The Structure of Turbulence in Newtonian and Viscoelastic flows: Polymers and Drag Reduction Lectures 3/4

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Structures of the mechanics of complex bodies

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Introduction

- A well known effect of dilute polymers in wall turbulence: very large *drag reduction* up to 70% (since Toms, 1948)

- Typical applications
  - channels or pipelines (e.g. Alaska oil pipe)
  - ships and boats could have great advantages ⋯ but environmental problems

- Several *phenomenological models* have been proposed in the past to explain such phenomena (e.g Lumley 1963, De Gennes 1986, and more recently L'vov et *al.* 2004) ⋯ but a complete physical comprehension is still missing (e.g. Sreenivasan and White 2000)

Introduction

- Firemen water cannons with *pure water* and *dilute polymer solution*

- Same power *but* different bulk velocity & throughput

Outline of the presentation

- Experimental evidence: the effect of polymers on wall turbulence
- How the polymers act: their physical model
- The numerical simulations: how reliable they are
- A scale by scale energy budget: a tool for physical understanding
- The analysis and the main findings

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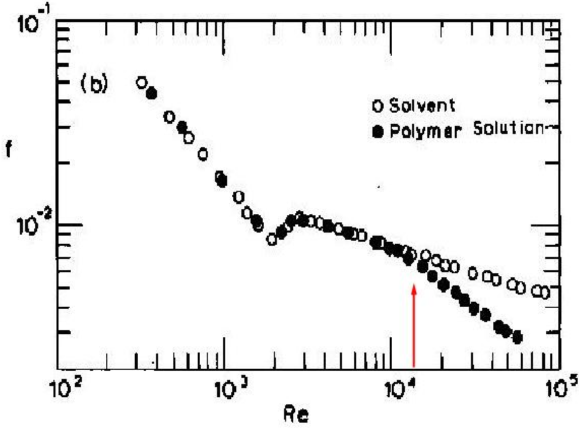
Experimental evidence: friction coefficient (I)

- Basic experiments by Virk (1975) show how the gross features of the flow are modified e.g. *friction coefficient*

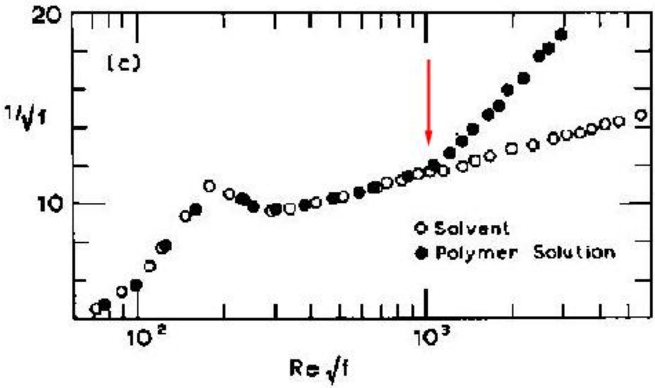
$$f = 2\,\tau_w/(\rho u_b^2)$$



Experimental evidence: friction coefficient (II)

- ▷ The decrease of drag is even more evident in the *Prandtl,Karman* coordinates

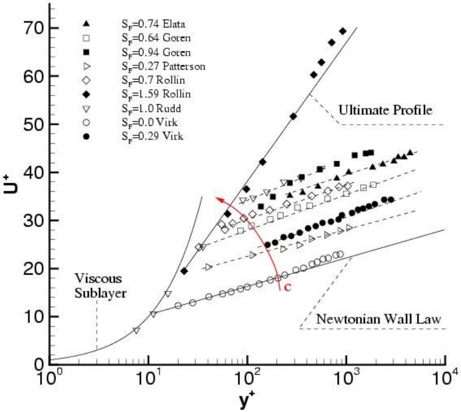
$$1/\sqrt{f} = U_0/u_* \qquad \sqrt{f}\,Re = Re_*$$



- ▷ In both cases it clearly appears an onset for a certain value of Re_* (or Re) i.e. for lower values the polymers have no effect

Experimental evidence: mean velocity profiles

- We report results by Virk (pipe flow), see also Warholic et *al.* (channel flow)



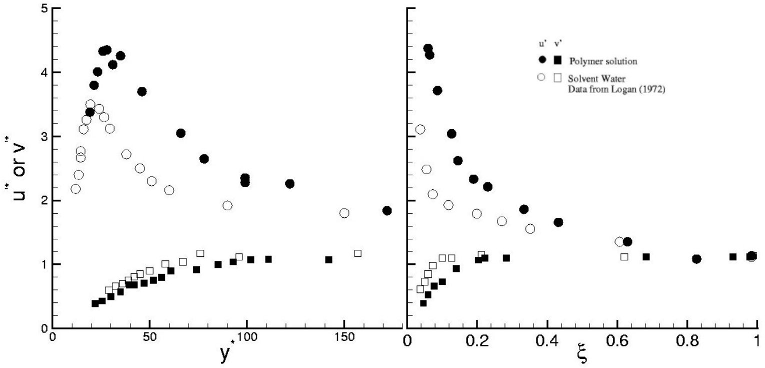
we see clearly the sequence of profiles for increasing concentration

Experimental evidence: mean velocity profiles

- We observe in both sets of experimets
  - a larger throughput for the *same* τ_w and increasing concentration of polymers
  - a logaritmic profile with the same slope but larger intercept: Newtonian plug
    $$u_* = 2.5 \log y^+ + B$$
  - a Maximum Drag Reduction (MDR) limit profile, which has a *universal* slope given by
    $$u_* = 11.7 \log y^+ - 17$$
    strikingly insensitive to polymer species and concentration

Experimental evidence: turbulence intensity

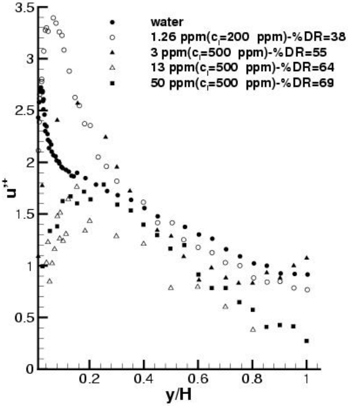
- ▷ The axial turbulence intensity shows a substantial increase for pipe flow (Virk)

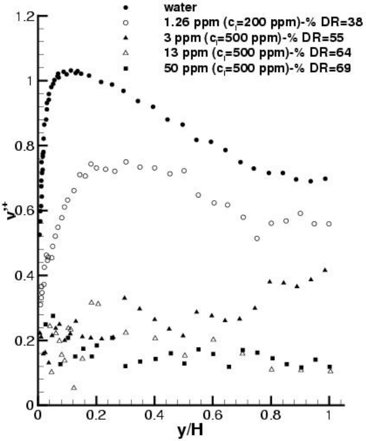


- ▷ On the contrary we observe a depletion of the radial component

Experimental evidence: turbulence intensity

- ▷ Analogous results for channel flow (Warholic et *al.*)





- ▷ We observe a decrease also of streamwise component for the case of larger DR

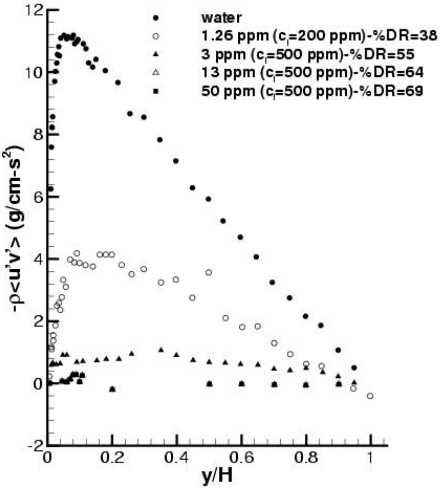
Experimental evidence: the Reynolds stresses

- ▷ In channel flow (Warholic et *al.*) we see a decrease in Reynolds stresses more and more substantial with larger DR

- ▷ The missing part to reach the total stress called *stress deficit* is given by the polymer stress τ_p

$$\tau > \mu \frac{dU}{dy} - \rho \langle u\, v \rangle$$

- ▷ Reynolds stresses become very small (approximately zero) for conditions close to MDR
- ▷ Analogous results in pipe flow (Virk)



Experimental evidence: the onset

- ▷ The *onset of drag reduction* occurs at a rather well defined critical value of the wall shear stress τ_w^c
- ▷ The *onset* is correlated with the random coil size $R_0 \ll \eta$

$$\tau_w^c = u_{*,c}^2 \rho = C R_0^{-3}$$

the critical viscous time

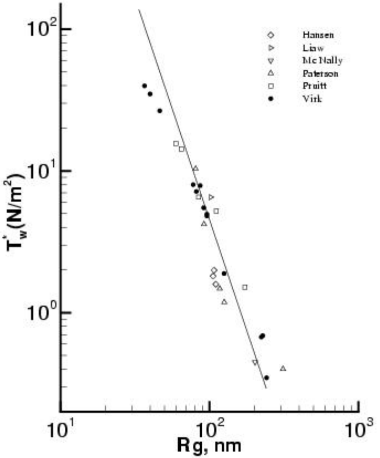
$$t_*^c = \frac{\nu}{u_{*,c}^2} = \frac{\mu}{\tau_w^c} = \frac{\mu}{C} R_0^3$$

the relaxation time (Zimm)

$$t_p = \alpha R_0^3$$

Time criterion (Lumley)

$$t_p \simeq t_*^c$$



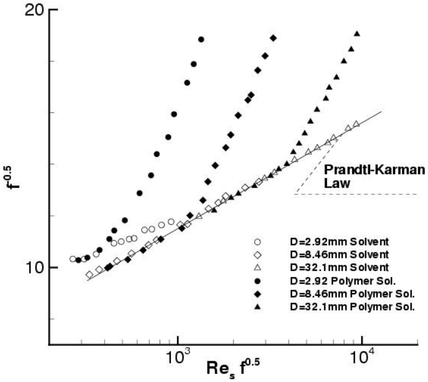
Experimental evidence: the onset

- De_* is the relevant parameter for the *onset*

$$De_*^c = \frac{t_p}{t_*^c} = \frac{\alpha R_0^3}{\mu / c R_0^3} = const.$$

$$Re_*^c = De_*^c \frac{h}{(t_p \nu)^{1/2}}$$

As shown by Virk same ratio of Re_*^c and pipe diameters



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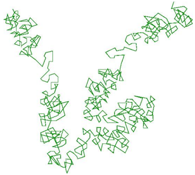
Physical aspects of drag reducing polymers

- Polymers are long linear chains of *monomers*

$$R_c = n\,b$$

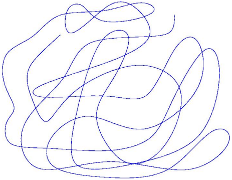
$(\simeq 6000 \quad nm)$



- At equilibrium they are random coils with

$$R_o \propto \left(nb^2\right)^{1/2}$$

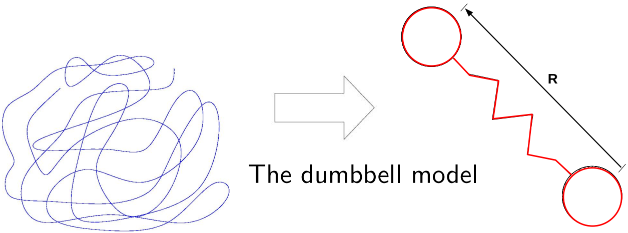
gyration radius
$(\simeq 100 \quad nm)$



- The coil deforms under shear and recovers equilibrium conditions by thermal motion (entropic elasticity)

Physical aspects of drag reducing polymers

- The relaxation to equilibrium is ruled by a spectrum characteristic of times $t_1 > t_2 > \cdots$
- *Only* the principal relaxation time $t_p = t_1$ is relevant for turbulence
- This opens the way for an ultra-simplified description of the polymer, as a system with a single internal degree of freedom: *the elastic dumbbell*



- Zimm relaxation time due to Brownian forcing
  $t_p = \mu_S \, R_o^3 / k_B \theta$

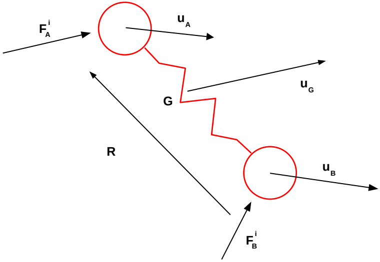
The micro-mechanics of a dumbbell

- Forces acting on the dumbbell
  - Idrodynamic forces on the beads

$$\mathbf{F}_A = f(\mathbf{u}_A - \dot{\mathbf{x}}_A)$$
$$\mathbf{F}_B = f(\mathbf{u}_B - \dot{\mathbf{x}}_B)$$

  - Elastic force

$$\mathbf{F}_{AB} = k(\mathbf{x}_A - \mathbf{x}_B)$$



- The mass of the beads is negligible

$$(\mathbf{u}_A - \mathbf{u}_B) = \nabla \mathbf{u}|_G(\mathbf{x}_A - \mathbf{x}_B) \quad \Rightarrow \quad \dot{\mathbf{R}} = \mathbf{R} \cdot \nabla \mathbf{u} - \frac{1}{t_p}\mathbf{R}$$

with $t_p = f/k$ relaxation time

- To account for the thermal motion a Brownian forcing is added

$$\dot{\mathbf{R}} = \mathbf{R} \cdot \nabla \mathbf{u} - \frac{1}{t_p}(\mathbf{R} - \xi)$$

The polymer stresses

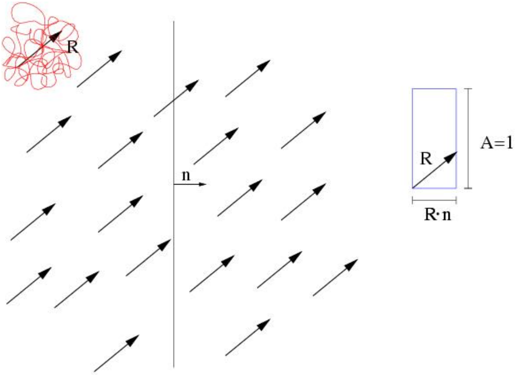
- Given the dumbbel ensemble with *number density* n_p

  - the force through a surface

    $$\mathbf{t} = n_p \langle \mathbf{F}\,\mathbf{R} \rangle \cdot \mathbf{n}$$

    hence

    $$\mathbf{F} = -\frac{3k_B\theta}{nb^2}\mathbf{R}$$



The polymer stresses

- In terms of the conformation tensor $\boldsymbol{\mathcal{R}} = \langle \mathbf{R} \otimes \mathbf{R} \rangle$, the extra-stress is

$$\mathbf{T}_p = \frac{n_p k_B \theta}{R_0^2/3} \langle \boldsymbol{\mathcal{R}} \rangle$$

  where $nb^2 = \langle R^2 \rangle_0 = R_0^2$

- Since at equilibrium condition the extra-stress vanishes

$$\mathbf{T}_p = \frac{\nu_p}{t_p} \left(\frac{\langle \boldsymbol{\mathcal{R}} \rangle}{R_0^2/3} - \mathbf{I} \right)$$

  where t_p is the relaxation time and ν_p is the contribution to viscosity due to polymers (Oldroyd-B)

- For finite extension non linear elasticity (FENE-P)

$$\mathbf{T}_p = \frac{\nu_p}{t_p} \left(f \frac{\langle \boldsymbol{\mathcal{R}} \rangle}{R_0^3/3} - \mathbf{I} \right)$$

  and $f = f(\langle R^2 \rangle)$ in the Peterlin approximation

The equation for the conformation tensor

- From the force balance, by averaging, we obtain the evolution equation for $\mathcal{R}$ in dimensioless form

$$\frac{D\mathcal{R}}{Dt} = \mathcal{R} \cdot \nabla \mathbf{u} - \nabla \mathbf{u}^T \cdot \mathcal{R} - \frac{1}{De^*}(\mathcal{R} - \mathbf{I})$$

- The model is completed by momentum equation for an incompressible flow ($\nabla \cdot \mathbf{u} = 0$), where the extra-stress $\mathbf{T}_p$ is included

$$\frac{D\mathbf{u}}{Dt} = -\nabla p + \frac{1}{Re^*}\nabla^2 \mathbf{u} + \nabla \cdot \mathbf{T}_p$$

with

$$De^* = \frac{\tau_p}{u_*^2/\nu} \quad Re^* = \frac{hu_*}{\nu} \quad \mathbf{T}_p = \frac{\nu_p}{De^*}(\mathcal{R} - \mathbf{I})$$

Energy balance for the polymers

- If we take the trace of the evolution equation for $\mathcal{R}$ we obtain for the elastic energy of the dumbbell population

$$\frac{DE_p}{Dt} = \Pi_p - \epsilon_p$$

where

$$E_p = \frac{\nu_p}{Re^*}\frac{1}{2}Tr(\mathcal{R}) \quad \Pi_p = Tr\left(\mathcal{R}\cdot\nabla\mathbf{u}\right)\frac{\nu_p}{Re^*}$$

$$\epsilon_p = \frac{1}{De^*}\frac{1}{2}Tr(\mathcal{R})\frac{\nu_p}{Re^*} = \frac{E_p}{Re^*}$$

with

Π_p	energy transfer to polymer microstructure
ϵ_p	total (average+fluctuation) dissipation by the polymers

Energy balance for the solvent

- The evolution equation for the total (average + fluctuation) kinetic energy of the carrier fluid is

$$\frac{DE_k}{Dt} = -\nabla\cdot(p\mathbf{u}) + \frac{1}{Re^*}\nabla\cdot\left[\left(\nabla\mathbf{u} + \nabla\mathbf{u}^T\right)\cdot\mathbf{u}\right] - \epsilon_N + \nabla\cdot(\mathbf{T}_p\cdot\mathbf{u}) - \Pi_p$$

  again Π_p is the energy transferd to the polymers

- By combining the two eqs, we obtain the equation for $E_T = E_k + E_p$

$$\frac{DE_T}{Dt} = \nabla\cdot\Phi - \epsilon_T$$

  where $\epsilon_T = \epsilon_N + \epsilon_p$

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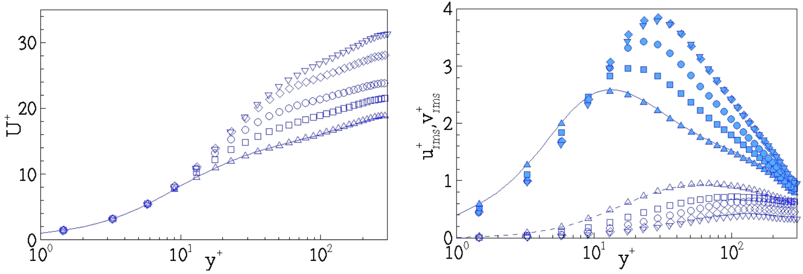
Numerical simulation

- The physical model reproduces the gross features seen in the experiments
  - mean velocity profile
  - Reynolds stresses
  - turbulence intensities
  - various components of the energy balance
  - correlations and the shape of the structures
- The increasing effect of polymers is here explored by increasing values of $De_* = t_p/t_*$

Mean profile and turbulent fluctuations

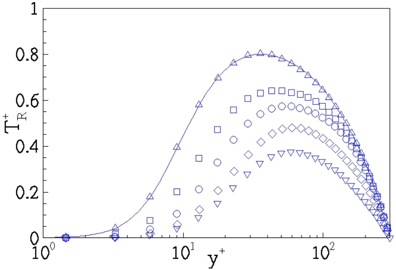
- ▷ A series of Newtoniamn plugs at increasing values of De_*
- ▷ Fluctuations
  - streamwise increase
  - normal to wall decrease

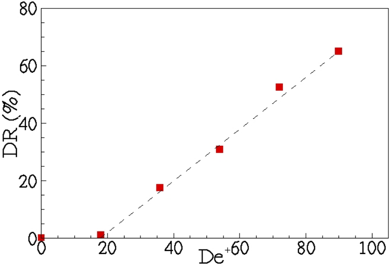


- ▷ Channel flow at $Re_* = 300$

Reynolds stresses & Drag Reduction

- ▷ Reynolds stresses decrease with De_*
- ▷ DR increases, almost linearly, with De_* up to MDR

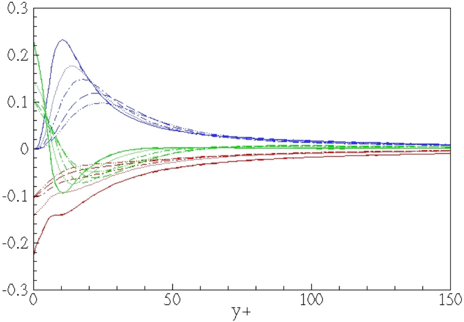




The energy balance (I)

- The T.K.E. shows the spatial redistibution due to inhomogeneity and the turbulence-polymers interaction

$$-\frac{d\Phi}{dy} - \frac{d}{dy}\langle T_p' \cdot u' \rangle - \langle u'\, v' \rangle \frac{dU}{dy} - \langle \epsilon_N \rangle - \langle \pi_p \rangle = 0$$

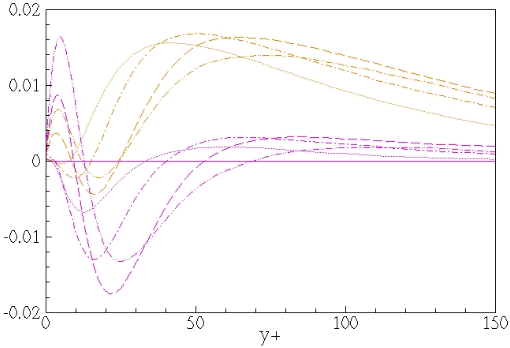


where $\Phi = \left(\frac{1}{2} \langle u'^2 v' \rangle - \frac{\nu}{2} \frac{d\langle u'^2 \rangle}{dy} + \frac{1}{\rho} \frac{d\langle p' v' \rangle}{dy} \right)$ spatial flux

The energy balance (II)

- The T.K.E. shows the spatial redistibution due to inhomogeneity and the turbulence-polymers interaction

$$-\frac{d\Phi}{dy} - \frac{d}{dy}\langle T_p' \cdot u' \rangle - \langle u' \, v' \rangle \frac{dU}{dy} - \langle \epsilon_N \rangle - \langle \pi_p \rangle = 0$$

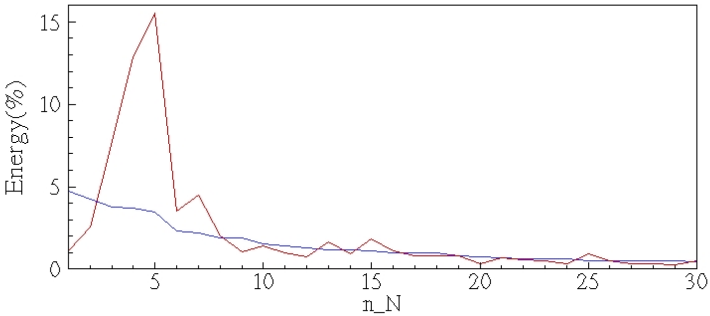


The striking effect on large scales

- DNS gives a good tool to analyze the alteration of turbulence due to polymers
- Polymers drain energy at small scales from the inertial cascade (see results fro isotropic turbulence De Angelis et *al.* 2005)
- However drag reduction is due to their ability to modify the large scales
- Sophisticated data analysis (POD) gives an expansion in terms of empirical, most energetic, modes

The striking effect on large scales

- ▷ The shape of the modes remain quite the same (De Angelis et *al.* 2003) *however* the amplitude change substantially with *De*



- ▷ The largest modes (in terms of scale) become more energetic w.r.t. Newtonian flow. *How it occurs?*

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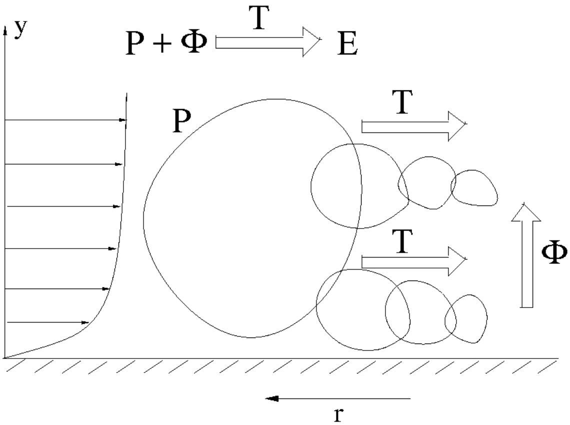
Scale by scale budget: physical picture



- Leads to a combined analysis of energy flux both in physical space (as the T.K.E. in wall turbulence) and in the space of scales (as Kolmogorov eq. for H.I. turbulence)

Scale energy

- To this purpose we consider the second order structure function

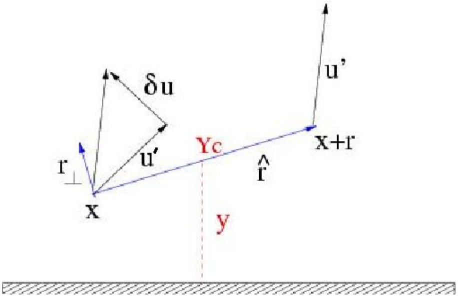
$$\delta \mathbf{u} = \mathbf{u}'(\mathbf{x}+\mathbf{r}) - \mathbf{u}'(\mathbf{x})$$

- energy at scale r

$$\langle \delta u^2(r|Y_c)\rangle = \langle \delta u_i \delta u_i \rangle$$

- at large scale velocities are uncorrelated

$$\lim_{r\to\infty} \langle \delta u^2(r|Y_c)\rangle = 2\langle u_i' u_i' \rangle$$



- We define $f^* = \left[f'(\mathbf{x}+\mathbf{r}) + f'(\mathbf{x}) \right]/2$

Kolmogorov equation

- Starting from the Navier-Sokes eqs. it may be obtained a generalized form of the Kolmogorov equation (See Hill 2001, Yakhot 2001, Danaila et *al.* 2001, Marati et *al.* 2004) which is here extended to polymer solutions
- In homogeneous conditions it reduces to

$$\nabla_r \cdot \langle \delta u^2 \delta \mathbf{u} \rangle = -4\langle \epsilon \rangle + 2\nu \nabla_r^2 \langle \delta u^2 \rangle$$

and in terms of longitudinal stucture functions $\delta u_\parallel = \delta \mathbf{u} \cdot \mathbf{r}/r$ give the well known *Four-fifth* law

$$\langle \delta u_\parallel^3 \rangle = -\frac{4}{5}\langle \epsilon \rangle r$$

which describes the energy cascade across scales in isotropic conditions

A generalized form of the Kolmogorov equation

- Extended to polymers and in conservative form

$$\nabla_r \cdot \Phi_r(r, Y_c) + \frac{d\Phi_s}{dY_c} = s(r, Y_c)$$

whith the flux Φ_r in the space of scales

$$\Phi_r = \frac{1}{4}\left(\langle \delta u^2 \delta \mathbf{u} \rangle - 2\nu \nabla_r \langle \delta u^2 \rangle + \langle \mathbf{T}_p^* \cdot \delta \mathbf{u} \rangle\right),$$

the flux Φ_s in physical space

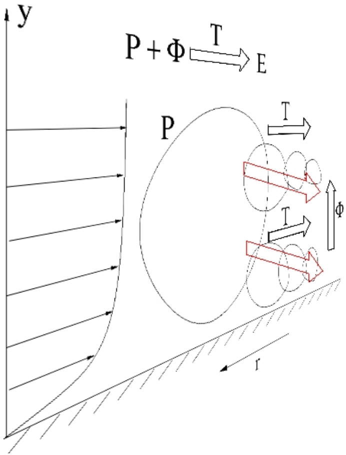
$$\Phi_s = \frac{1}{4}\left(\langle \delta u^2 v^* \rangle + \frac{2}{\rho}\langle \delta p \delta v \rangle - \frac{\nu}{2}\frac{d\langle \delta u^2 \rangle}{dY_c} + \hat{y} \cdot \langle \delta \mathbf{T}_p \cdot \delta \mathbf{u} \rangle\right)$$

and the source term

$$s(r, Y_c) = -\frac{1}{2}\langle \delta u \delta v \rangle \left(\frac{dU}{dY}\right)^* - \langle \epsilon_N^* \rangle - \langle \pi_p^* \rangle$$

- For $r \to \infty$ we recover the single point TKE balance

The physical picture with polymers



- ▷ The scale energy is partly drained by polymers from the energy cascade

Scale by scale analysis of data

- We use for the discussion a coincise form of the $r-$ averaged Kolmogorov equation

$$T_r(r, Y_c) + P_e(r, Y_c) = E_e(r, Y_c) + G_e(r, Y_c) + E_p(r, Y_c)$$

Scale by scale analysis of data

- We use for the discussion a coincise form of the $r-$ averaged Kolmogorov equation

$$T_r(r, Y_c) + P_e(r, Y_c) = E_e(r, Y_c) + G_e(r, Y_c) + E_p(r, Y_c)$$

where the inertial transfer is

$$T_r(r, Y_c) = \frac{1}{4}\nabla_r \cdot \langle \delta u^2 \, \delta \mathbf{u} \rangle$$

Scale by scale analysis of data

- We use for the discussion a coincise form of the $r-$ averaged Kolmogorov equation

$$T_r(r, Y_c) + P_e(r, Y_c) = E_e(r, Y_c) + G_e(r, Y_c) + E_p(r, Y_c)$$

the effective production is

$$P_e(r, Y_c) = \frac{1}{2}\left[\langle \delta u \, \delta v \rangle \left(\frac{dU}{dy}\right)^* + \frac{1}{2}\frac{d\langle \delta u^2 \, v^* \rangle}{dy} + \frac{1}{\rho}\frac{d\langle \delta p \, \delta v \rangle}{dy}\right]$$

Scale by scale analysis of data

- We use for the discussion a coincise form of the $r-$ averaged Kolmogorov equation

$$T_r(r, Y_c) + P_e(r, Y_c) = E_e(r, Y_c) + G_e(r, Y_c) + E_p(r, Y_c)$$

the scale energy flux due to polymers

$$G_e(r, Y_c) = \left[\nabla_r \cdot \langle \mathbf{T}_p^* \cdot \delta \mathbf{u} \rangle + \frac{1}{4} \frac{d}{dy} \left(\hat{y} \cdot \langle \delta \mathbf{T}_p \cdot \delta \mathbf{u} \rangle \right) \right]$$

Scale by scale analysis of data

- We use for the discussion a coincise form of the $r-$ averaged Kolmogorov equation

$$T_r(r, Y_c) + P_e(r, Y_c) = E_e(r, Y_c) + G_e(r, Y_c) + E_p(r, Y_c)$$

the effective dissipation due to viscosity

$$E_e(r, Y_c) = \frac{\nu}{2}\left(\nabla_r^2 \langle \delta u^2 \rangle + \frac{1}{4}\frac{d^2}{dY_c^2}\langle \delta u^2 \rangle\right) - \langle \epsilon_N^* \rangle$$

Scale by scale analysis of data

- We use for the discussion a coincise form of the $r-$ averaged Kolmogorov equation

$$T_r(r, Y_c) + P_e(r, Y_c) = E_e(r, Y_c) + G_e(r, Y_c) + E_p(r, Y_c)$$

the energy drained by polymers and eventually dissipated

$$E_p(r, Y_c) = -\langle \pi_p^* \rangle$$

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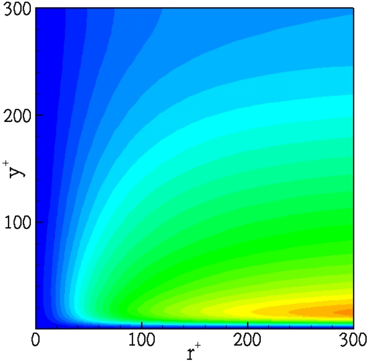
Polymers & the alteration of turbulence: scale energy

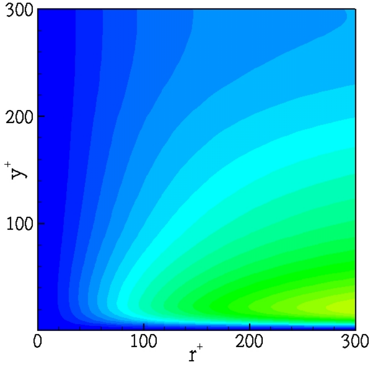
- ▷ Scale energy in the plane $x - z$ as function of wall normal distance and separation



- ▷ The maximum of scale energy moves towards large scales, i.e. the coherent structures grow with De_* up to MDR

Polymers & the alteration of turbulence: scale energy

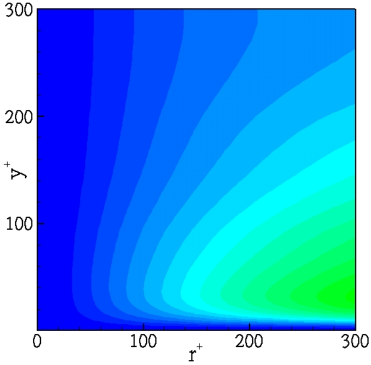
- Scale energy in the plane $x - z$ as function of wall normal distance and separation



- The maximum of scale energy moves towards large scales, i.e. the coherent structures grow with De_* up to MDR

Polymers & the alteration of turbulence: scale energy

- Scale energy in the plane $x - z$ as function of wall normal distance and separation



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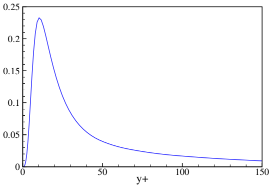
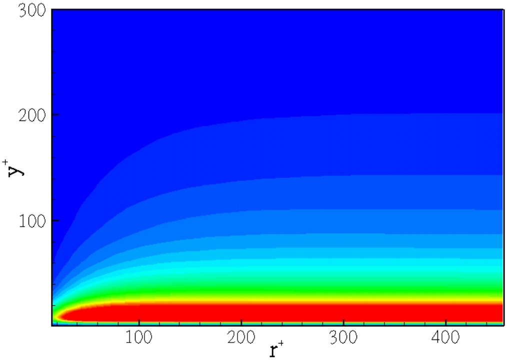
Polymers & the alteration of turbulence

- ▷ Effective production in the plane $x - z$

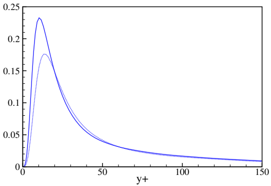


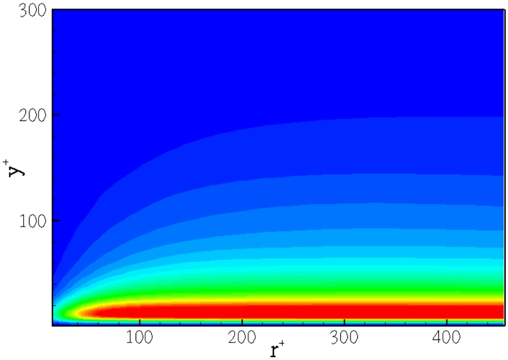


- ▷ The maximum of production decreases, becomes thicker in y and moves towards larger scales

Polymers & the alteration of turbulence

- ▷ Effective production in the plane $x - z$





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Polymers & the alteration of turbulence

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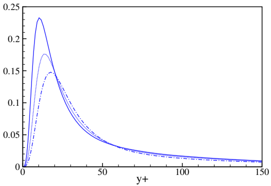

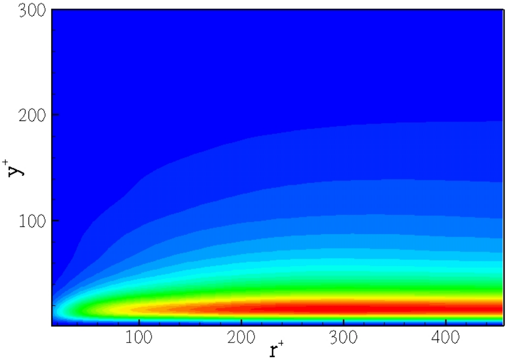

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Polymers & the alteration of turbulence

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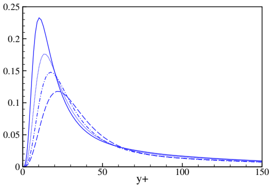

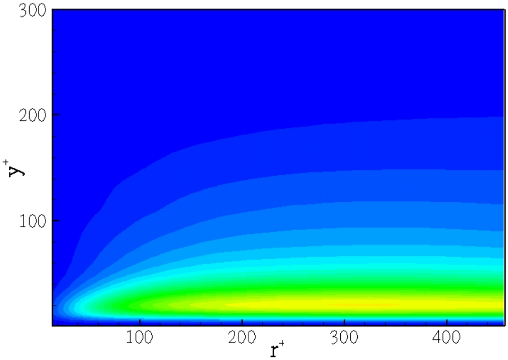

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Polymers & the alteration of turbulence

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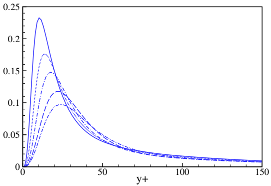

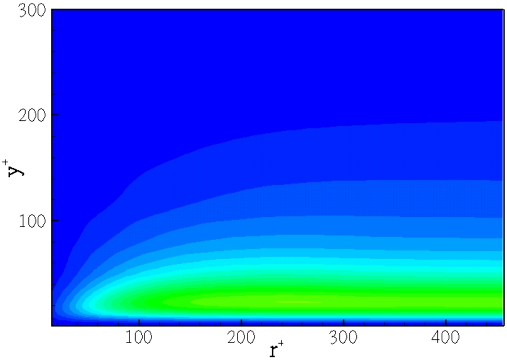

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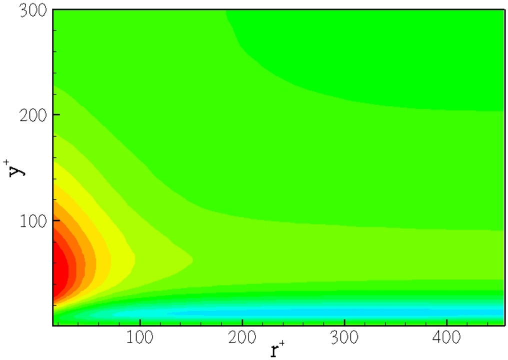
Polymers & the alteration of turbulence

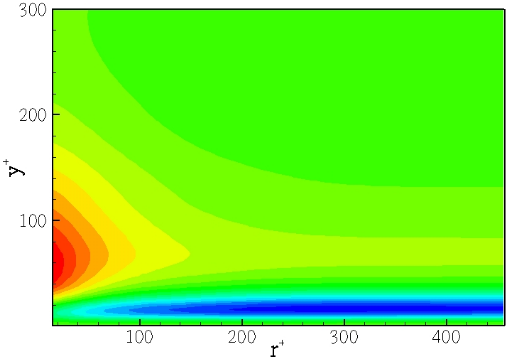
- ▷ Energy drained by the polymers in the plane $x - z$



- ▷ In the elastic layer (blue) the polymers force the large scales. In the Newtonian plug a draining of energy by polymers at small scales (red) is prevailing as in H.I. turbulence (De Angelis et *al.* 2004)

Polymers & the alteration of turbulence

- Energy drained by the polymers in the plane $x - z$



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Polymers & the alteration of turbulence

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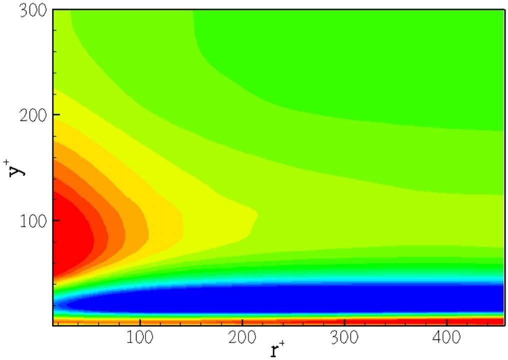

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Polymers & the alteration of turbulence

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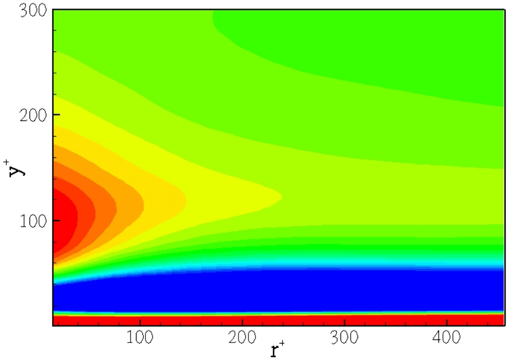

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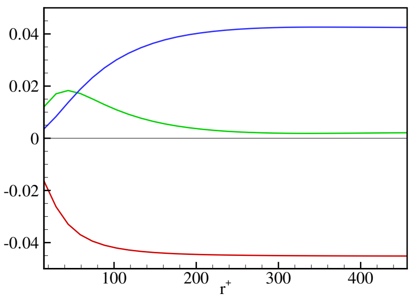
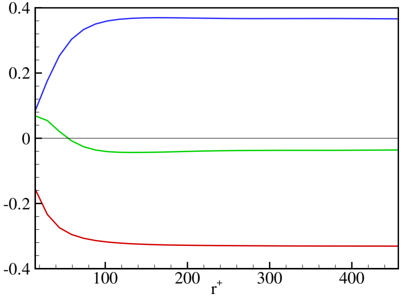
Scale budget for Newtonian flows



Log-layer direct cascade as H.I.

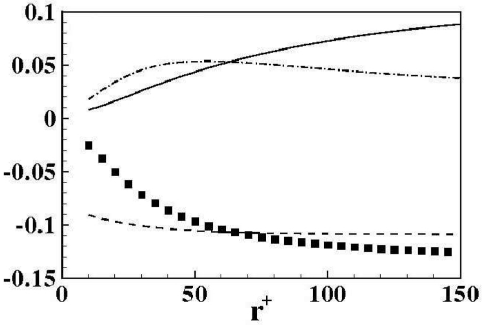


Buffer layer inverse cascade

- - Production
- - Inertial transfer
- - Viscous diffusion & dissipation

(Marati et *al.* 2004)

Production vs inertial transfer

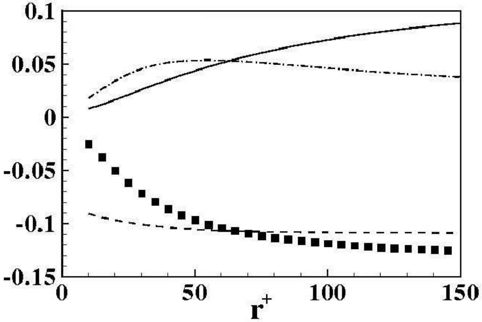


Production (solid) and Inertial transfer (dash-dotted)

ZPG Boundary layer $Re_\tau = 1100$, $y^+ = 100$

$$\mathbf{r} = (r_x, 0, r_z) \; r = \sqrt{r_x^2 + r_y^2}$$

Experiments, dual plane stereo PIV



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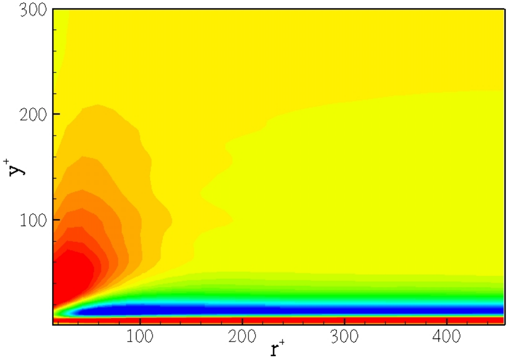
N.Saikrishnan, E.K. Longmire, I. Marusic

Polymers & the alteration of turbulence

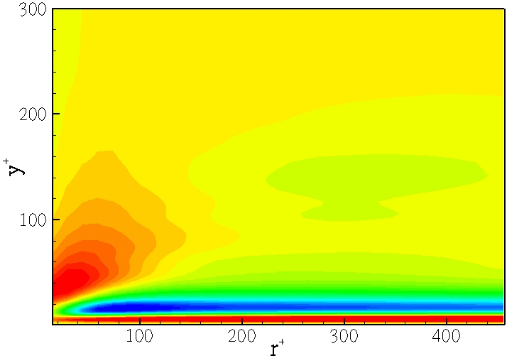
- Inertial transfer in the plane $x - z$



- we see a region (red) where a direct cascade is taking place and a region (blue) growing with De_* where an inverse cascade sets in

Polymers & the alteration of turbulence

- Inertial transfer in the plane $x - z$



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Polymers & the alteration of turbulence

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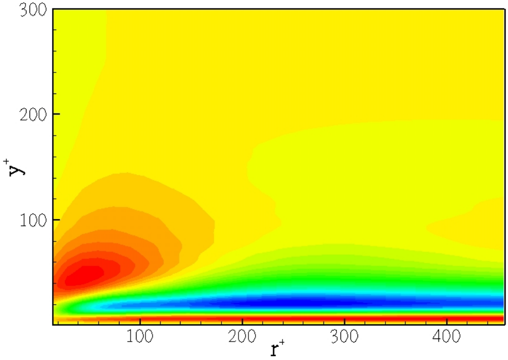

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Polymers & the alteration of turbulence

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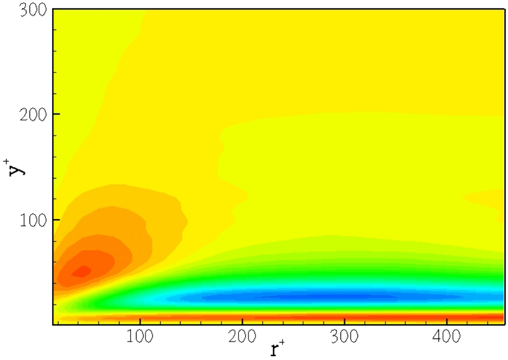

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Polymers & the alteration of turbulence

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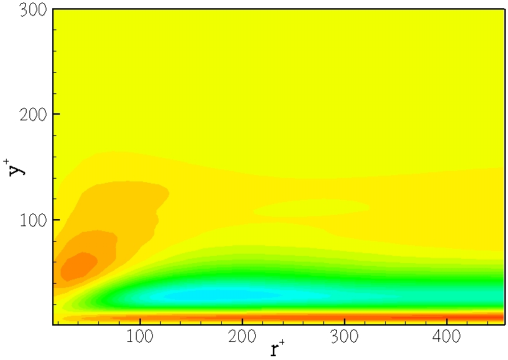

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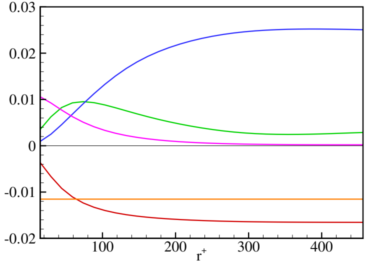
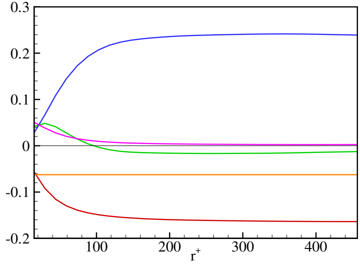
Final Remarks



Log layer



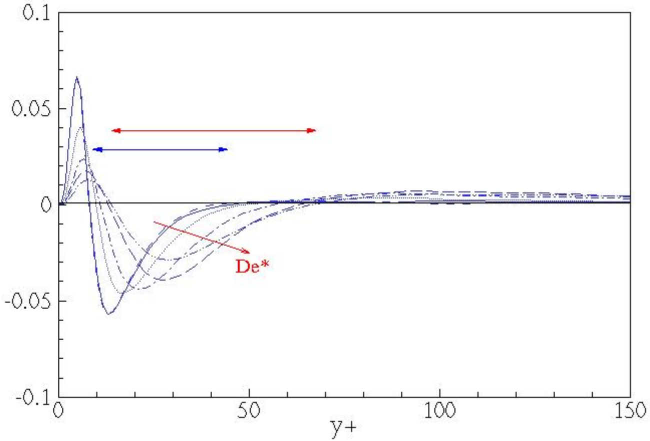
Buffer layer

- ● - Effective production
- ● - Inertial transfer
- ● - Polymer transfer
- ● - Polymer dissipation
- ● - Effective Newtonian dissipation

— In the log-layer polymers interact mainly with inertial transfer (as in H.I. turbulence)

— In the buffer layer polymers interact directly with the production

Final Remarks



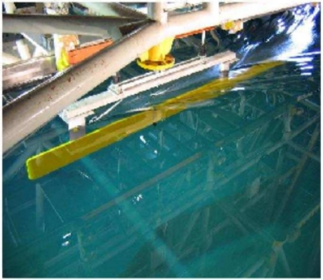
Inertial transfer in TKE equation

- ▷ The inverse cascade region grows in size and the maximum moves away from the wall, i.e. the buffer region, here more properly elastic layer, enlarges

Bubbly turbulent flows

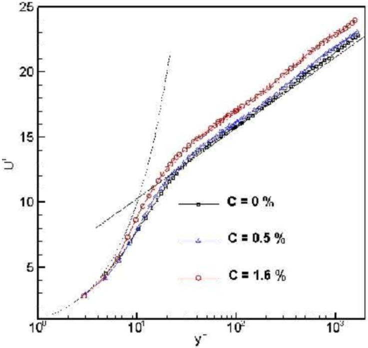
Flat Plate

- L=7 m, W =0.8 m, H= 0.06 m
- $U_\infty = 0.5 \div 2$ m/s



Experimental set-up (INSEAN, Roma)

The effect of bubbles



Mean velocity profile in the ZPG boundary layer

Thanks to

- my coworkers in Rome
  R. Piva, E. De Angelis, P. Gualtieri, B. Jacob, F. Picano, N. Marati
  &
  N. Saikrishnan, E. Longmire (Minnesota University), I. Marusic (Melbourne University) for dual plane Stereo PIV experiments
- INSEAN for providing data on bubbly flows
- CASPUR for assistance in optimizing codes and for providing the appropriate computational facilities.