What **can** polymer drag reducing flows **tell** us about the mechanisms of wall-flow transport?

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High Reynolds Number Boundary Layer Turbulence: Integrating Descriptions of Statistical Structure, Scaling and Dynamical Evolution
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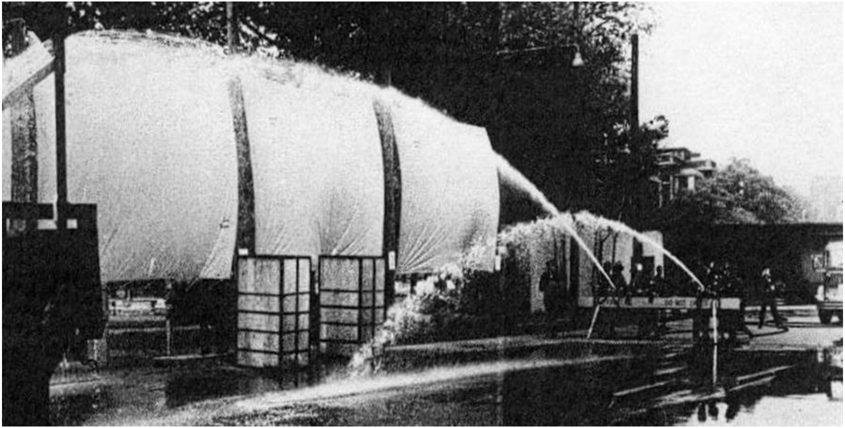
Brief Description of Polymer Drag Reduction Research

- Phenomenon: Dissolving parts-per-million quantities of long-chain flexible polymers into solution can reduce turbulent friction losses by as much as 70% compared with that of the solvent alone.
- Researchers study polymer drag reduction for both practical and fundamental purposes.
- Recent activity has led to an improved understanding of the underlying mechanisms at work. *This has been the primary focus of most recent activity.*
- Studying the effects of polymers on the turbulence provides valuable insight into the physics of fluid turbulence, particularly the self-sustaining mechanisms of wall turbulence. *Potential opportunities will be the topic of this talk.*

Wow Factor of Polymers



Underlying Mechanisms at Work[1,2]

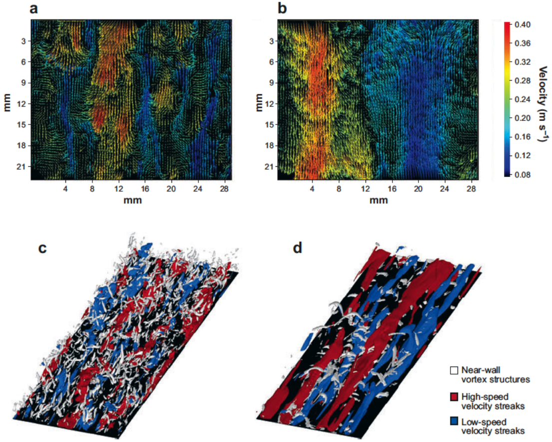
i. Polymers are strongly stretched in upwash and downwash flow generated by near-wall quasi-streamwise vortices.
ii. The strongly stretched polymers increases the local (extensional) viscosity of the fluid.
iii. The increased viscosity creates a negative torque on the vortices.
iv. The negative torque weakens the vortices.

Consequently, the dampening of the near-wall vortices modifies the bulk flow and underlying turbulence resulting in:

- reduced wall shear stress,
- increased mean velocity (for a given pressure gradient),
- strong attenuation of the Reynolds shear stress, and
- peak turbulent activity pushed further from the wall.

[1] Dubief *et al.* 2004. J. Fluid Mech. 514, 271–280. [2] Kim *et al.* 2007. Fluid Mech. 584, 281–299.

Polymers Strongly Modify the Turbulent Flow Structure[3]



(a) and (c) Newtonian (b) and (d) Polymer DR $\approx$ 60%

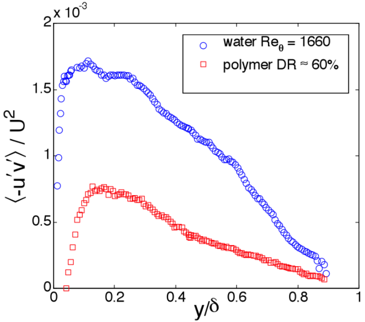
Observations with DR

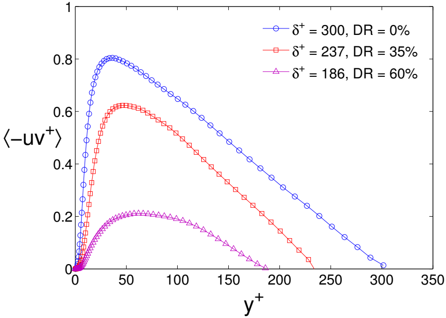
- spanwise streak spacing increases
- streamwise extent of streaks increases
- number and strength of near-wall vortices decreases

[3] White & Mungal. Ann. Rev. Fluid Mech. 2008. 40:235–256.

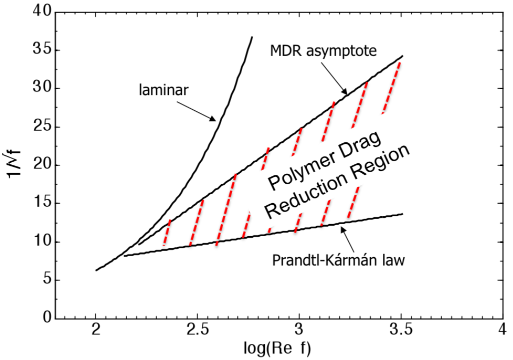
Polymers Strongly Modify the Turbulent Flow Statistics

- **Left:** - Experimental polymer data
- **Right:** - Numerical polymer data





Can Polymer DR flow be viewed and exploited as a "stable" transitional flow to provide insight into transition and other drag reducing strategies?

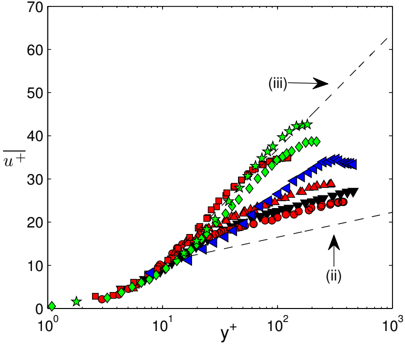


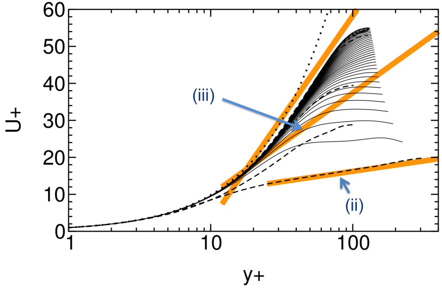
Justification

- Polymer DR region lies between laminar and turbulent flow regions.
- At a given DR, the flow is statistically steady.
- DR flow statistics closely resemble transitional Newtonian flow statistics.

Polymer DR and Transitional Newtonian Mean Profiles

- **Left:** - Experimental polymer data (see [4] White *et al.* 2012. Phys. Fluids. 24:021701.)
- **Right:** - Newtonian bypass transition ([5] Wu & Moin. 2009. J. Fluid Mech. 630, 5-41.)

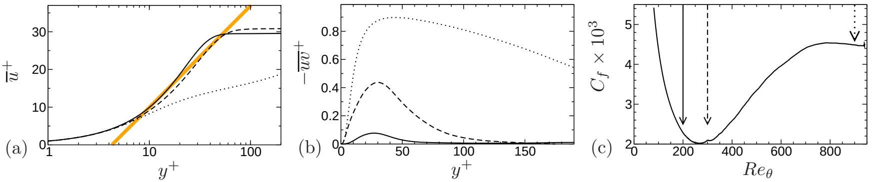




(ii) u^+=2.5 ln y^++5, and (iii) u^+=11.7 ln y^+-17

Note that (iii) is the so-called "ultimate profile" corresponding to MDR.

MDR-like flow statistics for Newtonian transition.



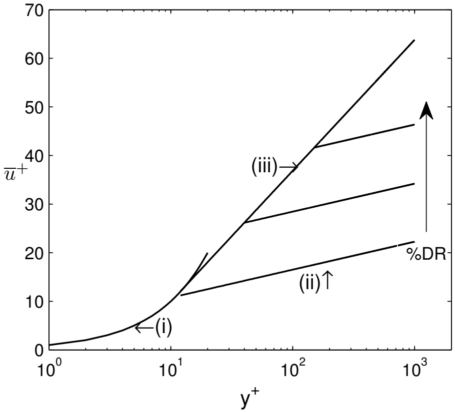
u^+=11.7 ln y^+-17 ———— , $Re_\theta = 200$ ——— , $Re_\theta = 300$ – – – – , and $Re_\theta = 900$ ········ (fully turbulent flow)

- MDR like-profile falls between $Re_\theta = 200$ and $Re_\theta = 300$ profiles.
- Reynolds shear-stress profiles are also similar (polymer DR case not shown).
- $Re_\theta = 200$ and $Re_\theta = 300$ brackets the minimum in C_f.
- Polymer DR-like statistics occur in the non-linear development state of transition ($250 \le Re_\theta \le 900$).

Observations and Potential Areas to Explore

- Flow statistics of polymer DR flow closely resemble flow statistics of Newtonian bypass transitional flow.
  $\rightarrow$ Explore to gain an improved understanding of the non-linear development state of transition.
- Polymers affect the underlying turbulence (near-wall vortices and streaks) such that a "transitional" flow state is statistically stable.
  $\rightarrow$ Explore to understand the potential stabilization of transitional flow (or conversely the destabilization).
  $\rightarrow$ Explore to understand and improve other drag reducing strategies, in particular the Re dependence of the stabilization.
- Polymers DR flows may be more amendable than fully turbulent flows to Exact Coherent State (ECS) type analysis.

Effect of Polymers on the Inertial Layer: Long-held view[6] — polymers do not affect the von Kármán coefficient.



(i) $u^+ = y^+$, (ii) u^+=2.5 ln y^++5, and (iii) u^+=11.7 ln y^+-17

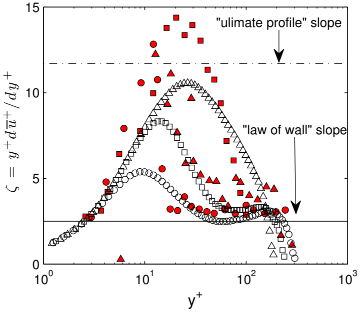
Primary characteristics

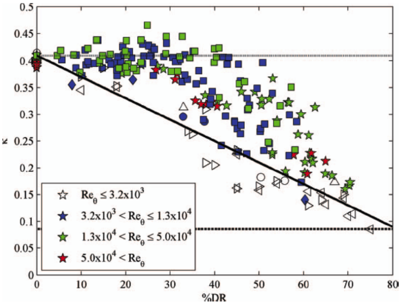
- At zero DR, profile goes (i) → (ii)
- At maximum DR, the profile goes (i) → (iii), where (iii) is the "ultimate profile".
- At intermediate DR, the profile goes (i) → (iii) → vertically shifted (ii), i.e., the log-layer is parallel to (ii) with a y-intercept that increases with increasing DR.

[6] Virk J. Am. Inst. Chem. Eng. 21 (4), 625656.

Recent View: Polymers modify the von Kármán coefficient (at HDR) and the “ultimate profile” corresponding to MDR is not logarithmic[4,7]

Can the fact that polymers modify the von Kármán coefficient be exploited to better understand the formation and dynamics of the inertial layer?





[4] White *et al.* 2012. Phys. Fluids. 24:021701. [7] Elbing *et al.* 2013. Phys. Fluids. 25, 085103.

One Investigative Approach: Mean Momentum (MMB) Analysis[8,9]

- Mean momentum equation based analysis (i.e., MMB analysis) of turbulent wall flows shows that the slope and curvature of the Reynolds stress profile underlie logarithmic-like behavior of the mean velocity.
- The Reynolds stress profile is strongly modified in polymer drag reduced (DR) flow.
- It follows that the MMB analysis of polymer DR flow may reveal further insights into the formation and dynamics of the inertial layer.

[8] Wei *et al.* 2005. J. Fluid Mech. 522, 303. [9] Klewicki *et al.* 2009. J. Fluid Mech. 638, 73.

Describing the Mean Dynamics of Polymeric Turbulence

The inner-normalized RANS equation for a statistically-steady, fully developed channel flow of polymer solution is

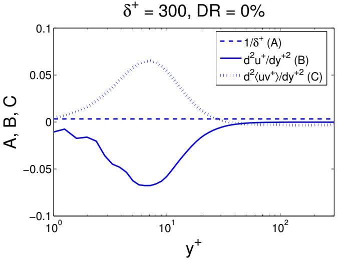
$$0 = \underbrace{\frac{1}{\delta^+}}_{A} + \underbrace{\frac{d^2 U^+}{dy^{+2}}}_{B} - \underbrace{\frac{d\langle uv\rangle^+}{dy^+}}_{C} + \underbrace{\frac{d\langle \tau_p\rangle^+}{dy^+}}_{D}, \quad (1)$$

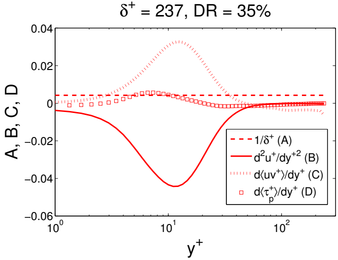
where τ_p is the polymer shear stress, caused by stretching of the polymers by the flow.

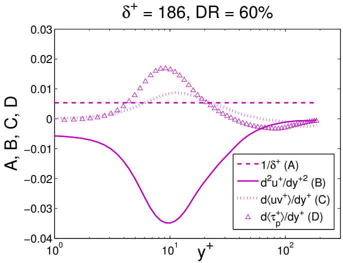
MMB Analysis

The starting point of the analysis is to determine the relative magnitude of terms in Eq. 1 over $0 \leq y \leq \delta$.

Stress Gradients (using DNS data of [1] Dubief *et al.* 2004. J. Fluid Mech. 514, 271–280.)

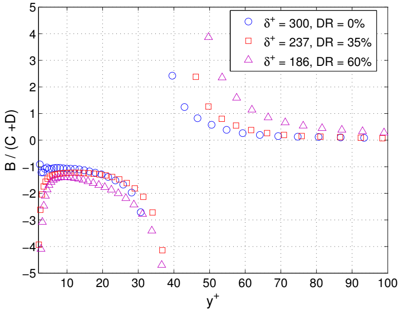


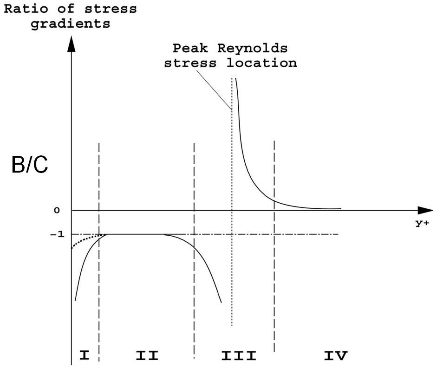




- At DR $= 0\%$, the peak in the viscous stress gradient and the peak in the Reynolds stress gradient occur at $y^+ \approx 7$
- With DR, the peak in the viscous stress gradient and Reynolds stress gradient move outward from the wall.
- Observe a dual role of polymer: (i) reduce the wall shear stress (i.e., drag reduction), (ii) "relieve" the Reynolds stress gradient of its duty in the MMB.

Four Layer Structure in Polymer DR Channel Flow

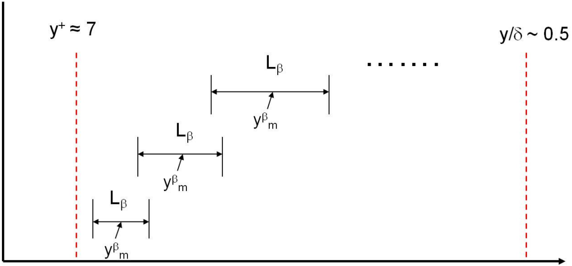




Layer Structure

- We have used $C + D$ since they serve the same role in the MMB.
- A four-layer structure is maintained.
- Across the stress-gradient balance layer ($|B| > |C + D|$).

MMB Admits A Layer Hierarchy



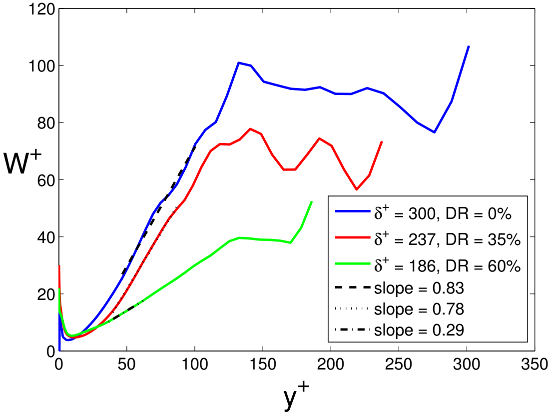
y^{β} is the outcome of a re-scaling that leads to a parameter-free invariant MMB equation on each layer of the hierarchy. The subscript m denotes a local maxima in the re-scaled Reynolds stress function.

- The width distribution of the hierarchy layers behave like

$$W(y^+) = \mathcal{O}\left(\frac{d\langle uv\rangle^+}{dy^+} + \frac{1}{\delta^+}\right)^{-1/2} = \mathcal{O}\left(\frac{d^2U^+}{dy^{+2}}\right)^{-1/2} \tag{2}$$

- W is an asymptotically linear function on the hierarchy
- The slope of W is related to the von Kármán "constant".

Linear Behavior of W in Polymer DR channel flow

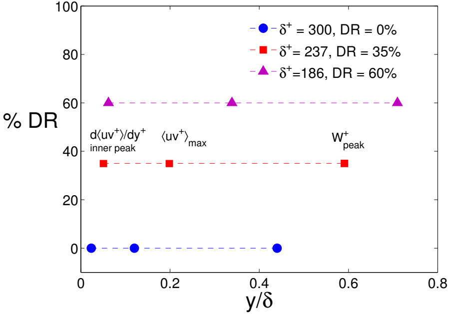


$$W(y^+) = \mathcal{O}\left(\frac{d^2U^+}{dy^{+2}}\right)^{-1/2} \quad (3)$$

Layer Structure

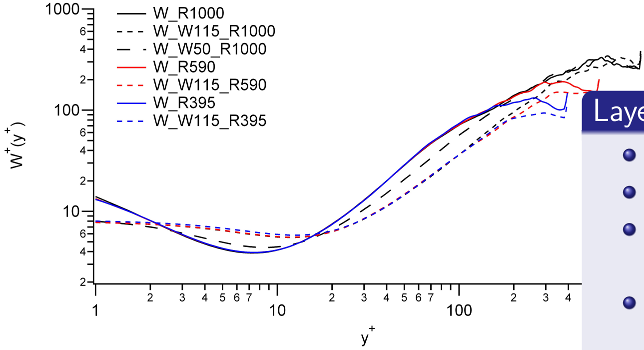
- The linear behavior of **W** suggests new self-similar hierarchies as the turbulence adjusts to the new force-like quantity in the MMB.
- However, the lack of a log layer in the mean velocity suggests that the hierarchies may not be exactly self-similar.
- Difficulty with interpretation is (a) low Re (b) decreasing Re with DR.

Physical Extent of the Hierarchy



- Hierarchy spans $(-d\langle uv^+\rangle/dy^+_{inner-peak}) \lessapprox \mathbf{y} \lessapprox W_{max}$
- For Newtonian fluids, hierarchy spans $(y^+ \approx 7) \lessapprox \mathbf{y} \lessapprox (y/\delta \approx 0.5)$
- For polymer DR flows, hierarchy starts further from the wall but spans a wider range of length scale, with the range increasing for increasing DR.
- Conjecture that the motions on the modified hierarchy are still self-similar (at least at lower DR) but start at a larger size, and thus span a broader fraction of the flow.

Preliminary Results from Higher Re DR channel flow[10]



$$W(y^+) = \mathcal{O}\left(\frac{d^2U^+}{dy^{+2}}\right)^{-1/2} \quad (4)$$

Layer Structure

- W50 → DR ≈ 30%.
- W115 → DR ≈ 55%.
- Hierarchy starts/ends further from wall.
- Smaller change in slope compared to low DR simulations.

[10] Thais *et al.* 2012 J. Turbulence 13:1-26.

Concluding Observations

- Polymer drag reduced channel flow admits a four-layer structure.
- **W** exhibits linear behavior for polymer flow suggesting a layer hierarchy, but a change in the slope of W suggests different dynamics on the hierarchy.
- For polymer DR flows, hierarchy starts further from the wall but spans a wider range of length scale, with the range increasing for increasing DR. This modifies the inertial layer dynamics
- At some high value of DR, the self similarity of the hierarchy breaks down and the inertial layer is obliterated.

Data Sets Analyzed

Study/Symbol (channel)	polymer	%DR
†Escudier *et al.*[1](●)	XG	42
†Escudier *et al.*[1](▲)	XG	59
†Escudier *et al.* [1](■)	XG	67
Ptanski *et al.*[2](♦)	PAM	63
Ptanski *et al.*[2](★)	PAM	65
Den Toonder *et al.*[3](▼)	PAM	24
Warholic *et al.*[4](◀)	PAM	55
†Dubief *et al.*[5](○)	NA	0
†Dubief *et al.*[5](△)	FENE-P	35
†Dubief *et al.* [5](□)	FENE-P	60

Study/Symbol (TBL)	polymer	%DR
†Hou *et al.*[6](♦)	NA	0
†Hou *et al.*[6](▼)	PEO	34
†Tamano *et al.*[7](◊)	NA	0
†Tamano *et al.*[7](▽)	Oldroyd-B	34

Experimental data (closed symbols); DNS data (open symbols)

† data provided by authors otherwise digitally extracted

1. M. Escudier, F. Presti, and S. Smith, Drag reduction in the turbulent pipe flow of polymers." J. Non-Newtonian Fluid Mech., 81, 197:213 (1999).
2. P. K. Ptasinski, F. T. M. Nieuwstadt, B. H. A. A. V. D. Brule, and M. A. Hulsen, Experiments in turbulent pipe flow with polymer additives at maximum drag reduction." Flow, Turbulence and Combustion, 66, 159 182 (2001).
3. J. M. J. Den Toonder, M. A. Hulsen, G. D. C. Kuiken, and F. T. M. Niewstadt, Drag reduction by polymer additives in a turbulent pipe flow: numerical and laboratory experiments." J. Fluid Mech., 337, 193:231 (1997)
4. M. D. Warholic, H. Massah, and T. J. Hanratty, Infuence of drag-reducing polymers on turbulence: effects of reynolds number, concentration and mixing." Exp. Fluids, 27, 461:472 (1999)
5. Y. Dubief, C. M. White, V. E. Terrapon, E. S. G. Shaqfeh, P. Moin, and S. K. Lele, On the coherent drag-reducing turbulence-enhanching behaviour of polymers in wall flows." J. Fluid Mech., 514, 271 280 (2004).
6. Y. Hou, V. S. R. Somandepalli, and M. G. Mungal, Streamwise development of turbulent boundary layer drag reduction with polymer injection." J. Fluid Mech., 597 (2008).
7. S. Tamano, M. Itoh, K. Hoshizaki, and K. Yokota, numerical simulation of the drag-reducing turbulent boundary layer of viscoelastic fluid," Phys. Fluids, 19, 075106 (2007).