Turbulent Boundary Layer Drag Reduction with Polymer Injection

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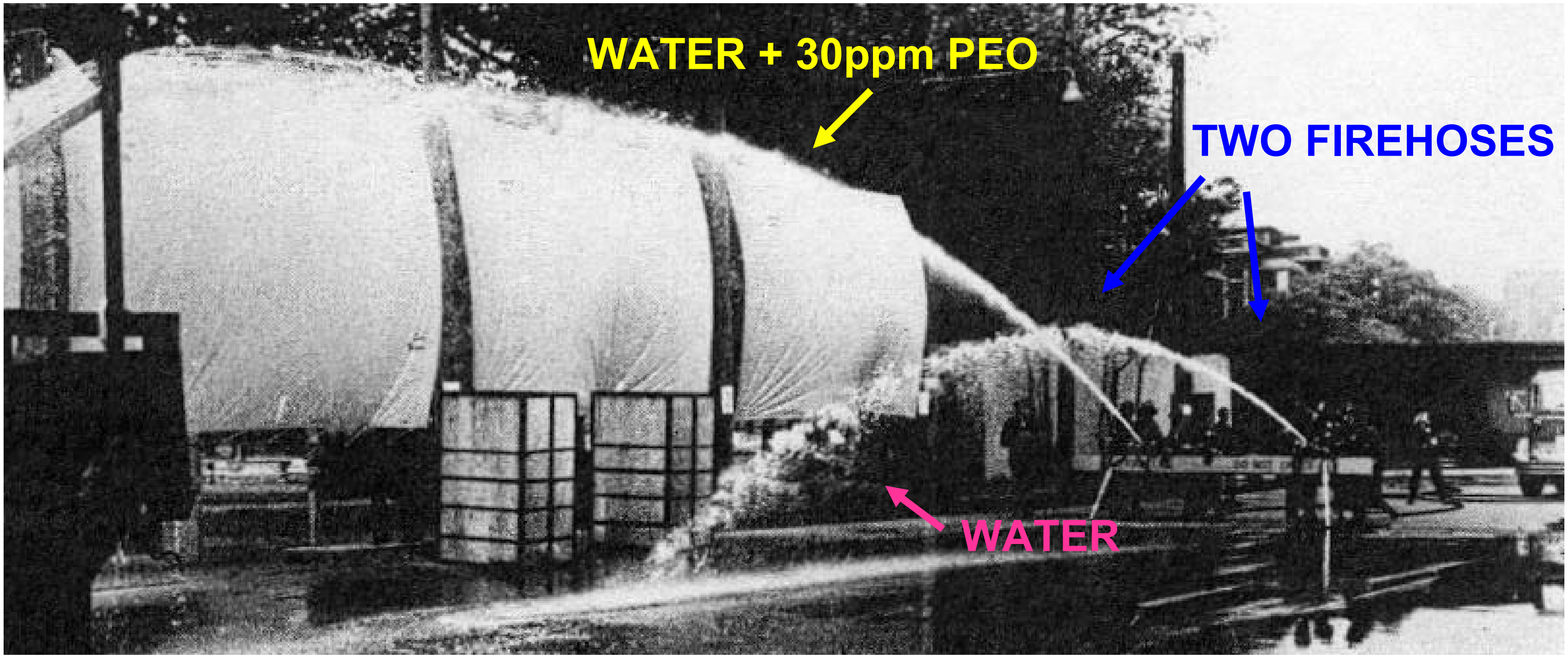
Drag Reduction by Polymer Additives

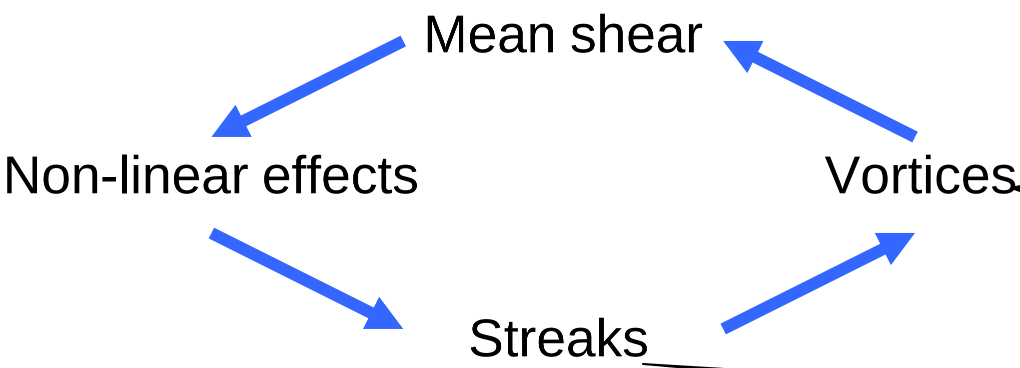
Addition of few ppm of a high molecular weight polymer to a turbulent flow can result in large (up to 80%) reduction of skin friction drag (Toms effect, 1949)

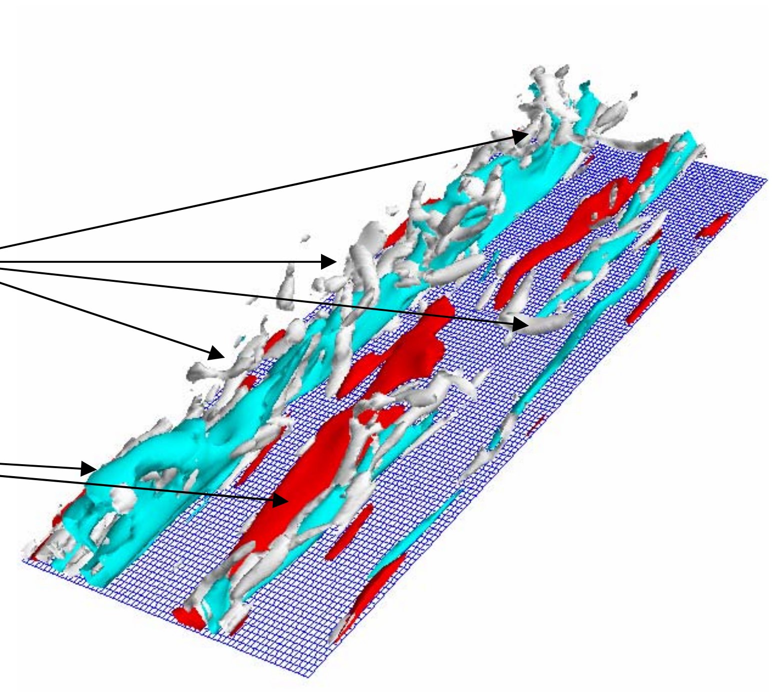


(Bailey F.E. & Koleske J.V., 1973)

Near-wall turbulence and drag reduction

Origin and self sustenance of near wall turbulence





Autonomous generation cycle of near-wall turbulence (Jimenez & Pinelli, 1999)

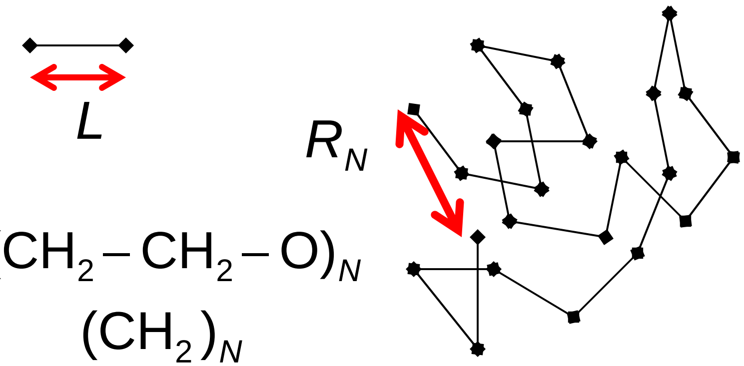
A turbulent flow experiences up to 10 times the drag of a laminar flow at the same Reynolds number

Reduction of this friction drag, if possible, can lead to huge savings!

Flow – polymer interaction

High molecular weight long chain polymers

one monomer repeated N times = polymer



$(CH_2-CH_2-O)_N$

$(CH_2)_N$

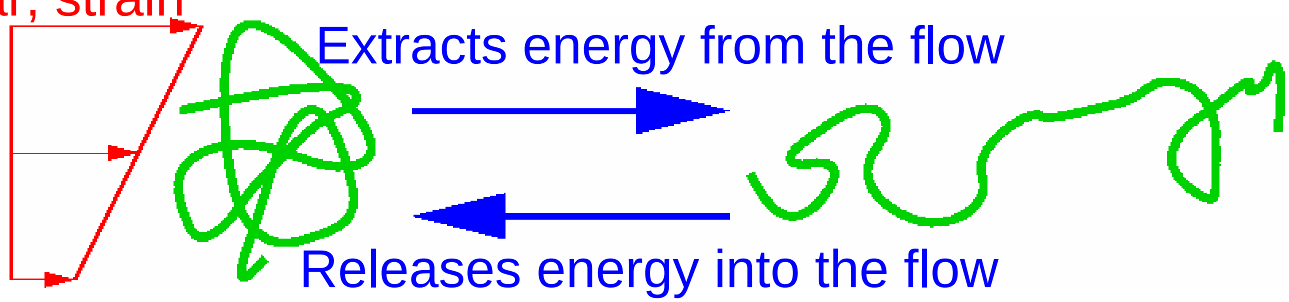
Ideal chain (random walk): $\langle R_N{}^2 \rangle^{1/2} = N^{1/2} L$

Real chain (self - avoidance): $\langle R_N{}^2 \rangle^{1/2} \propto N^{3/5}$

Typically, $N \approx 10^6$ and $R_N \approx 100\,\text{nm}$

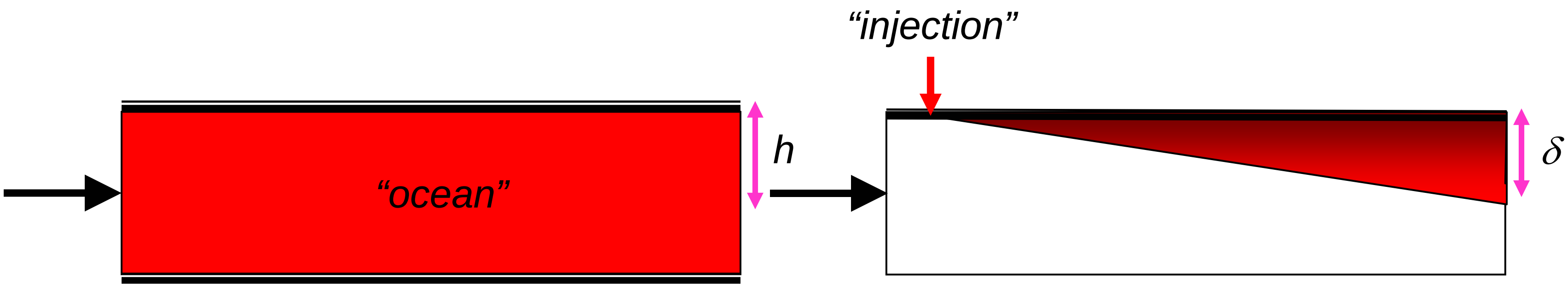
N: No. of monomers, R_N: Radius of gyration

Dynamics of a polymer in a flow



Drag reduction due to polymers

Past work mainly on <u>homogeneous</u> channel flow – not realistic for BLs
Present work on <u>inhomogeneous</u> concentrations of polymers in boundary layers



Channel flow with homogeneous polymer concentrations
Single point – Statistics only

Some injection experiments (Tiederman, Hanratty)

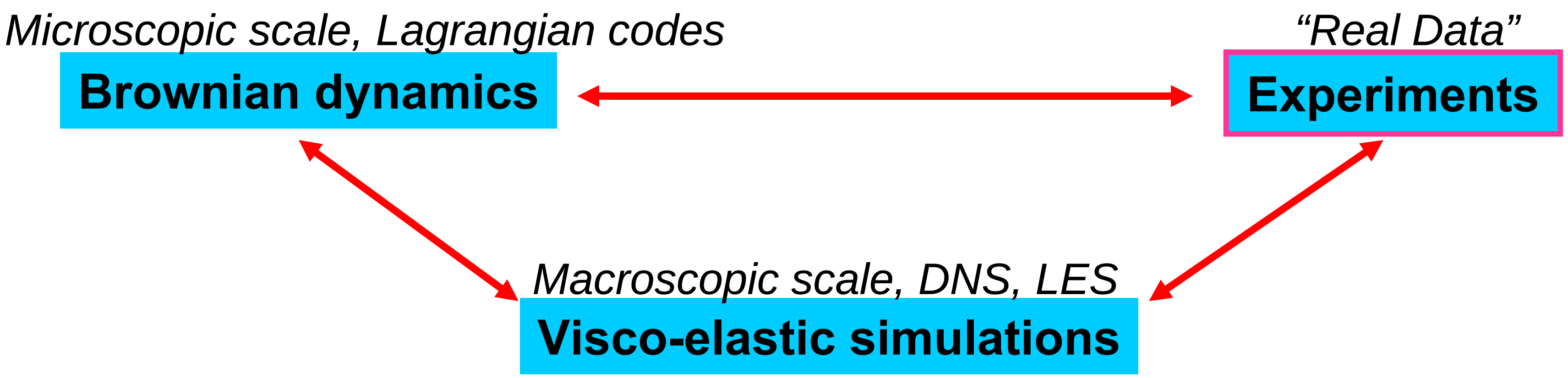
BL flow with polymer injected near leading edge, inhomogeneous.
Planar measurements –

Statistics and Structure
(Petrie and Fontaine)

Tools and techniques used:
PIV in different planes for turbulence statistics and structure
PLIF in different planes for polymer concentration and localization measurements

Friction drag reduction program at Stanford

Multi-disciplinary and multi-scale



Experiments:

Flow structure in a developing turbulent boundary layer with and without polymer interaction

Tools:

Velocity fields using **PIV**

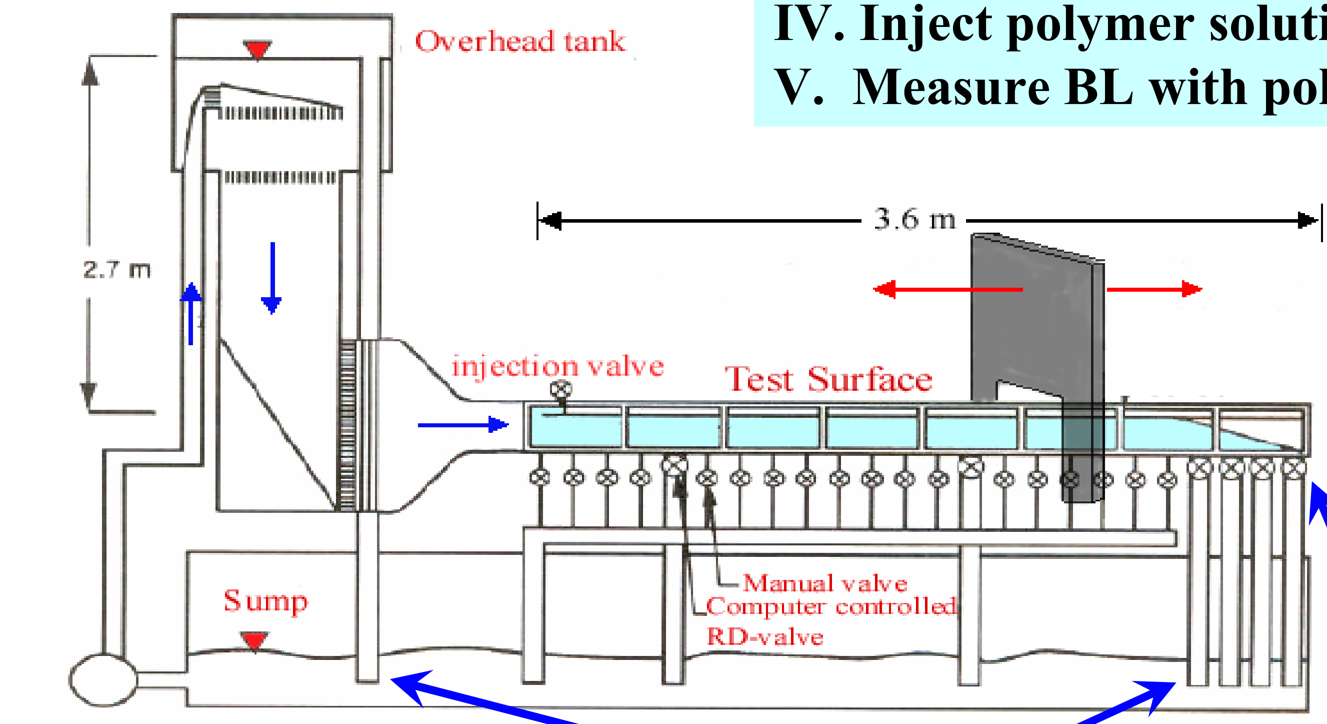
Polymer concentration using **simultaneous PIV and PLIF** of dye mixed in the polymer solution

Outline of talk

- **Background**
- **Experimental facility**
- ***DR* plot (universal curve)**
- **PIV results velocity field changes**
  - **mean profiles,**
  - **u_{rms}, v_{rms}, -u'v', equilibrium in BL**
- ***"Relaminarization"***
- ***DR* plot (re-interpretation)**
- **Conclusions**

Experimental facility

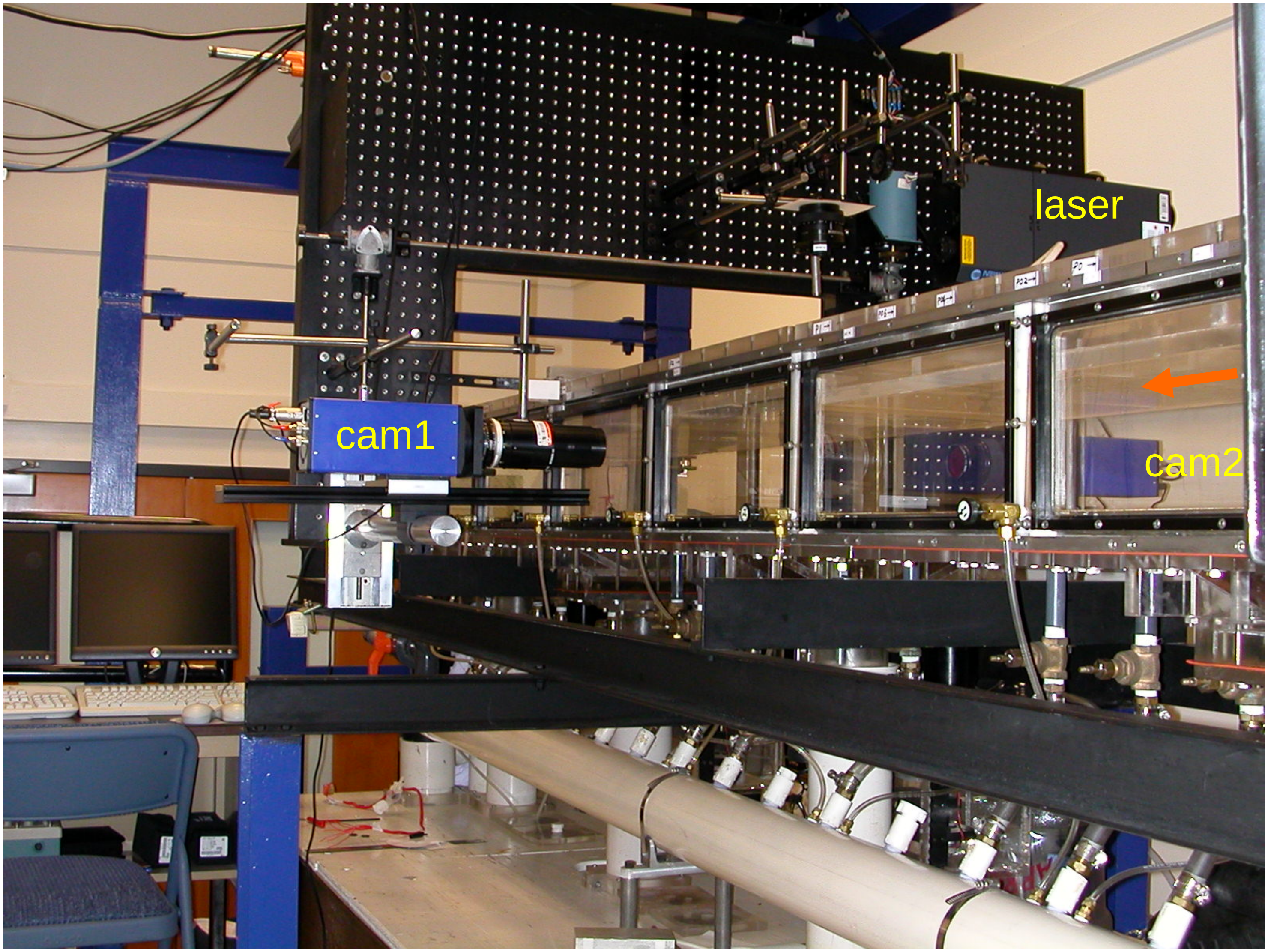
I. Set free stream velocity U
II. Balance pressure gradient (du/dx=0)
III. Measure BL in water
IV. Inject polymer solution
V. Measure BL with polymer



Fiber bags at outlets

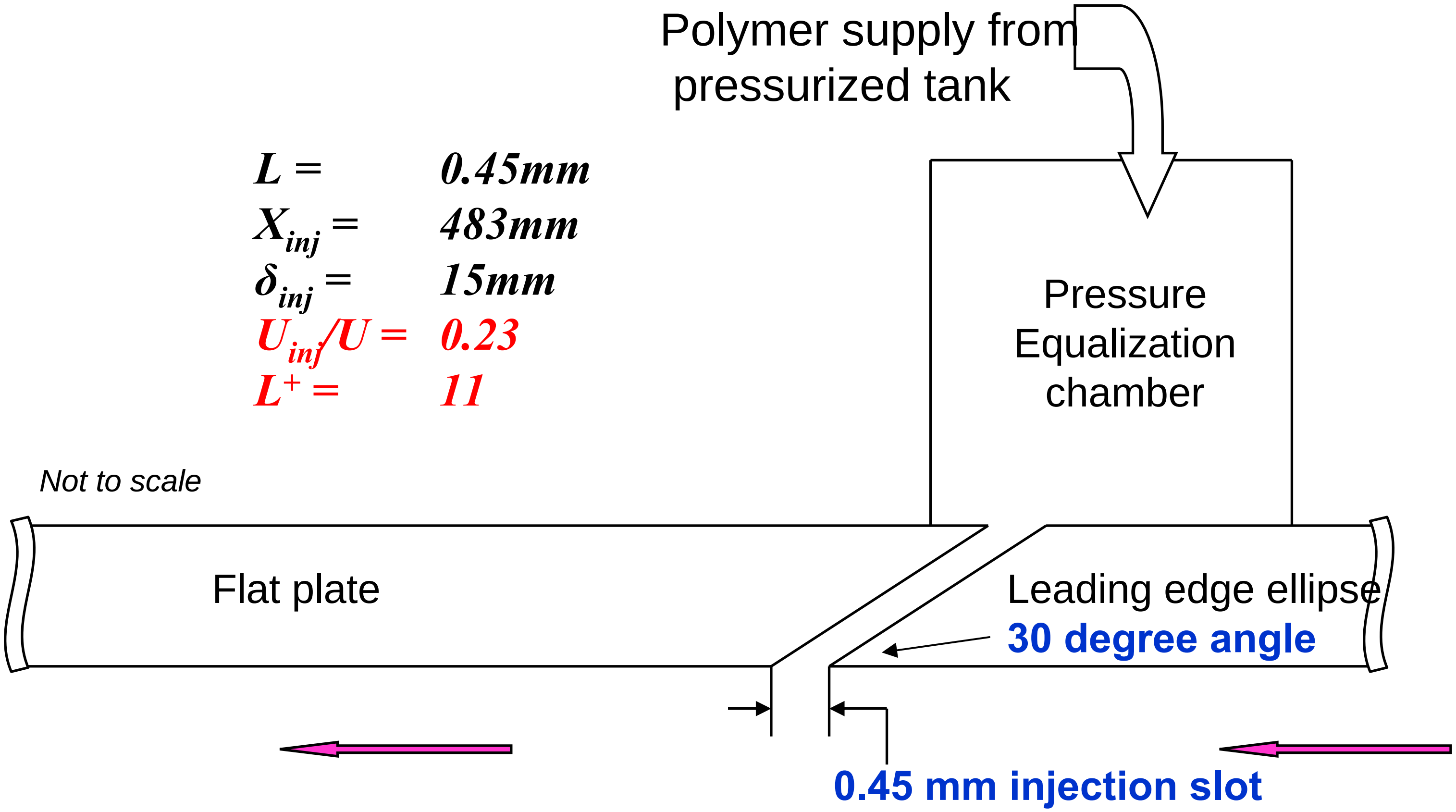
Eliminate air entrainment

Experimental facility



Schematic of injection slot

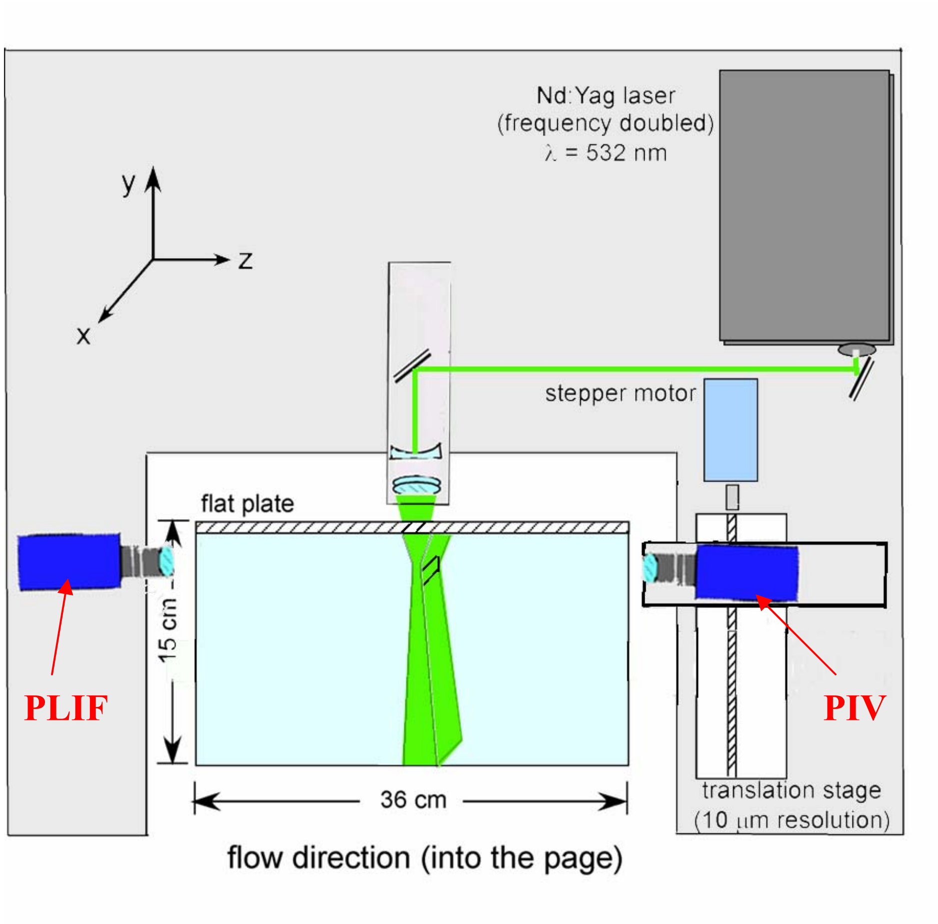
$L = 0.45mm$
$X_{inj} = 483mm$
$\delta_{inj} = 15mm$
$U_{inj}/U = 0.23$
$L^+ = 11$



Polymer injected at the volume flow rate in viscous sublayer.
Qi/Qs ~ 1; (Qs=67.3ν)
Flow rate controlled by overpressure of polymer storage tank.

Experimental facility

Simultaneous PIV and PLIF in x-y plane (sideview)



Experiments:

- **Injection slot: 0.45mm wide, @30^0**
- **Polymers used: PEO, WSR – 301**

  Mean MW: ~ 4 million

  Polydispersity: 1.4

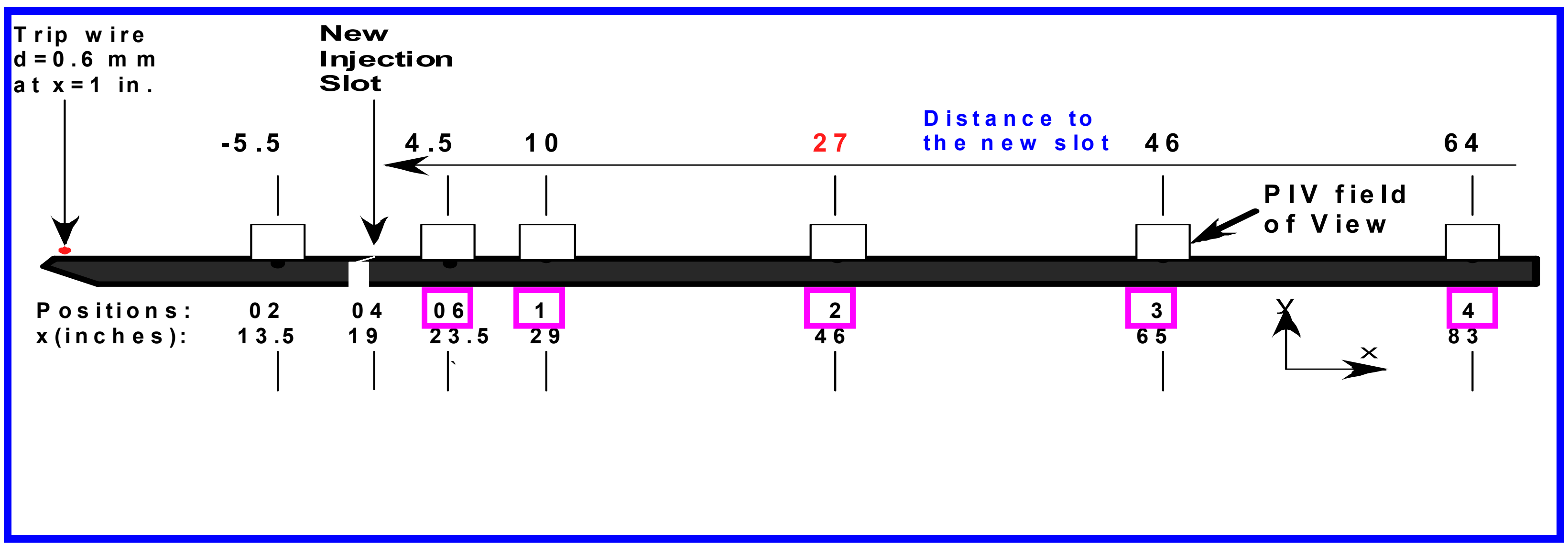
  WSR – Coagulant

PIV: natural seeding (< 20 micron size)
Imaged area: 16.5mm x 13.5mm

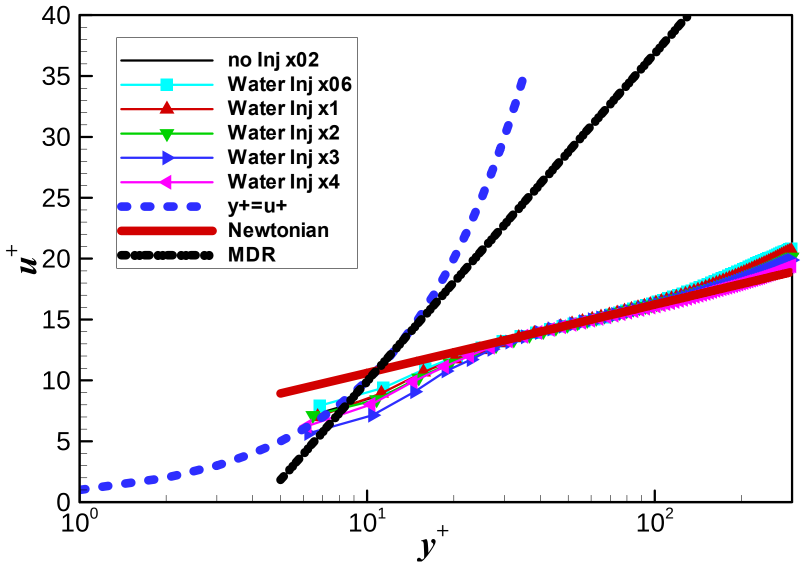
Data acquisition:
1000 image pairs at each station @ 4fps

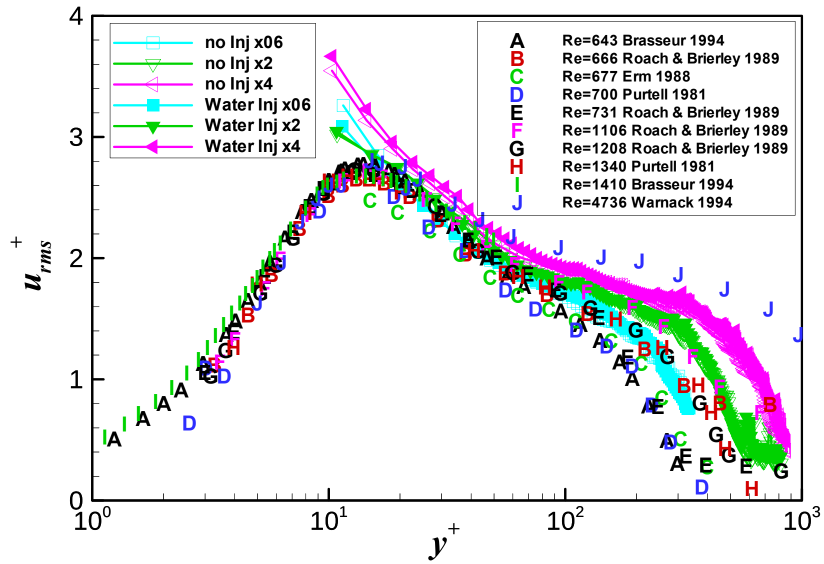
Measurement positions

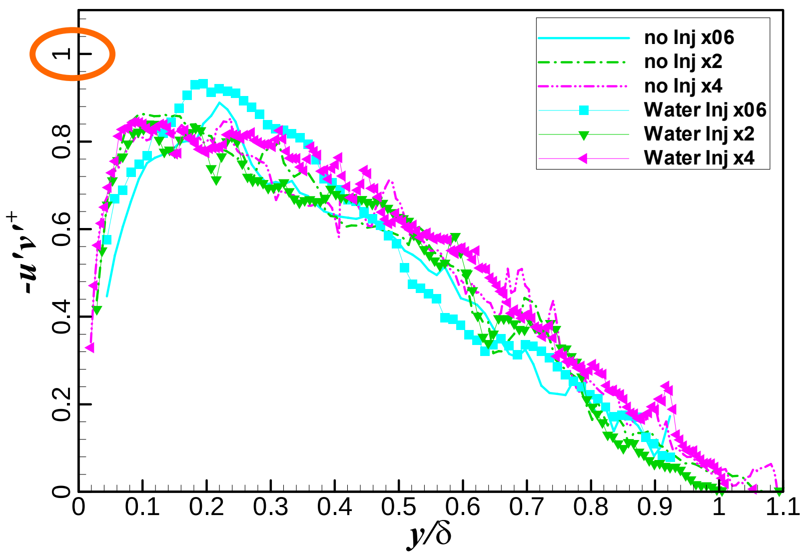
Typical parameters for U = 0.5 m/s				
Position	X(mm) (X^+)	δ (mm) (δ^+)	θ (mm)	Re_θ
pos02	343	13	1.56	700
Injection slot (0.45 mm at 30º)	483	16	1.8	840
pos06	597 (12500)	18 (376)	2.19	990
pos1	737 (15400)	20 (420)	2.54	1150
pos2	1168 (24000)	27 (565)	3.43	1550
pos3	1651 (31500)	35 (730)	4.47	2030
pos4	2108 (40200)	42 (900)	5.26	2380



Experimental Facility Validation and Injection Effects



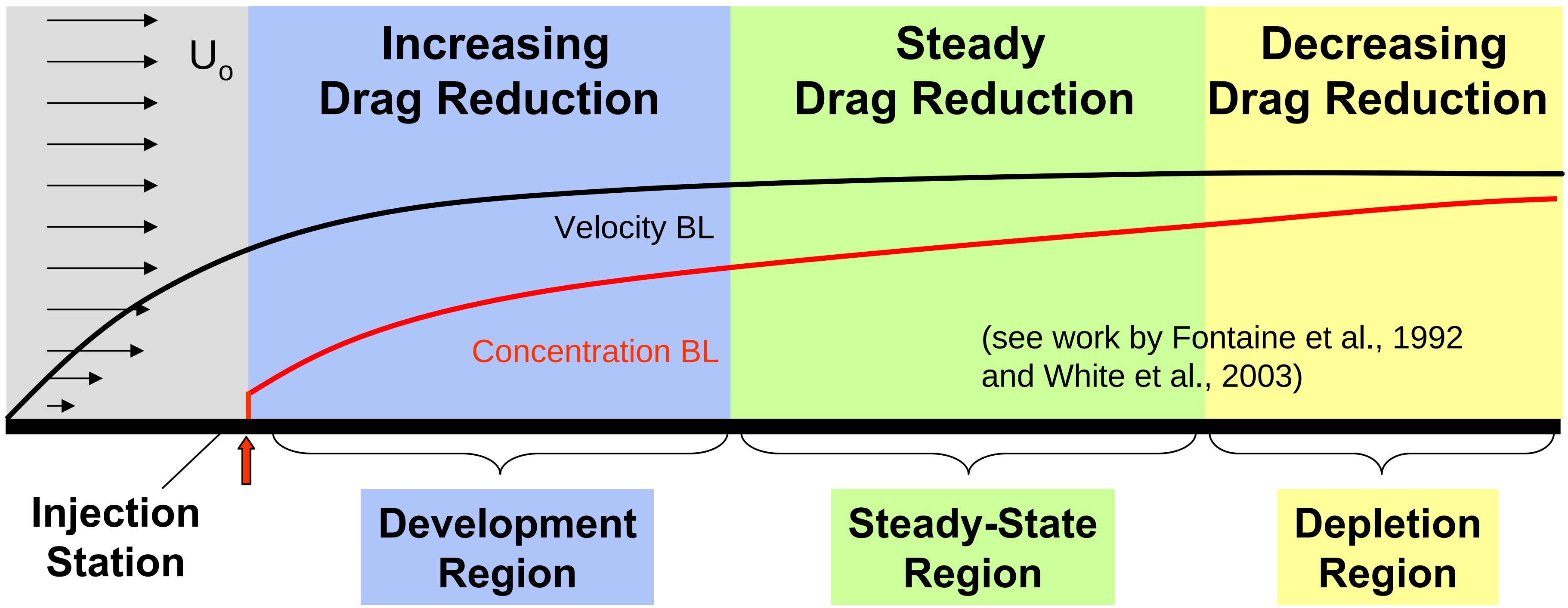




Injection of water:

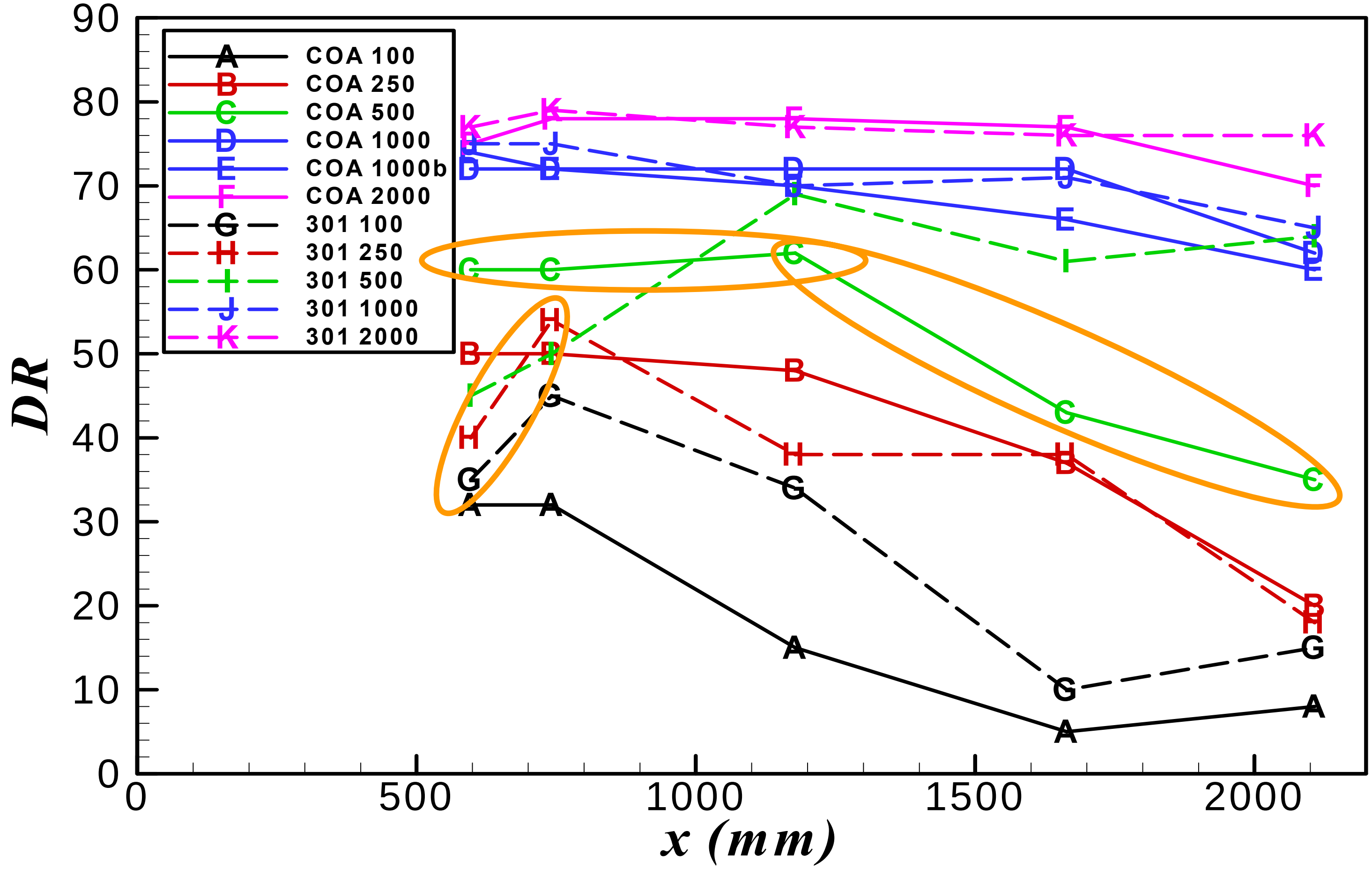
- Has no effects on mean and u_{rms}
- Has very small effect on *u'v'*

Polymer Injection in a TBL – Complications



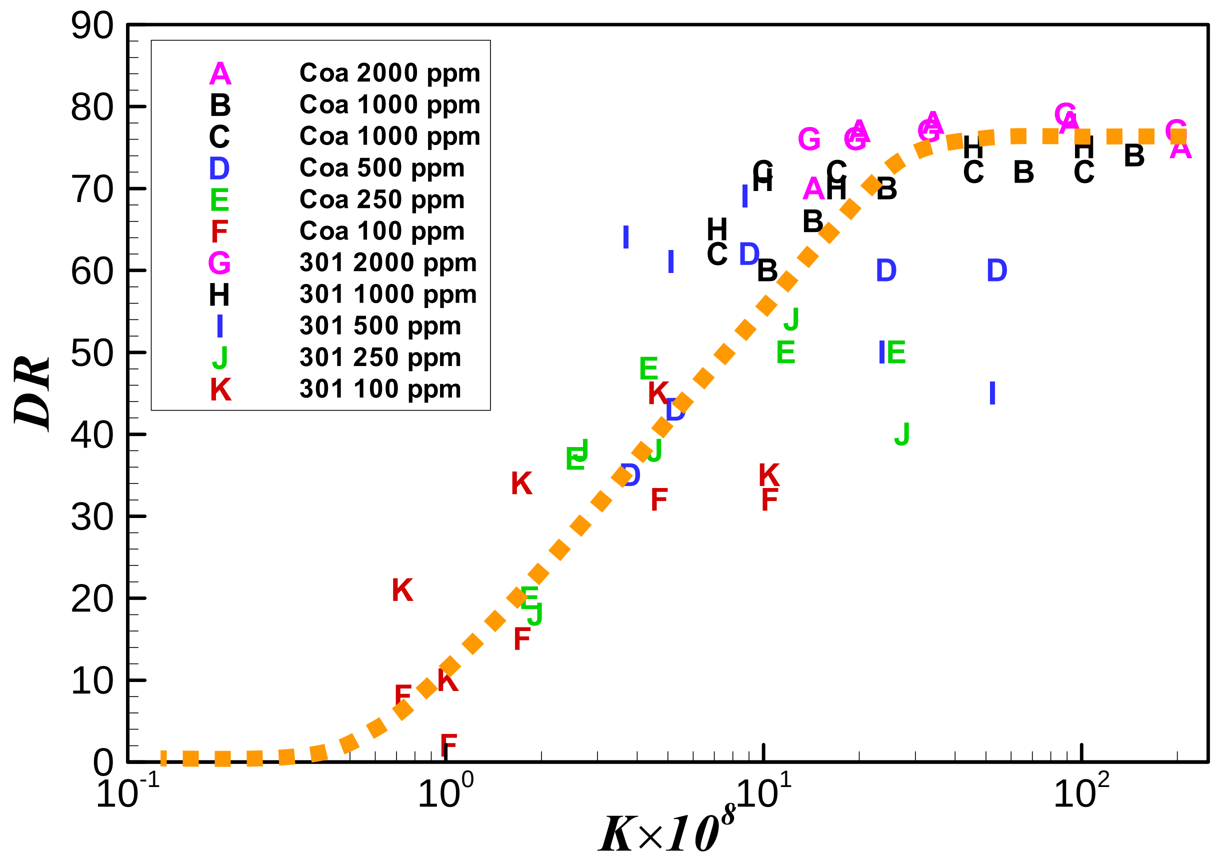
- **Drag reduction increases gradually as stretched polymer interacts with damped turbulence**
- **Drag reduction decreases when the amount of polymer close to the wall becomes sufficiently small**
- **Drag reduction evolves depending on the combination of vortex strength, polymer concentration and polymer deformation**

Streamwise Development of Drag Reduction



- **High injection concentration maintains high DR over longer streamwise distance**

Drag Reduction (DR%) vs. K



- ➢Agree well with Petrie *et al.* (2003)
- ➢Coagulant and WSR-301 are similar in DR-K plot.
- ➢Coagulant is slightly less scattered.

$$K = \frac{QC_I}{\rho U_0 X_S}$$

Q: Volume flux of injected polymer solution per unit span

C_I: weight concentration of polymer solution

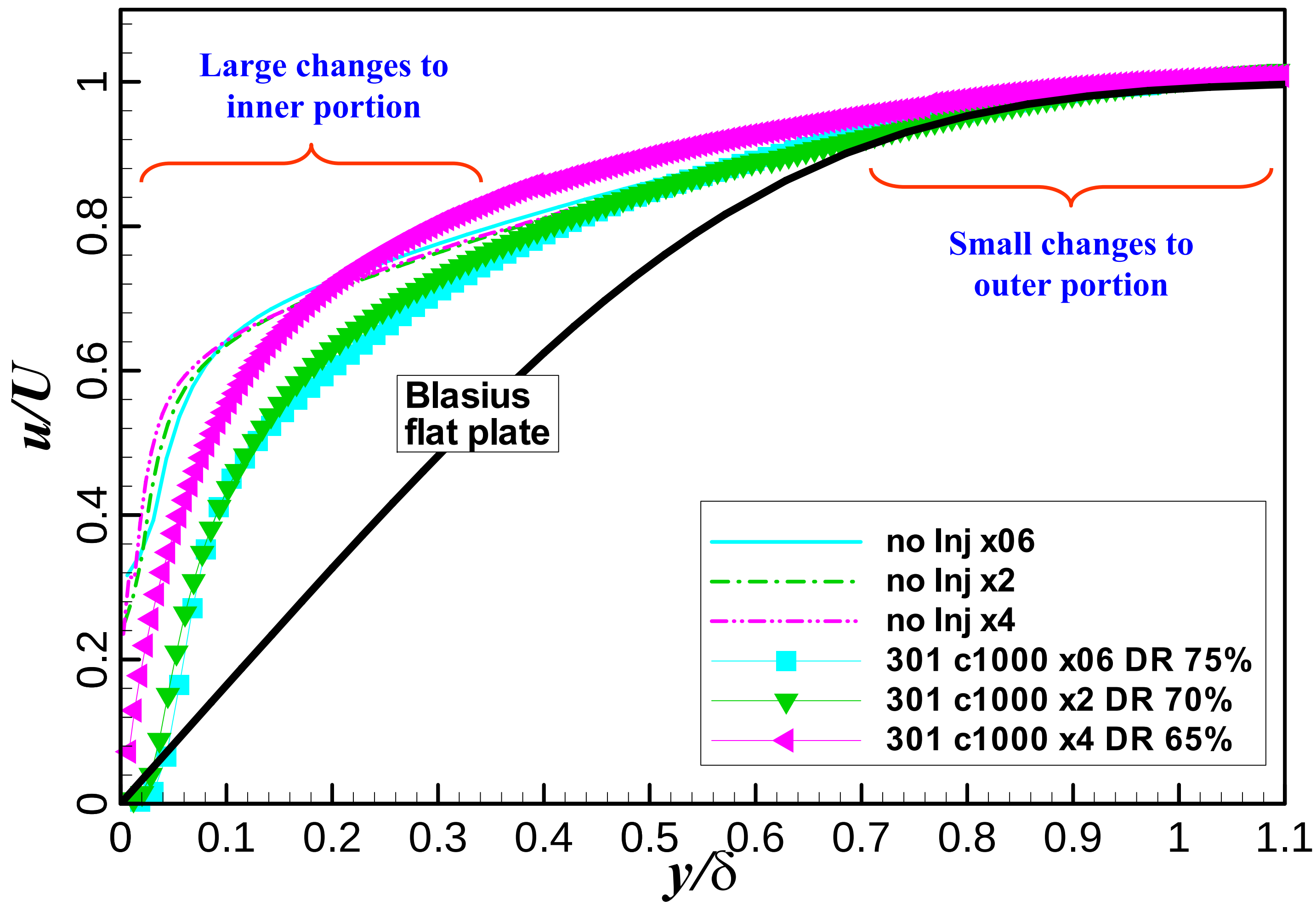
ρ: water density

U_0: freestream velocity

X_S: downstream measurement location

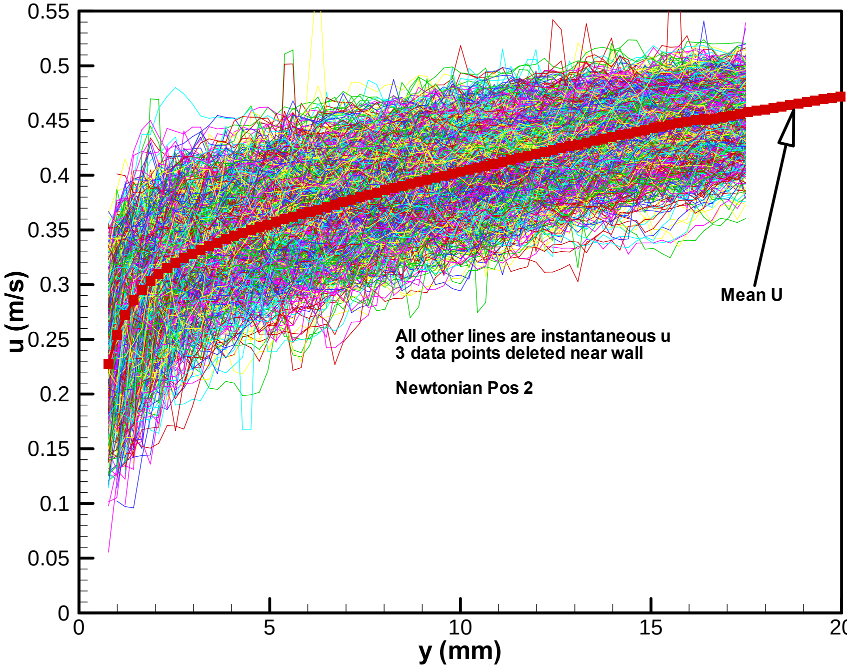
Following: Vdovin & Smol'yakov 1981, Petrie & Fontaine 1996, Petrie *et al*. 2003

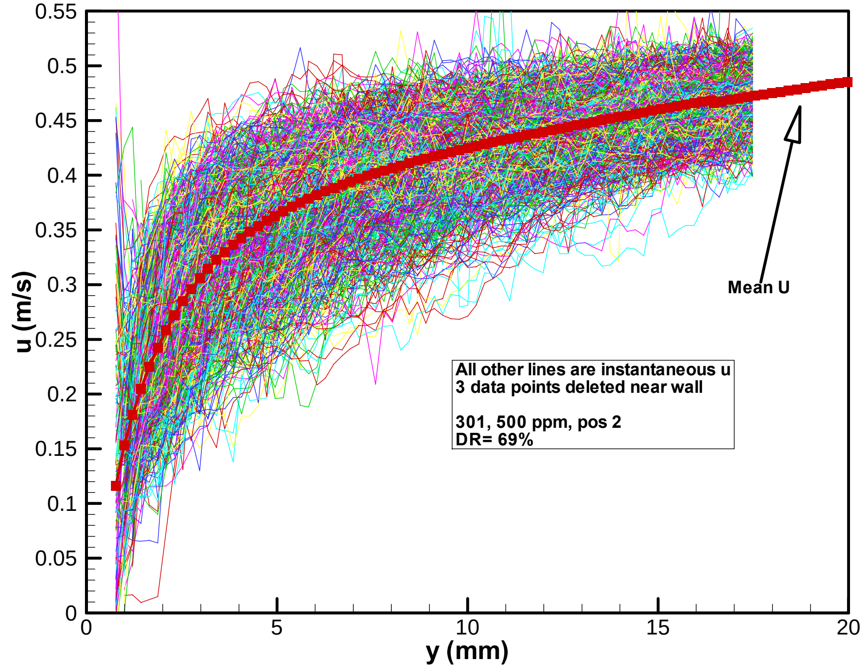
Mean Velocity Profile In Polymer Flow



Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; C_i=1000 wppm; Q_i/Q_s=0.77; (Q_s=67.3ν)

Side by Side Comparison

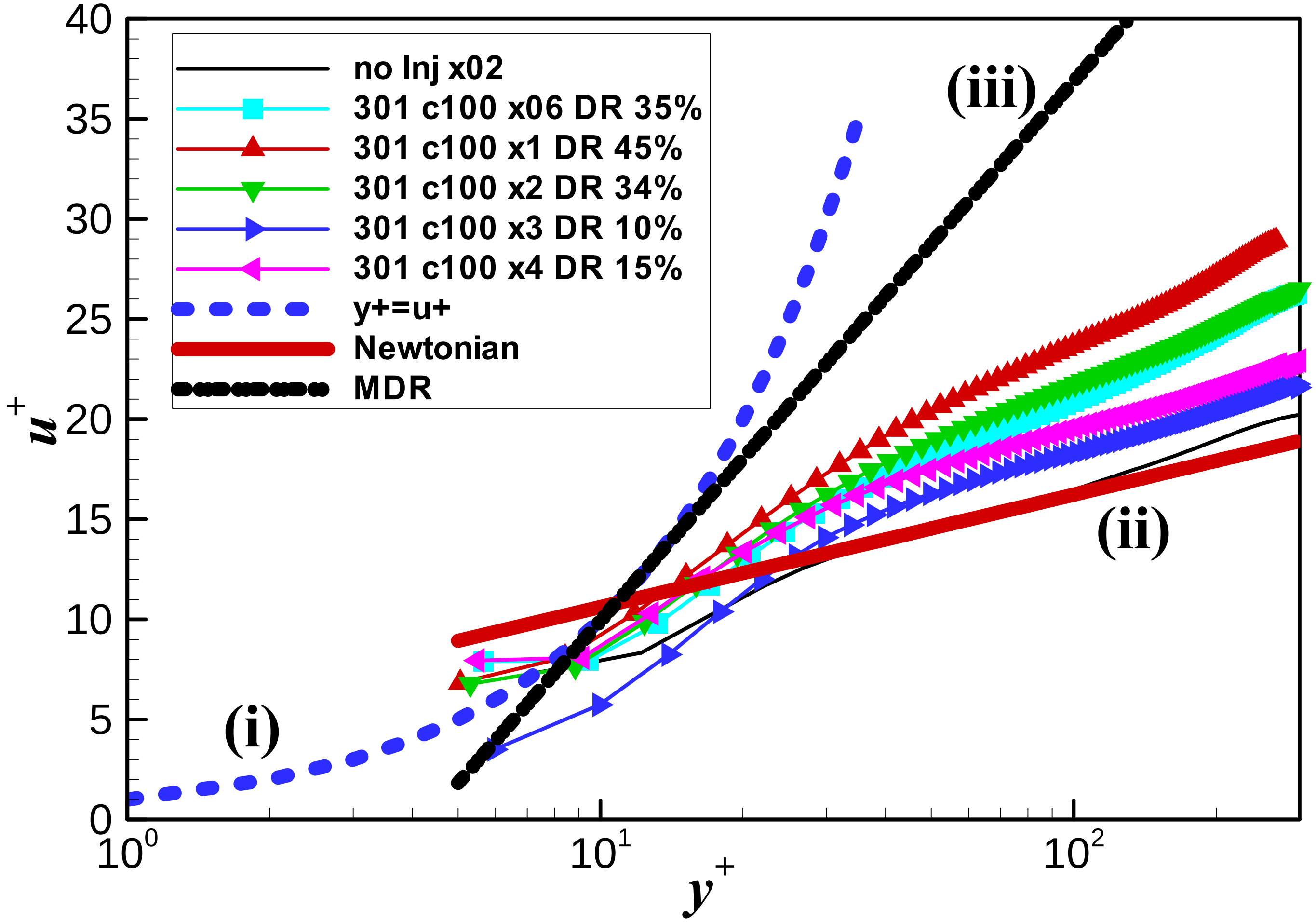




Water, Posn 2, DR 0%

Polymer, Posn 2, DR 69%

Mean Velocity Profile In Polymer Flow – 100 ppm



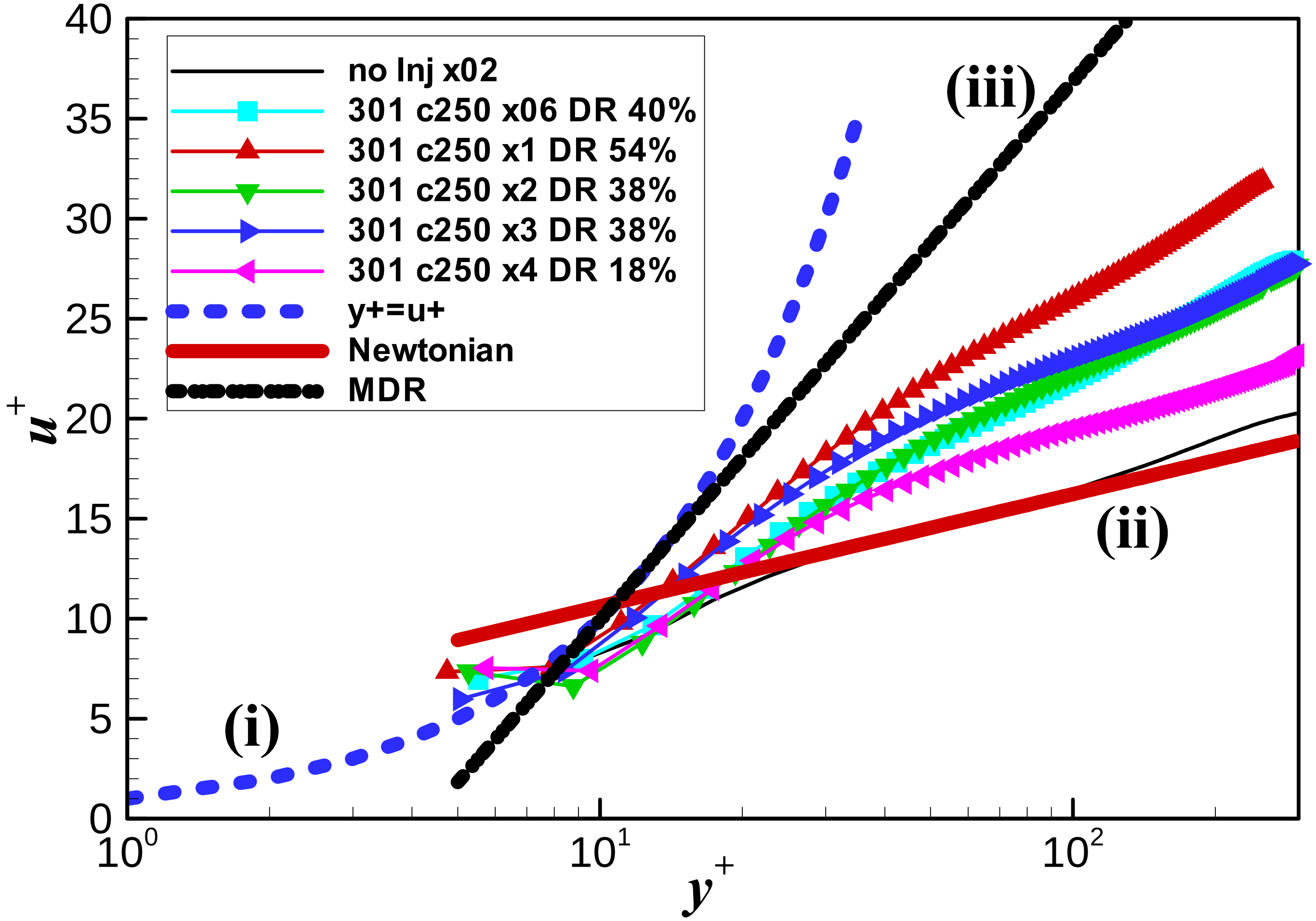
Poly-Ethylene Oxide (PEO) WSR-301

U=0.5 m/s;
C_i=100 wppm;
Q_i/Q_s=0.78;
(Q_s=67.3ν)

$U^+ = U/u^*$;
$y^+ = yu^*/\nu$;
$u^* = (\tau_w/\rho)^{1/2}$

(i) $U^+ = y^+$; (ii) $U^+ = 2.44 \ln(y^+) + 5.1$; (iii) $U^+ = 11.7 \ln (y^+) - 17.0$

Mean Velocity Profile In Polymer Flow – 250 ppm



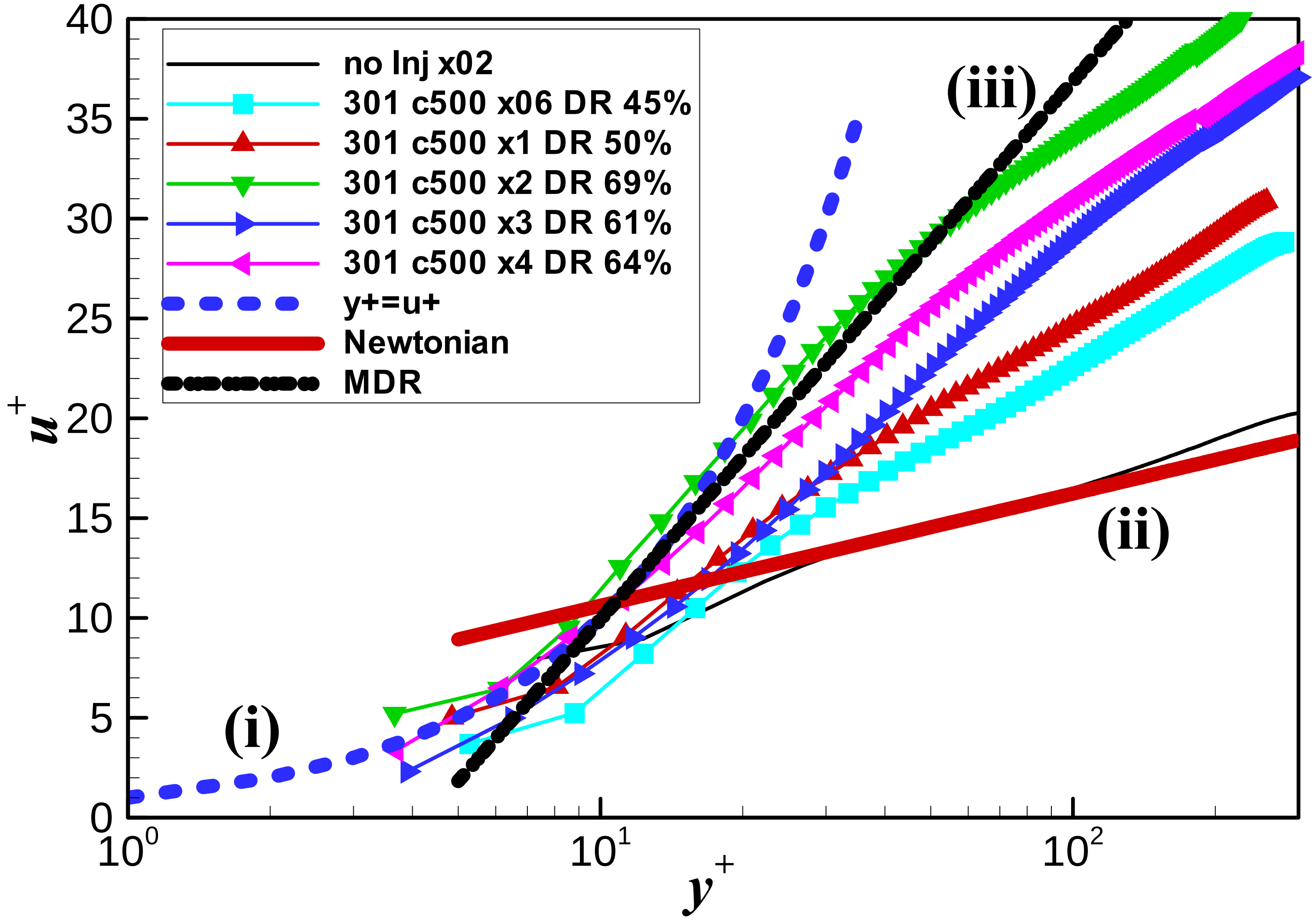
Poly-Ethylene Oxide (PEO) WSR-301

U=0.5 m/s;
C_i=250 wppm;
Q_i/Q_s=0.82;
(Q_s=67.3ν)

$U^+ = U/u^*$;
$y^+ = yu^*/\nu$;
$u^* = (\tau_w/\rho)^{1/2}$

(i) $U^+ = y^+$; (ii) $U^+ = 2.44 \ln(y^+) + 5.1$; (iii) $U^+ = 11.7 \ln(y^+) - 17.0$

Mean Velocity Profile In Polymer Flow – 500 ppm



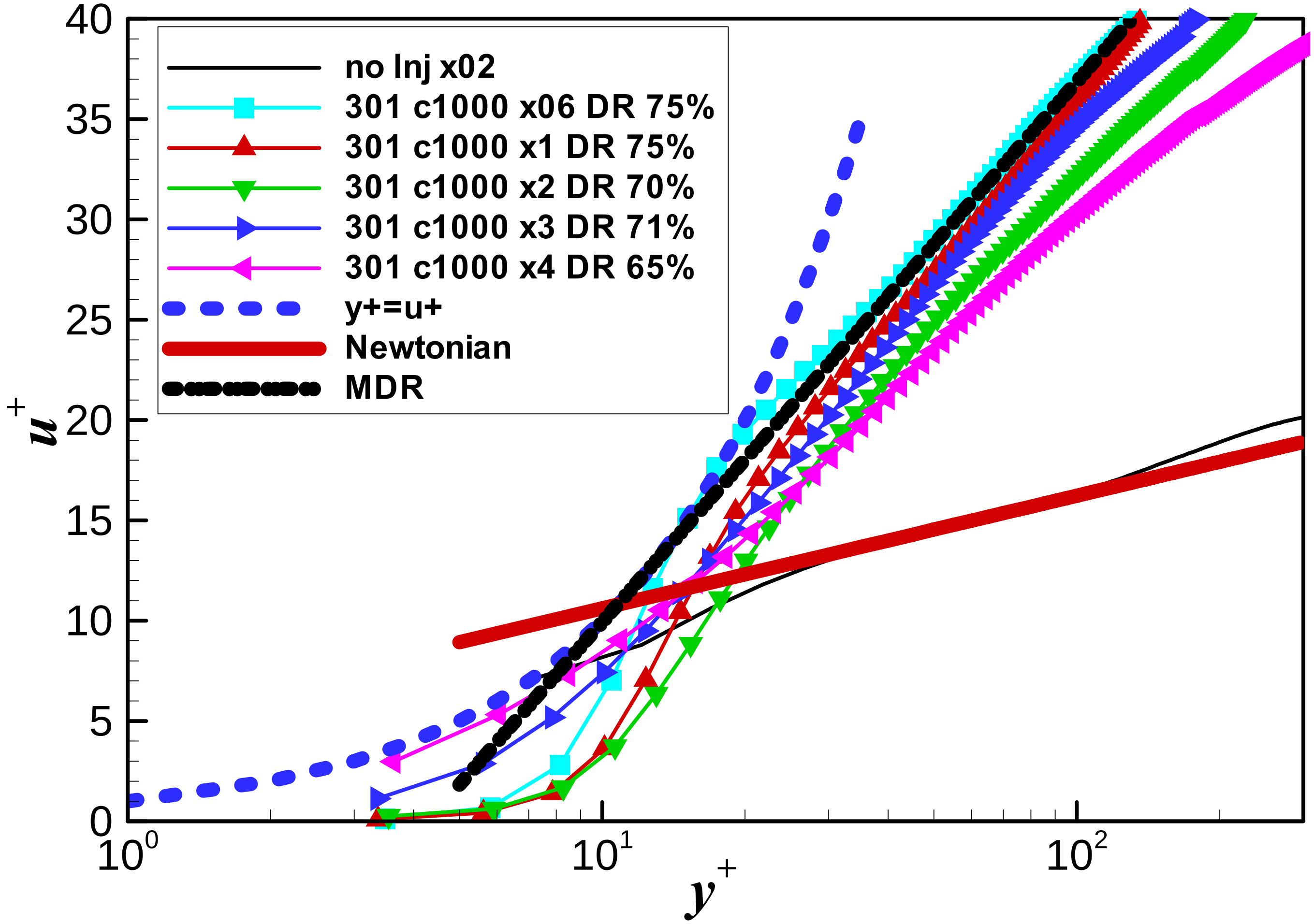
Poly-Ethylene Oxide (PEO) WSR-301

U=0.5 m/s;
C_i=500 wppm;
Q_i/Q_s=0.79;
(Q_s=67.3ν)

$U^+ = U/u^*$;
$y^+ = yu^*/\nu$;
$u^* = (\tau_w/\rho)^{1/2}$

(i) $U^+ = y^+$; (ii) $U^+ = 2.44 \ln(y^+) + 5.1$; (iii) $U^+ = 11.7 \ln(y^+) - 17.0$

Mean Velocity Profile In Polymer Flow – 1000 ppm



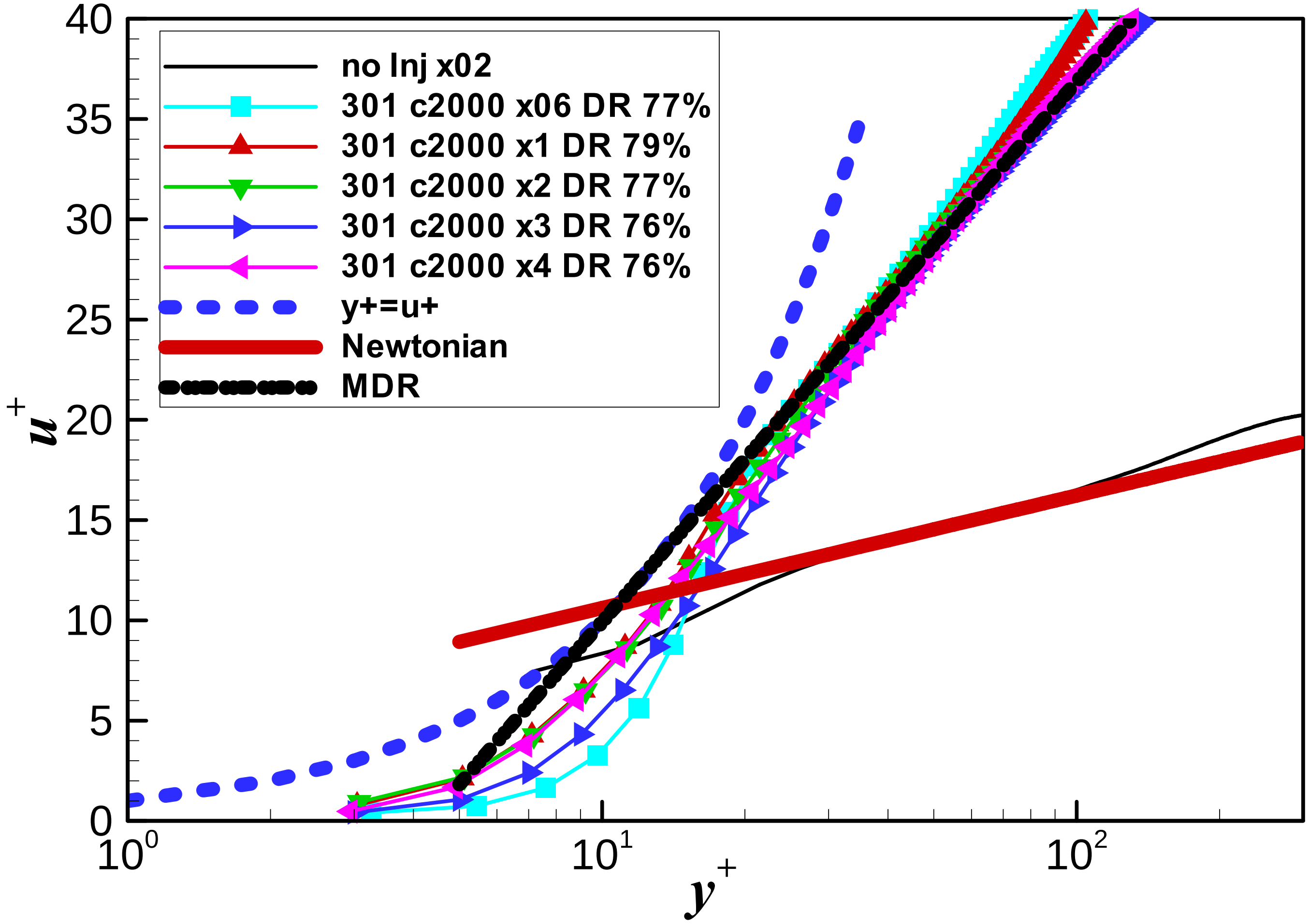
Poly-Ethylene Oxide (PEO) WSR-301

$U=0.5$ m/s;
$C_i=1000$ wppm;
$Q_i/Q_s=0.77$;
($Q_s=67.3\nu$)

$U^+ = U/u^*$;
$y^+ = yu^*/\nu$;
$u^* = (\tau_w/\rho)^{1/2}$

(i) $U^+ = y^+$; (ii) $U^+ = 2.44 \ln(y^+) + 5.1$; (iii) $U^+ = 11.7 \ln (y^+) - 17.0$

Mean Velocity Profile In Polymer Flow – 2000 ppm



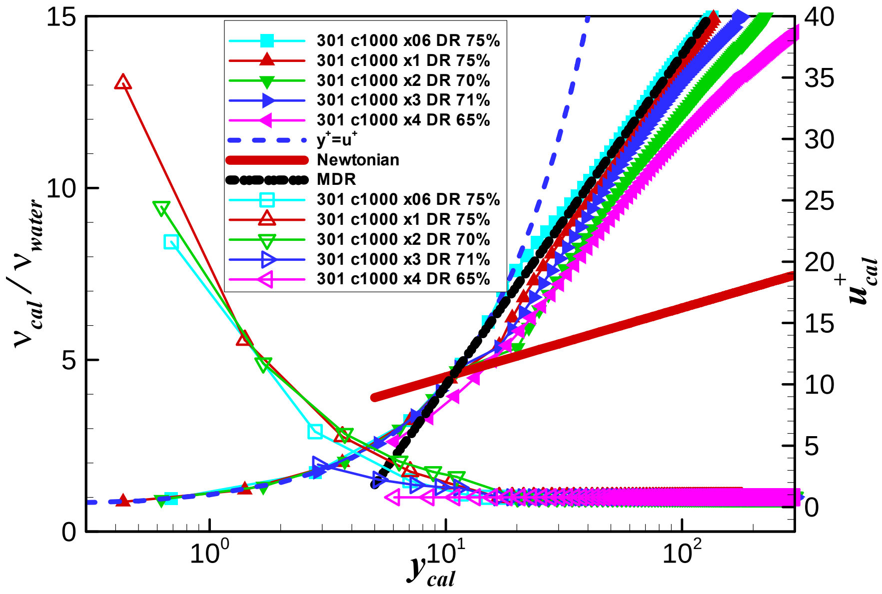
Poly-Ethylene Oxide (PEO) WSR-301

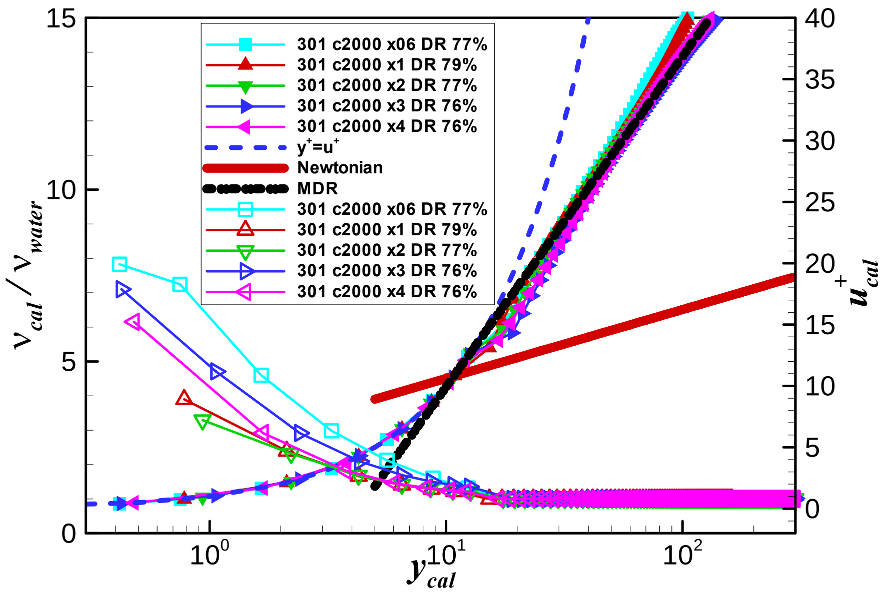
U=0.5 m/s;
C_i=2000 wppm;
Q_i/Q_s=0.75;
(Q_s=67.3ν)

$U^+ = U/u^*$;
$y^+ = yu^*/\nu$;
$u^* = (\tau_w/\rho)^{1/2}$

(i) $U^+ = y^+$; (ii) $U^+ = 2.44 \ln(y^+) + 5.1$; (iii) $U^+ = 11.7 \ln(y^+) - 17.0$

Near Wall Polymer Solution Viscosity

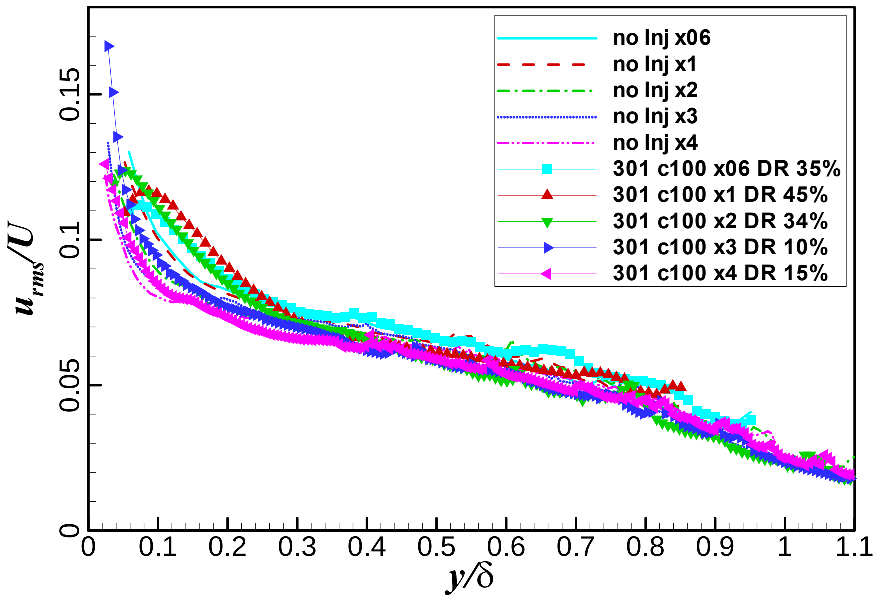


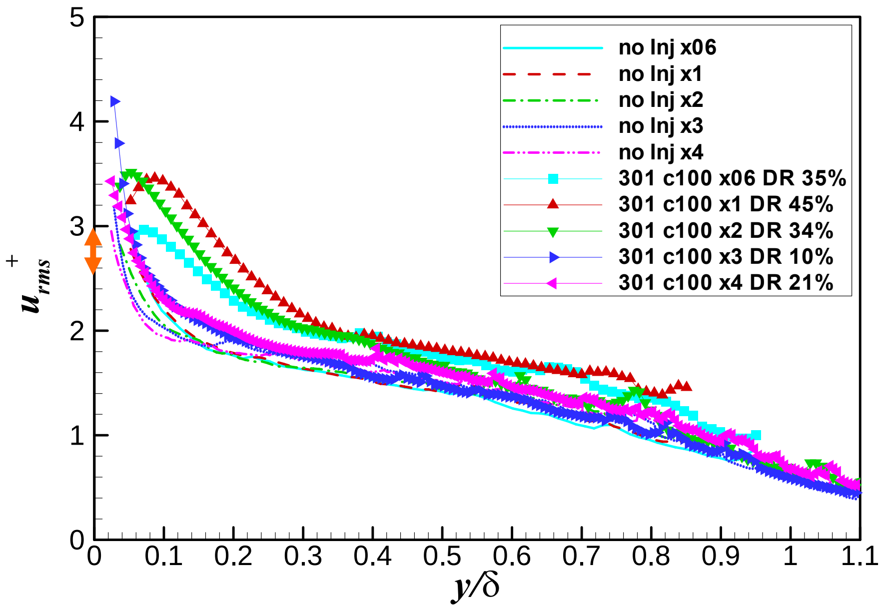


Obtained by forcing $u^+ = y^+$ in the sublayer

The viscosity of polymer solution in the near wall region is higher than water and cannot be ingored

u_{rms} Profiles In Polymer Flow – 100 ppm



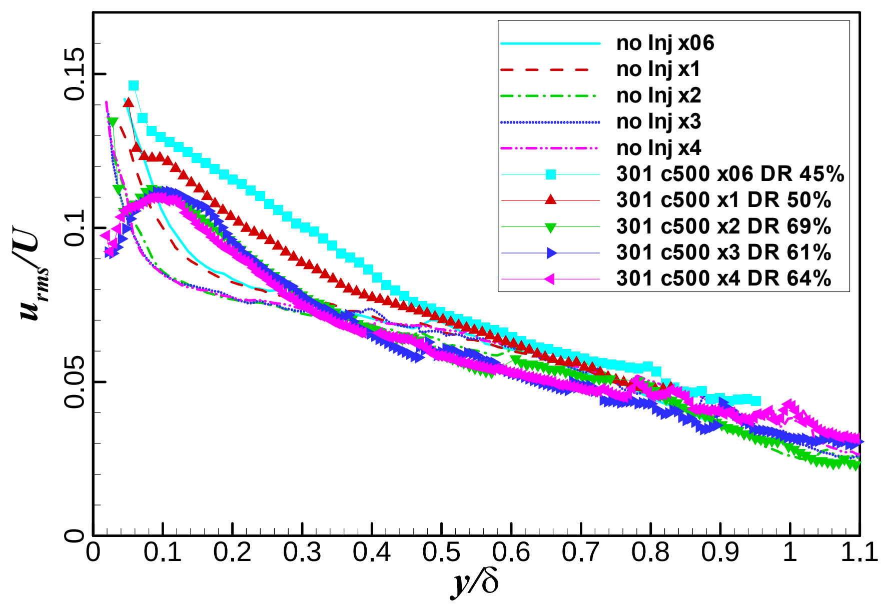


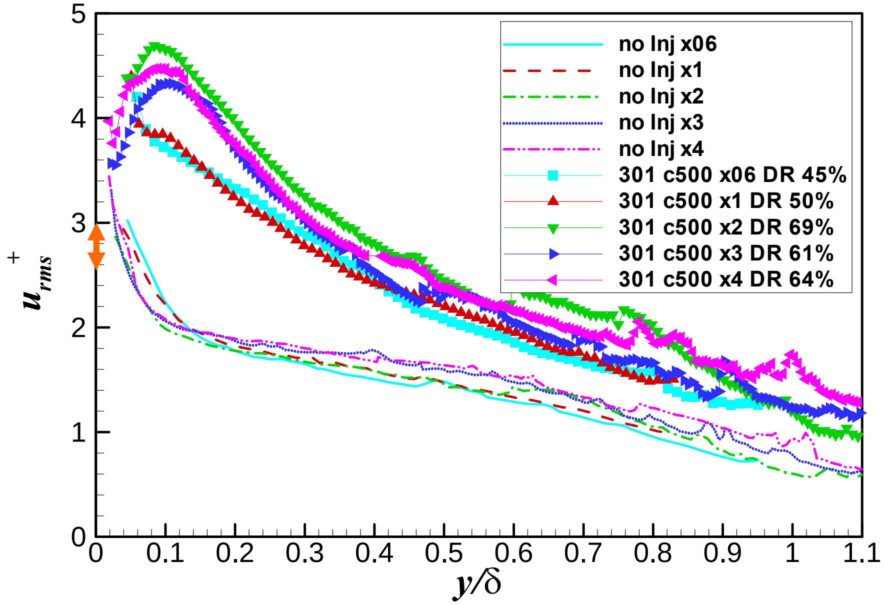
Compared to Newtonian flow:

- **Peak of u_{rms} shifts outward and is smaller**
- **The value of u_{rms}^+ is much higher**

Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; Ci=500 wppm; Qi/Qs=0.79; (Qs=67.3ν)

u_{rms} Profiles In Polymer Flow – 500 ppm





Compared to Newtonian flow:

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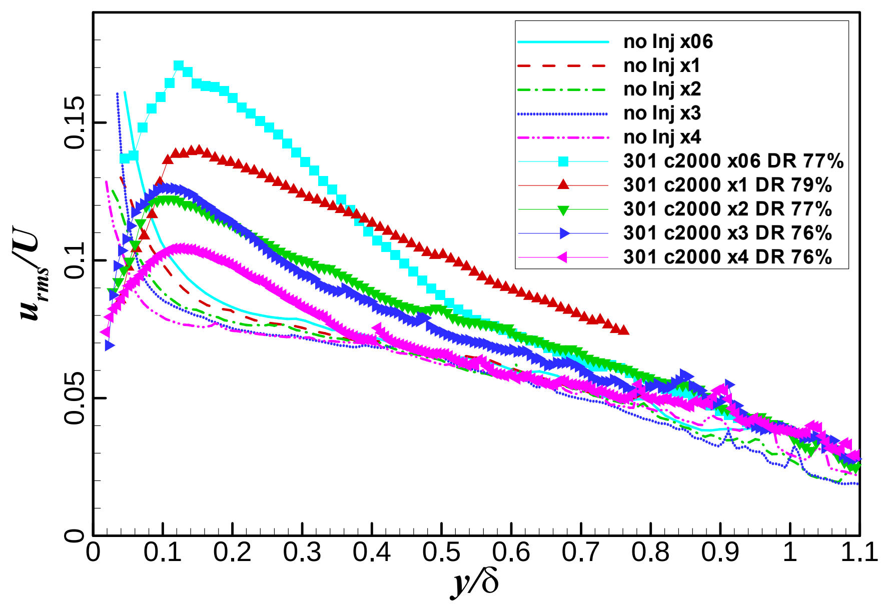
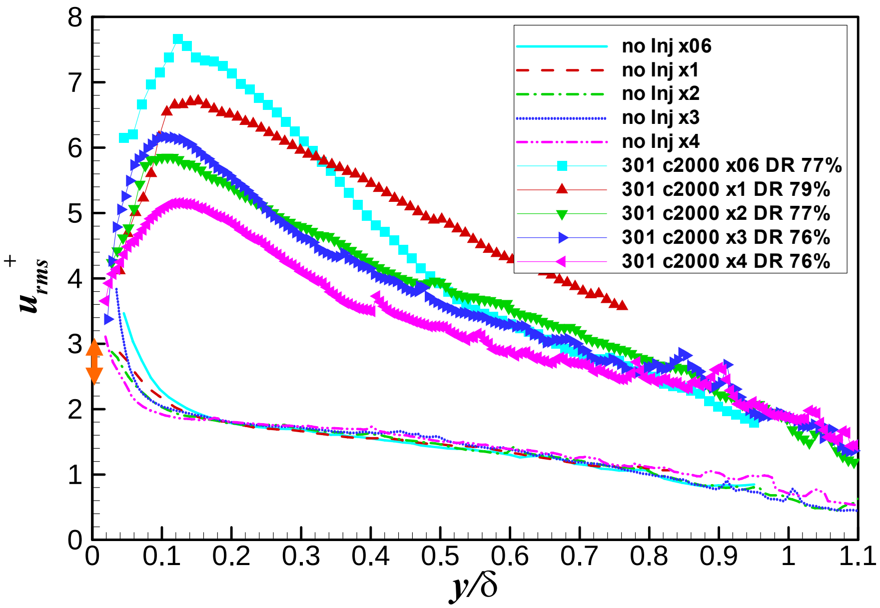
Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; Ci=500 wppm; Qi/Qs=0.79; (Qs=67.3ν)

u_{rms} Profiles In Polymer Flow – 2000 ppm





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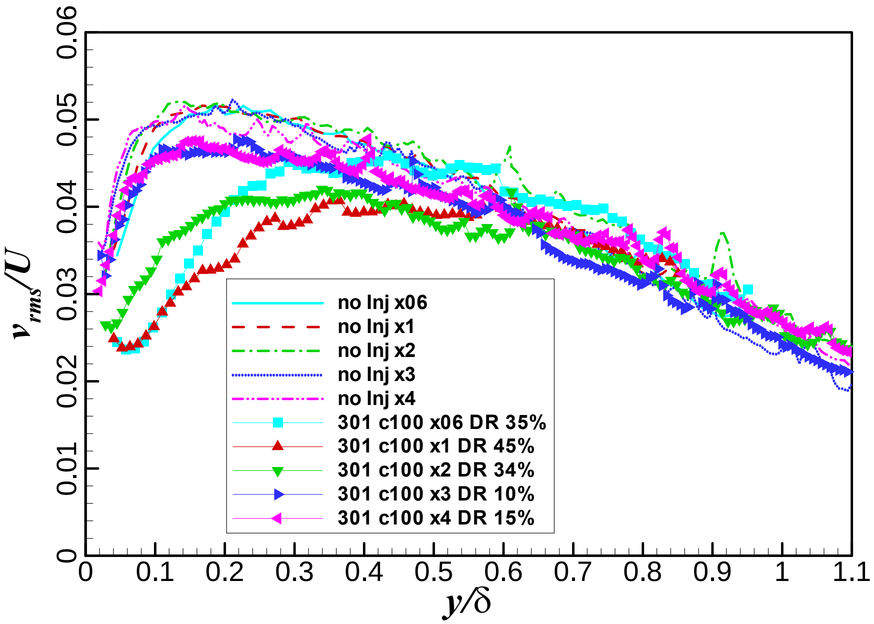
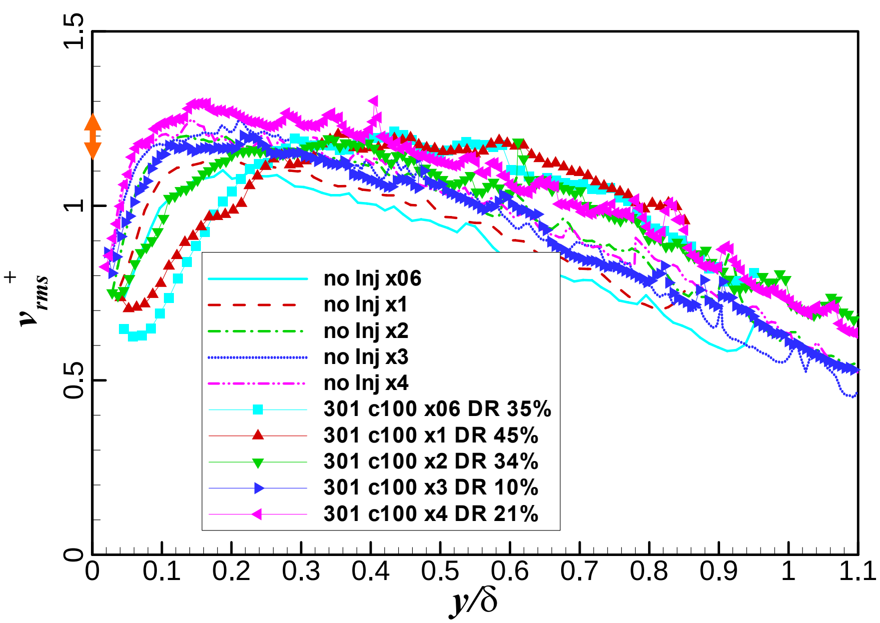
Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; Ci=500 wppm; Qi/Qs=0.79; (Qs=67.3ν)

v_{rms} Profiles In Polymer Flow – 100 ppm





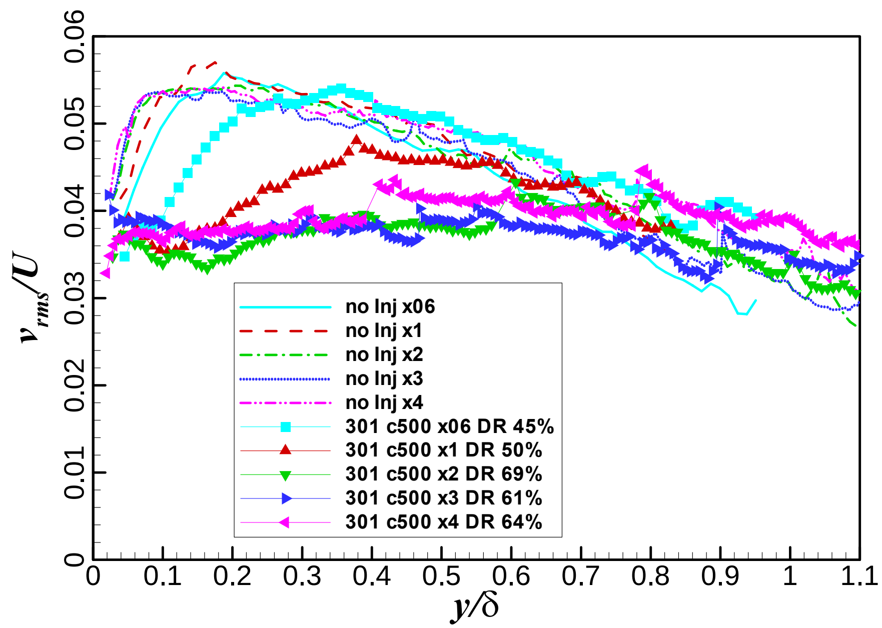
Compared to Newtonian flow:

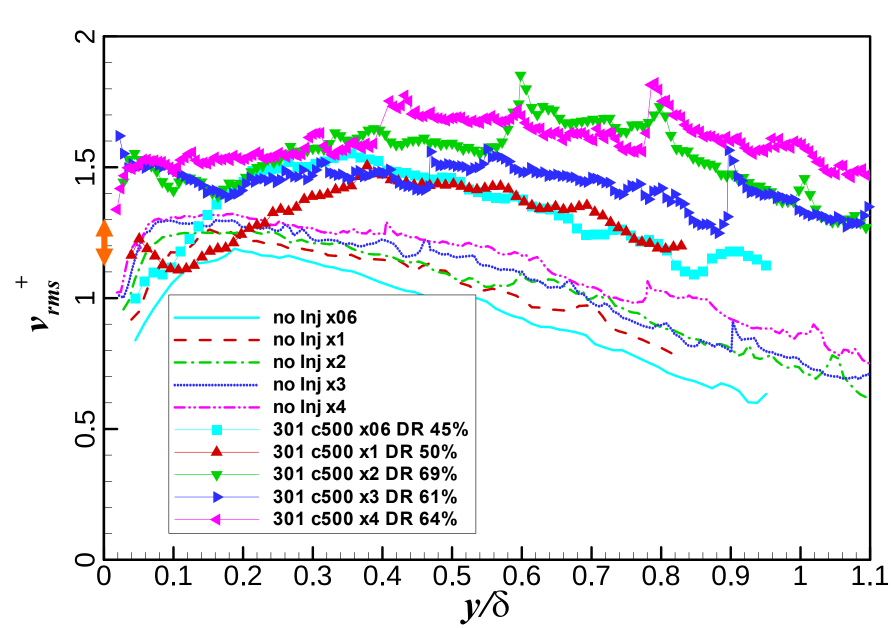
- ➢**Magnitude of of v_{rms} is reduced physically**
- ➢**The value of v_{rms}^+ is much higher**

Poly-Ethylene Oxide (PEO) WSR-301

U=0.5 m/s; C_i=500 wppm; Q_i/Q_s=0.79; (Q_s=67.3ν)

v_{rms} Profiles In Polymer Flow – 500 ppm





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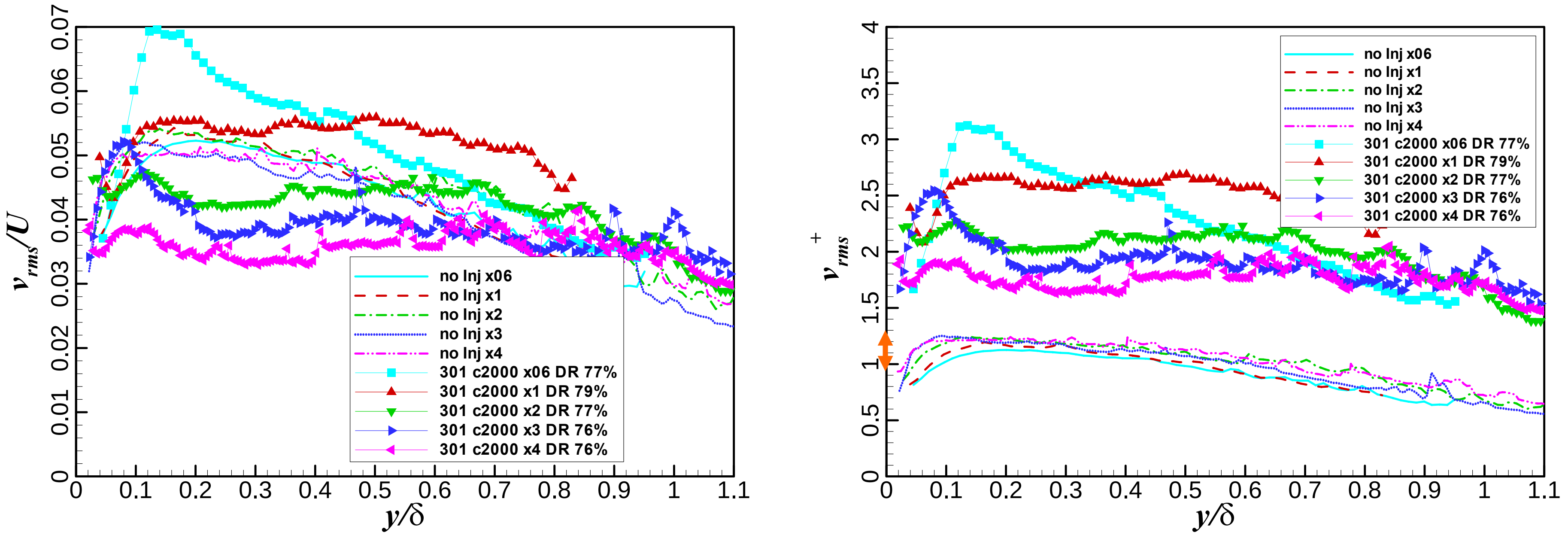
Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; C_i=500 wppm; Q_i/Q_s=0.79; (Q_s=67.3ν)

v_{rms} Profiles In Polymer Flow – 2000 ppm



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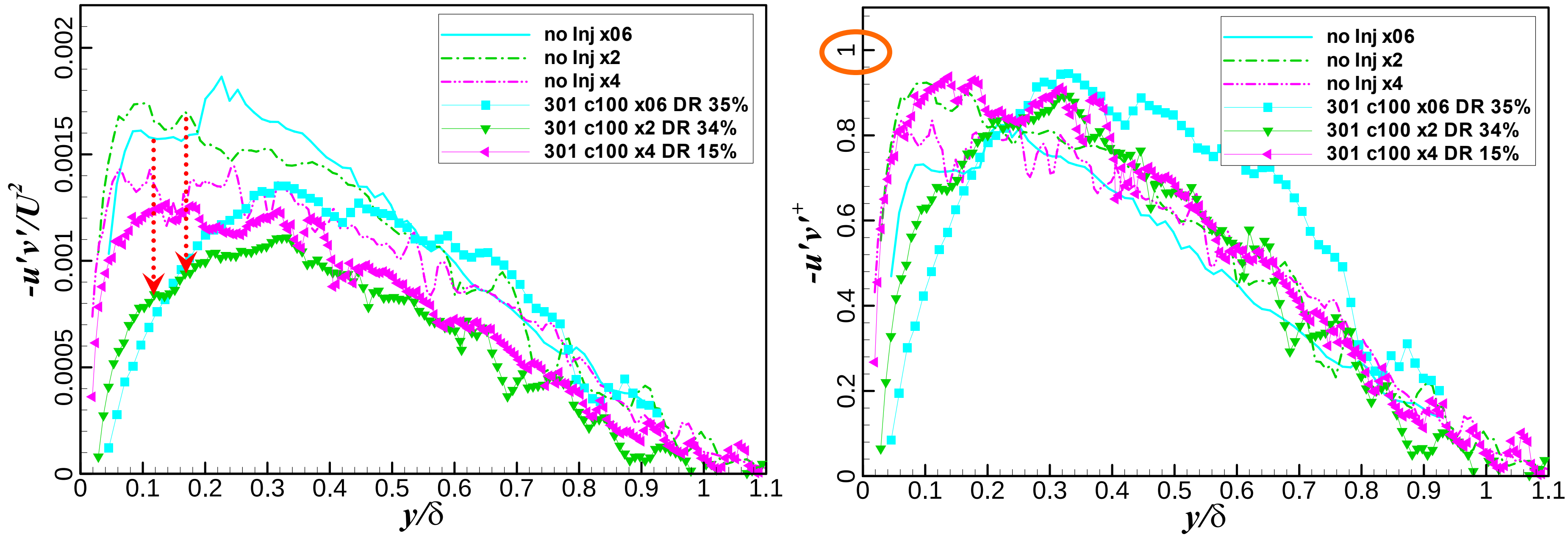
Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; C_i=500 wppm; Q_i/Q_s=0.79; (Q_s=67.3ν)

Reynolds Shear Stress In Polymer Flow – 100 ppm

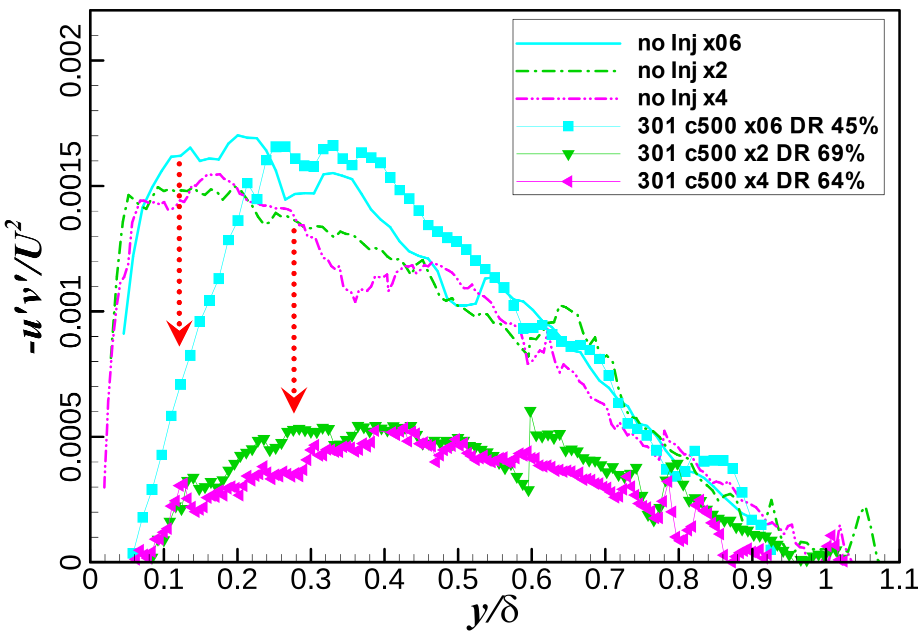


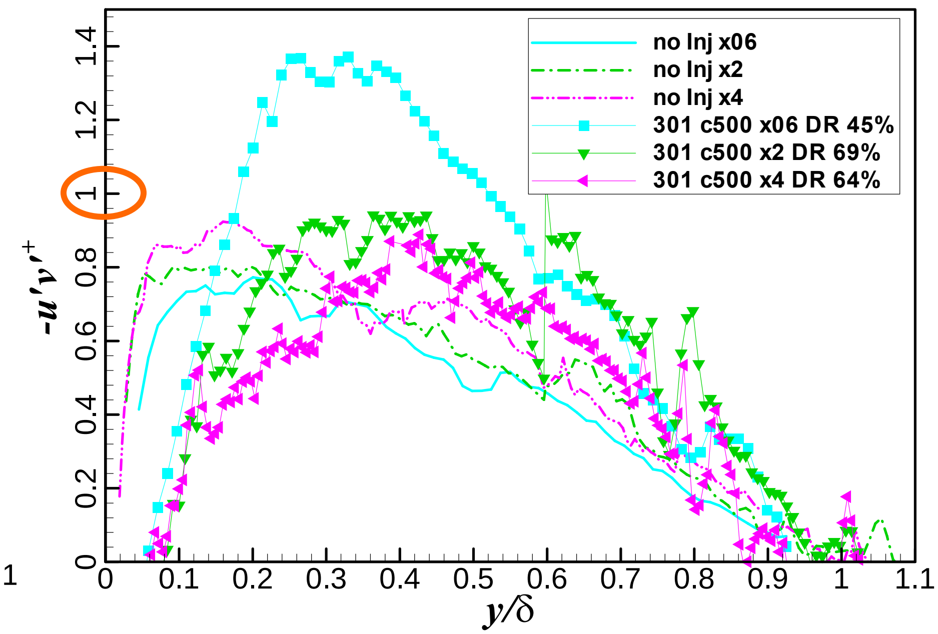
- Near wall region adjusted to drag reduction
- Smaller polymer-effect away far from wall

- Peak values are the same (unity) for both Newtonian flow and polymer flow

Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; C_i=100 wppm; Q_i/Q_s=0.78; (Q_s=67.3ν)

Reynolds Shear Stress In Polymer Flow – 500 ppm



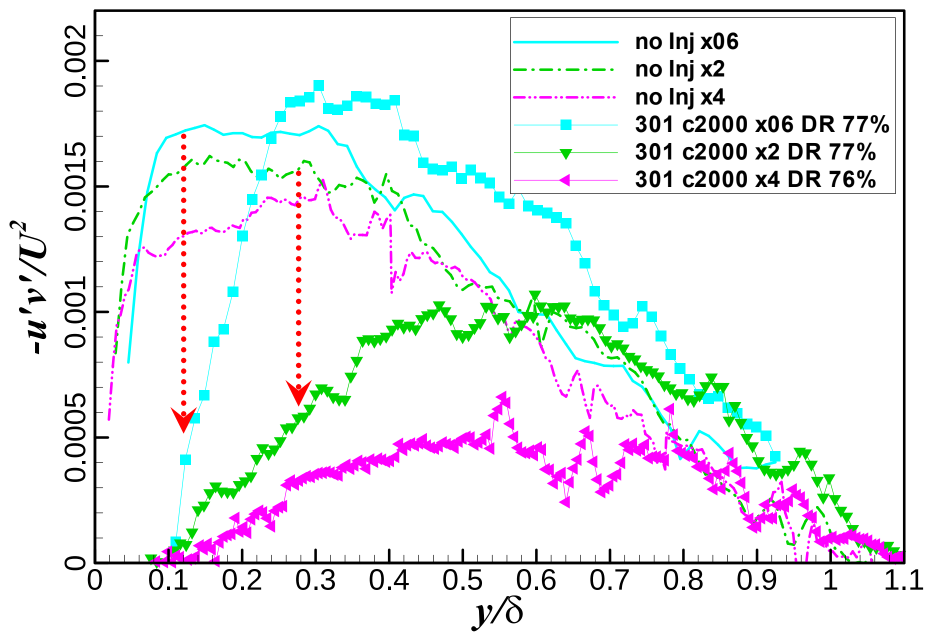


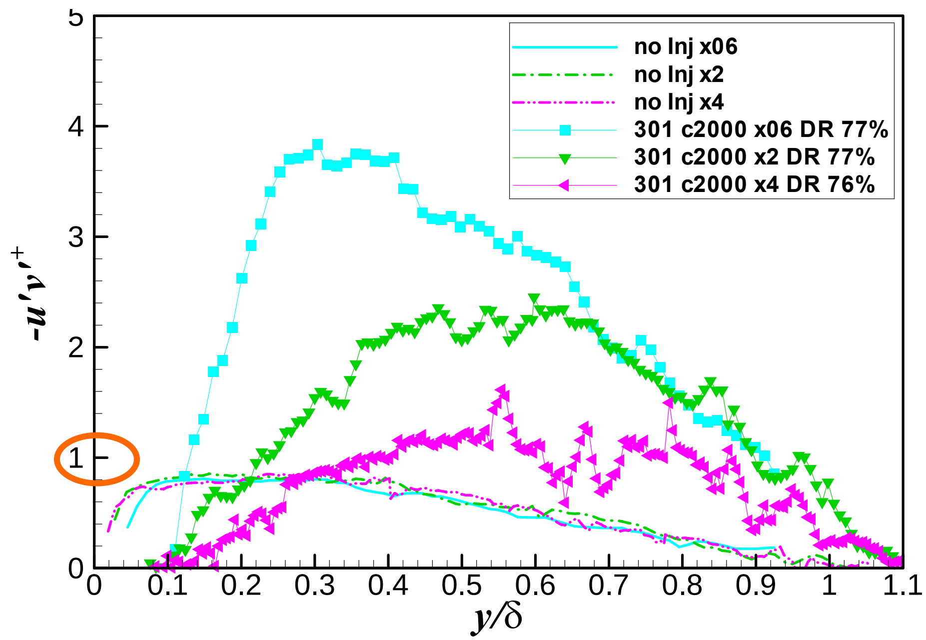
- **Part *(x06)* or whole *(x2, x4)* Reynolds stress is reduced**
- **Pos. *x06*: Mean vel. adjusted to drag reduction quicker than shear stress**
- **No polymer/polymer-effect away far from wall**

- **Higher Peak value of polymer flow at pos. *x06* → not equilibrium flow**
- **Same (unity) peak values at downstream positions**

Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; C_i=500 wppm; Q_i/Q_s=0.79; (Q_s=67.3ν)

Reynolds Shear Stress In Polymer Flow – 2000 ppm





- **Part *(x06)* or whole *(x2, x4)* Reynolds stress is reduced**
- **Pos. *x06*: Mean vel. adjusted to drag reduction quicker than shear stress**
- **No polymer/polymer-effect away far from wall**

- **Higher Peak value of polymer flow at all positions**
  → non-equilibrium flow

Poly-Ethylene Oxide (PEO) WSR-301
U=0.5 m/s; C_i=2000 wppm; Q_i/Q_s=0.75; (Q_s=67.3ν)

Non-Equilibrium Effects in BL

Weak relaminarization of a BL by strong convective acceleration - White (1991):

- "… the turbulence does not disappear, but mean parameters such as the velocity profile and skin friction approach laminar values."
- "Turbulence becomes smaller only in an absolute sense: (-u'v') remains almost constant during the laminarization process but is a sharply decreasing fraction of the stream energy U^2"

“Relaminarization”

Experimental investigation of streaky structures in a relaminarizing boundary layer
Alessandro Talamelli, Nicola Fornaciari, K Johan A Westin and P Henrik Alfredsson, JoT (2002)

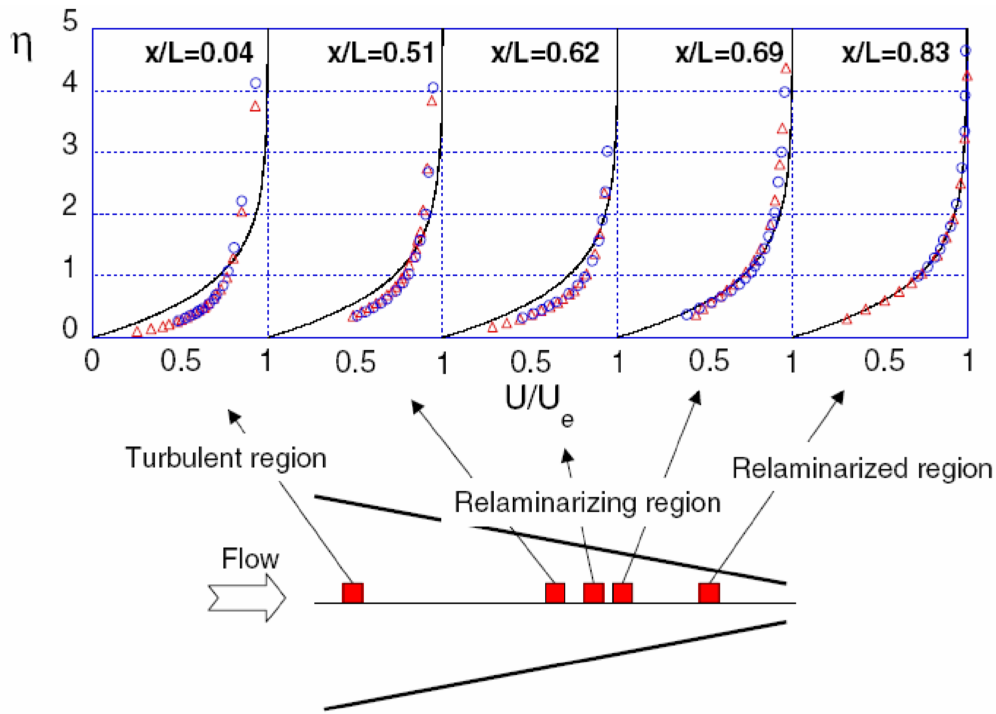


Figure 5. Mean velocity profiles versus non-dimensional wall coordinate η at different streamwise positions: (○): low level of FST; (△): high level of FST; (——): self-similar solution.

“Relaminarization”

Experimental investigation of streaky structures in a relaminarizing boundary layer
Alessandro Talamelli, Nicola Fornaciari, K Johan A Westin and P Henrik Alfredsson, JoT (2002)

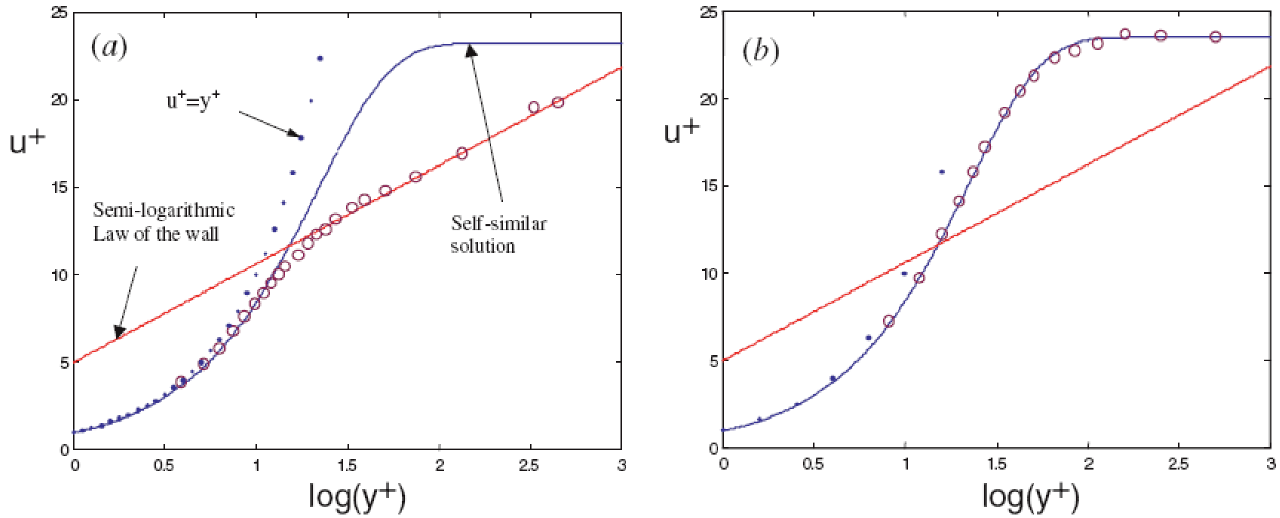
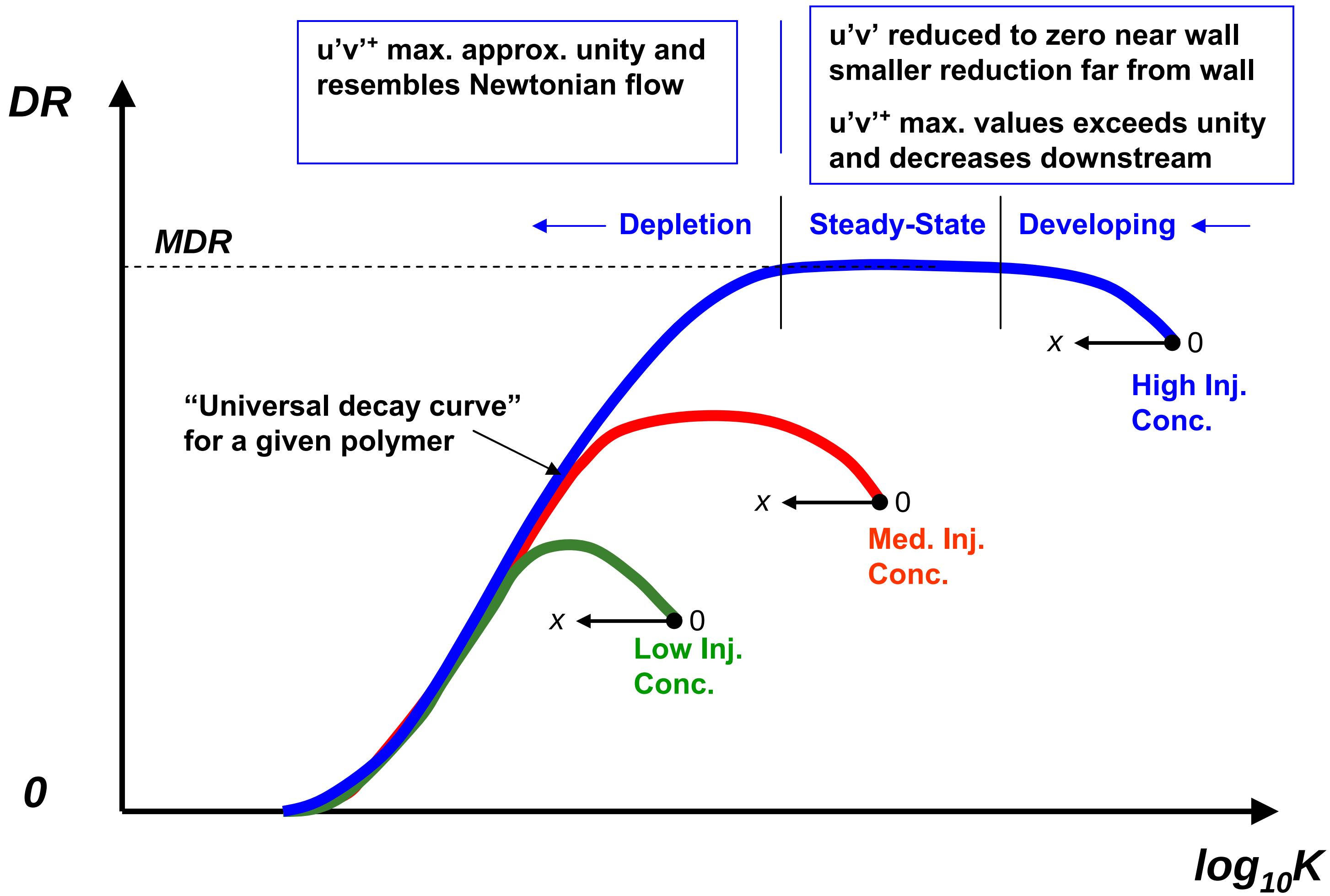


Figure 6. Mean velocity profile in wall-coordinates. (*a*) Turbulent region ($x/L = 0.04$). (*b*) Re-laminarized region ($x/L = 0.83$); (○): measured data; ——: self-similar solution; - - - -: $u^+ = 1/0.38^* \log(y^+) + 4.1$; ······: $u^+ = y^+$.

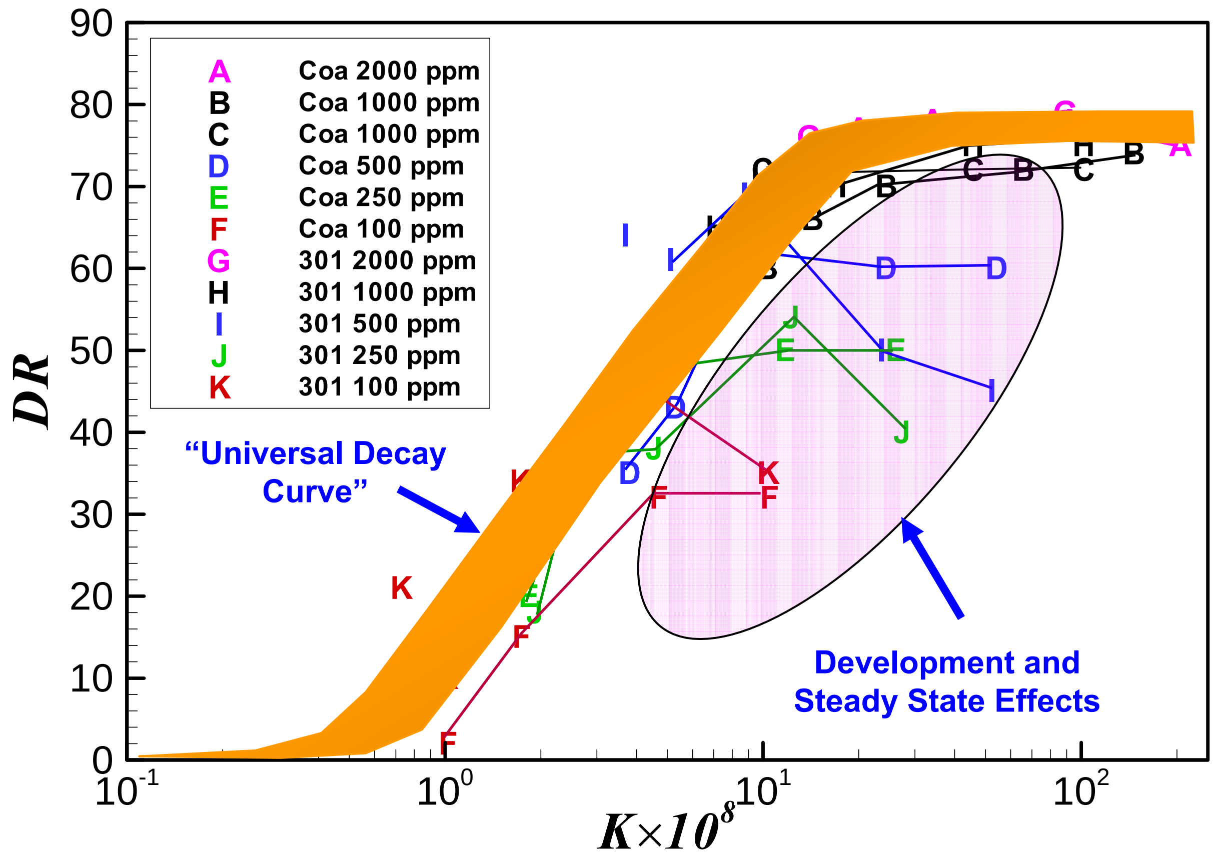
- **the streak spacing increases from about $60l^+$ in the turbulent region to about 150–180l^+ at the end of the contraction.**

Summary of Velocity Results



The three DR regions are sketched for the high injection concentration only

Summary of Results - Improved



- More careful interpretation of scatter of data
  - ➢ Universal curve to left
  - ➢ Development effects to right

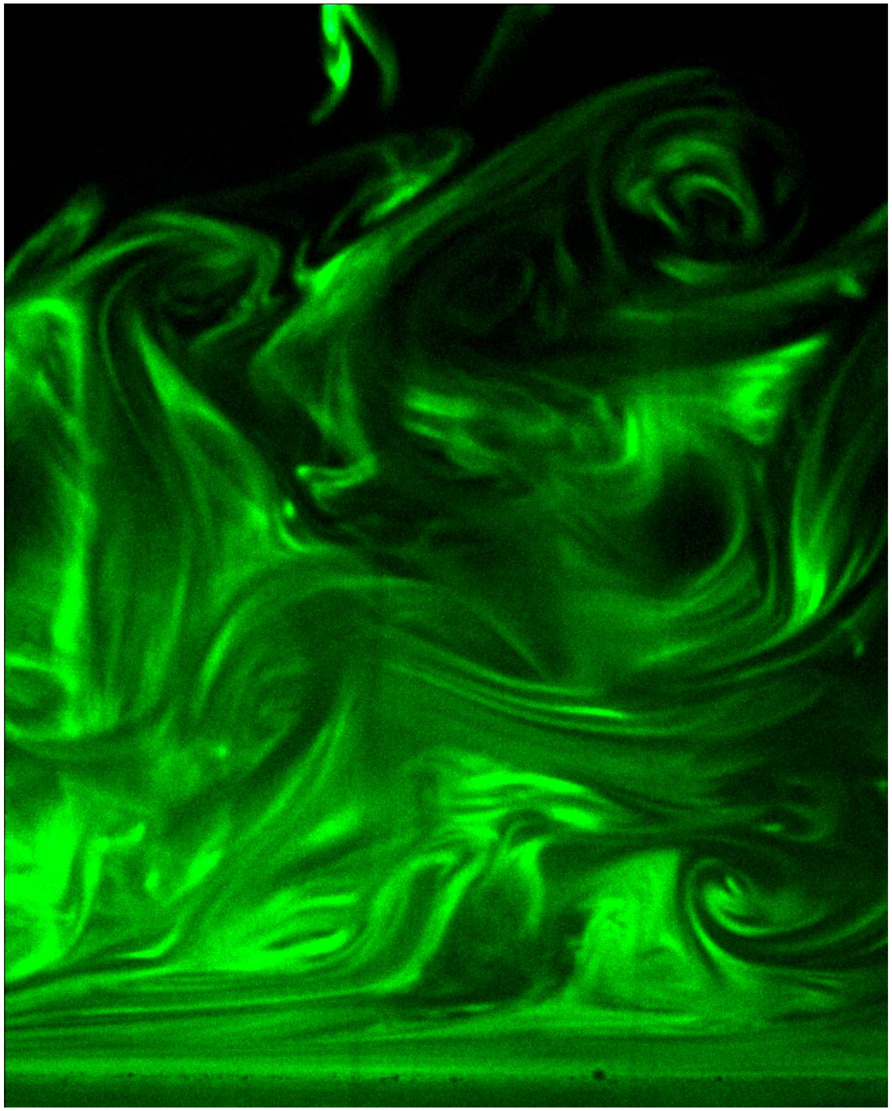
Summary

Studied evolution of DR due to polymers in a TBL on a flat plate

- **Development, steady-state and depletion regions**
  - ***DR* vs. *K* plot for TBL**
- **Mean velocity profiles****
  - **shift upwards , then rotate to MDR asymptote**
  - **responds quickly to injection**
- **Rms profiles****
  - **unormalized u_{rms} ↑, v_{rms} ↓ but normalized ↑**
- **Re-stress**
  - **reduces to zero close to wall, then entire BL**
  - **Non-equilibrium BLs possible, $-u'v'^{+} > 1$**
  - **Re-stress lags velocity development**
- **Some similarity to relaminarization in accelerating TBL**
- **Reinterpret the *DR* vs. *K* plot to exclude the development and steady-state regions**

** - similar to homogeneous channel flows**

Thank you!



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