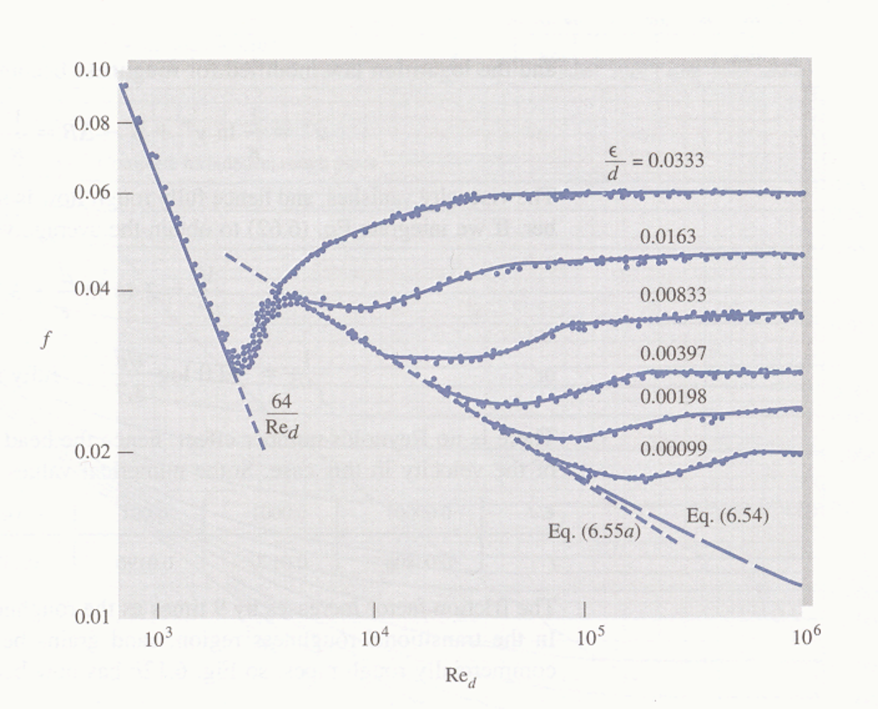
Some effects of surface roughness on turbulent flows

Per-Åge Krogstad
The Norwegian University of Science and Technology, Trondheim, Norway

Surface roughness

Surface roughness is well known to increase surface drag and increase mixing.



Question:
How does it affect the turbulent motion?

Townsend’s wall similarity hypothesis

- In the logarithmic layer the flow is fully turbulent. The flow does not know about the wall condition that generates the turbulence.
- Only a region y<5-6k is directly affected by the roughness.
- Implication: All quantities in the outer layer are unaffected by the wall condition

Some observations:

➘ The strength of the wake in a rough wall boundary layer is increased, no measurable effects in channel flows

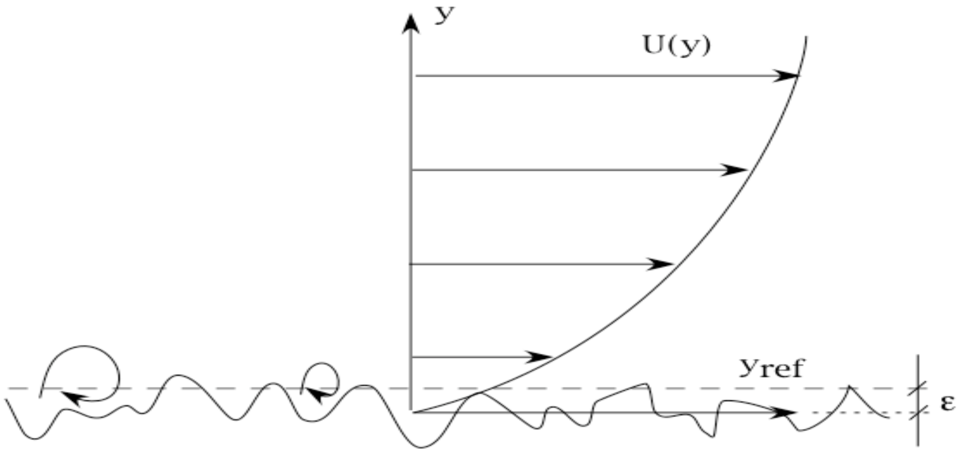
➘Boundary layer:

Streamwise normal stress affected near the wall, but not in the outer layer.
Significant effects sometimes observed in the wall-normal normal stress and shear stress in the outer layer

➘Channel flow:

Small effects on the stresses in the outer layer, some effects on higher order moments.

Added complication with rough wall layers:



Where is the system origin?

Law of the wall

- Smooth wall: $U^+ = \frac{1}{\kappa} \ln y^+ + B$

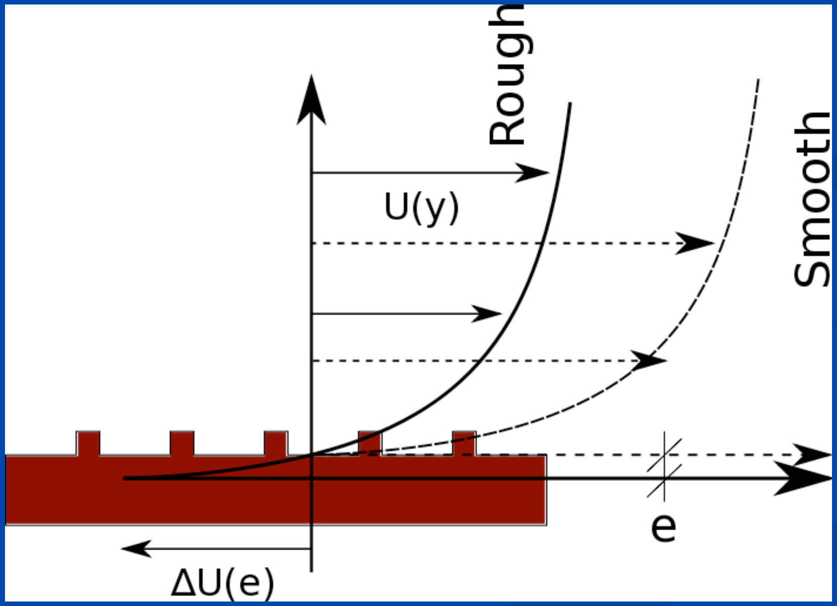
- May be derived by assuming Prod = Diss,
  constant shear stress and a linear length scale distribution

- Rough wall: $U^+ = \frac{1}{\kappa} \ln\left(y^+ + \varepsilon^+\right) + B - \Delta U^+$

- ΔU^+, often called the roughness function, represents the roughness effect on the mean velocity.
  ε^+ is the shift in the wall position
- Problem 1: Two new variables which are difficult to determine
- Problem 2: Does the law of the wall apply also in the rough case?

Rotta, 1962:

"The action of the roughness can be interpreted as being equivalent to a reduction of the viscous sublayer. This suggests the following simple model for the representation of the mean profile: It is assumed that the universal law of the wall applies when the plane of reference is shifted beneath the surface by an amount ε. The plane moves with the velocity ΔU(ε) opposed to the main flow direction"



Rotta, 1962:

If the smooth wall velocity distribution may be written

$$U^+ = f\left(y^+\right)$$

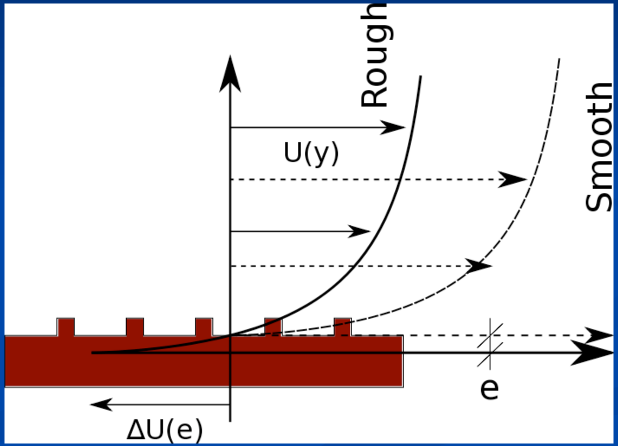
then the rough wall equivalent is

$$U^+ + \Delta U^+ = f\left(y^+ + \varepsilon^+\right)$$

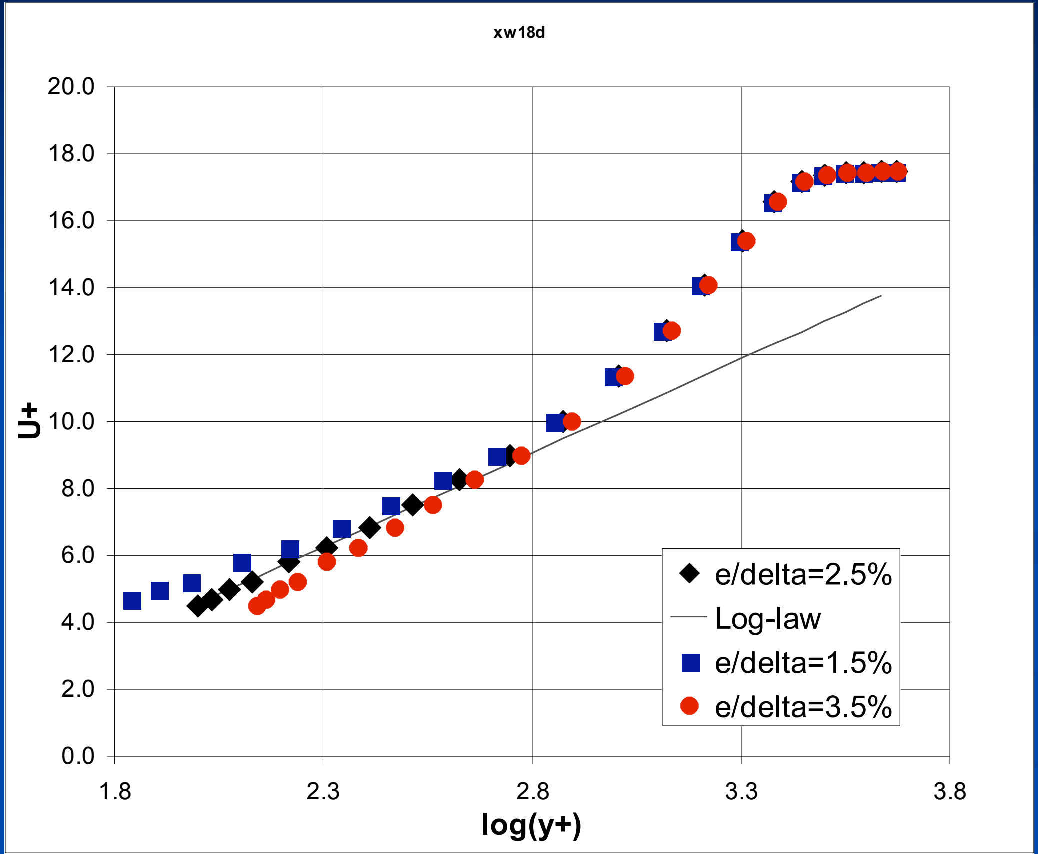
or

$$U^+ = \frac{1}{\kappa}\ln y^+ + B$$

$$\Rightarrow U^+ = \frac{1}{\kappa}\ln\left(y^+ + \varepsilon^+\right) + B - \Delta U^+$$



Traditionally the law of the wall is assumed to apply also for rough surfaces. ε and ΔU adjusted to force a logarithmic region.



Considerable uncertainty in ε which also affects the values obtained

for ΔU and C_f. ε includes probe positioning errors.

Jackson, 1981:

ε defines the location where the drag force acts. Fixes ε and reduces number of unknowns. Sounds plausible, but WHY should $U^+=1/k\ \ln(\varepsilon^+)+B-\Delta U^+$ represent the position where the drag force acts....?

Hama, 1954:

Outer layer similarity implies that the wake strength should be the same for both cases.

Hence there should be only two new unknowns in the rough wall law of the wall:

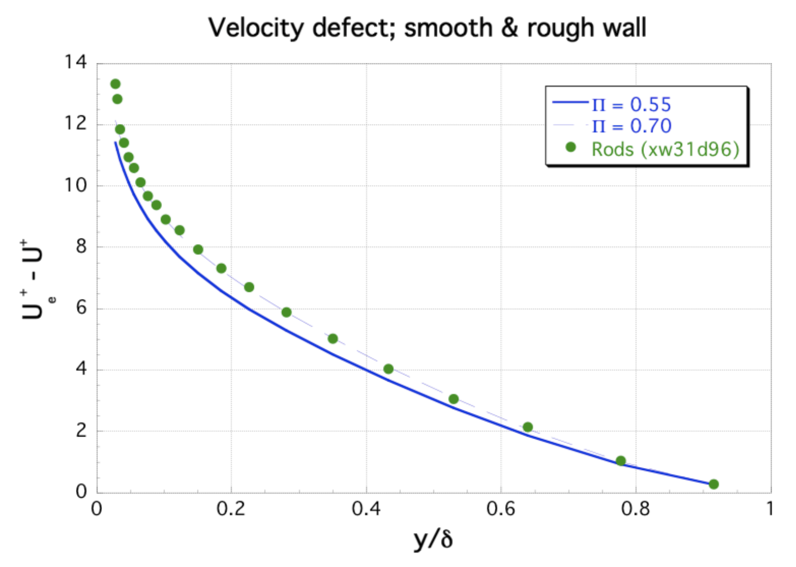
$$\varepsilon \text{ and } u_\tau$$

But what if the wake strength is **NOT** the same (as suggested by many experiments)....?

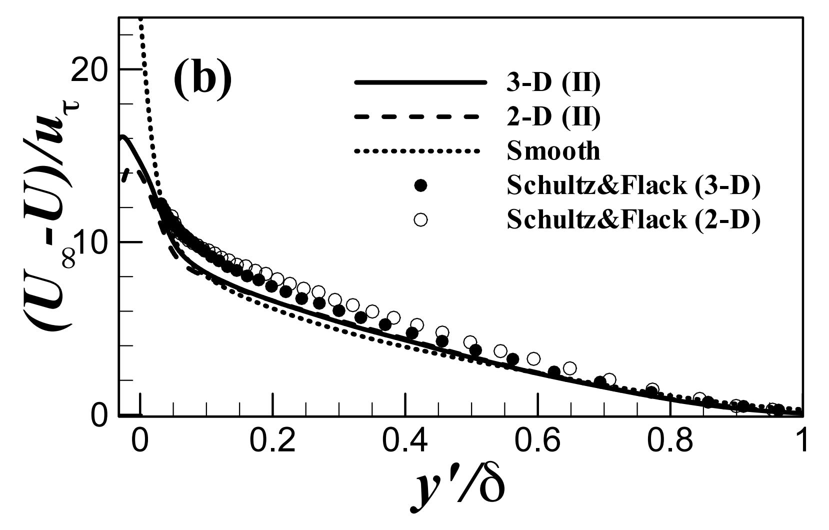
Error in u_τ due to wrong estimate of Π :

$$\frac{U}{u_\tau(1+e_\tau)} = \frac{1}{\kappa}\ln\left(y^+ + \varepsilon^+\right) + B - \Delta U^+ + \frac{2\Pi(1+e_\Pi)}{\kappa} w\left(\frac{y}{\delta}\right)$$

$$\Rightarrow \frac{e_\tau}{e_\Pi} \approx -\frac{\dfrac{2\Pi}{\kappa}\left[1 - w\left(\dfrac{y}{\delta}\right)\right]}{U_e^+ - U^+}$$

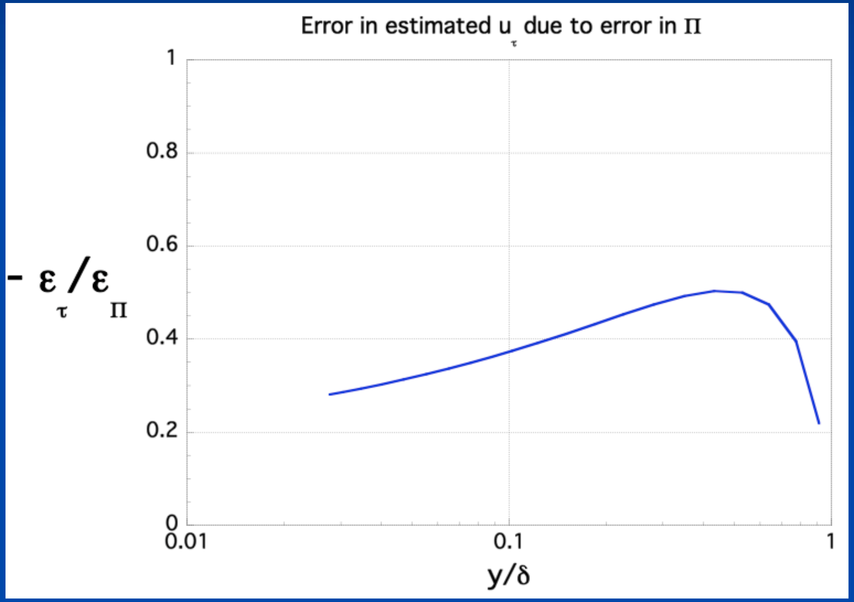


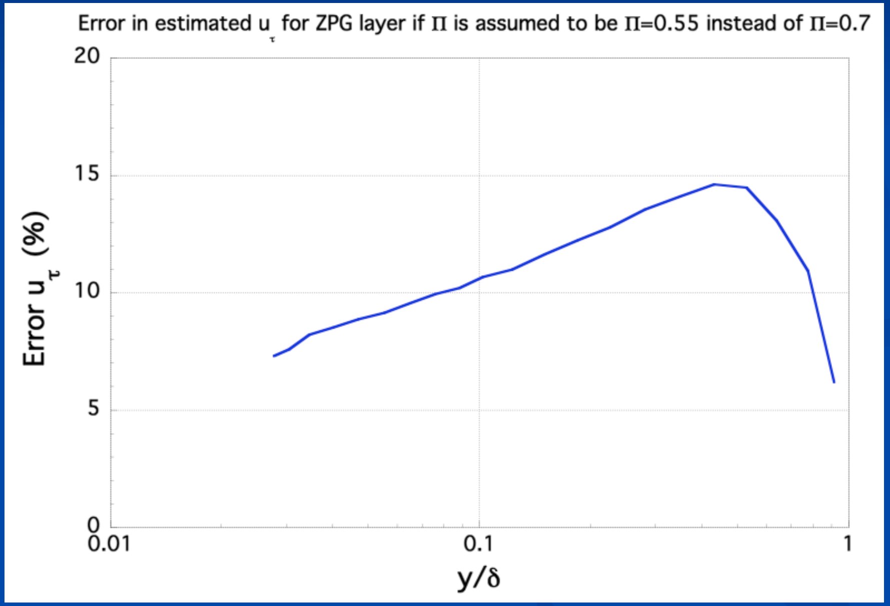
Exp. Krogstad&Antonia (1999)



DNS Lee et al. (2010), Exp. Schulz&Flack (2007)

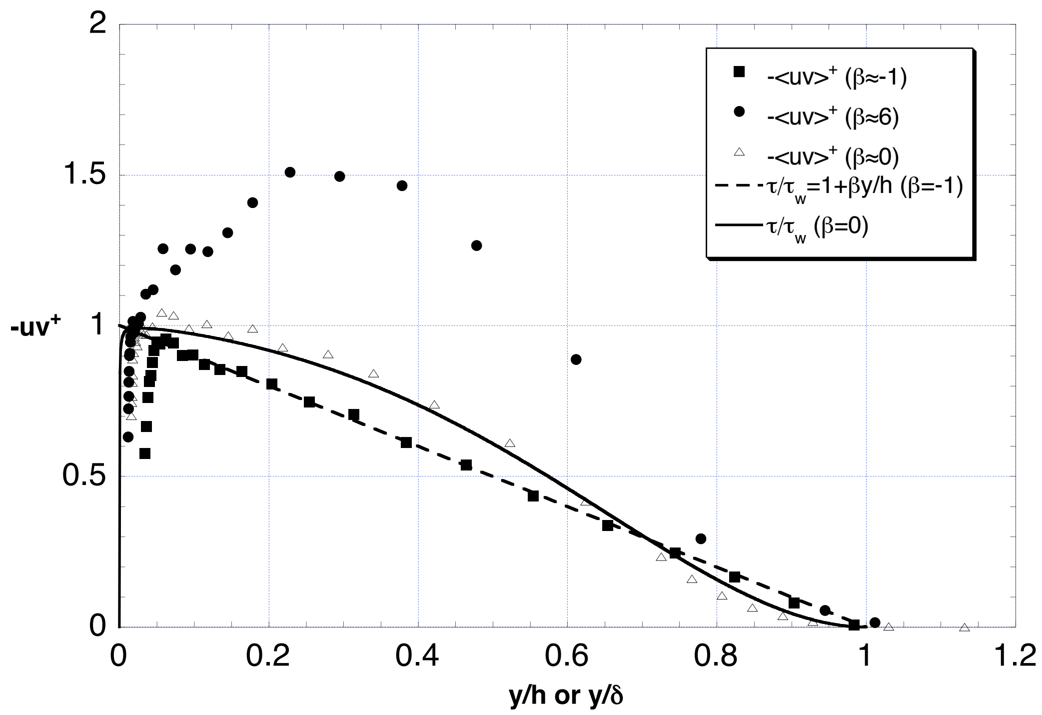
Estimated error in u_τ for the experiment of Krogstad&Antonia due to wrong estimate of Π :



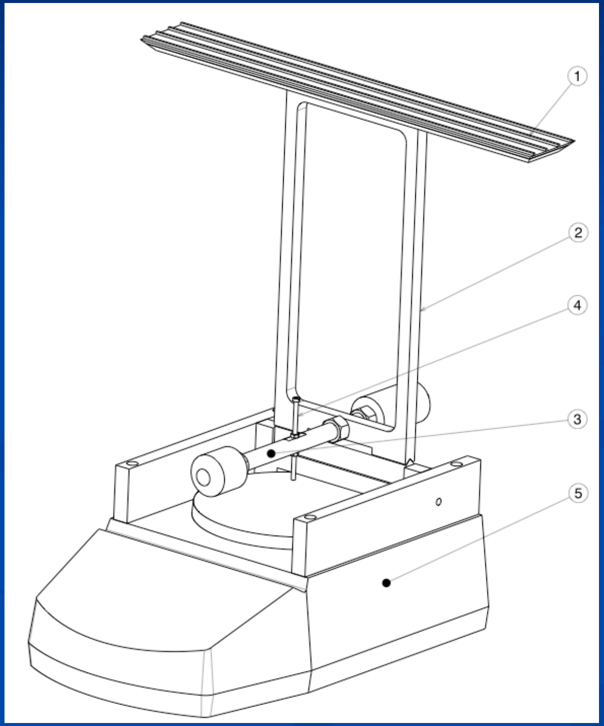


Note: An error in Π will also lead to an error in the estimate of the von Karman constant, κ, in a fitting procedure.....

Considerable uncertainty may be eliminated if u_τ is measured directly



Rough wall channel flow, diffusor & ZPG boundary layer



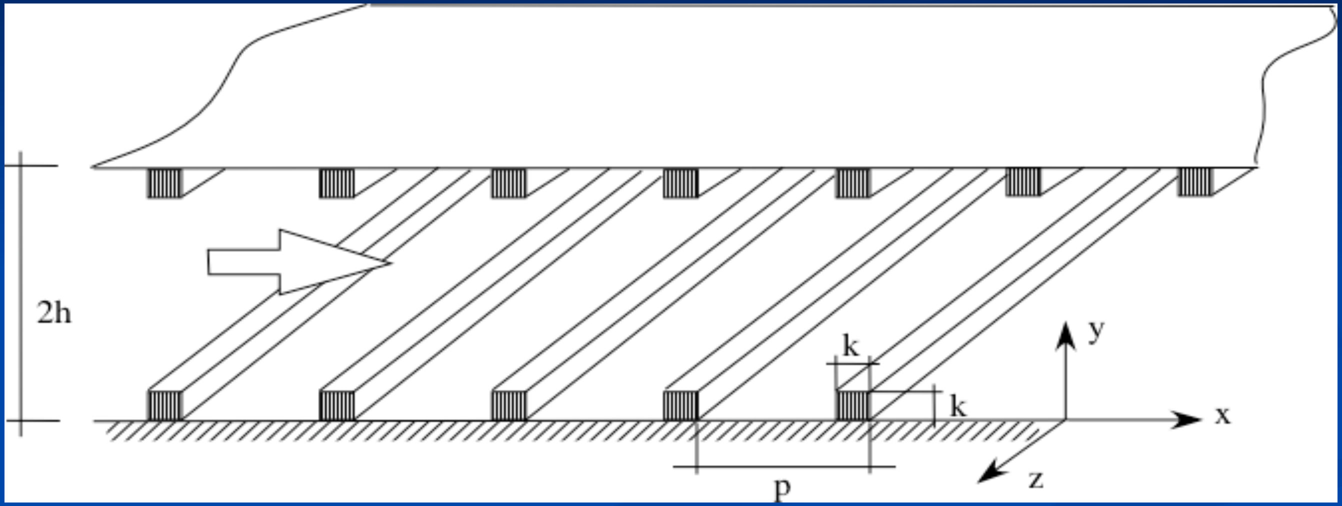
Friction balance

Efros&Krogstad (2009)

Channel flow

[Ph.D. work by Ashrafian (DNS) and Bakken (Exp.)]

Roughness height:
k/h=0.034
Roughness pitch:
p/k=8

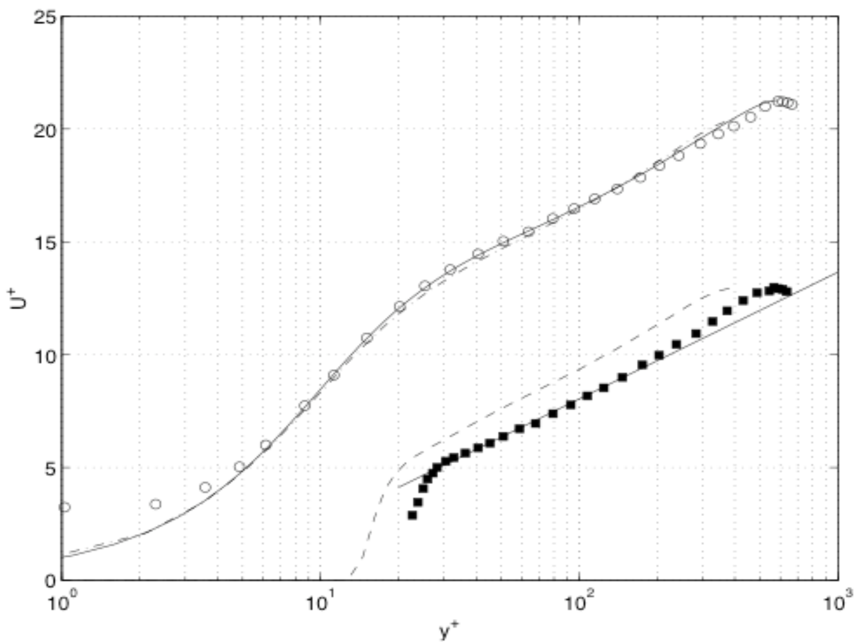


Exp: Hot-wire anemometry, L=5m, 2h=0.1m, Re_τ=600-6000, Re_b=6000-56000, k^+=20-200.

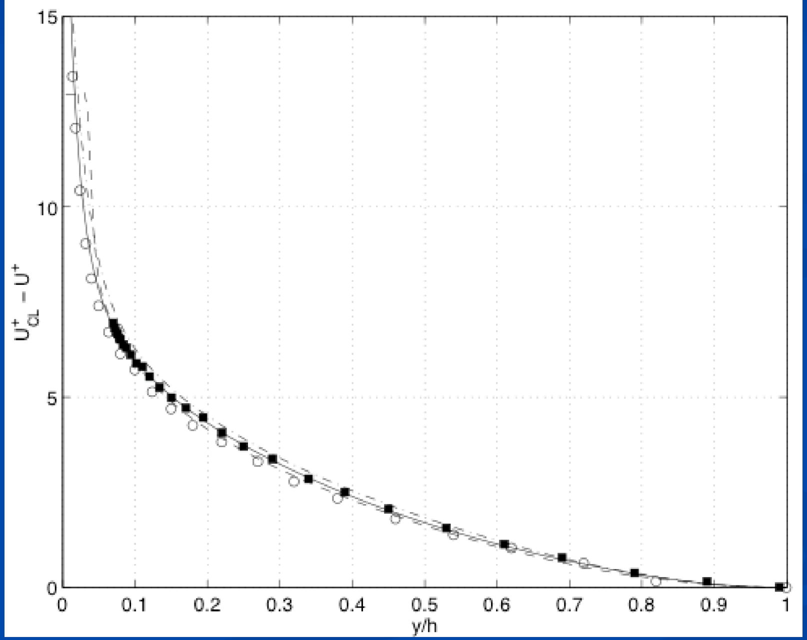
DNS: Finite difference method, periodic boundaries, (Lx,Ly,Lz)=(6.28h,2h,πh) 24 elements on each surface, Re_τ=400 , Re_b=4200, k^+=13.4

Mean velocity channel flow

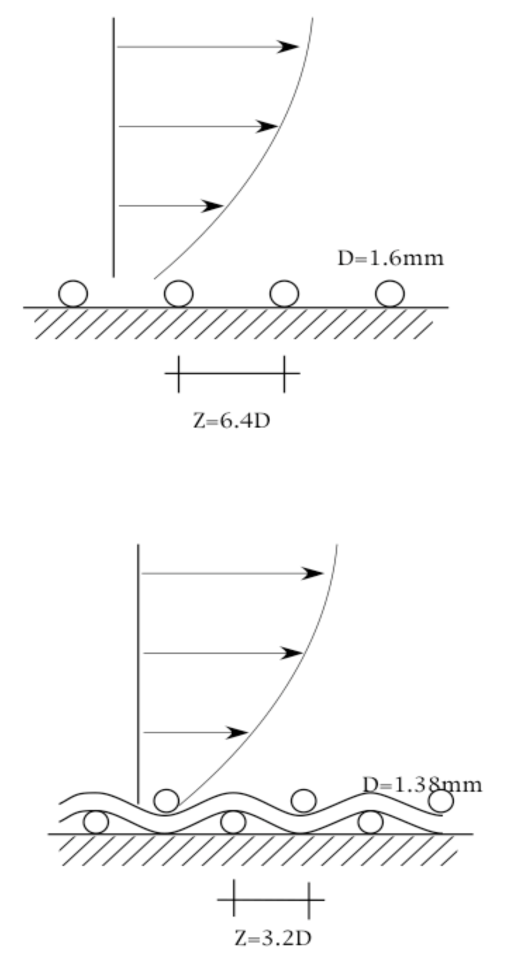
Inner variables



Outer variables



Boundary layer



- Rod roughness: $k/\delta = D/\delta \sim 0.02$
- $Re_\theta = 4810$, $k^+ = 41.9$, $\Delta U^+ = 11.4$

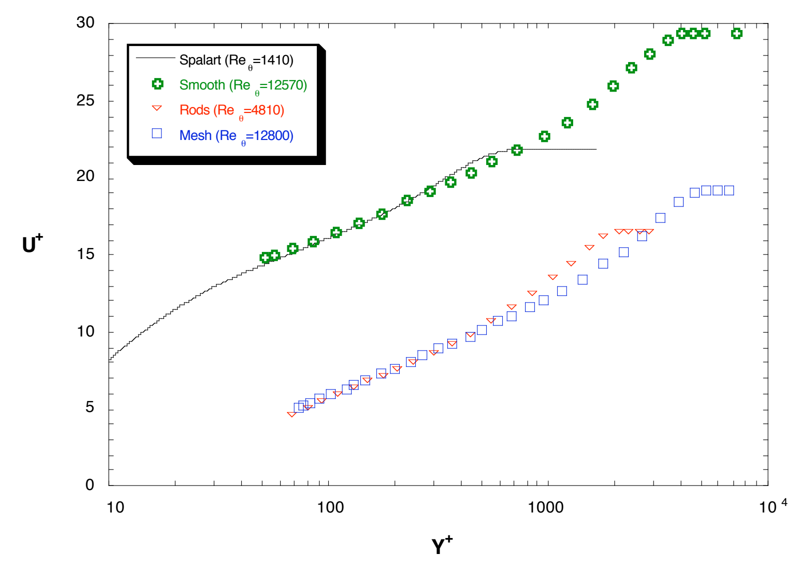
(Krogstad&Antonia, Exp. Fluids 1999)

- Mesh roughness: $k/\delta = D/\delta \sim 0.02$
- $Re_\theta = 12800$, $k^+ = 95.6$, $\Delta U^+ = 11.0$

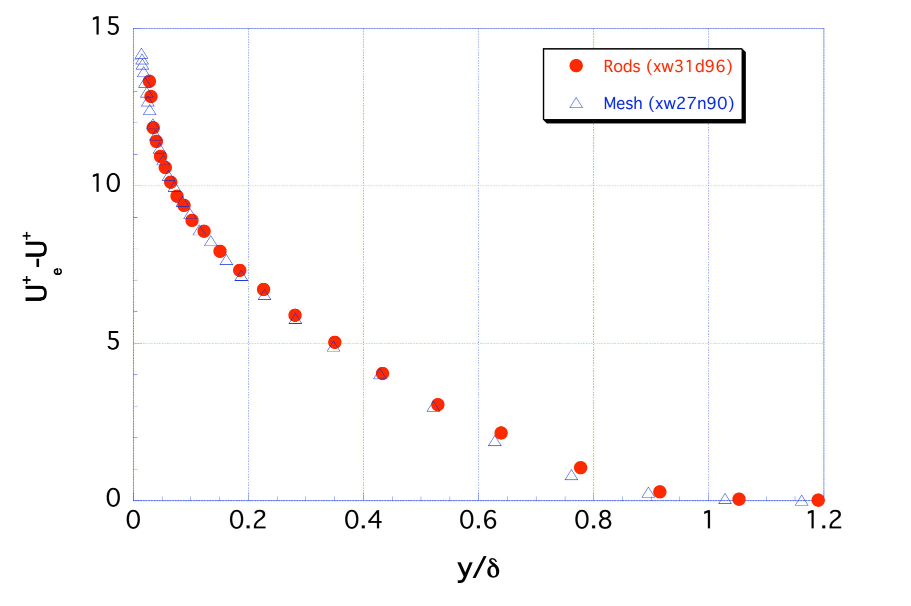
(Krogstad,Antonia&Browne, J. Fluid Mech. 1992)

Mean velocity, boundary layer

Inner variables



Outer variables

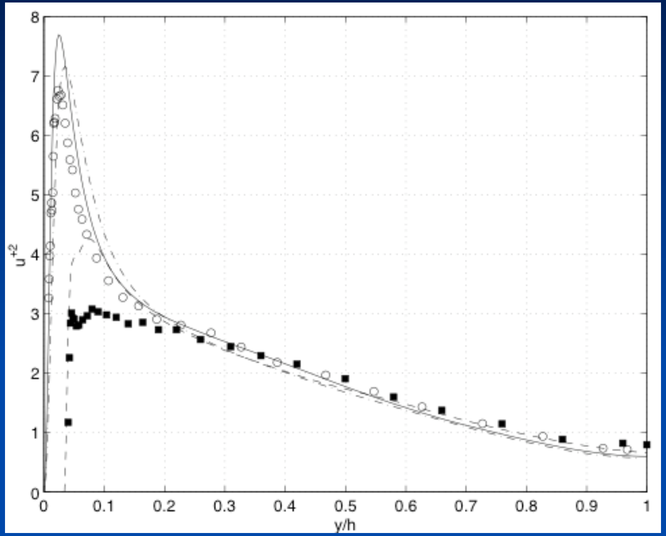


Expected rough wall effects on turbulence statistics

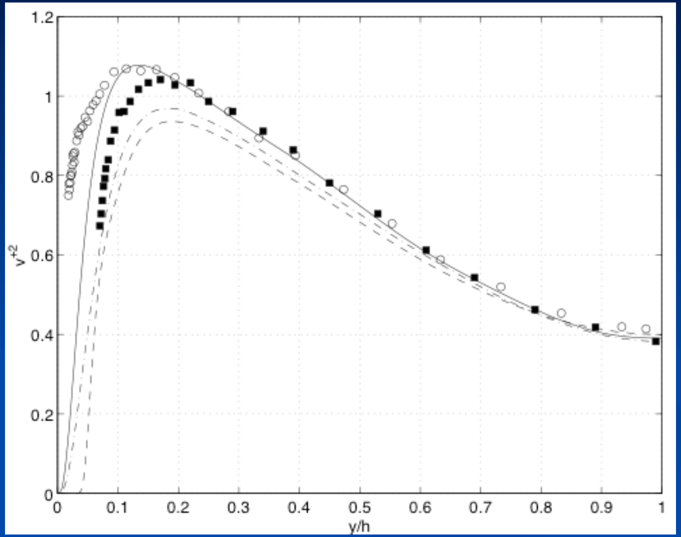
- Streamwise motion obstructed; reduced $\overline{u^2}$ stress
- Wall "porous"; reduced damping of wall normal motion, $\overline{v^2}$ increased. Flow impinging on elements may also increase $\overline{v^2}$. Increased wall normal diffusion.
- Pressure drag from roughness elements increases total drag, $-\overline{uv}$ reduced near the roughness elements

Stresses, channel flow

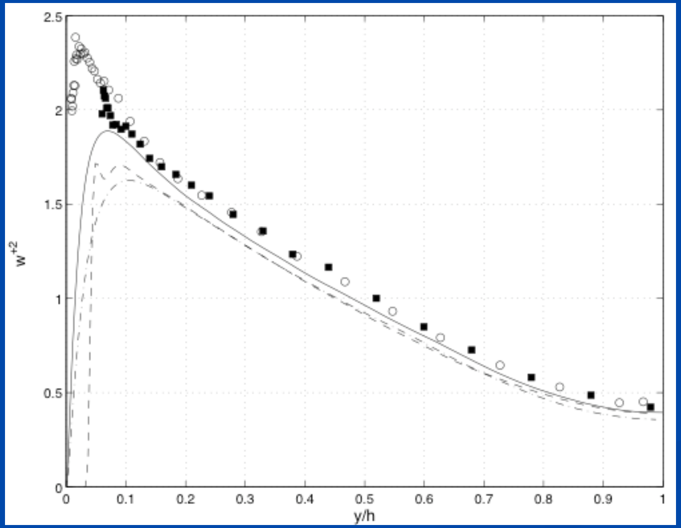
$<u^2>^+$



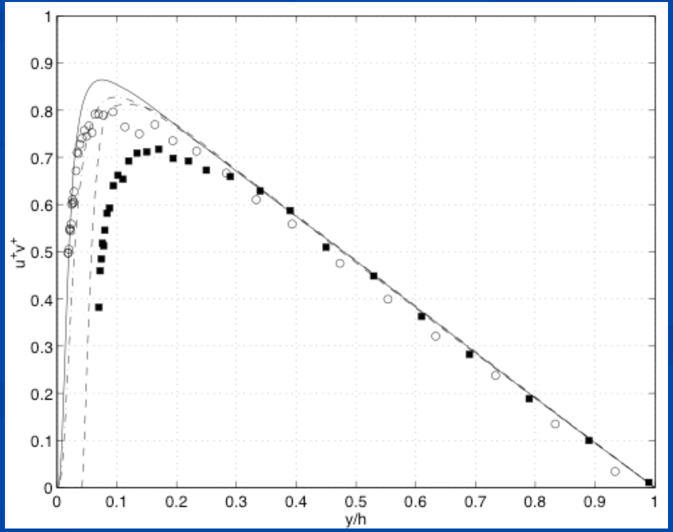
$<v^2>^+$



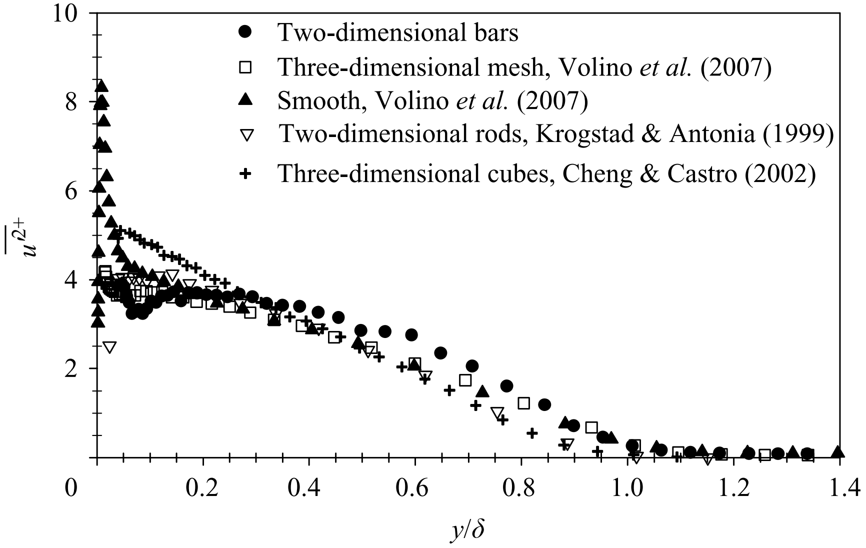
$<w^2>^+$

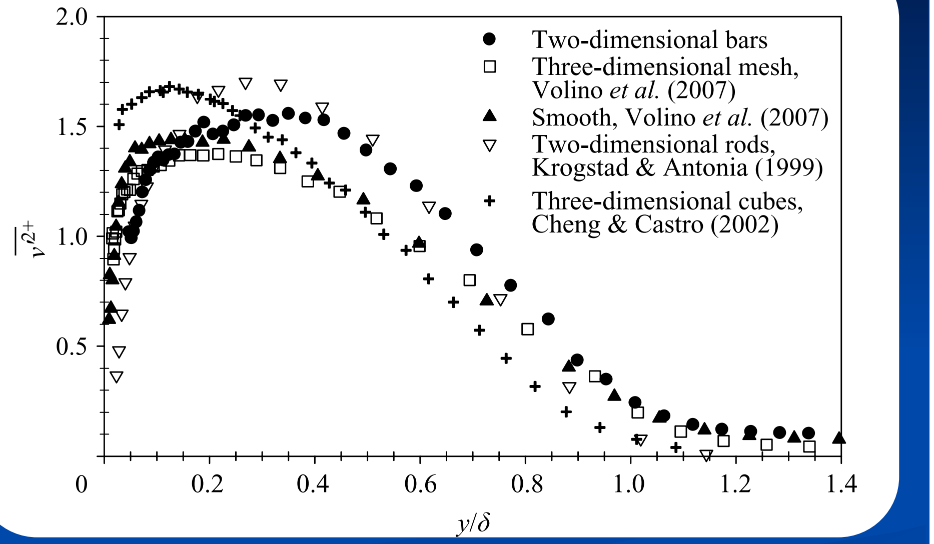


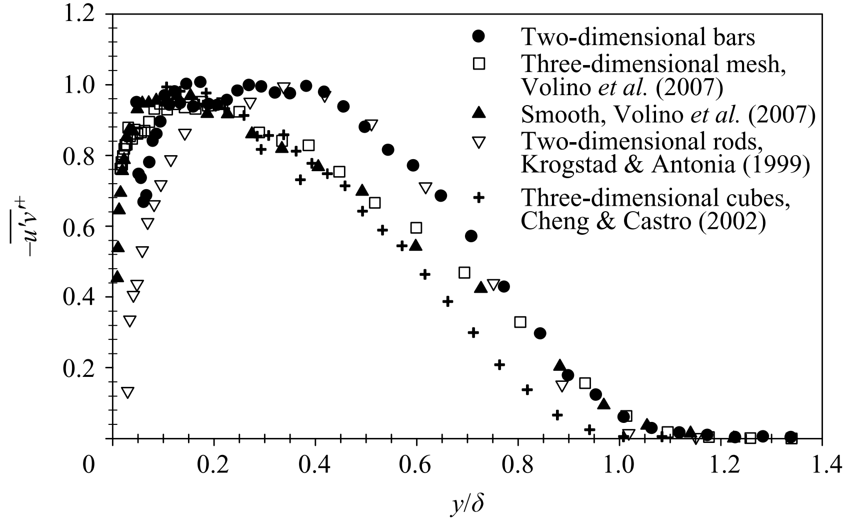
$<-uv>^+$



Stresses, boundary layer





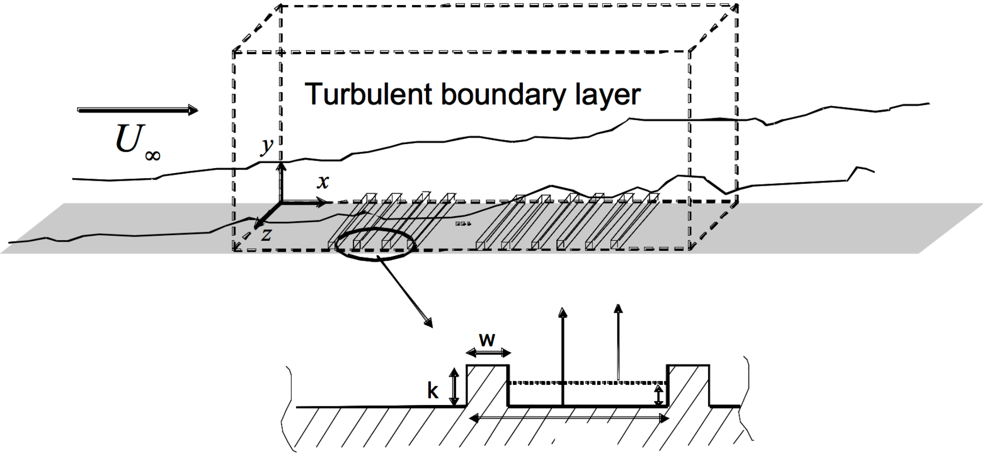


Rough wall boundary layer DNS (I)

Lee & Sung, JFM, 2007

Computational details

- domain size : 768 $\theta_{in}\times$ 60 $\theta_{in}\times$ 800θ_{in}
- mesh : 2049×150×257 points
- grid resolution : $\Delta x^{+}=6.0$, $\Delta z^{+}=5.0$, $\Delta y^{+}_{min}=0.2$, $\Delta y^{+}_{max}=24.0$
- roughness geometry : $\lambda/k = 8$
- roughness height: $\delta/k = 8$ to 21

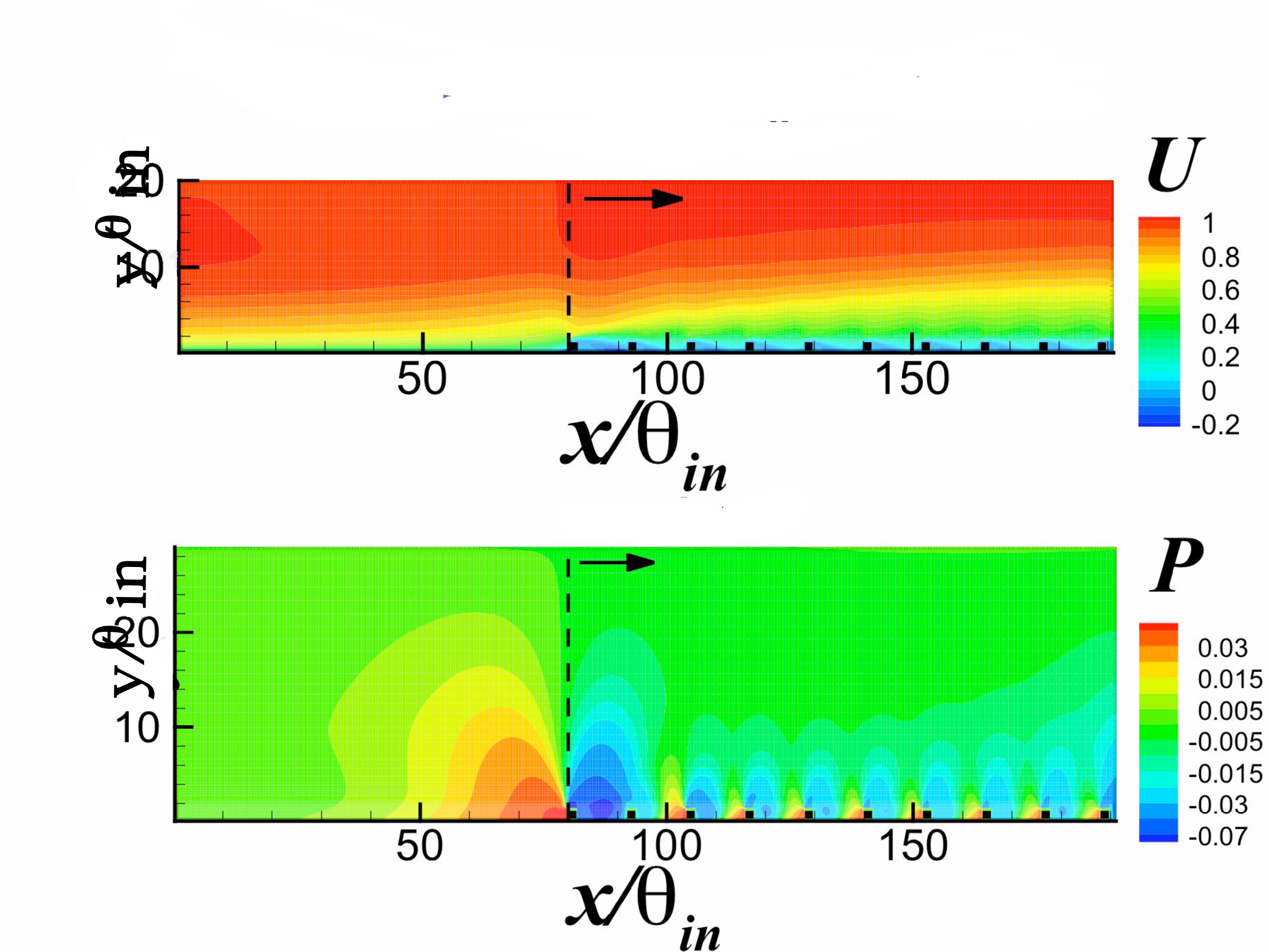


Schematic diagram of computational domain

Boundary conditions

- inflow condition : the inflow generation method by Lund et al. (1998)
- outflow condition : convective boundary condition
- no-slip boundary condition at the wall
- far-field boundary condition : $u=U_\infty$, $\partial v/\partial y=0$, $\partial w/\partial y=0$
- periodic boundary condition in the spanwise direction

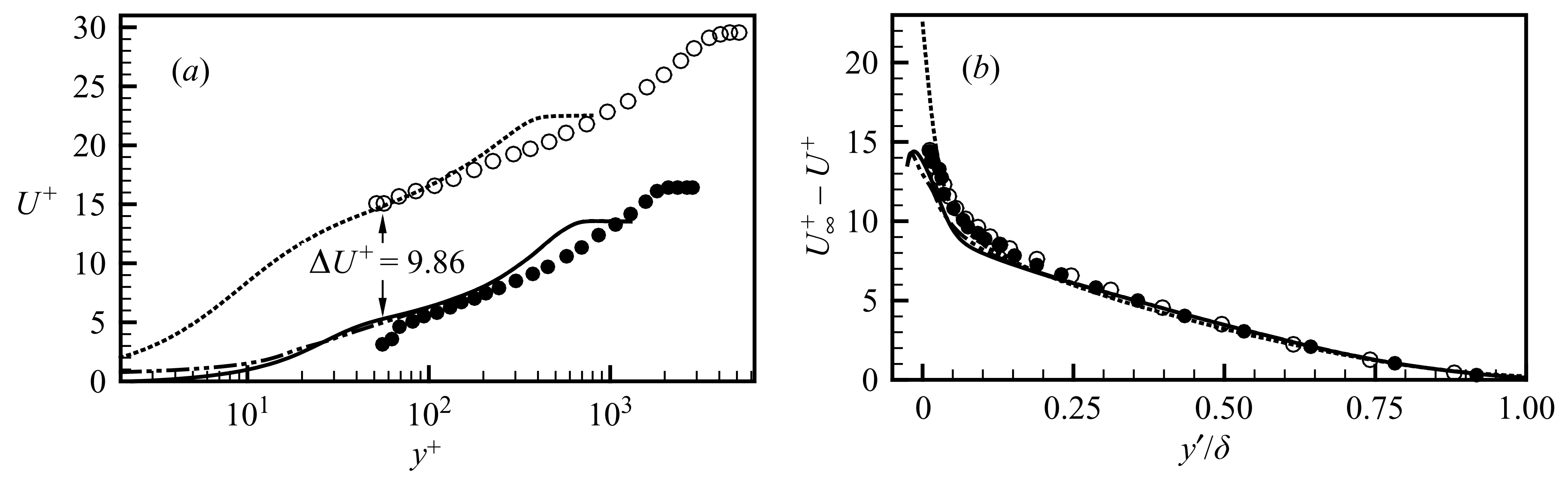
Rough wall boundary layer DNS (II)



Roughness effect on mean flow

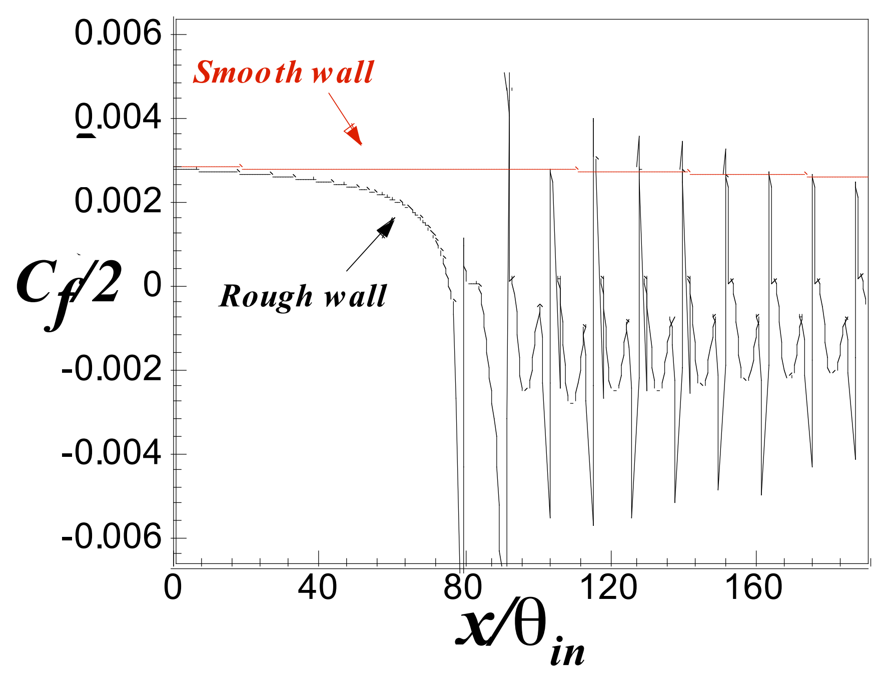
- DNS of Lee&Sung, 2007, Experiment by Krogstad&Antonia, 1999
- DNS roughness function, $\Delta U^+ \approx$ **9.9** [Krogstad et al.(1999): $\Delta U^+ \approx$ **11.4**]

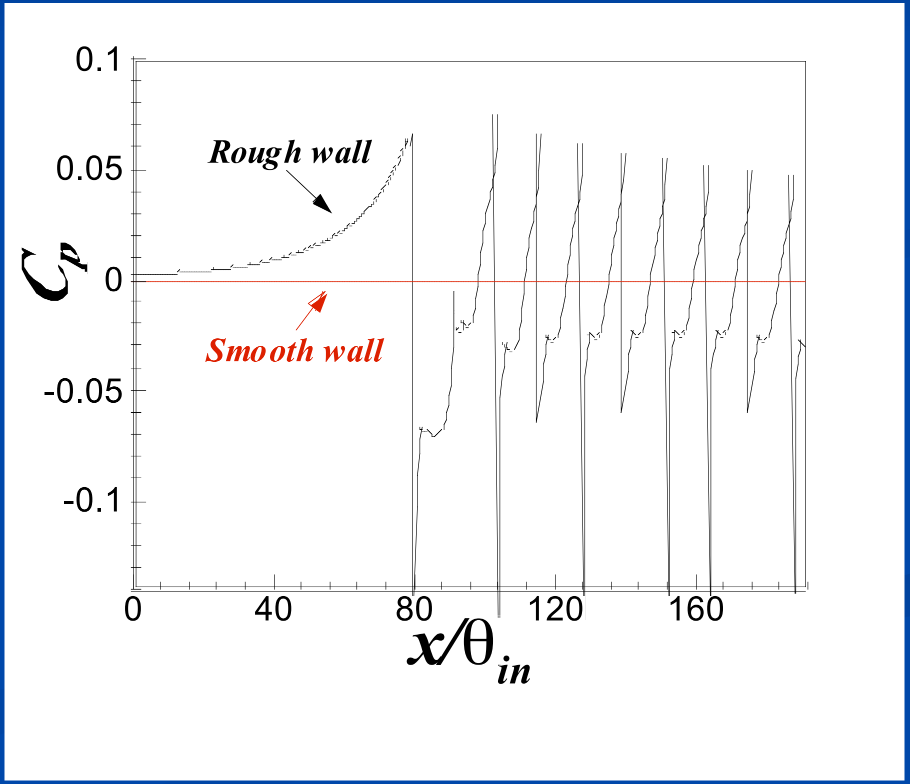
$$\Delta U^+ = \frac{1}{\kappa} \ln k^+ + 1.2$$



Pressure and viscous drag

- The inlet boundary was located far upstream of the first rod.
- From the 3rd rod, C_f and C_p variations show similar *periodic* patterns, but asymptotic solution not reached.

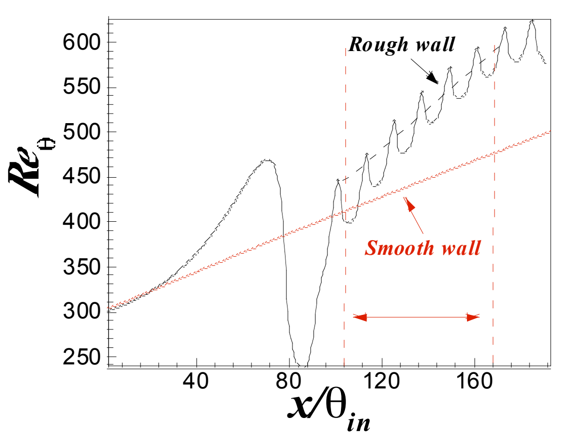


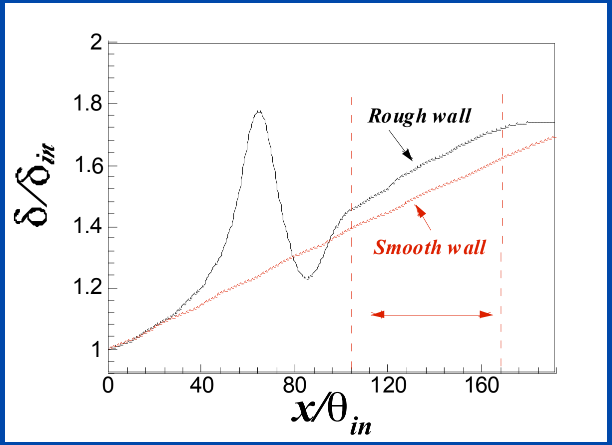


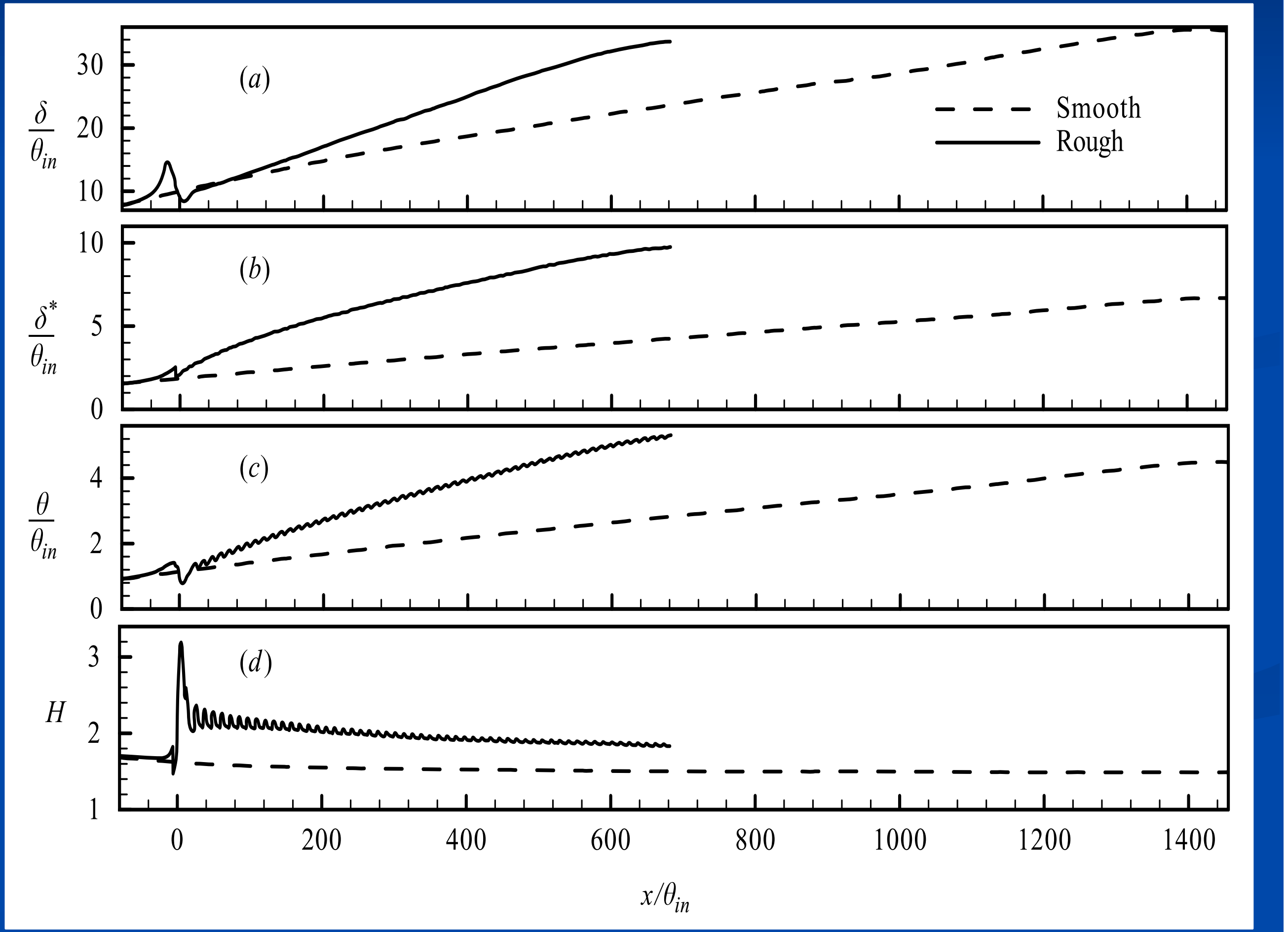
Length scale development

Fully developed rough boundary layer with constant skin friction coefficient:

H = const and length scales grow ~ x.

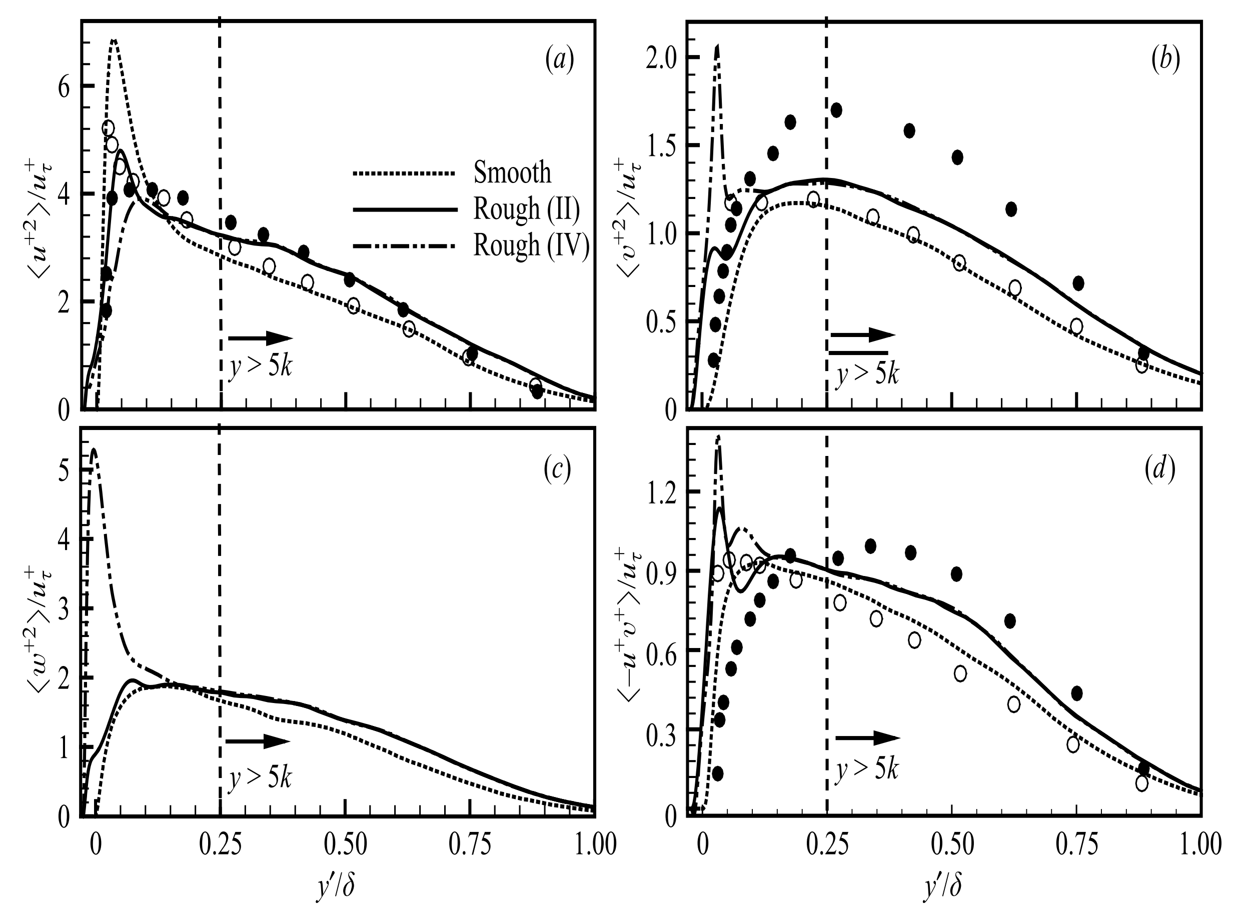






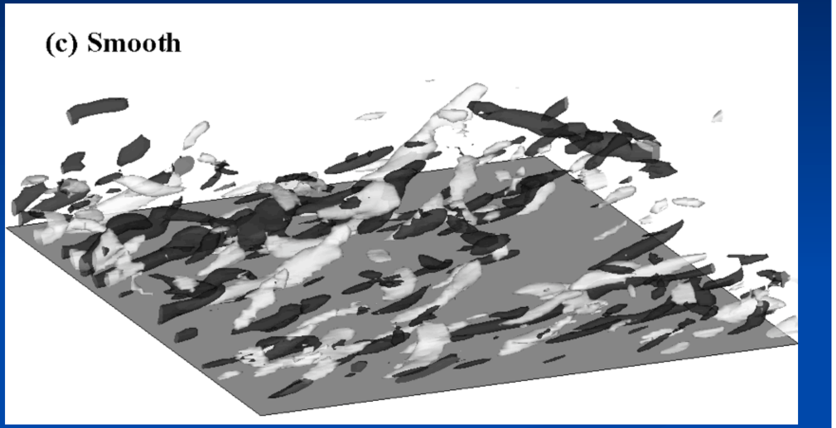
Roughness effects on turbulent stresses

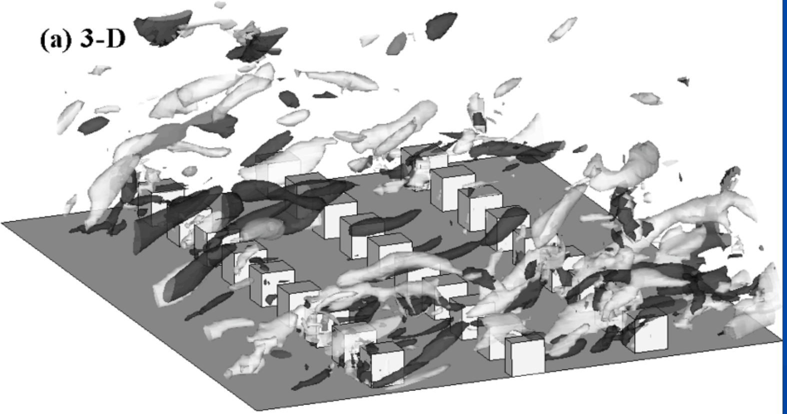
- Streamwise turbulent stress decreases in the roughness sublayer but increases in the outer layer.
- Wall-normal and spanwise stresses increased significantly in the outer layer.
- Surface roughness affects the turbulent stresses not only in the roughness sublayer but also in the outer layer.

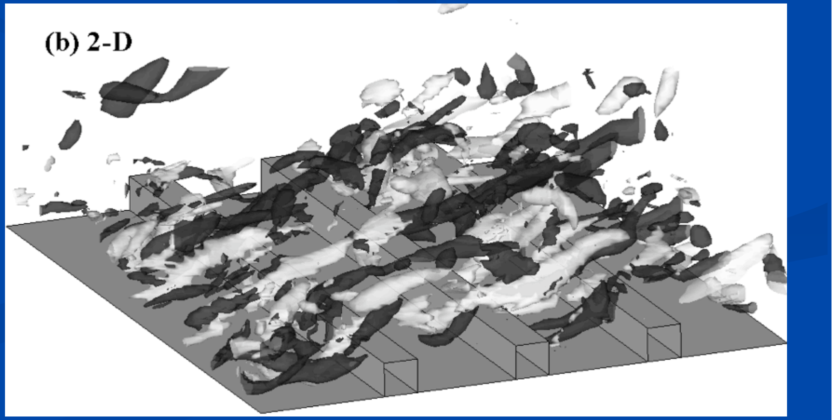


Effects of roughness geometry

- It has been suggested that some of the contradicting observations on roughness effects may be caused by different geometries giving different signatures in the outer layer (e.g. Krogstad et al, 1992, 1999, 2005)
- Recent DNS (Lee&Sung, 2010) show differences in outer layer vortex structure for 2D and 3D roughness



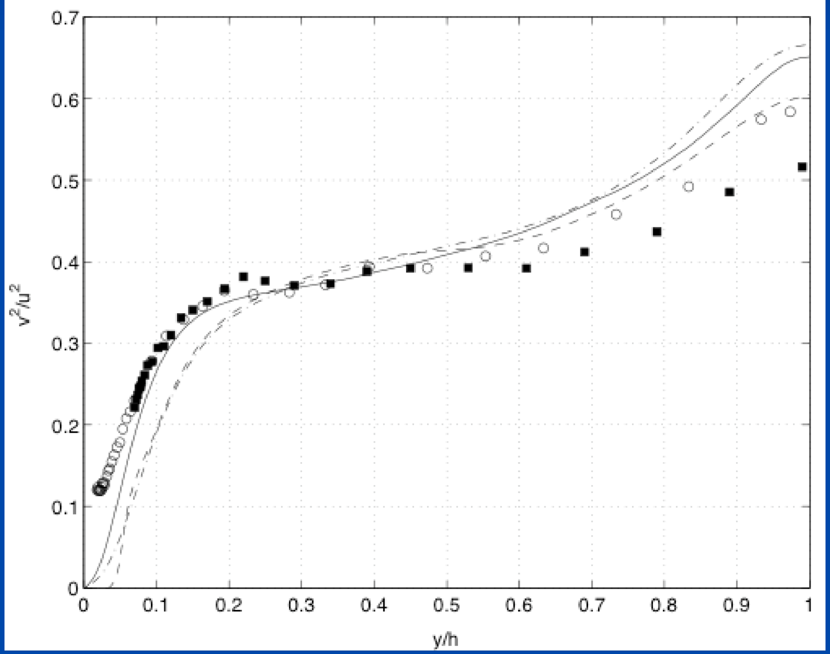




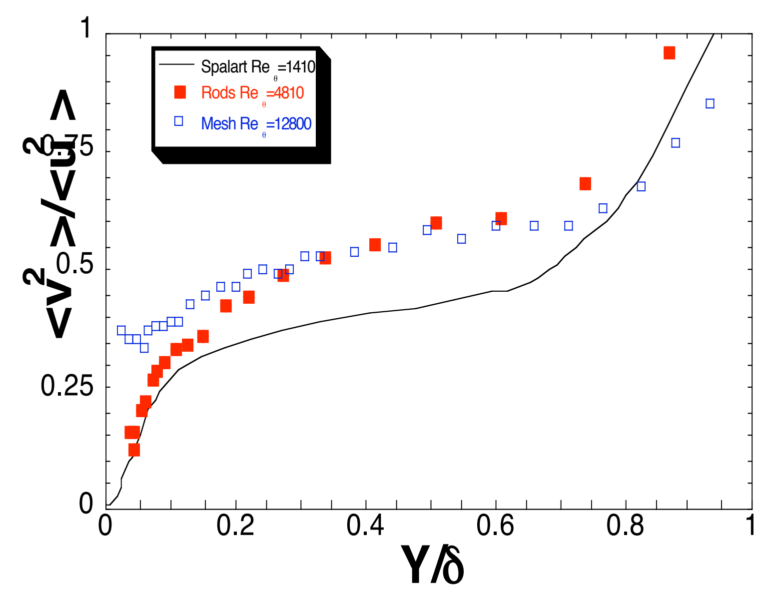
Flow anisotropy: $<v^2>/<u^2>$

(Isotropic turbulence $<v^2>/<u^2>=1$)

Channel flow



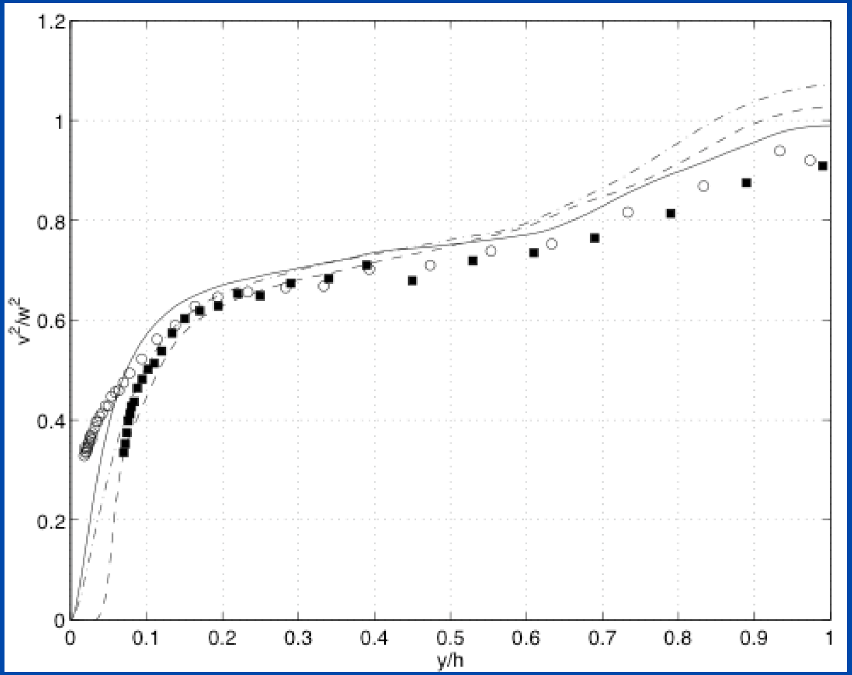
Boundary layer



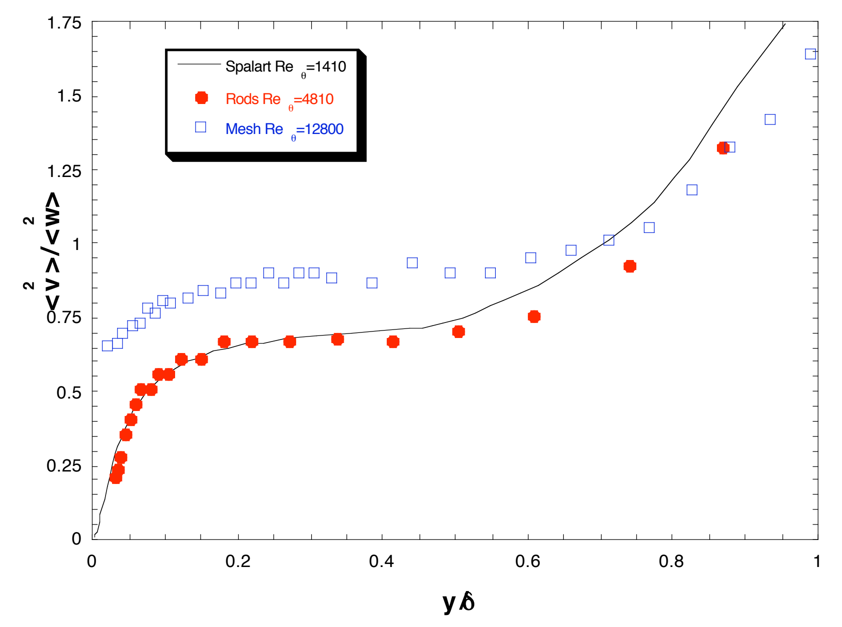
Flow anisotropy: $\langle v^2\rangle/\langle w^2\rangle$

(Isotropic turbulence $\langle v^2\rangle/\langle w^2\rangle=1$)

Channel flow



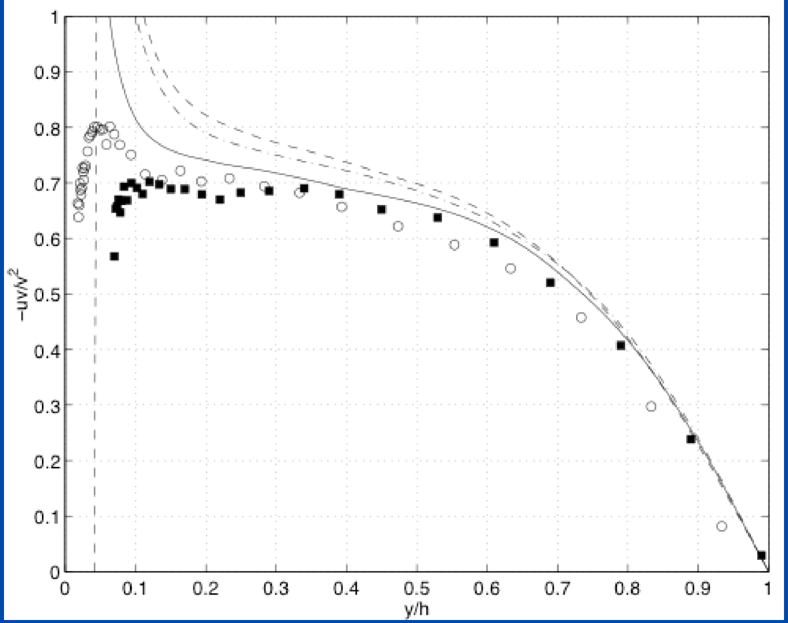
Boundary layer



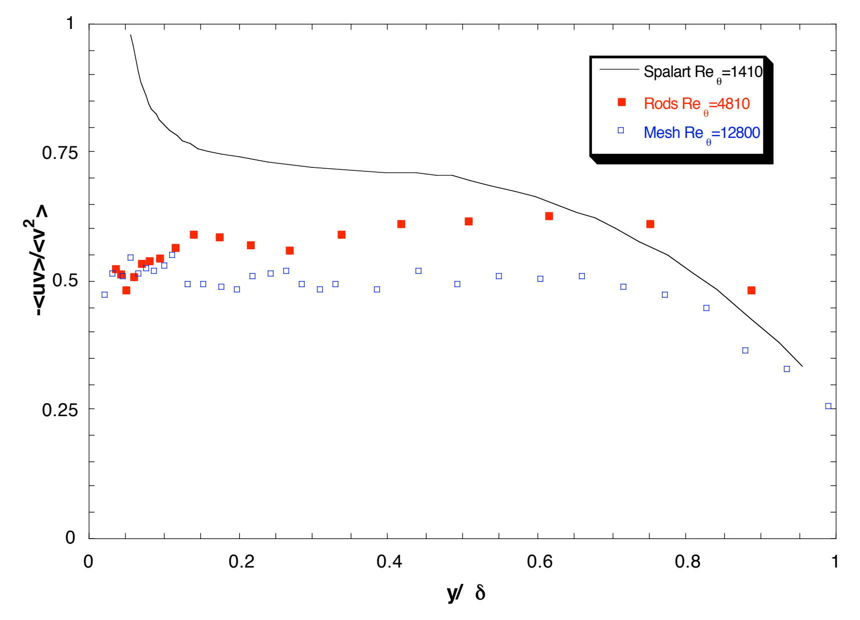
Flow anisotropy: $-\langle uv\rangle/\langle v^2\rangle$

(Isotropic turbulence $-\langle uv\rangle/\langle v^2\rangle=0$)

Channel flow



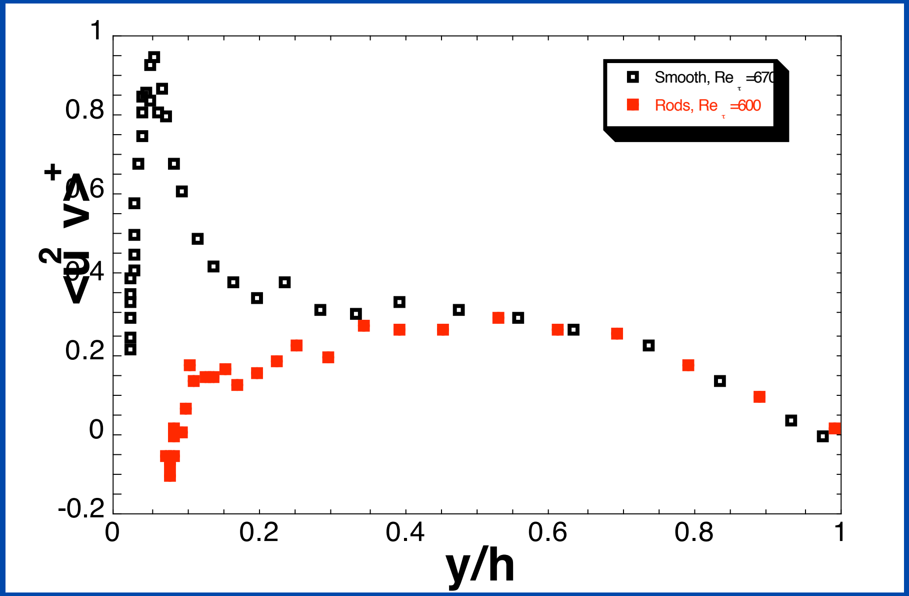
Boundary layer



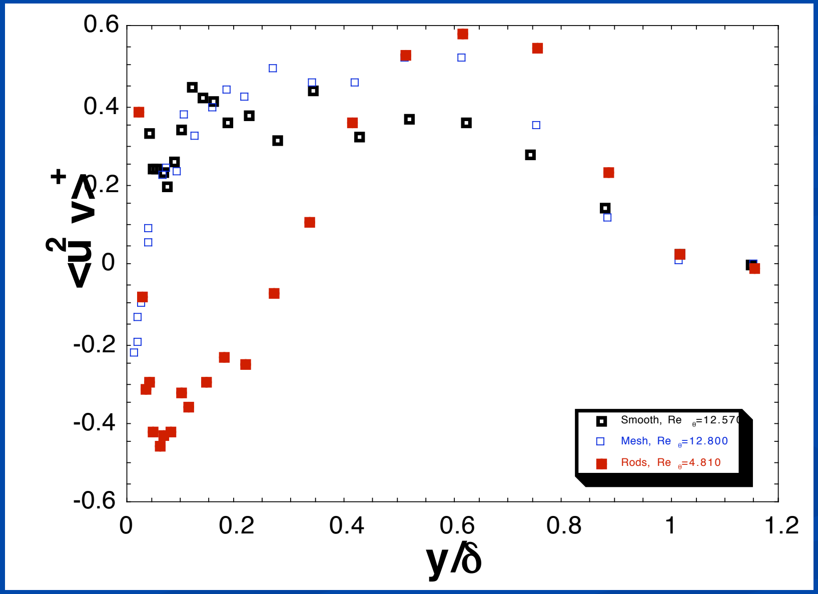
Third order terms: $\langle u^2 v\rangle^+$

(vertical transport of $\langle u^2\rangle$)

Channel flow



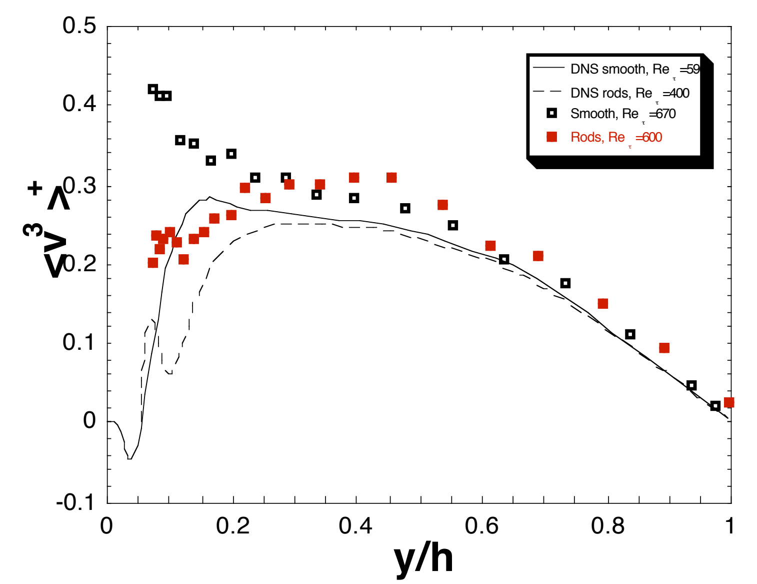
Boundary layer



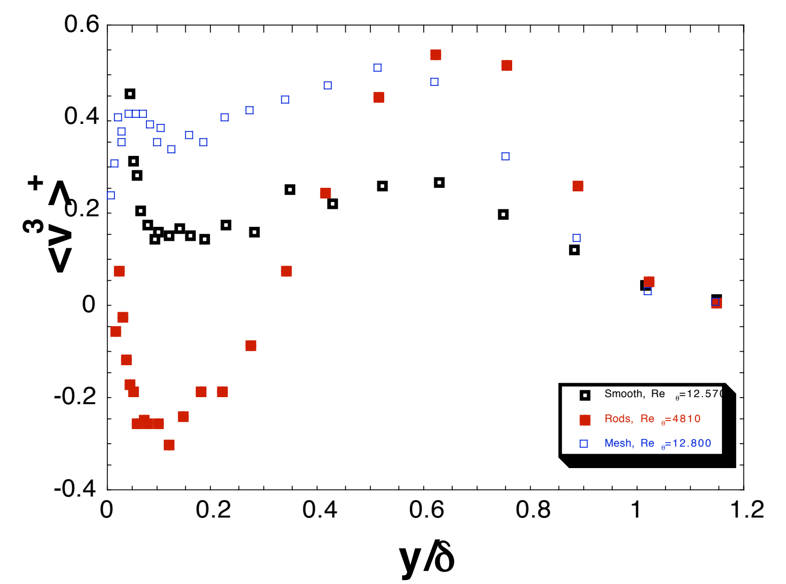
Third order terms: $\langle v^3 \rangle^+$

(vertical transport of $\langle v^2 \rangle$)

Channel flow



Boundary layer



Summary

- Significant roughness effects in the roughness layer $y/k<5$ verified for all cases
- Channel flow:

  Outer layer very little affected (DNS & exp.)
- Boundary layer:

  Mesh surface (exp.):

  Mainly $\langle v^2 \rangle^+$ affected in the outer layer

  Rod surface (DNS & exp.): All stresses affected
- Third order moments affected in the outer layer for all cases
- Roughness effects flow and geometry dependent?