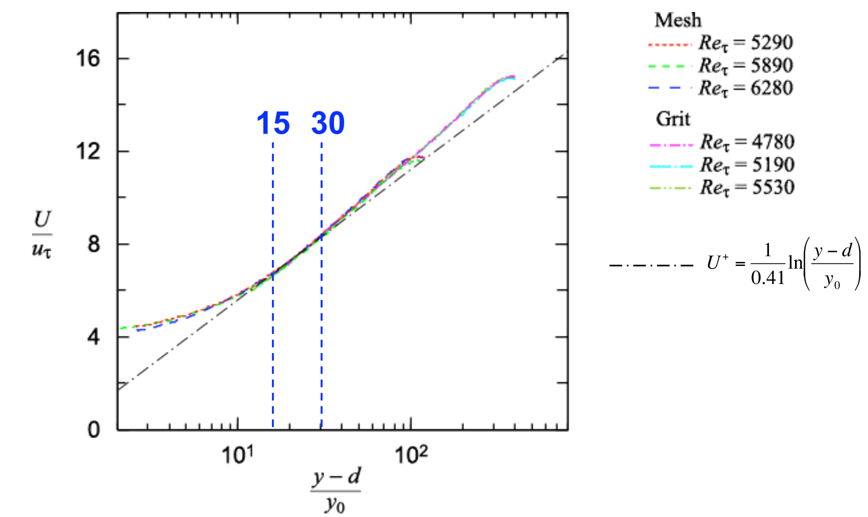
Grit and mesh roughness

- Grit peak-to-peak $k_{max} \approx 1.8$ mm, $k/h = 3.5\%$
  - Isotropic
  - Non-Gaussian, positively skewed
- Mesh $k_{max} \approx 4.0$ mm, $k/h = 7.9\%$
  - Anisotropic
  - $L_z/L_x = 2.6$, $L_z/k_{max} = 7.5$, $L_x/k_{max} = 2.9$ - "2.5D"
- Single-wire results $\ell^+ \approx 40 - 60$

Mean velocity: viscous scaling



Mean velocity: inner scaling



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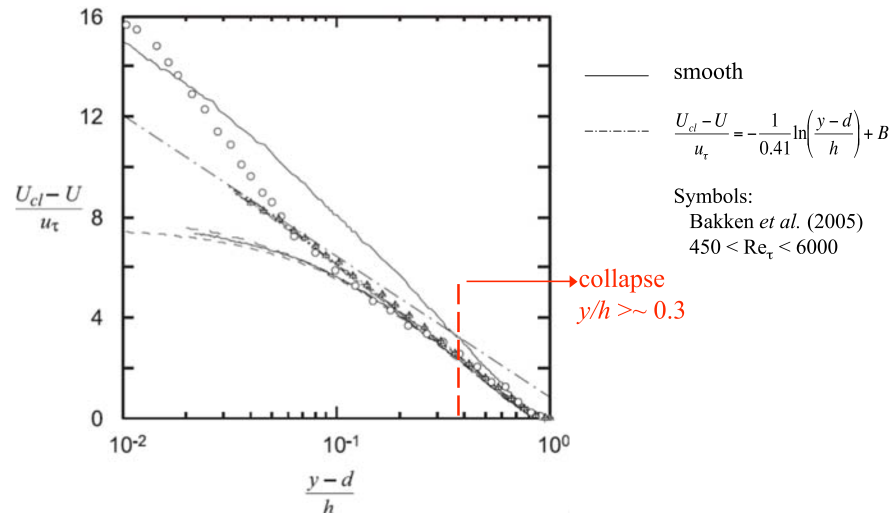
Outer scaling - detail



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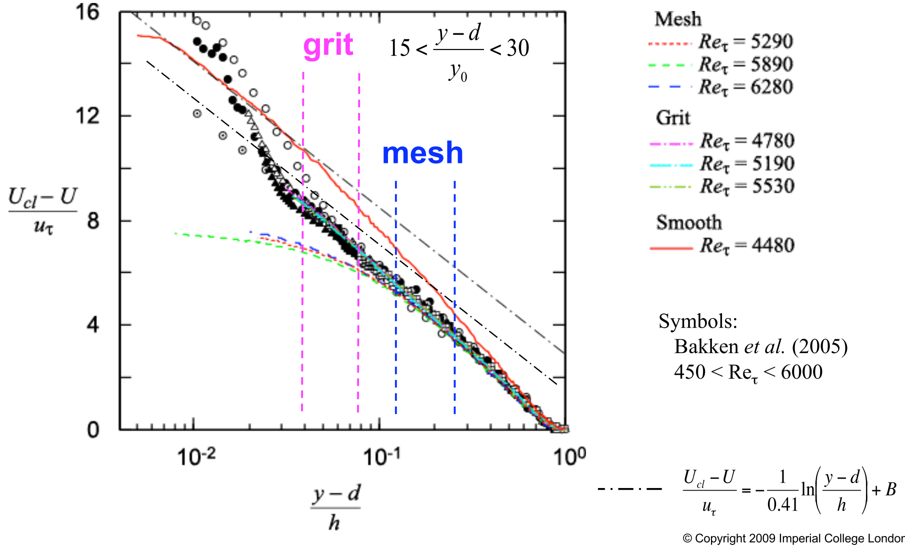
Mean velocity: outer scaling



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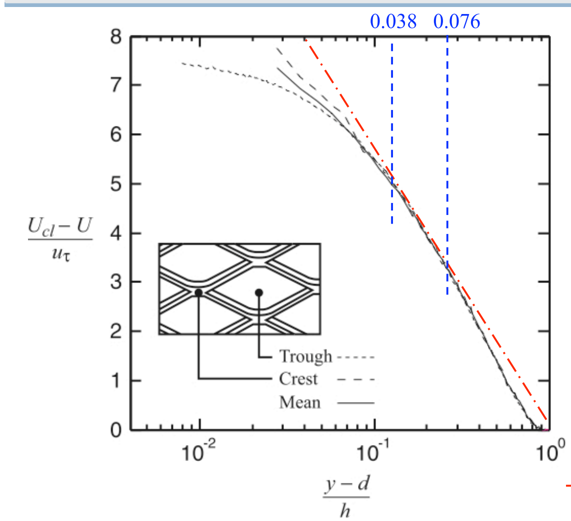
Mean velocity: outer scaling - mesh detail



Profiles become spanwise homogeneous *(y-d)/h* > 0.8

Profiles collapse $y/h >\sim 0.3$

$$\frac{U_{cl}-U}{u_\tau} = -\frac{1}{0.41}\ln\left(\frac{y-d}{h}\right)+B$$

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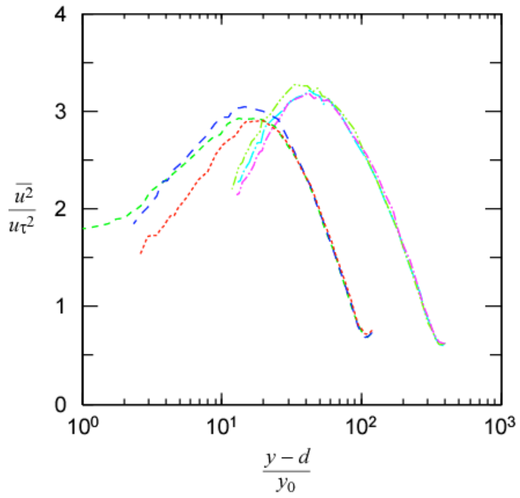
Second moment: inner scaling



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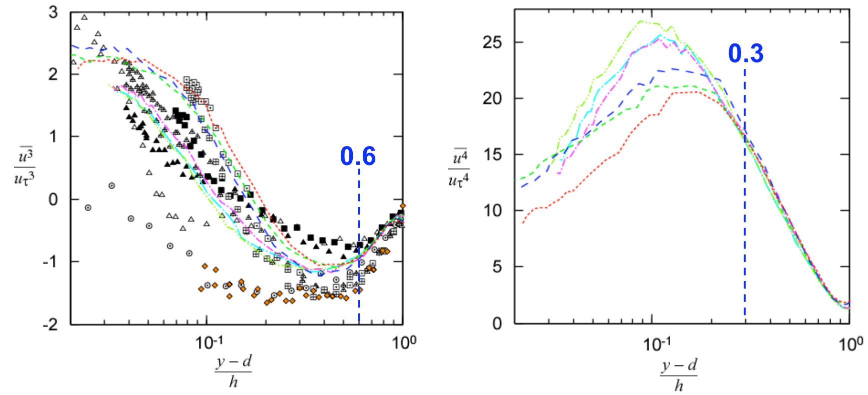
Higher-order moments: outer scaling



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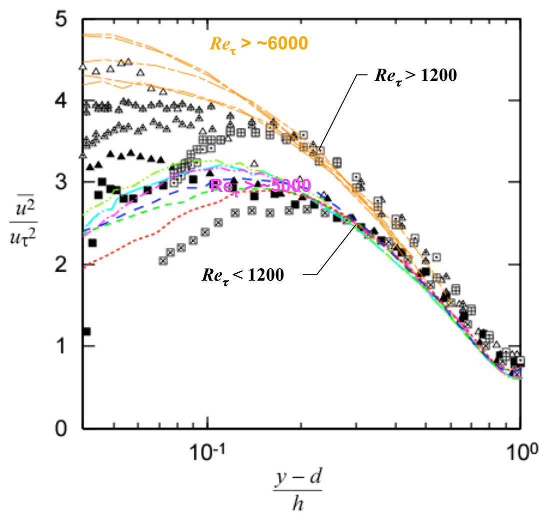
Second moment: outer scaling



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Very-rough channel flow: summary

- While mean velocity profile on isotropic grit ($k/h \approx 4\%$) shows self-similarity, that on '2.5D' mesh ($k/h \approx 8\%$) does not
- The lack of self-similarity on the mesh surface extends above the point at which mean velocity profiles become spanwise-homogeneous
- Coles' wake parameter, "wake strength", $\Delta U^+ = 2\Pi/\kappa$ decreases with increasing roughness (smooth: 3.2; grit: 0.82; mesh 0.61)
- Note however, that Π may only be defined once the log law is established
- All u-component moments scale with outer variables - Townsend outer-layer scaling: y/h at which this begins varies with order of moment
- Fully-developed channel flow requires dp/dx to be a constant at all y even if $\frac{1}{\rho}\frac{\partial p}{\partial y} = \frac{\partial \overline{v^2}}{\partial y}$: therefore it is perhaps unsurprising that scaling with u_τ is robust

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5. Boundary layers: differences & similarities

- Does mean velocity profile show self-similarity?
- Is wake parameter independent of surface roughness, these effects being represented by ΔU_R^+ alone (Tani 1987)?
- Do boundary layers show Townsend's outer-layer similarity?
- Are there differences in structure?

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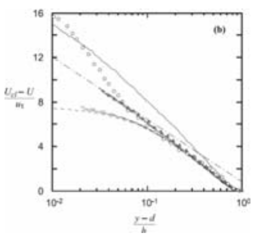
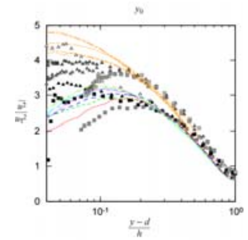
Townsend outer-layer similarity

- Townsend (1956, 1976): Outside of the sublayer, flow scales with u_τ only

- Roughness does not affect u_τ scaling in either pipes or boundary layers (e.g. Shockling *et al.* 2006 Schultz & Flack 2007, Flack *et al.* 2005)
- Outer-layer similarity holds even for very-rough-wall Boundary-layers (Flack *et al.* 2007, Castro 2007)
- Roughness geometry does not affect u_τ scaling in a ribbed channel (Krogstad *et al.* 2005)

- Open question: Krogstad *et al.* (1992) suggested that outer layer is affected by roughness: differences in wake strength and shear stresses
- These results not yet reproduced but there may be fundamental differences between channel and boundary layer flows





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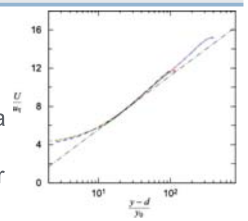
Self-similarity of mean velocity

- Typically, u_τ is estimated using Preston tube, by assuming a "constant stress" layer, $-\overline{uv} = u_\tau^2$ or by a Clauser chart: more measurements are required using a drag balance
- It is clearly not possible in the atmospheric surface layer to perform a rigorous check of simultaneous overlap to determine extent of self-similarity
- Flack *et al.* (2007), Connelly *et al.* (2006), Castro (2007) all demonstrate collapse of velocity defect profiles in outer layer for $k/\delta \leq 20\%$
- But Krogstad *et al.* (1992) and Keirsbulck *et al.* (2002) show that wake strength increases on rough walls - is this inconsistent?
- Flack *et al.* (2007) also show that, as k/δ increases, the growth rate of the boundary layer increases - i.e. boundary layer 'rides' over the roughness



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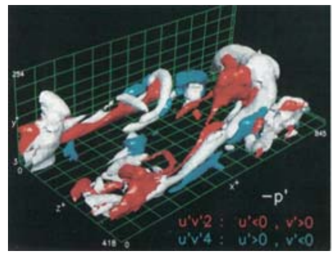
Near-wall structure

- Near-wall cycle changes obviously
- Roughness improves isotropy near wall: $\overline{u^2}$ depressed but $\overline{v^2}$ increases
- Increased frequency and magnitude of sweep and ejection events
- May be related to an increase in hairpin inclinations in boundary layers relative to smooth-wall (Krogstad *et al.* 1992, Krogstad & Antonia 1994, Bakken *et al.* 2005)



Robinson 1991

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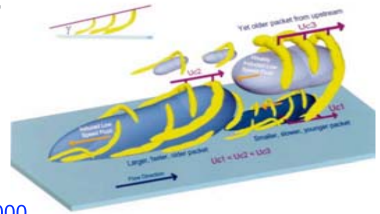
6. Large structures

- In smooth pipe flow, “Very-Large Scale Modules” (VLSMs) clearly identified (Kim & Adrian 1999)
- In smooth-wall boundary layers, “superstructures” (Hutchins & Marusic 2007) have also been identified
- These are dynamically significant: typically they carry about half the shear-stress and energy
- In rough-wall boundary layers:
  - Wu & Christensen (2007) suggest “similarity of spatial structure” but using autocorrelations
  - Volino *et al.* (2007) suggest that “hairpin packets are ….a prominent feature and much the same as its smooth-wall counterpart”

- packets carry roughly half the turbulence kinetic energy and shear stress
- fill most of the boundary layer
- at least 20δ in length – “meandering”



Adrian *et al.* 2000

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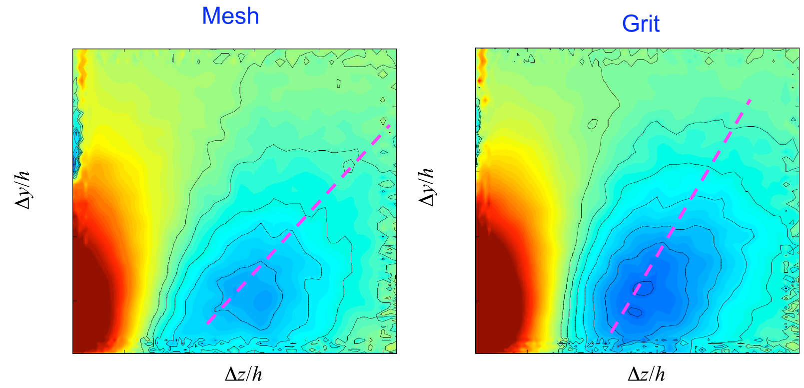
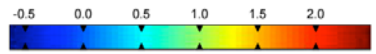
Two-point correlations: channel flow



$$R_{11}(\Delta y,\Delta z)=\frac{\overline{u(y_0,z_0)u(y_0+\Delta y,z_0+\Delta z)}}{\overline{u^2(y_0,z_0)}}$$



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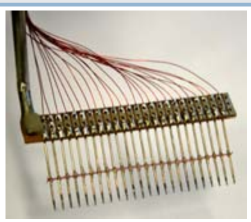
Large structures: time histories - channel flow



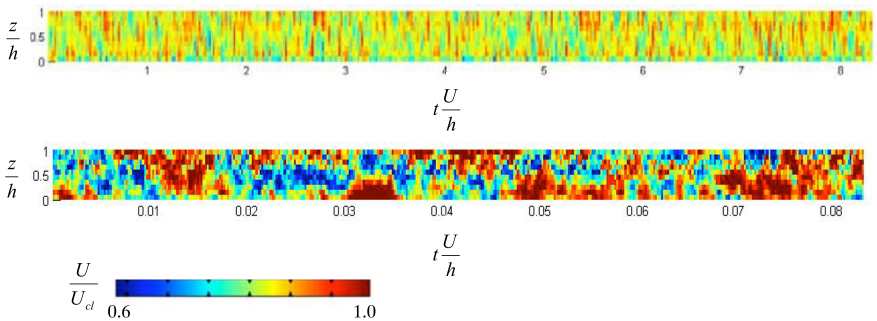
Δz = 5.08 mm

n = 12

y/h = 0.2

Re_τ = 5190

Grit surface



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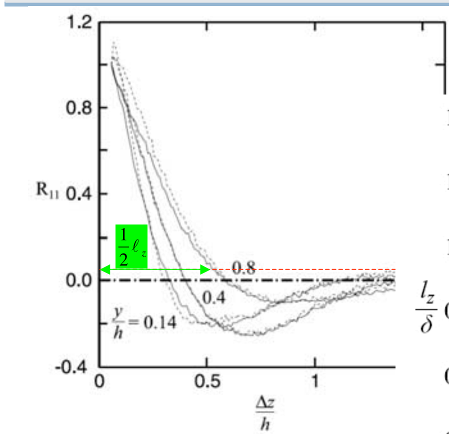
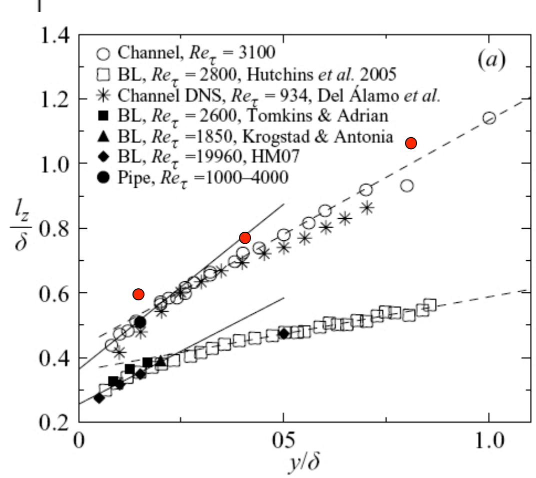
Two-point correlations: channel flow



$\Delta z/h$ at R_{11}=0.05

“Spanwise width scale”

Monty *et al.* (2008)



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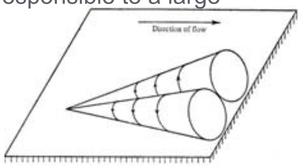
Large structures: summary

- VLSMs appear on both rough and smooth surfaces
- In two-point correlations these appear as Townsend's "backflow" region
- Likely that large structures elongated in x and with circulation in (y,z)-plane result from non-normality - essentially not a viscous process and therefore relating to strain rate rather than viscous shear
- Townsend's "attached wall eddies" - probably responsible to a large extent for outer-layer similarity



- Differences in detail: on rough surfaces, l_z is larger
- Spatial correlation on a rough surface is essential - vigorous "jitter" rather than "meandering"

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References

1. Bakken, O. M., Krogstad, P.-A., Ashrafian, A. and Andersson, H. I. 2005 Reynolds number effects in the outer layer of the turbulent flow in a channel with rough walls. *Phys. Fluids* **17**, 065101
2. Bradshaw P. 2000 A note on "critical roughness" height and "transitional roughness". *Phys. Fluids* **6** 1611–1614
3. Clauser F. H. 1956 The turbulent boundary layer. *Adv. Appl. Mech.* **4** 1–51
4. Colebrook C. F. 1939 Turbulent flow in pipes with particular reference to the transition region between the smooth- and rough-pipe laws. *J. Inst. Civil Eng.* **11** 133–156
5. Colebrook C. F. and White C. M. 1937 Experiments with fluid friction in roughened pipes. *Proc. R. Soc. London Ser. A* **161** 367–381
6. Castro, I. P. 2007 Rough-wall boundary layers: mean flow universality. *J. Fluid Mech.* **585** 469-485
7. Connelly, J. S., Schultz, M. P. and Flack, K. A. 2006 Velocity-defect scaling for turbulent boundary layers with a range of relative roughness. *Exps. Fluids* **40** 188-195
8. Fernholz, H. H. and Finley, P. J. 1996 The incompressible zero-pressure-gradient turbulent boundary layer: an assessment of the data. Prog. Aerospace Sci. **32** 245-311
9. Finnigan J. 2000 Turbulence in plant canopies. *Ann. Rev. Fluid Mech.* **32** 519–571
10. Flack, K. A., Schultz, M. P. and Shapiro, T. A. 2005 Expermental support for Townsend's Reynolds number similarity hypothesis on rough walls. *Phys Fluids* **17**, 035102
11. Hama F. R. 1954. Boundary layer characteristics for smooth and rough surfaces. *Trans. Soc. Naval Archit. Mar. Eng.* **62** 333–358
12. Hunt J. C. R. and Morrison J. F. 2000 Eddy structure in turbulent boundary layers. *Eur. J. Mech.(B) - Fluids* **19**, 673-694
13. Hutchins, N. and Marusic, I. 2007 Evidence of very long meandering features in the logarithmic region of turbulent boundary layers. *J. Fluid Mech.* **579** 1-28
14. Jiménez J. 2004 Turbulent flows over rough walls. *Ann. Rev. Fluid Mech.* **36** 173-196
15. Keirsbulck, L., Labraga, L., Mazouz, A. and Tournier, C. 2002 Surface roughness effects on turbulent boundary layer structures. J. Fluids Engng. 124, 127-135
16. Kim, K. C. and Adrian, R. J. 1999 Very large-scale potion in the outer layer. *Phys. Fluids* **11** 417-422
17. Krogstad, P.-A. and Antonia, R. A. 1994 Structure of turbulent boundary layers on smooth and rough walls *J. Fluid Mech.* **277** 1-21

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7. Outlook

- Definition of surface topology in a useful way is a key challenge
- The Moody chart offers some further challenges in the "transitional" zone
- In order to identify real differences between channel and boundary layer flows, accurate, independent and direct estimates of u_τ are required in experiments using large relative roughness
- It has been suggested that the effect of roughness on wake strength is not the same for channel and boundary layer flows: this cannot be unravelled without an unambiguous definition of the log law.
- Self-similarity requires a demonstration of simultaneous overlap
- The extent of Townsend outer-layer similarity has yet to be fully assessed
- Large streamwise vortices appear to be a dominant feature irrespective of the surface condition

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References

1. Krogstad, P.-A., Antonia, R. A. and Browne, L. W. B. 1992 Comparison between rough- and smooth-wall turbulent boundary layers. *J. Fluid Mech.* **245** 599-617
2. Krogstad, P.-A., Andersson, H. I., Bakken, O. M. and Ashrafian, A. 2005 An experimental and numerical study of channel flow with rough walls. *J. Fluid Mech.* **530**, 327-352
3. Moody L. F. 1944 Friction factors for pipe flow.*Trans. ASME* **66** 671–84
4. Monty, J. P., Stewart, J. A., Williams, R. C. and Chong, M. S. 2007 Large-scale features in turbulent pipe and channel flows. *J. Fluid Mech.* **589** 147-156
5. Morrison, J. F. 2007 The interaction between inner and outer regions of turbulent wall-bounded flow. *Phil. Trans. Roy. Soc.* A **365**, 683-698
6. Morrison, J. F. 2010 Turbulent boundary layers. *Encyclopedia of Aerospace Engineering.* Eds. Richard Blockley & Wei Shyy. John Wiley & Sons Ltd.
7. Nikuradse, J. 1932 Gesetzmäßigkeiten der turbulenten Strömung in glatten Rohren. Tech. Rep.356. Forsch. Arb. Ing.-Wes., English transl. Laws of turbulent flow in smooth pipes, NACA TT F-10, 359
8. Nikuradse, J. 1933 Strömungsgesetze in rauhen Rohren. Tech. Rep. 361. Forsch. Arb. Ing.-Wes., English transl. Laws of flow in rough pipes, NACA TM 1292
9. Raupach, M.R., Antonia, R. A. & Rajagopalan, S. 1991 Rough-wall turbulent boundary layers. *Appl. Mech. Rev.* **44** (1), 1–25
10. Robinson, S. K. 1991 Coherent motions in the turbulent boundary layer. *Ann. Rev. Fluid Mech.* **23**, 601
11. Rotta, J. C. 1962 Turbulent boundary layers in incompressible flow. *Prog. Aero. Sci.* **2**, 1–219
12. Schlichting H. 1968. *Boundary Layer Theory*. New York, McGraw-Hill. *6th ed.*
13. Schultz, M. P. & Flack, K. A. 2007 The rough-wall turbulent boundary layer from the hydraulically smooth to the fully rough regime. *J. Fluid Mech.* **580**, 381–405
14. Shockling, M. A., Allen, J. J. & Smits, A. J. 2006 Roughness effects in turbulent pipe flow. *J. Fluid Mech.* **564**, 267–285
15. Tani, I. 1987 Turbulent boundary layer development over rough surfaces. In: *Perspectives in Turbulence Studies* (ed. H. U. Meier & P. Bradshaw), pp. 223–249. Springer
16. Townsend A. A. 1976 *The Structure of Turbulent Shear Flows.* Cambridge Univ. Press. *2nd ed.*
17. Wu, Y. & Christensen, K. T. 2007 Outer-layer similarity in the presence of a practical rough-wall topography. *Phys. Fluids* **19**, 085108