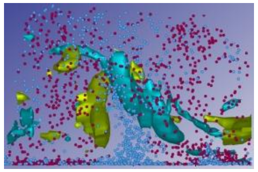

5th Joint MC/WG Meeting and SIG43 Workshop

Drag reduction by fibers and polymers: open issues

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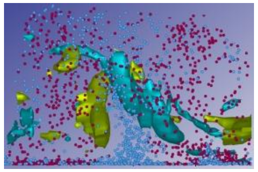
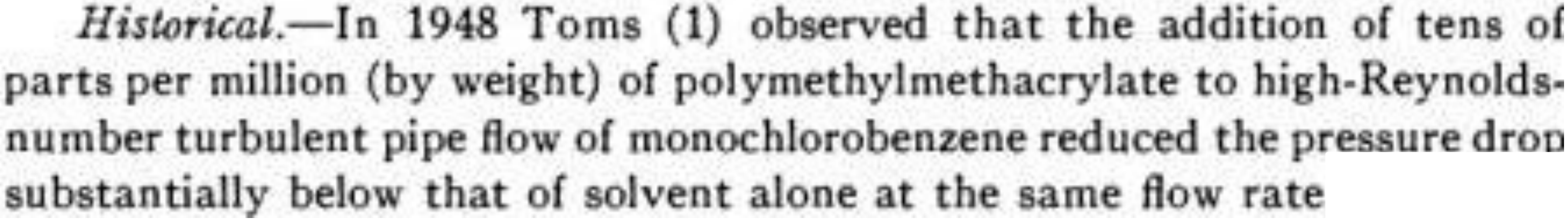
Coimbra, 5-8 March, 2013

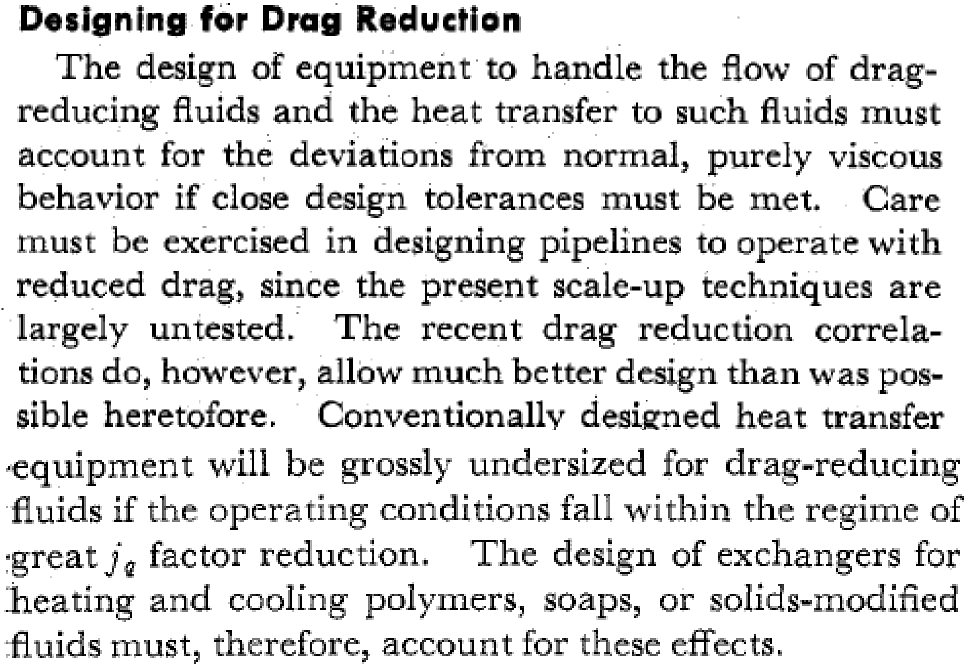


Drag reduction in pipe



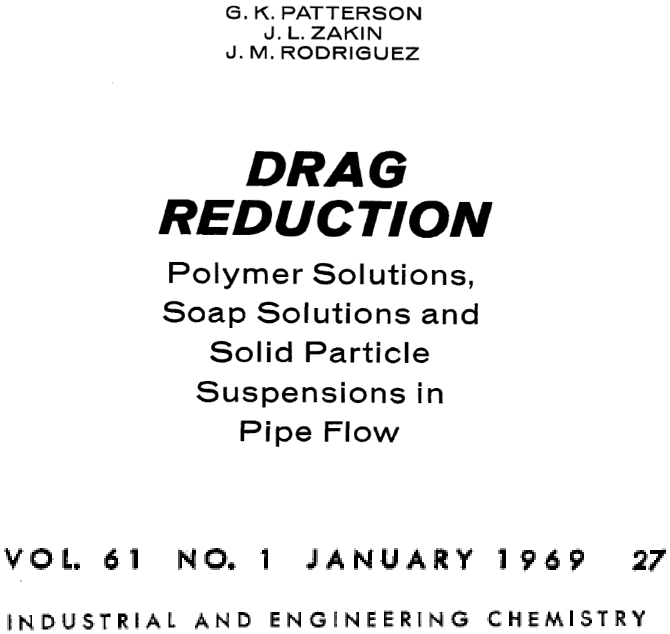
Historical.—In 1948 Toms (1) observed that the addition of tens of parts per million (by weight) of polymethylmethacrylate to high-Reynolds-number turbulent pipe flow of monochlorobenzene reduced the pressure drop substantially below that of solvent alone at the same flow rate

This means lower pumping costs with same through-put or larger through-put with same pumping costs, but also:



Designing for Drag Reduction

The design of equipment to handle the flow of drag-reducing fluids and the heat transfer to such fluids must account for the deviations from normal, purely viscous behavior if close design tolerances must be met. Care must be exercised in designing pipelines to operate with reduced drag, since the present scale-up techniques are largely untested. The recent drag reduction correlations do, however, allow much better design than was possible heretofore. Conventionally designed heat transfer equipment will be grossly undersized for drag-reducing fluids if the operating conditions fall within the regime of great j_q factor reduction. The design of exchangers for heating and cooling polymers, soaps, or solids-modified fluids must, therefore, account for these effects.



G. K. PATTERSON
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DRAG REDUCTION

Polymer Solutions,
Soap Solutions and
Solid Particle
Suspensions in
Pipe Flow

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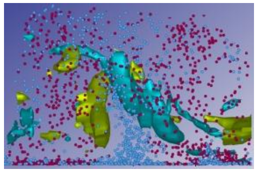
INDUSTRIAL AND ENGINEERING CHEMISTRY



How has been quantified/measured?

Macroscopically: from gross flow variables, Q, ΔP

$$DR\% = 100 \cdot \frac{\Delta P_N - \Delta P_A}{\Delta P_N}$$

Sharma, Canadian J. Chem. Eng., 1981

$$DR\% = 100 \cdot \frac{Q_A - Q_N}{Q_A}$$

Den Toonder et al., J. Fluid Mech., 1997

$$DR\% = 100 \, \frac{(\Delta T / \Delta t)_N - (\Delta T / \Delta t)_A}{(\Delta T / \Delta t)_N}$$

Amarouchene et al., Pys. Fluids, 2008

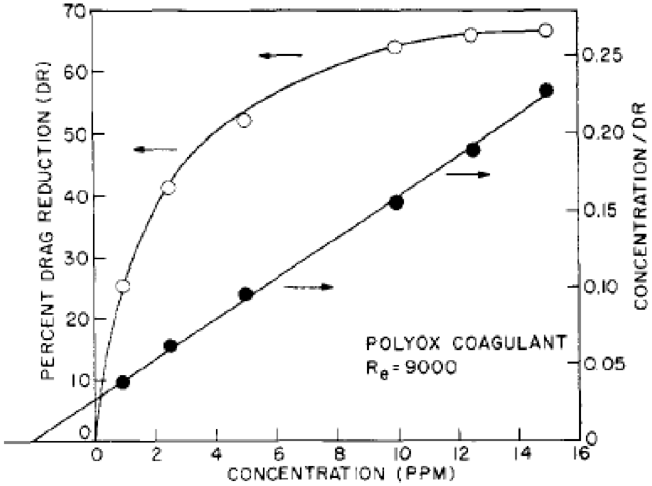
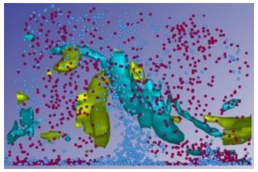


Figure 4. Drag reduction of polyox coagulant, concentration dependence and conformity to the universal drag reduction relation

Little et al., Ind.Eng. Chem. Fundam., 1975

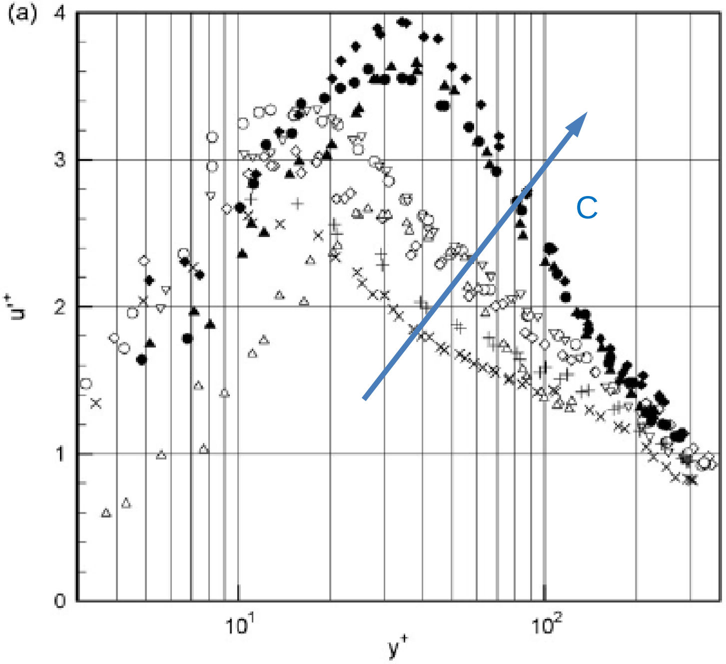


How has been quantified/measured?

Microscopically: from changes in velocity profile & turbulence intensity

$$\bar{u}^{+} = 2.5\log(y^{+}) + 5.5$$

$$\bar{u}^{+} = 2.5\log(y^{+}) + 5.5 + \Delta$$



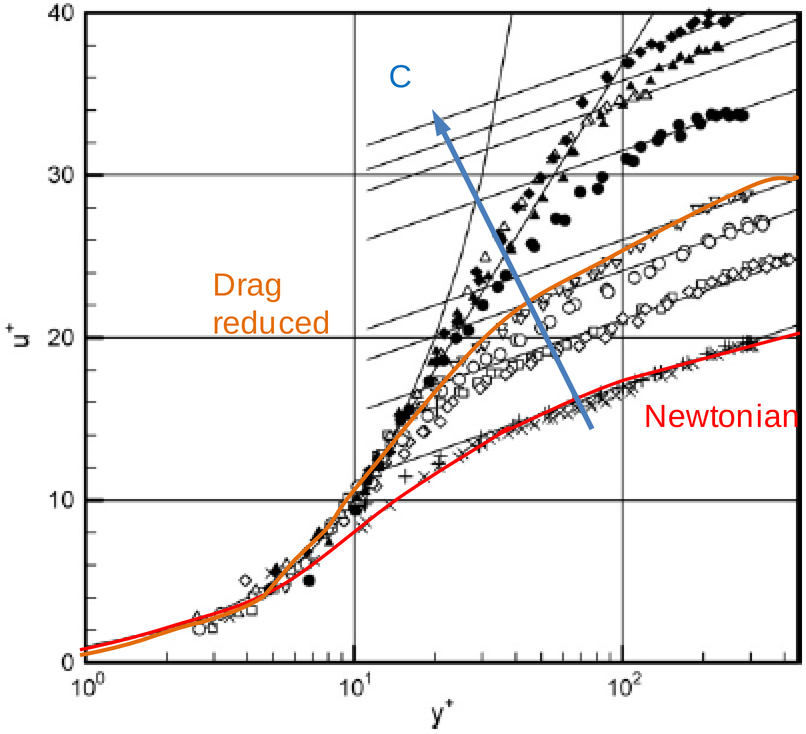
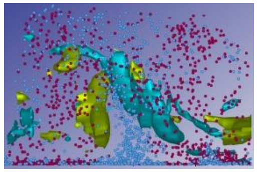


Fig. 5. Mean velocity profiles in wall coordinates u^+ vs log y^+ for all data: + water, × glycerol, □ 0.03% XG, ◊ 0.05% XG, ○ 0.067% XG, ▽ 0.08% XG, △ 0.15% XG, ● 0.01% PAA, ◆ 0.03% PAA, ▲ 0.05% PAA. Associated flow parameter values are listed in Table 3.

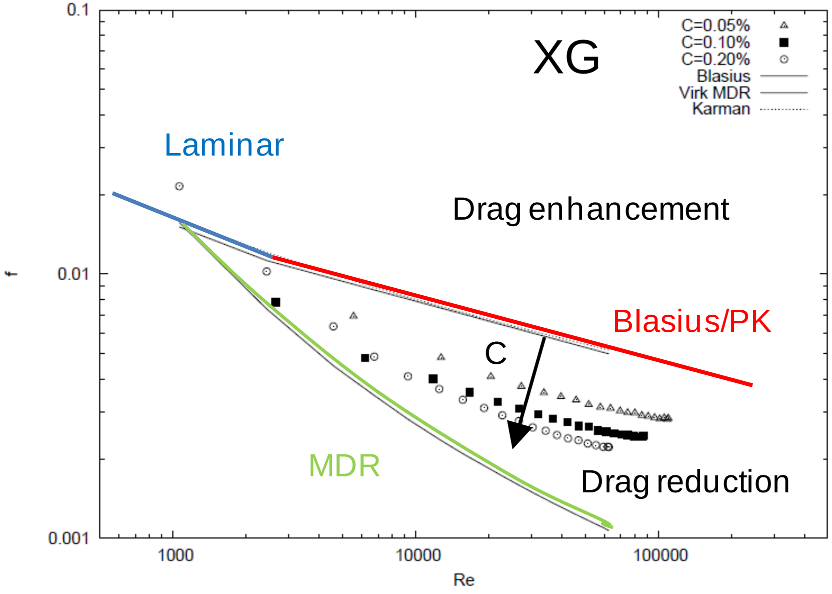
Escudier et al., J. Non Newtonian Fluid Mech., 2009

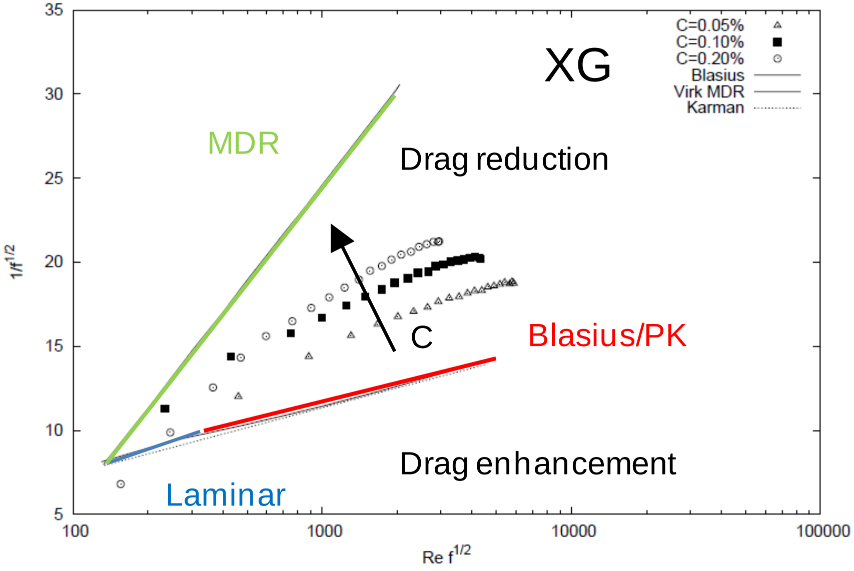


Other graphical representations usually adopted

f-Re coordinates

Prandtl-Karman coordinates





Laminar/Blasius friction factor

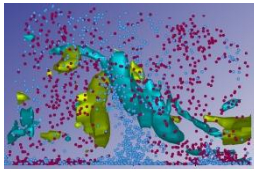
$$f=\frac{16}{\mathrm{Re}};\ f=0.079\cdot\mathrm{Re}^{-0.25}$$

Prandtl-Karman

$$\frac{1}{\sqrt{f}}=4.\cdot\log_{10}(\mathrm{Re}\cdot\sqrt{f})-0.4$$

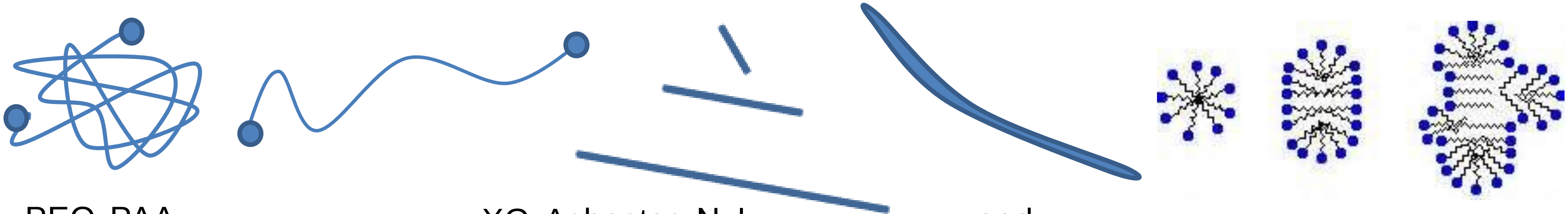
MDR = Maximum Drag Reduction

$$\frac{1}{\sqrt{f}}=19.\cdot\log_{10}(\mathrm{Re}\cdot\sqrt{f})-32.4$$



A very similar effect is produced by polymers, fibers, surfactants…

	Polymers	Fibers	Surfactants
Concentration w/w	10^{-6} (ppm)	10^{-3}	>MMC
Size	$< \eta$	$> \eta$	variable
Degradation	Significant, irreversible	Less significant, irreversible	reversible
Flexibility	Depends on chemical structure & solvent	Depends on aspect ratio/fiber meterial	Large
	Coiled/stretched Flexible/rod-like	Rigid/flexible	Dynamic change in cluster size

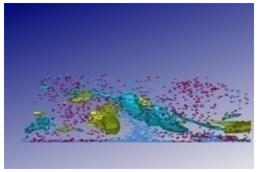


PEO, PAA

XG, Asbestos, Nylon, …

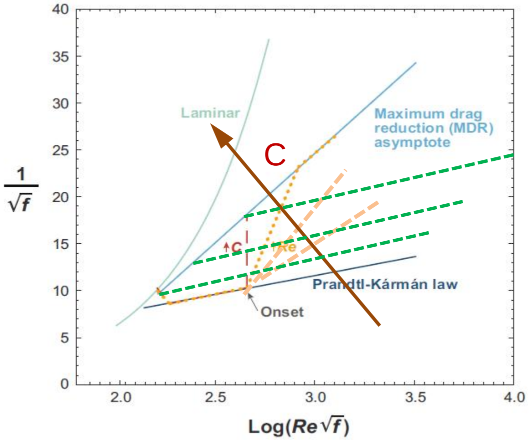
wood

surfactant

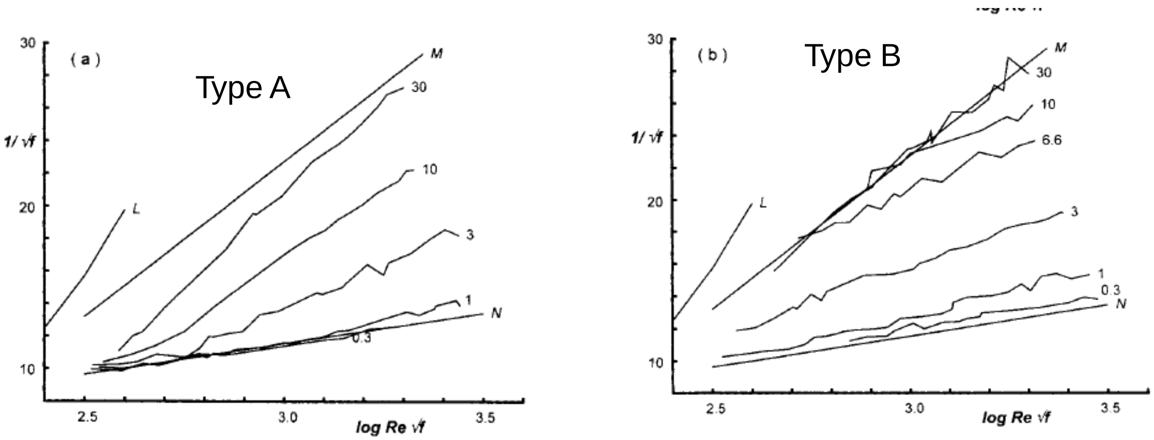


Experimental approach

Effect of polymer type (M_w), concentration, solvent (tap/distilled water), pipe diameter



White & Mungal, Annu. Rev. Fluid Mech., 2008



Virk et al., AIChE J., 1997

Effect of fiber length, concentration, pipe diameter, injection mode (boundary/central)

Sharma, Canad. J. Chem. Eng. 1981

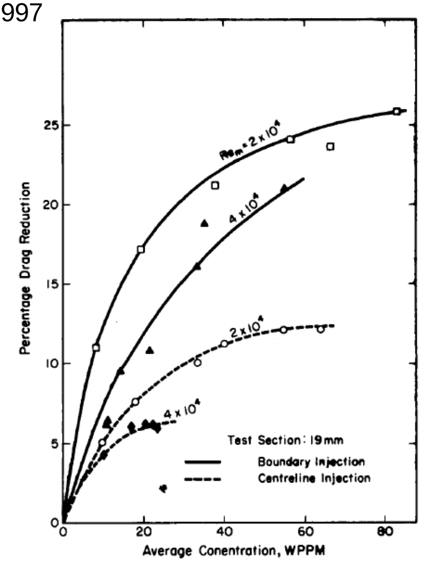


Figure 10 – Comparison of drag reduction by boundary and centerline injections of fibers in the 19 mm pipe.

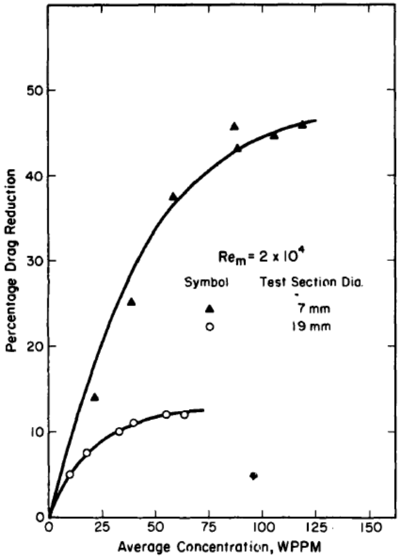
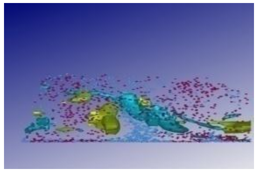


Figure 11 – Diameter effect on drag reduction by centerline injection of fibers.



Numerical approach (I)

Coupled simulation: DNS of flow + rigid-rodlike polymer (SG) [or short, rigid fibers!]

$$\frac{\partial u_i}{\partial x_i} = 0,$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j},$$

$$\tau = \tau^N + \tau^F = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \boxed{+ \tau^F}.$$

$$\tau^f_{ij} = 2\mu\phi\big[2AE_{lk}a_{ijkl} + 2B(E_{ik}a_{kj} + E_{kj}a_{ik}) + CE_{ij} + Fd_r\, a_{ij}\big],$$

Paschkewitz et al., Phys. Fluids, 2005

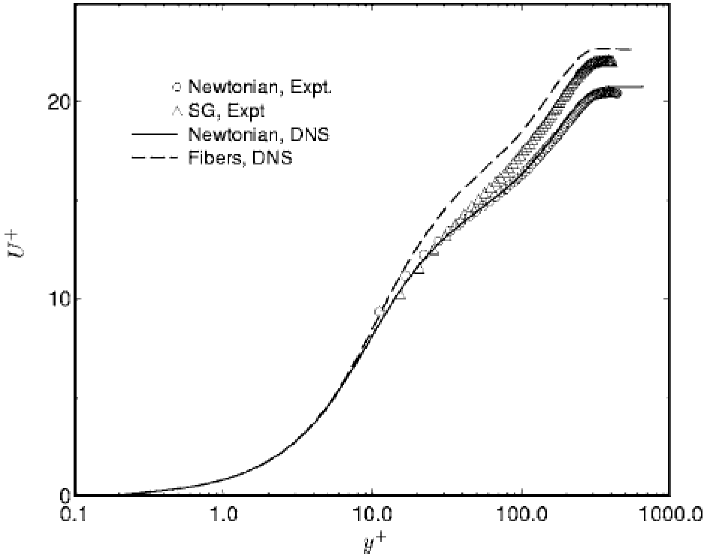
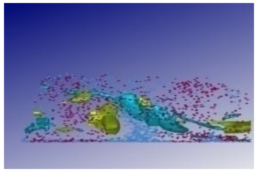


FIG. 21. Comparison of experimental and numerical mean streamwise velocity profiles at a position $23\delta_{inlet}$ from the inlet.

A, B and C(r_e), r_e “effective” aspect ratio of extended polymer
A, B and C(r), r aspect ratio of fibers



Numerical approach (II)

Coupled simulation: DNS of flow + FENE-P (finitely extensible non linear elastic) for extensible polymers

$$\frac{\partial u_i}{\partial x_i}=0,$$

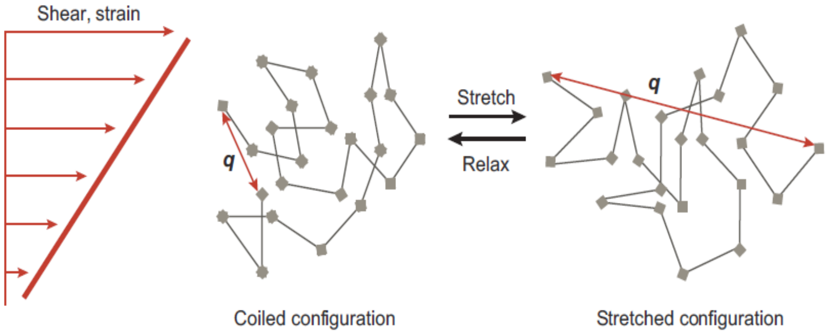
$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\beta}{Re_{\tau o}}\frac{\partial^2 u_i}{\partial x_j^2}+\underbrace{\frac{(1-\beta)}{Re_{\tau o}}\frac{\partial \tau_{ij}}{\partial x_j}}_{f_i}+\delta_{i1},$$

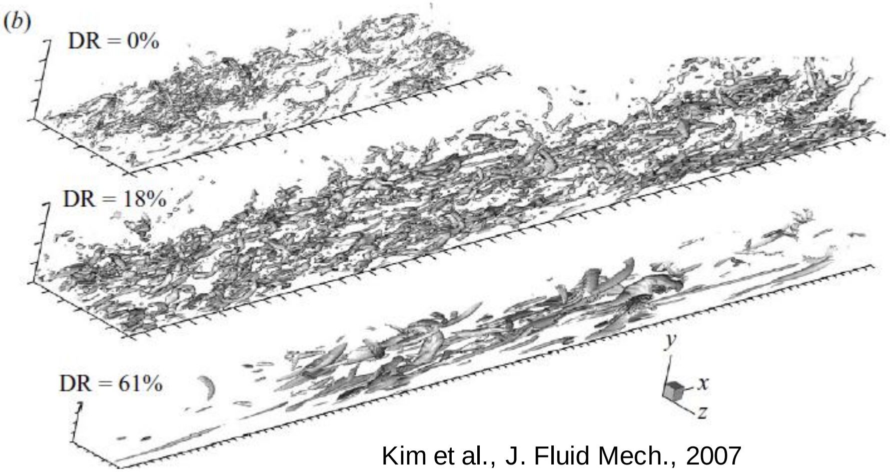
$$\frac{\partial c_{ij}}{\partial t}+u_k\frac{\partial c_{ij}}{\partial x_k}=c_{ik}\frac{\partial u_j}{\partial x_k}+\frac{\partial u_i}{\partial x_k}c_{kj}-\underbrace{\frac{Re_{\tau o}}{We_{\tau o}}\left(\frac{L^2-3}{L^2-c_{kk}}c_{ij}-\delta_{ij}\right)}_{\tau_{ij}}$$

τ_{ij} , polymer stress

c_{ij} , conformation tensor (average second moment of q, end to end vector distance

$We_{\tau 0} = \lambda\, u_t^2/\nu_0$ polymer relaxation time/flow time scale



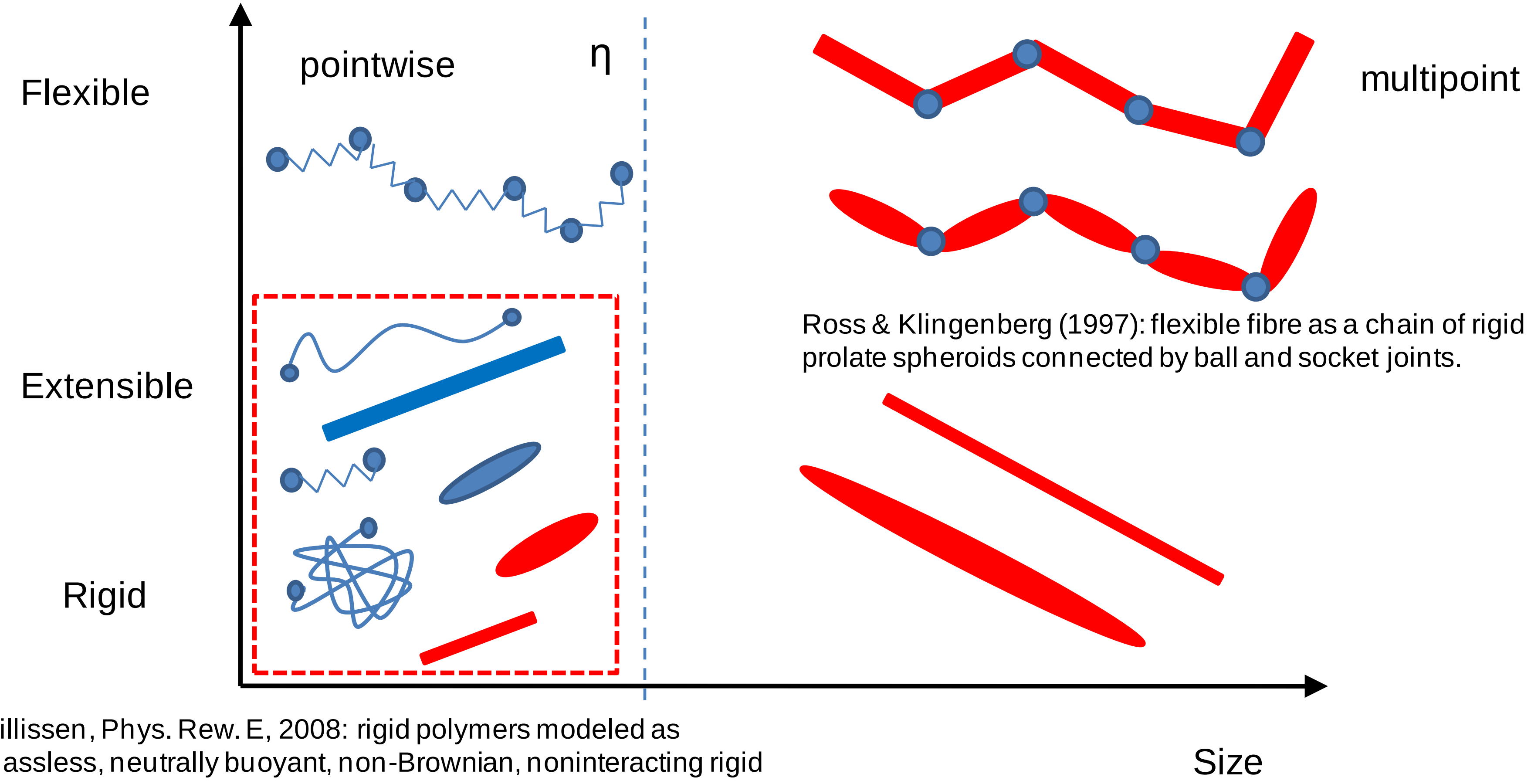


Kim et al., J. Fluid Mech., 2007

Numerical approach (III)

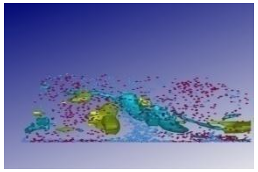
Yamamoto & Matsuoka (1992):
flexible fibre as a chain of spring-linked spheres.

Schmid, Switzer & Klingenberg (2000):
flexible fibres as chains of rigid rods.



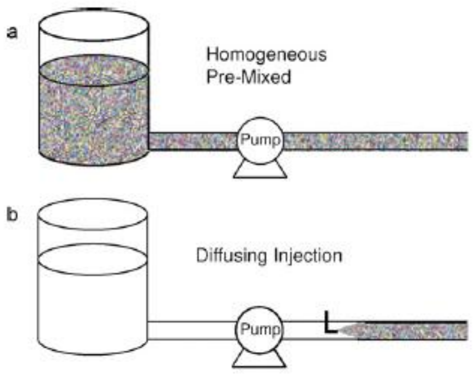
Ross & Klingenberg (1997): flexible fibre as a chain of rigid prolate spheroids connected by ball and socket joints.

Gillissen, Phys. Rew. E, 2008: rigid polymers modeled as massless, neutrally buoyant, non-Brownian, noninteracting rigid dumb-bells; flexible polymers are modeled as finitely extensible nonlinear elastic dumb-bells (FENE-P)



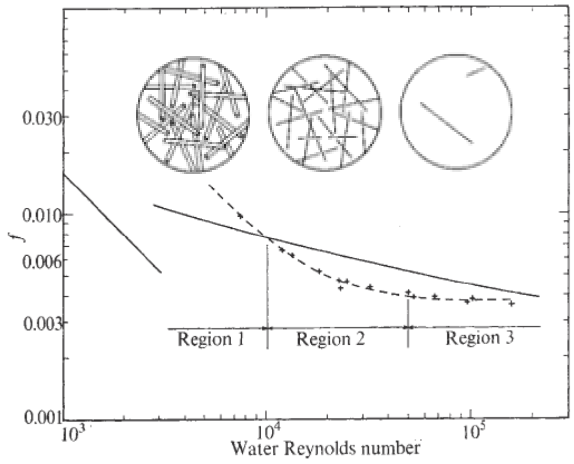
What is current knowledge…

Amarouchene et al., Phys. Fluids, 2008; Sreenivasan & White, J.Fluid Mech., 2000, Wyatt et al., J. Non Newtnian Fluid Mech, 2011



Polymer drag reduction depends on

- polymer type (M_w, radius of gyration, characteristic relaxation time vs flow time scale)
- solvent environments (salt free versus salt solution)
- delivery configurations (homogeneous versus stock solution dilution).
- Method of preparation of polymer mixture (dilution of entangled solution/solutions prepared in the dilute regime)
- Polymer concentration (above/below critical concentration DR in unaffected by solvent)
- Degradation of DR depends on polymer flexibility and preparation mode



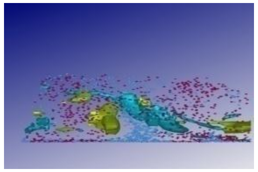
Radin et al., Nature Phys. Sci, 1973

Fiber drag reduction

- depends on size/aspect ratio
- depends on concentration and flow regime (dilute, semi-dilute, concentrated/dense)
- shows a maximum before ‘’clogging’’ of pipe

Fiber +Polymer

Bilgen & Boulos (Can.J.Chem. Eng., 1973) “The use of friction reducing additives **(**PEO, GG) in the turbulent flow of paper making fibre suspensions results in a friction reduction comparable to that in water and the quality of fibre suspensions can be improved”



… and what we need to understand better

Rheological characterization of polymer/fiber/solvent mixtures

- Which is the best approach to measure effective viscosity?

Polymer

- Effect of additives (salt, other chemicals) on polymer configuration
- Effect of pipe size on drag reduction
- Effect of polymer degradation over time

Fibers

- Effect of size/aspect ratio on drag reduction
- Effect of size/pipe diameter on drag reduction
- Clogging limit

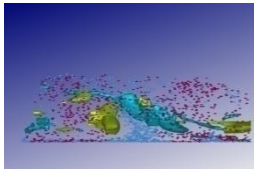
Fibers + Polymers

- Which is the effect of polymers on DR in fibers suspension?
- Any practical benefit to intensify pulp & paper processes?

Fibers + surfactants + polymers

- Which is the benefit of using surfactants to improve fiber dispersion? Any interaction with drag reducing polymers? Can pulp consistency be improved in this way?

Gross flow data and microscopic data both necessary!!



Benchmark test proposal

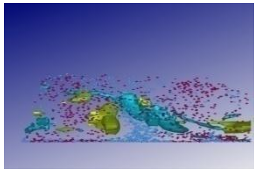
Benchmark experiment (to be proposed at WG1 Meeting):
Perform systematic tests according to a matrix of (previously agreed on) parameters to build incremental knowledge on DR in fiber suspensions

Many research groups participating with their own facilities (different circulation loop, different methodologies used for rheological characterization of test mixtures, different techniques available for the acquisition of gross flow parameters and local velocity/turbulence/concentration data)

Benefits:
Controlled condition (+ few degrees of freedom)
(shared testing protocol + one common test based on one polymer and model fibers to assess “inter-labs equipment variability”)
→ Reliability of results

Reduced set of parameters selected for testing by each lab
(one polymer type, one fiber material for benchmark and additional “free” tests)
→Not too large time spent for testing

Agreed on format for reporting of tests results
→Large data-base available to participants: extra considerations possible
  -Any effect of pipe diameter ?
  -Any effect on polymer/fiber degradation due to pumping devices available?
  -…



Benchmark test steps

Step 1:

XG or any other polymer (MFC?) with “certified” characteristics (known, sharp M_w distribution):

1. Characterization of mixture apparent viscosity
2. Evaluation of ΔP vs Q in defined range of Re numbers
3. Inter-comparison of results and comparison against literature data
4. Feed-back to labs on differences

(OPTIONAL) extra test with other polymer (e.g. rigid/flexible) or solvent (e.g. tap/distilled water) of interest for the local lab

Step 2:

Model fibers (Nylon or Polyammide, fixed dtex, d_f , different cut-length/aspect ratio)

1. Characterization of mixture apparent viscosity
2. Evaluation of ΔP vs Q in defined range of Re numbers
3. Inter-comparison of results and comparison against literature data
4. Feed-back to labs on differences

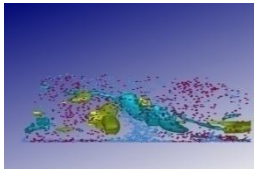
(OPTIONAL) Additional Model fibers of interest for the lab (e.g. for a specific application)

Step 3:

Reference Fiber + polymer mixture (step 1 and 2)

1. Characterization of mixture apparent viscosity
2. Evaluation of ΔP vs Q in defined range of Re numbers
3. Inter-comparison of results and comparison against literature data (if any)
4. Feed-back to labs on differences

(OPTIONAL) Additional fiber and polymer combination of interest for the lab (e.g. pulp fibers and PAM)



Milestone and deliverables

Date	Milestone	Deliverables
March, half	Invitation to labs potentially interested in participating; collection of data on equipment available and tests to be performed	
April, 1st week	Feedback to labs enrolled; revision and approval of the test matrix	
April, end	Collection of results of rheological tests	
May, half	Feedback on rheological tests	Comments on results → Reccomendation /guidelines for rheological tests?
May, end	Collection of test results (reference polymer)	
June, half	Feedback on polymer tests	
June, end	Collection of test results on reference fiber	
July, half	Feedback on fiber tests	
July end	Collection of results on reference fiber+polymer	
August,half	Feedback on fiber+ploymer tests	
Sept, half	Discussion of results (validation data + OPTIONAL data)	Paper on benchmark tests + paper(s) from DB of OPTIONAL data (?)