Experiments on drag reduction by fibres in turbulent pipe flow

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FOM

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Outline

Background

Theory

Experimental set-up

Results & Interpretation

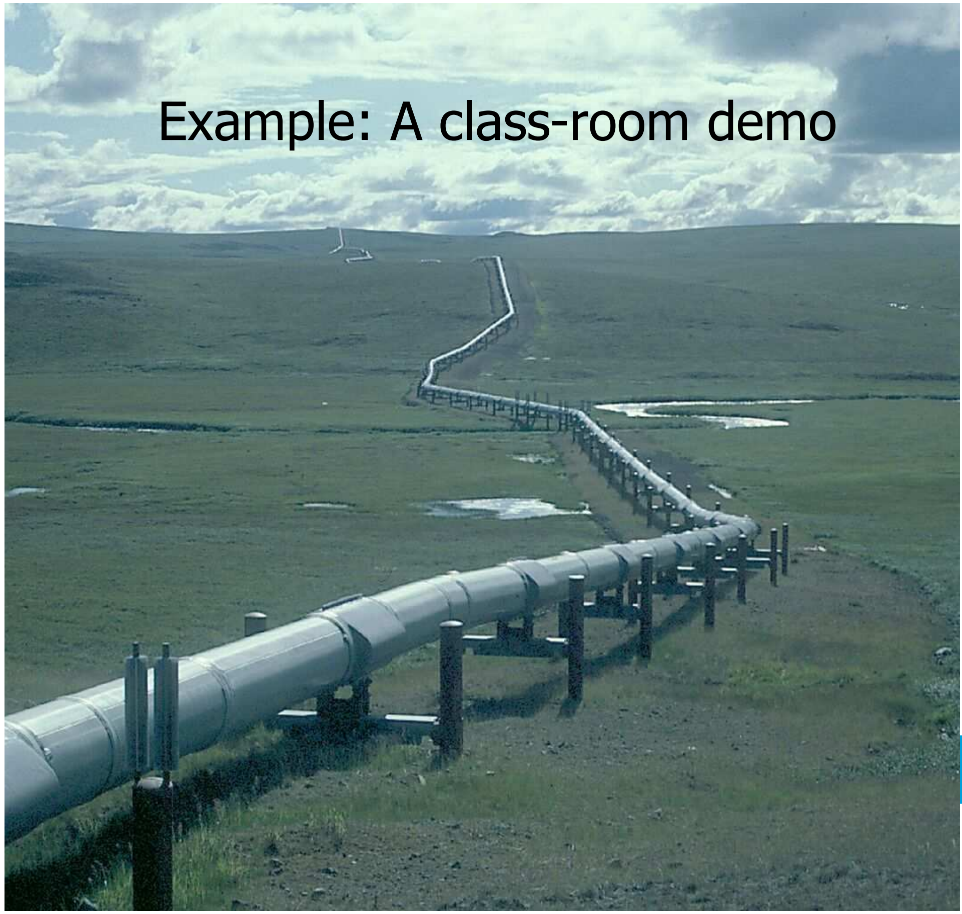
Conclusions & Recommendations

Background

Polymers used as drag reducers in liquid pipe transport

Can gas flow be improved using additives as well?

- Classical polymers do not dissolve in gases -> fibres?
- Fibres should be cheap & and safe & easy to handle



Cooperation TUDelft – NTNU
(Nieuwstadt, Andersen, Boersma
Gillissen, Mortenson;
various others)

- How to scale from 'point particles' to 'finite size'?
- What would then a possible mechanism for DR be?

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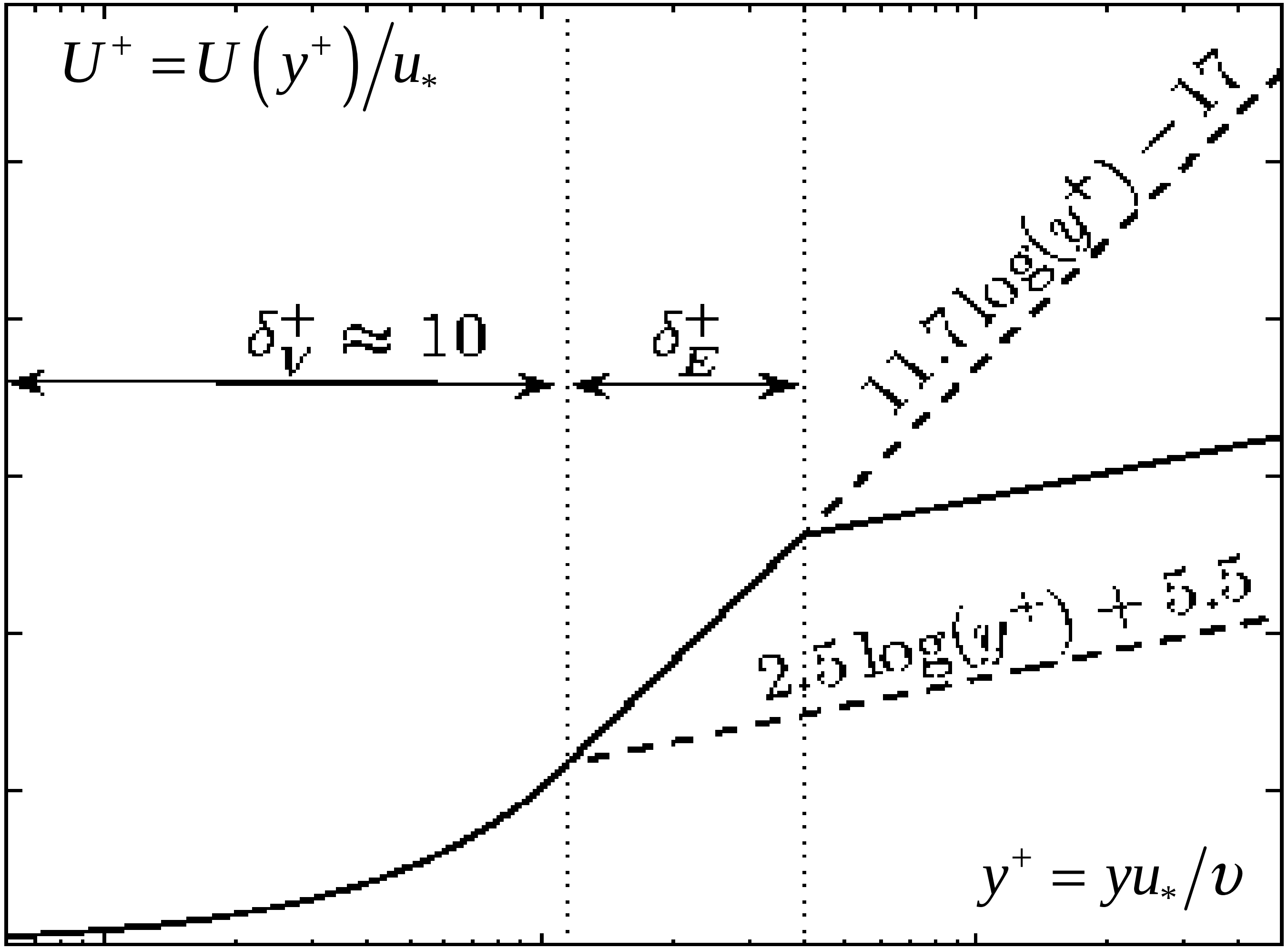
In Memoriam – Frans Nieuwstadt
April 8, 1946 – May 18 2005

Theory: Velocity profile in pipe flow

$$u_* = \sqrt{\tau_W / \rho}$$

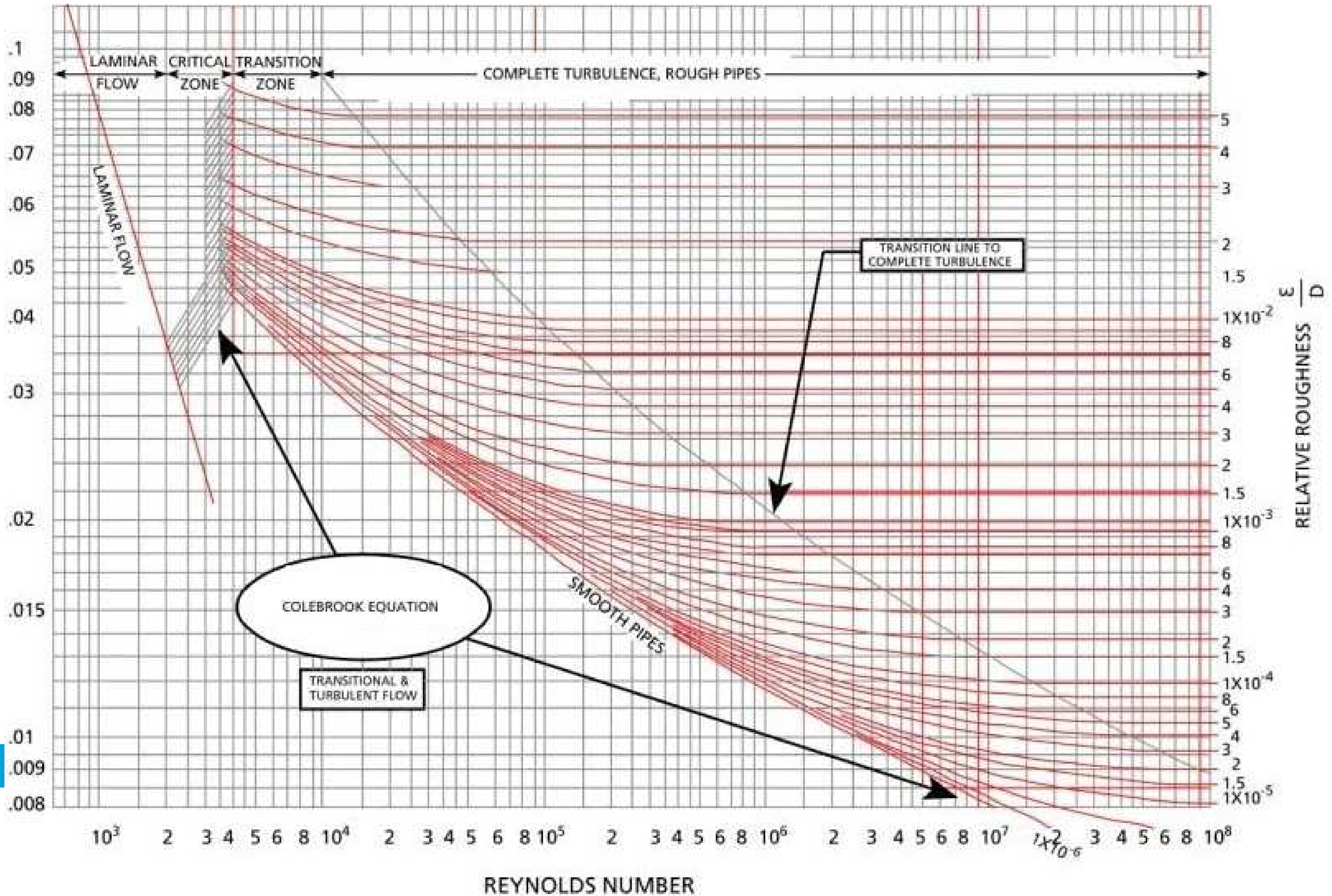
'friction velocity'



- Drag reduction?
  Shift of log-layer;
  thicker buffer-layer
  or 'Elastic layer'
- MDR / Virk?
  Elastic layer fills
  'complete pipe'

- With fibres??? Difficult to assess in a real flow;
  local measurement required in obscured pipe…

Theory: Bulk velocity in pipe flow



Theory: Bulk velocity in pipe flow

Flow rate - Pressure drop relation

$$\Delta P/\Delta L = \tfrac{1}{2}\rho U_B^2 \cdot f/D$$

$$f(\mathrm{Re}_B, e/D) = f(U_B D/\upsilon)$$

$$f = 0.316 * \mathrm{Re}_B^{-1/4}$$

Smooth pipe; moderate Re

- Moody plot

$$\tfrac{1}{2}\rho U_B^2 \cdot f/D = 4\rho u_*^2/D \rightarrow u_*/U_B = \sqrt{8f}$$

$$U_B/u_* = U^+ = g(\mathrm{Re}_*) = g(u_* D/\upsilon)$$

equivalent to Flow rate - friction velocity relation

- Prandtl-Kármán plot

Theory: Parameters in particle-laden flow

Inertia-to-viscosity: Reynolds

Response-to-Kolmogorov time: Stokes $St = \tau_P \left(\Delta\rho / \rho\right) / \tau_{Kol}$

Inertia-to-gravity: (densimetric) Froude $Fr = u_* / \sqrt{gD\Delta\rho/\rho}$

Fibre concentration by volume *c*, or number density, *n*

Fibre aspect ratio $r = l/d$

To simplify but keep essential, we use

a density matched system of water and nylon.

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Fibres: Suspension regimes

With increasing concentration *c*, or number density *n*:

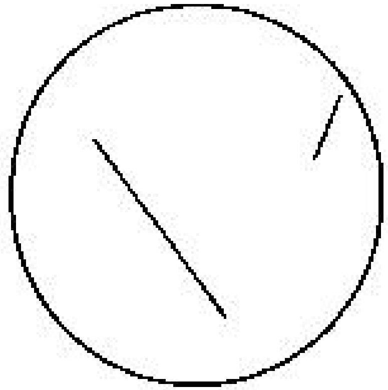
(a) <u>Dilute</u> $n \cdot l^3 = \left(n \cdot ld^2\right) \cdot \left(l/d\right)^2 = cr^2 \ll 1$

Distance between particles large

where c = *particle volume fraction*

and r = *particle aspect ratio* = l/d

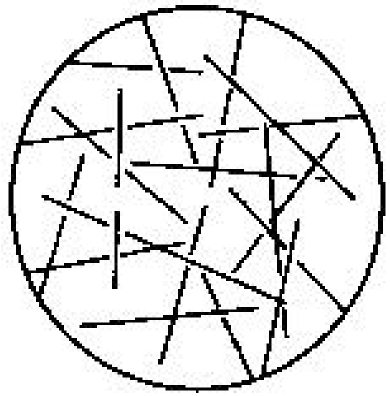
- <u>No drag reduction</u>



(b) Semi-dilute $cr^2 > 1; cr \ll 1$

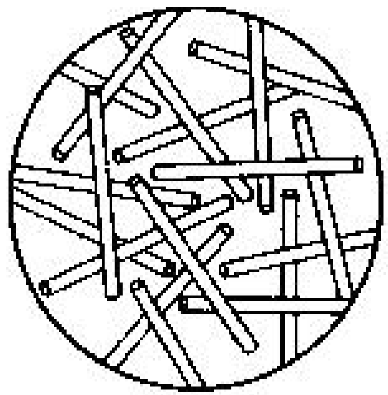
distance between particles of order particle diameter

- <u>Drag reduction</u>



(c) Concentrated / Dense; $cr > 1$

- <u>Clogging</u>



Theory: Drag reduction definitions

Pressure drop <u>decrease</u>:

$$DR\% = \frac{f_N - f_F}{f_N} = \frac{\Delta f}{f_N}$$

with *N* condition without fibers at equal bulk velocity (Re_B)

Flow rate <u>increase</u>:

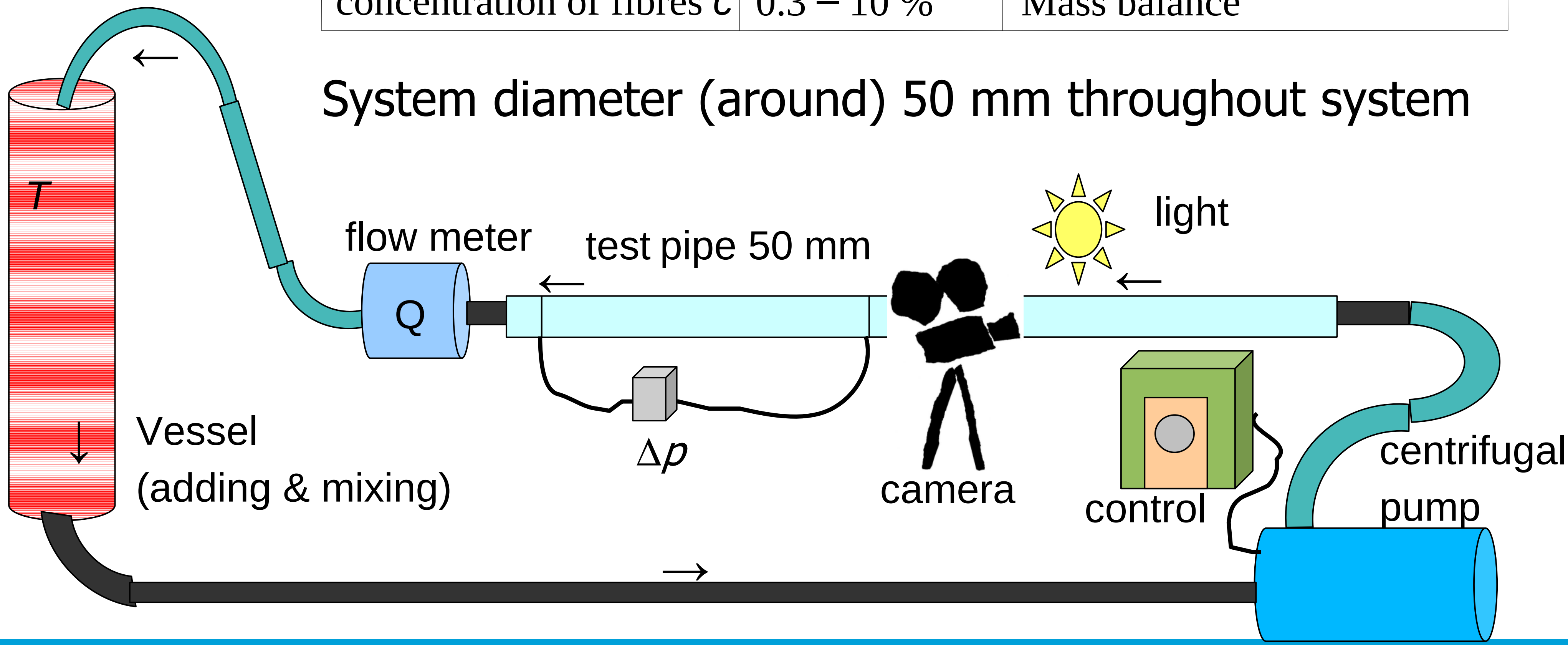
$$\Delta U^+ = \frac{U_N^+ - U_F^+}{u_*} = \frac{\Delta U^+}{u_*}$$

i.e at equal friction velocity (Re_*)

Set-up

Measured quantities	*Range*	*Devices*
Volume flux Q	0.3 - 6 l/s	Krohne Altometer IFS 4000
Pressure difference Δp	15 - 3500 Pa	Validyne DP15 & DP45
Temperature T	20 – 37 °C	Thermocouple
concentration of fibres c	0.3 – 10 %	Mass balance

System diameter (around) 50 mm throughout system

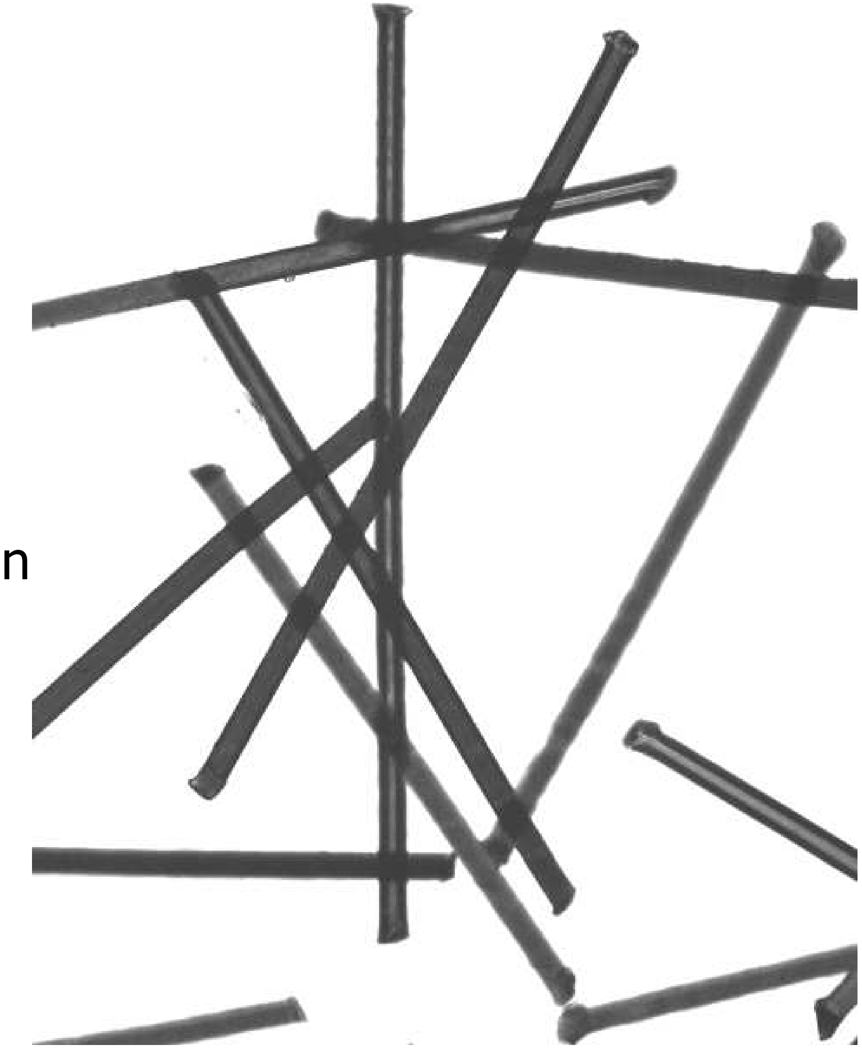


Fibres

Nylon from Swiss Flock:

+ precision cut; size well known
  mono-disperse (σ =10%
+ low density; near neutral buoyancy
  inertia negligible
+ high resistance to abrasion; no visible degradation
+ low absorption of water
+ rigidity no elongation
  bending ???
+ round cylinders; of density ρ = 1090 kg/m^3

coating	*l* (mm)	*d* (μm)	*D/l*	*r* = *l/d*
black	0.5	10	100	49
no	1	10	50	98
no	2	10	25	195
no	4	10	12.5	390 **'Spaghetti'**
no	0.5	19.5	100	26
black	1	19.5	50	51
no	2	19.5	25	102



Microscope image,

L=0.5 mm, d=19.5 μm

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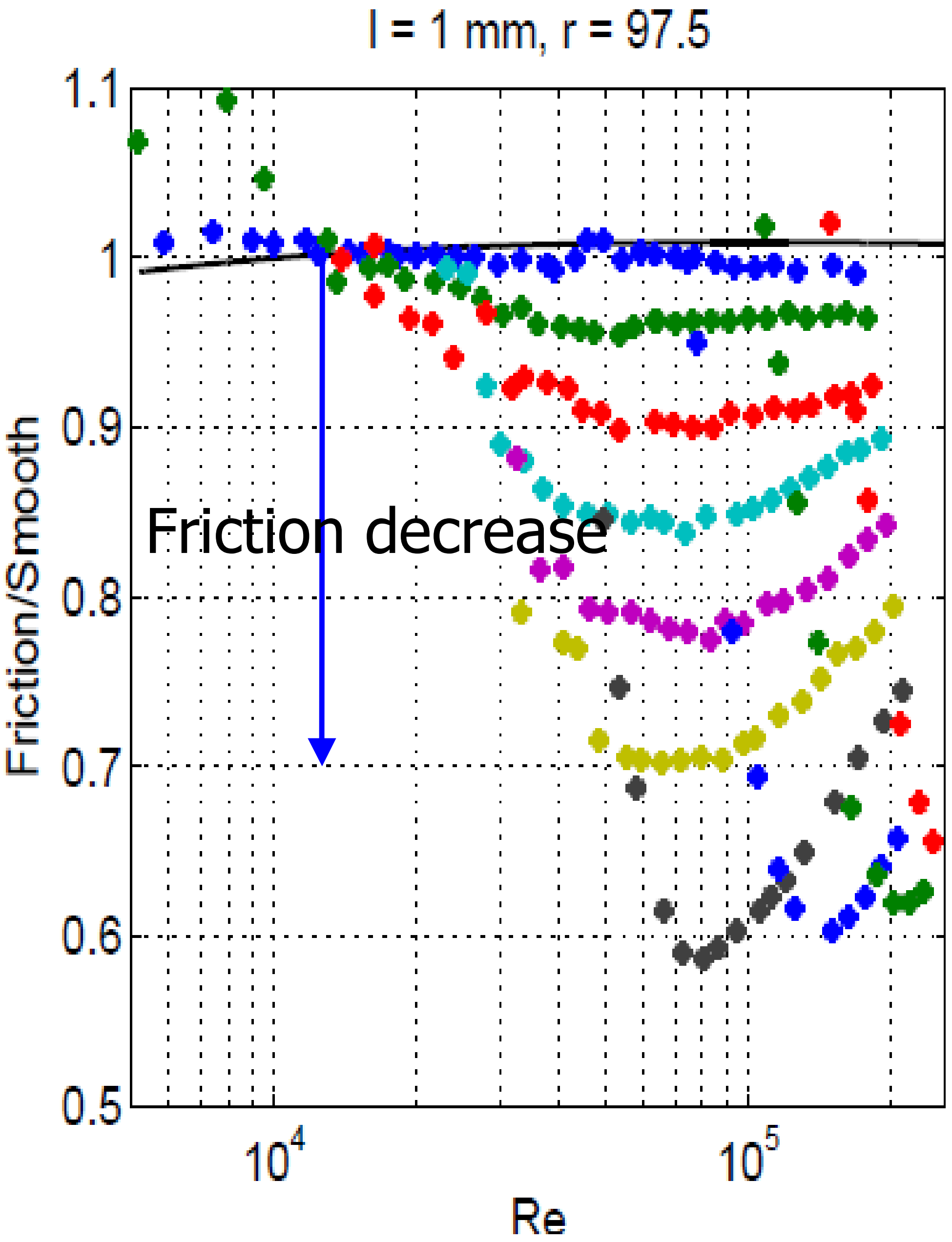
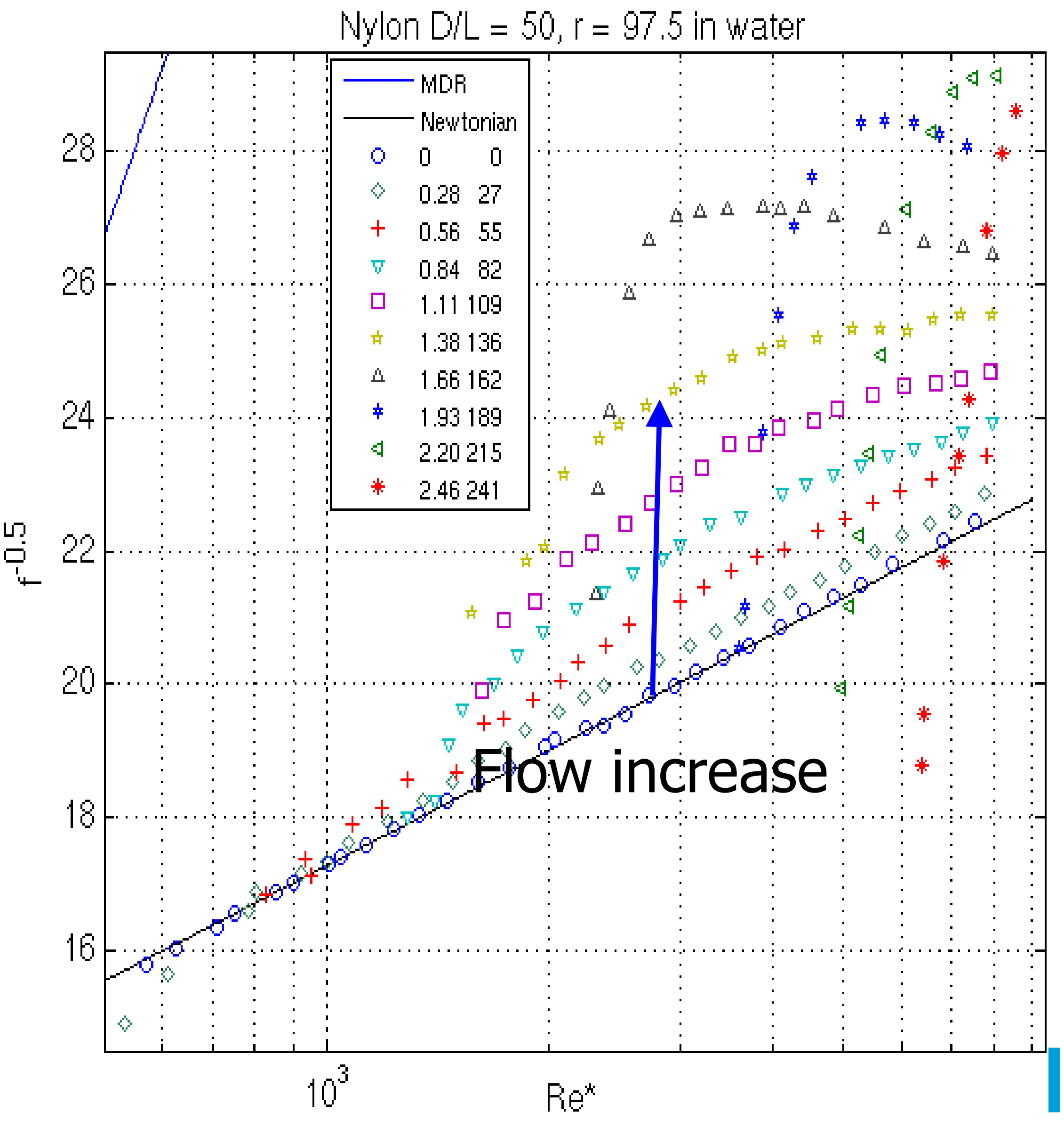
Results: 'Moody' vs 'Prandtl-Kármán'





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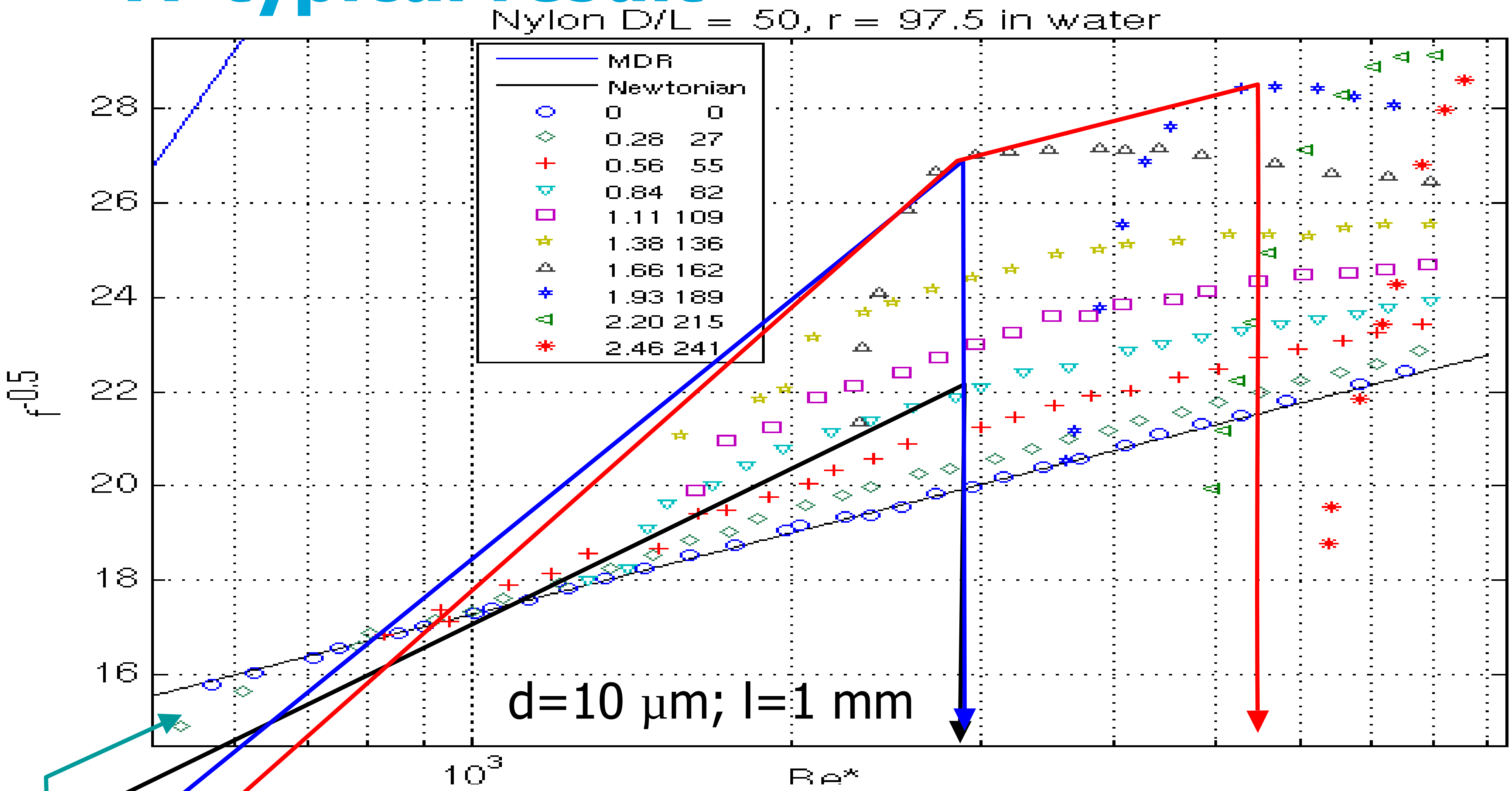
A 'typical result'

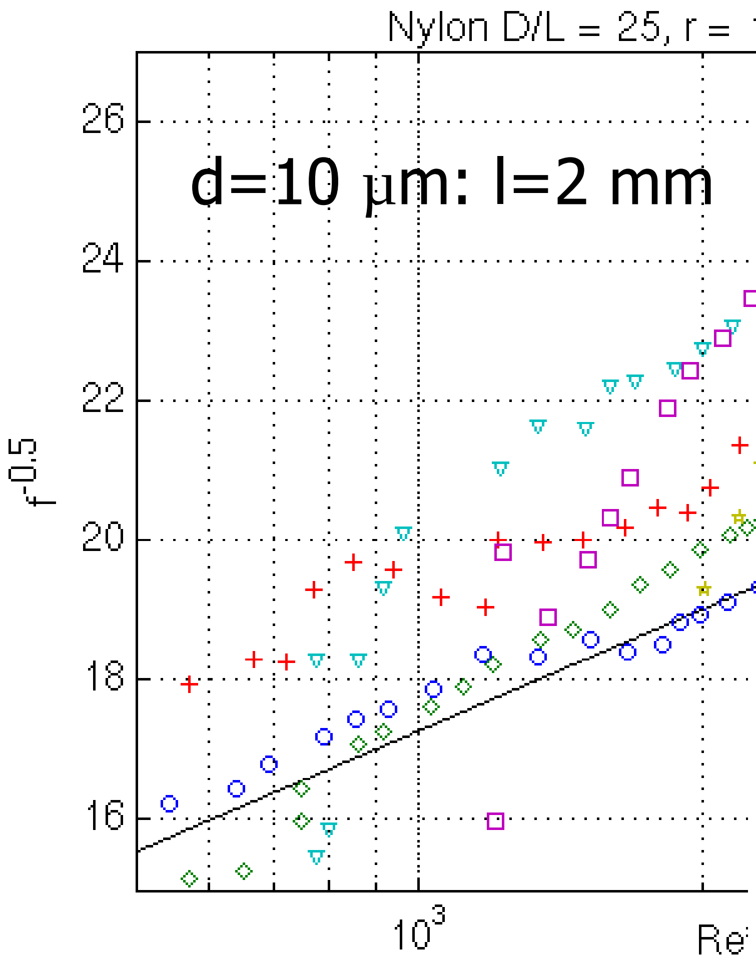


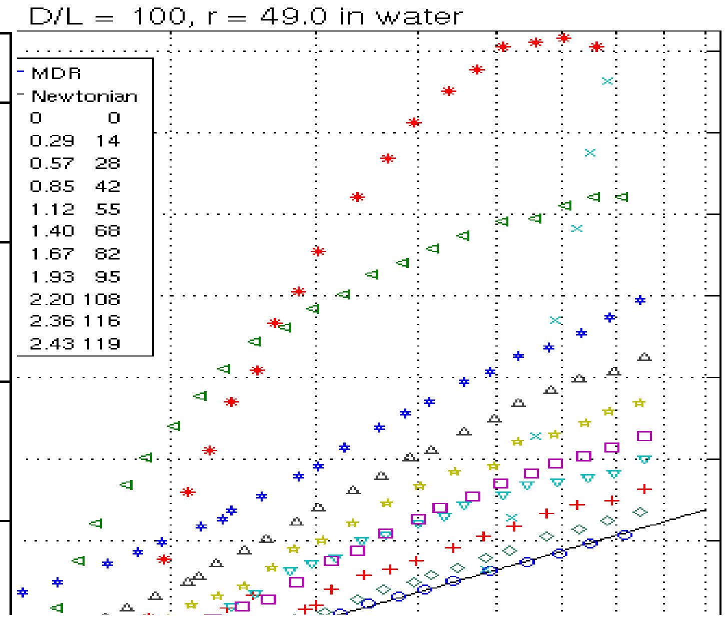
DR = g(Re*); maximum at intermediate $Re_* = Re_{*,max}$ for low c

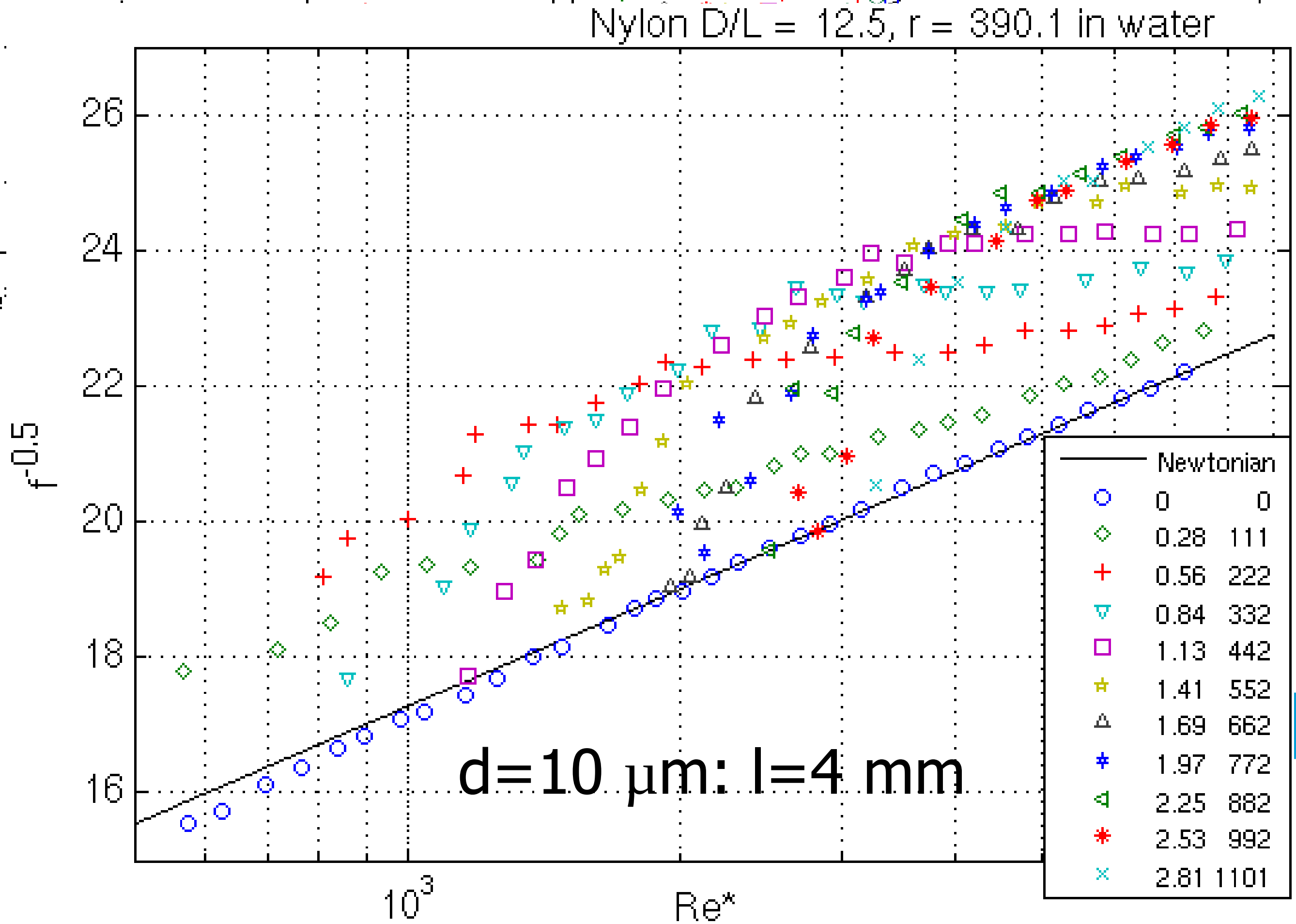
MDR at Re_{*MDR} for $c = c_{MDR}$

Re_{*MDR} increases for $c > c_{MDR}$

Drag increase (settling fibres)



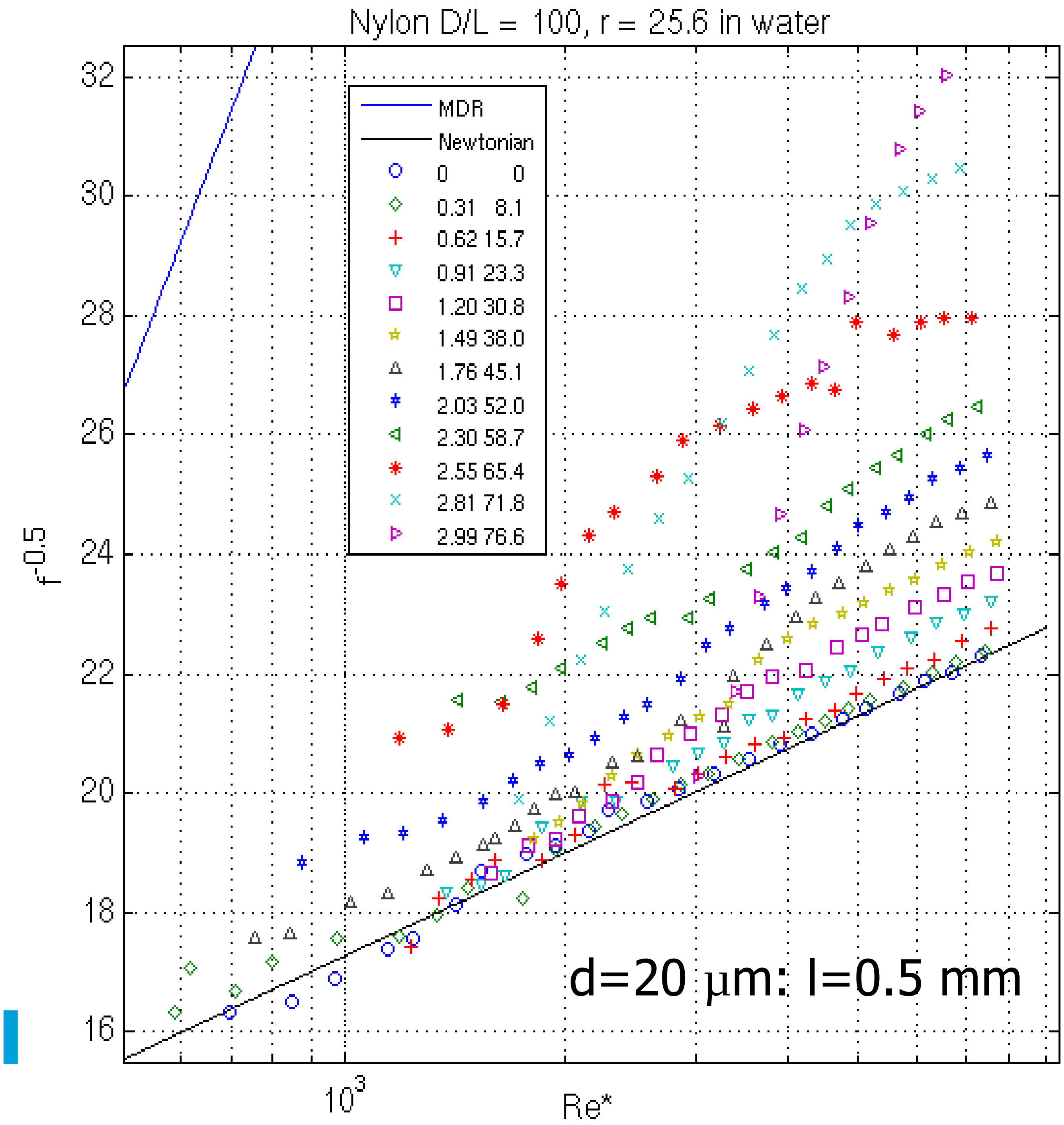




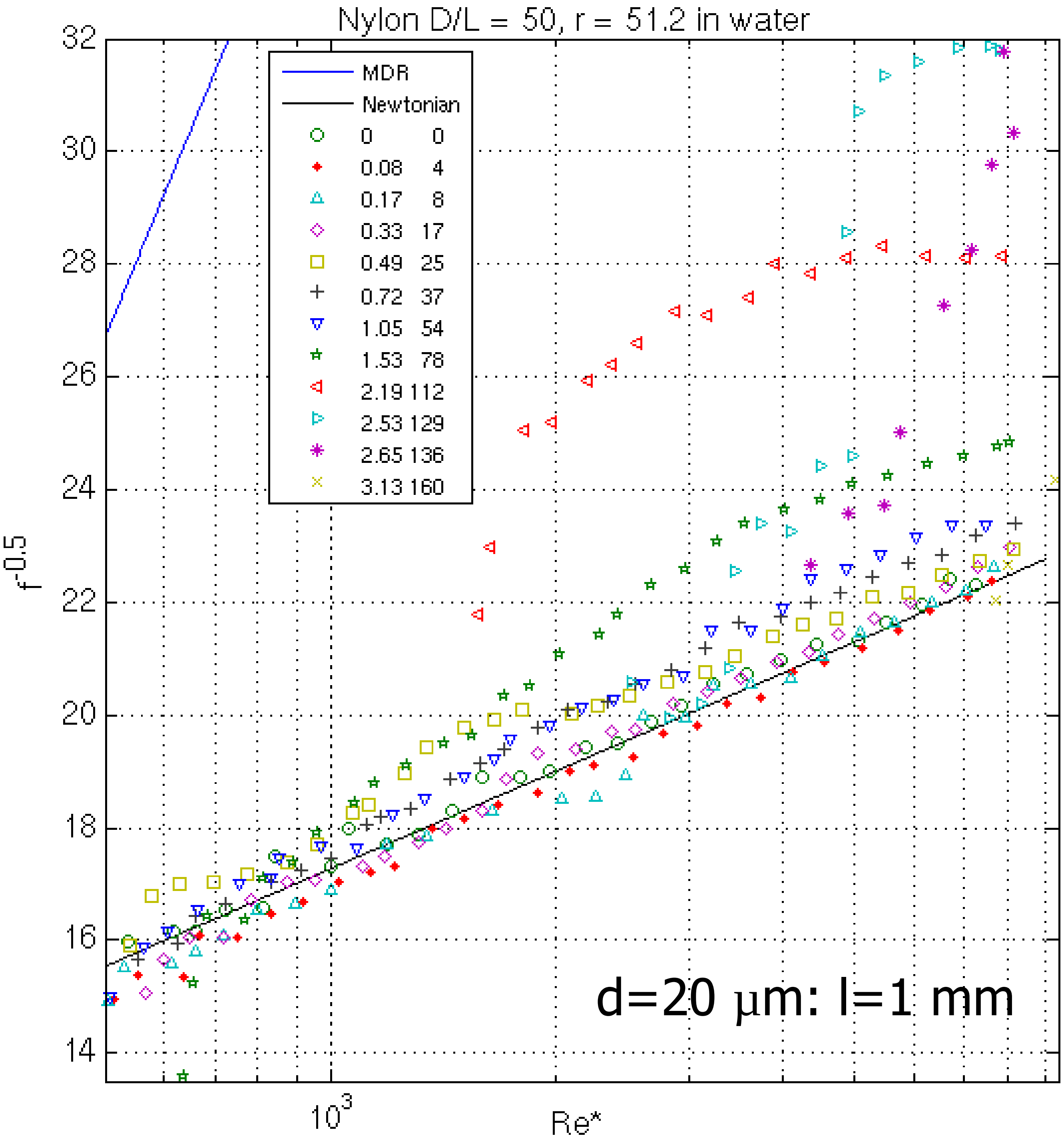
The other 10 μm fibres:

Increasing fibre length:

- less effective
- but at much lower c
- and at much lower Re_*



The 20 µm fibres:

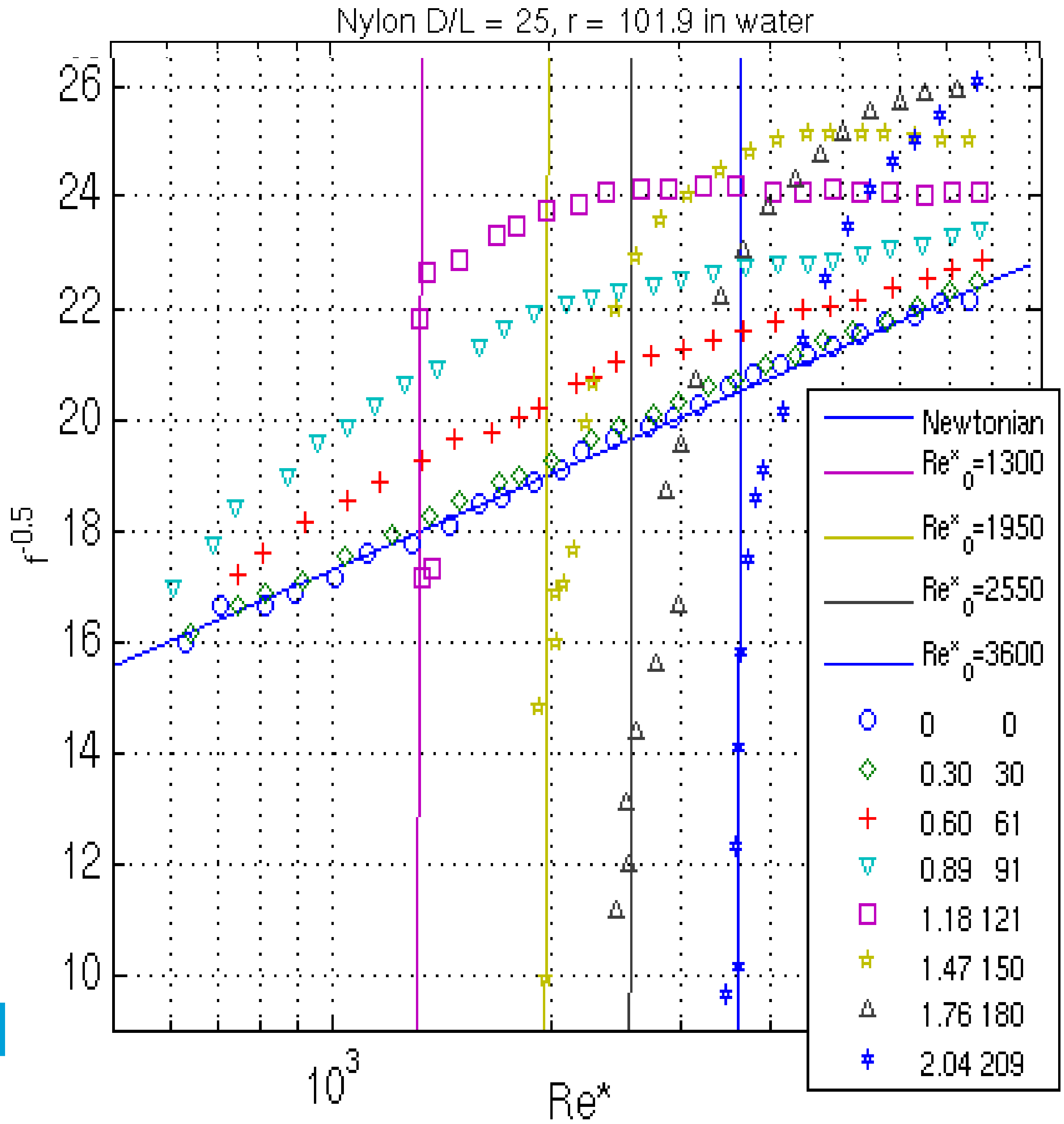


Nylon D/L = 50, r = 51.2 in water
MDR
Newtonian
0 0
0.08 4
0.17 8
0.33 17
0.49 25
0.72 37
1.05 54
1.53 78
2.19 112
2.53 129
2.65 136
3.13 160
$f^{-0.5}$
Re*
10^3
32
30
28
26
24
22
20
18
16
14
d=20 μm: l=1 mm

The 20 μm fibres:

They behave similar…

- less effective than 10
- with even stronger tendency for clogging



All compiled into numbers...

L µm	d µm	D/L	r	c_{max} %	c_{DRmax} %	DR_{max} %	Re^*_{min}	Re^*_{DRmax}	ΔU^+_{bmax}	$[DR/c]_{max}$
500	10.2	100	49.0	4.96	$\geq$ 4.82	$\geq$ 57	7000	$\geq$ 5090	$\geq$ 12.8	12
1000	10.2	50	97.5	2.52	1.69	41	2800	2880	7.1	24
2000	10.2	25	195.1	1.00	0.57	31	2200	2810	4.5	84
4000	10.2	12.5	390.1	0.72	0.22	27	1050	2455	3.7	250
500	19.5	100	25.6	11.70	$\geq$10.97	$\geq$ 49	6500	$\geq$ 6574	$\geq$ 10.0	4
1000	19.5	50	51.2	6.12	4.94	49	3500	$\pm$ 3900	9.8	$\pm$ 12
2000	19.5	25	101.9	2.00	1.15	33	2100	1950	4.8	28

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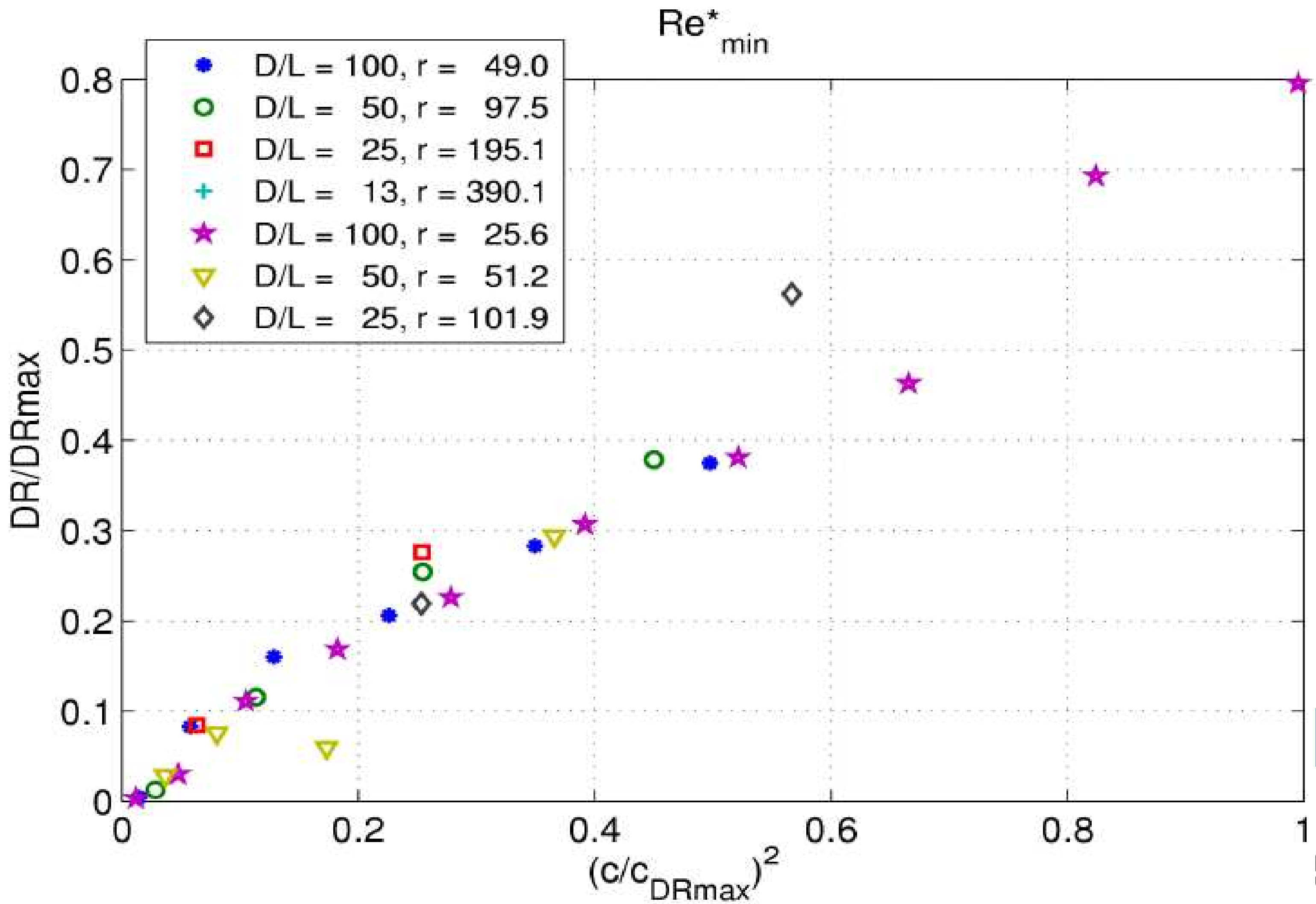
Analysis: low concentrations

Drag reduction DR varies with Re_*

At $Re_* = Re_{*,max}$, DR% increases with c: $DR/DR_{max} \approx 0.8 \cdot (c/c_{MDR})^2$

(indeed, dilute there is no effect!)



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Analysis: low concentrations

Drag reduction varies with Re_*

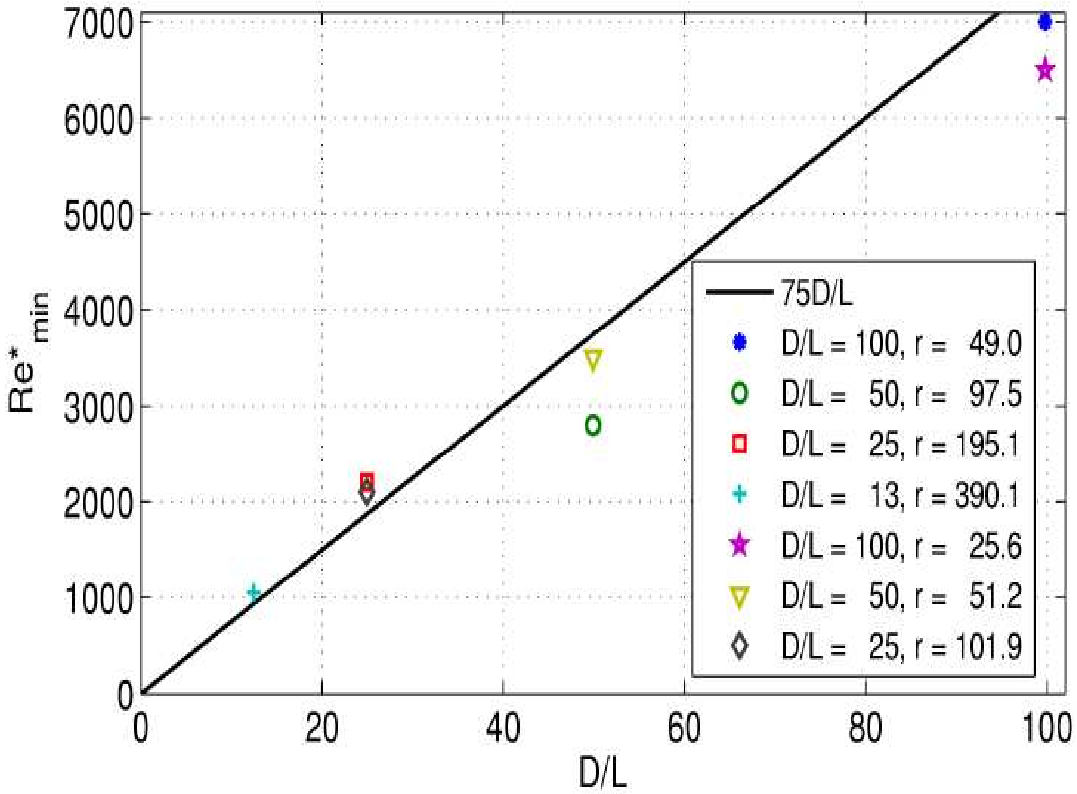
$Re_{*,max}$ varies with fibre length:

$$Re_* = u_* D/\upsilon = 75\, D/L$$

$$\rightarrow \boxed{L u_*/\upsilon = \underline{L^+ = 75}}$$

(much) larger than

'Kolmogorov scale'



Correlating with wall units;

L^+ = 75 is more like (spanwise) separation of vortices in buffer layer

'Direct interaction' essentially different from that with polymers!

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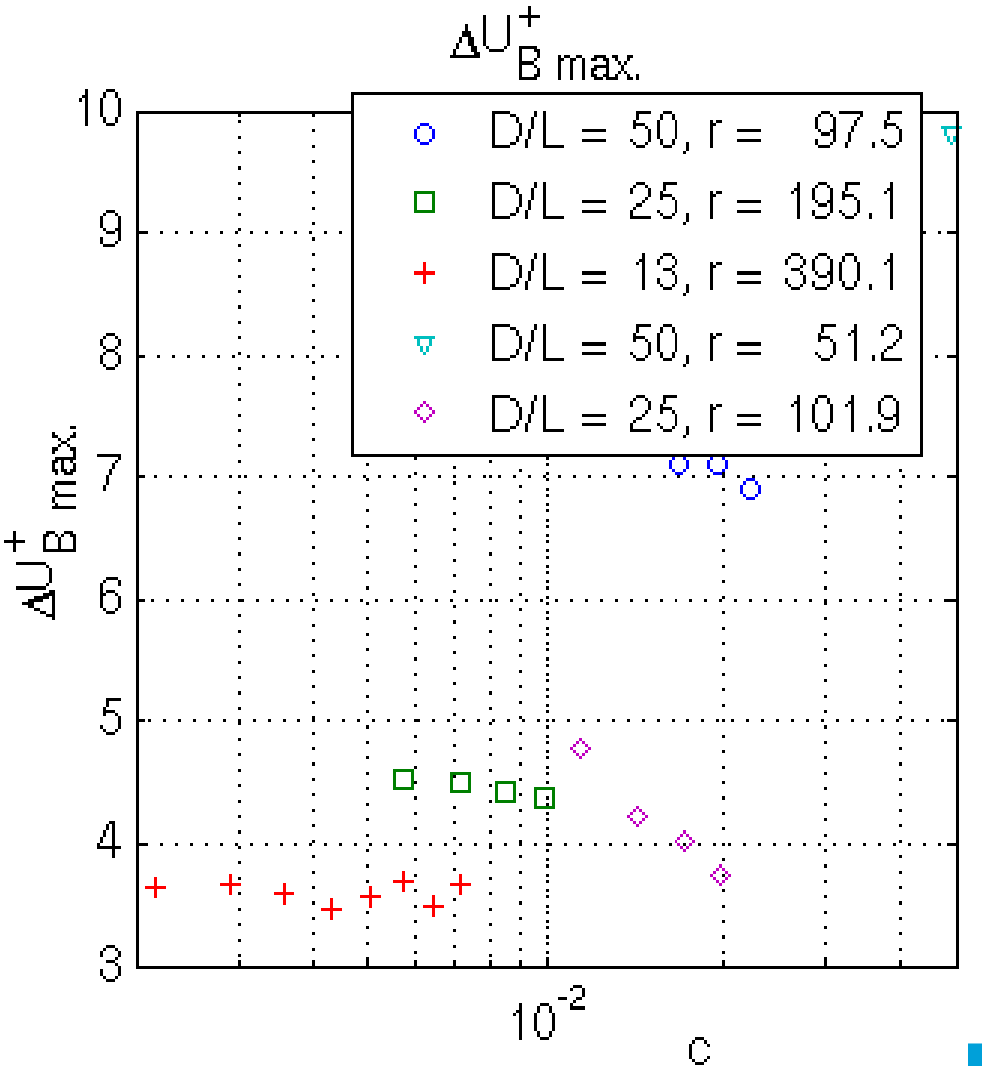
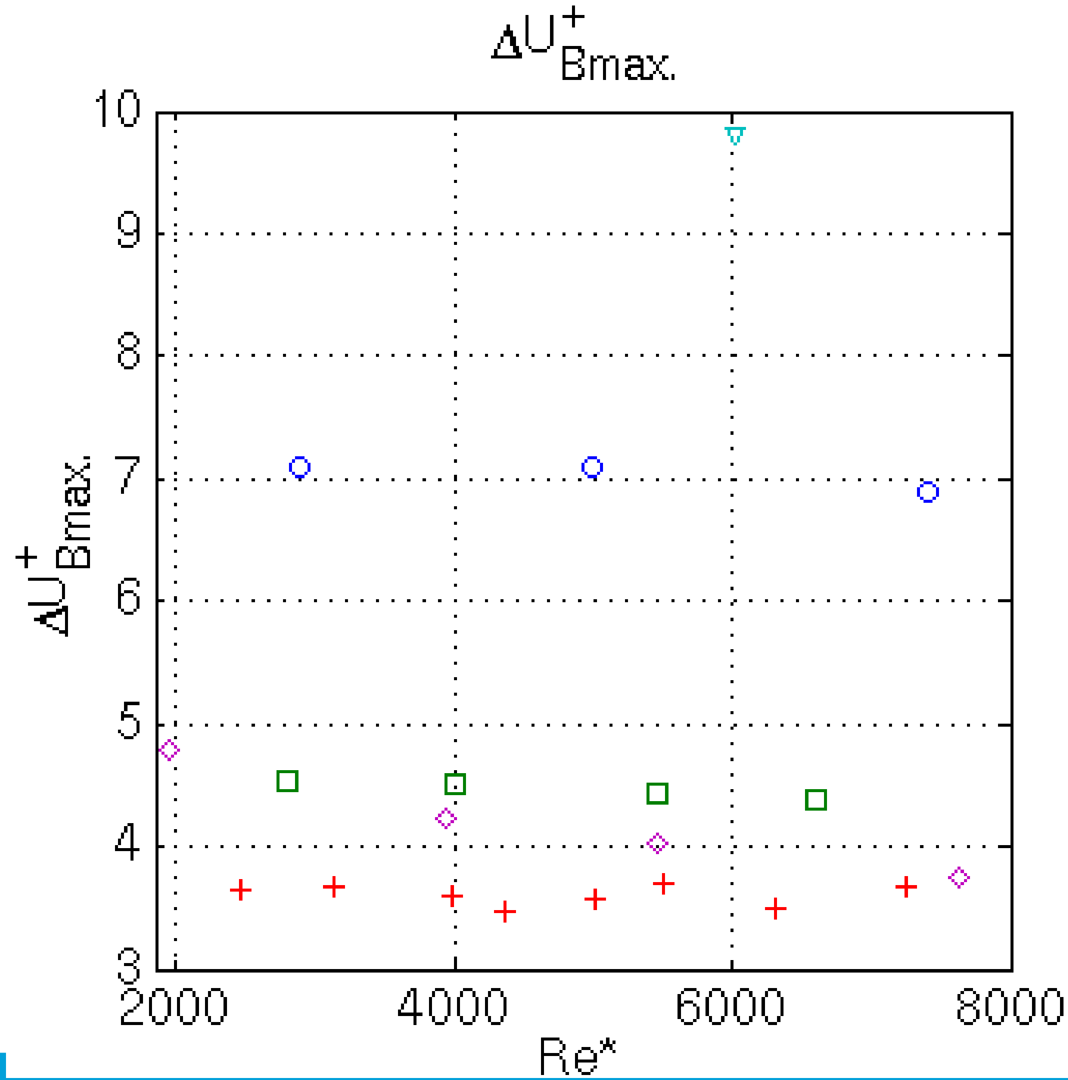
Analysis: high concentrations

Comparing: Maximum velocity increase





Fairly constant with concentration beyond c_{MDR}

much variation among different fibres

Analysis: high concentrations

Alternative for cr^2 (Ph.D.-thesis Gillissen, 2008);

takes into account for aspect ratio

$$\alpha = cr^2 / (\ln r - 0.8) > 40$$

coating	*l* (mm)	d (μm)	D/l	r = l/d	c_{MDR}	cr^2	α
black	0.5	10	100	49	4.8	115	**37**
no	1	10	50	98	1.7	163	**43**
no	2	10	25	195	0.57	217	**48**
no	4	10	12.5	390	0.12	183	**35**
no	0.5	19.5	100	26	11	74	**30**
black	1	19.5	50	51	4.9	127	**41**
no	2	19.5	25	102	1.15	120	**31**
						143±45	**38±6**

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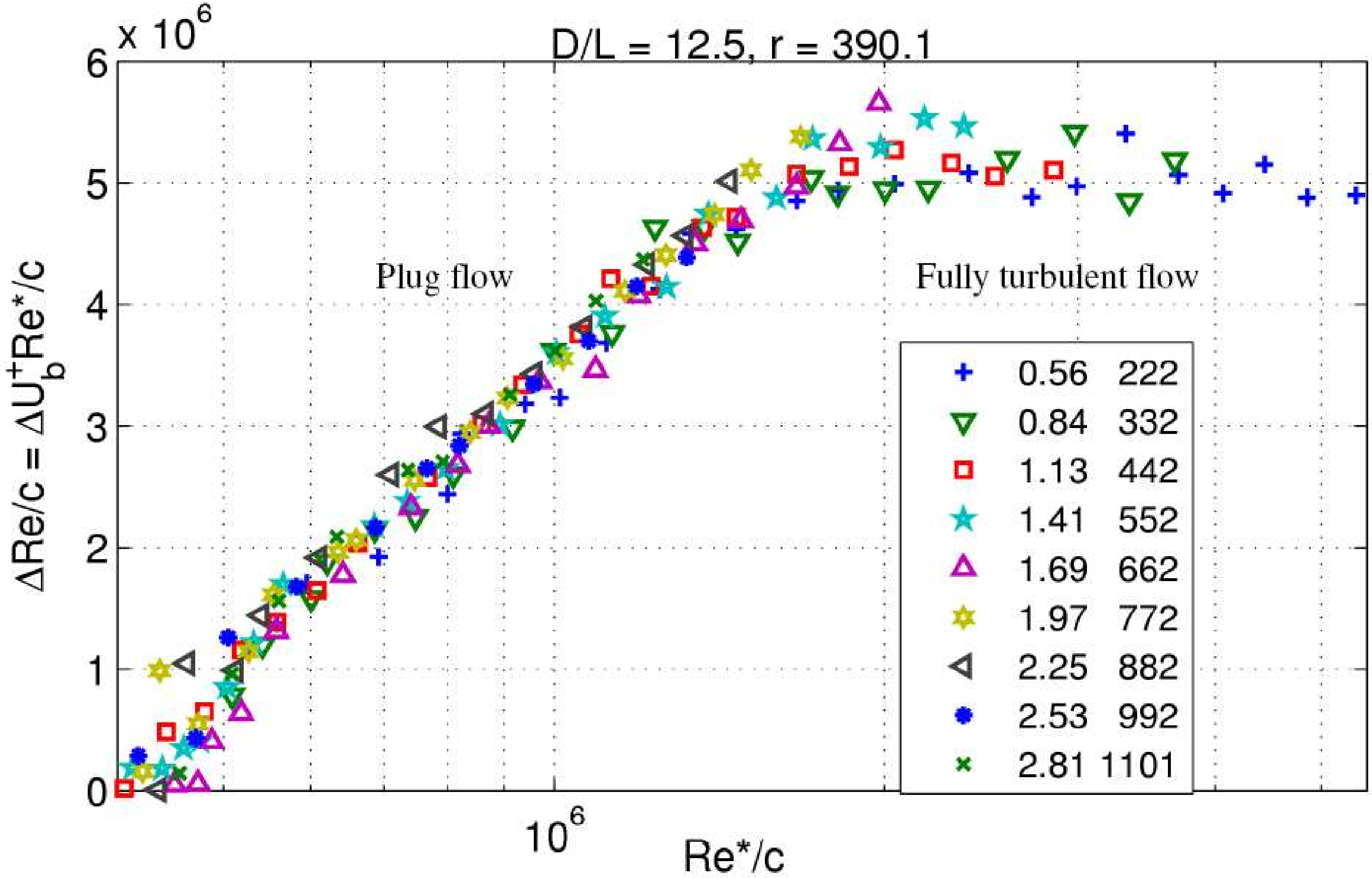
Reynolds number and concentration

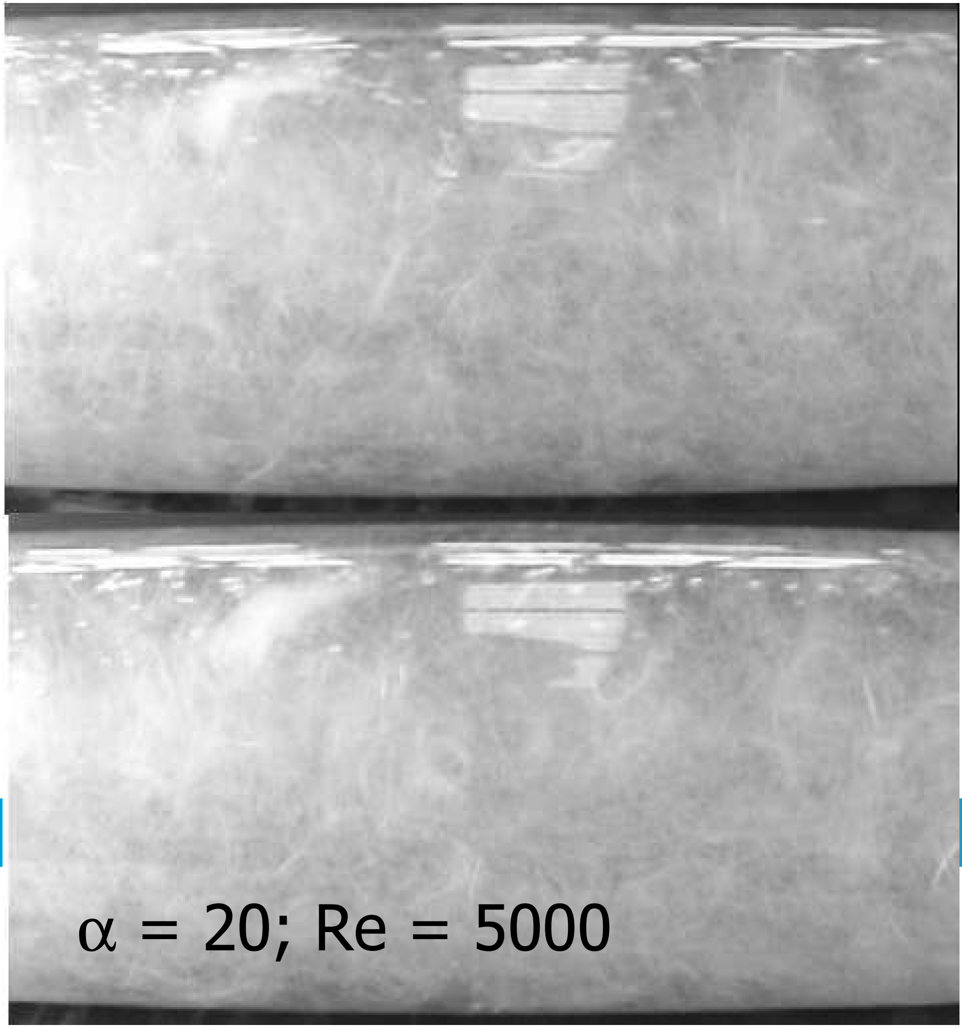


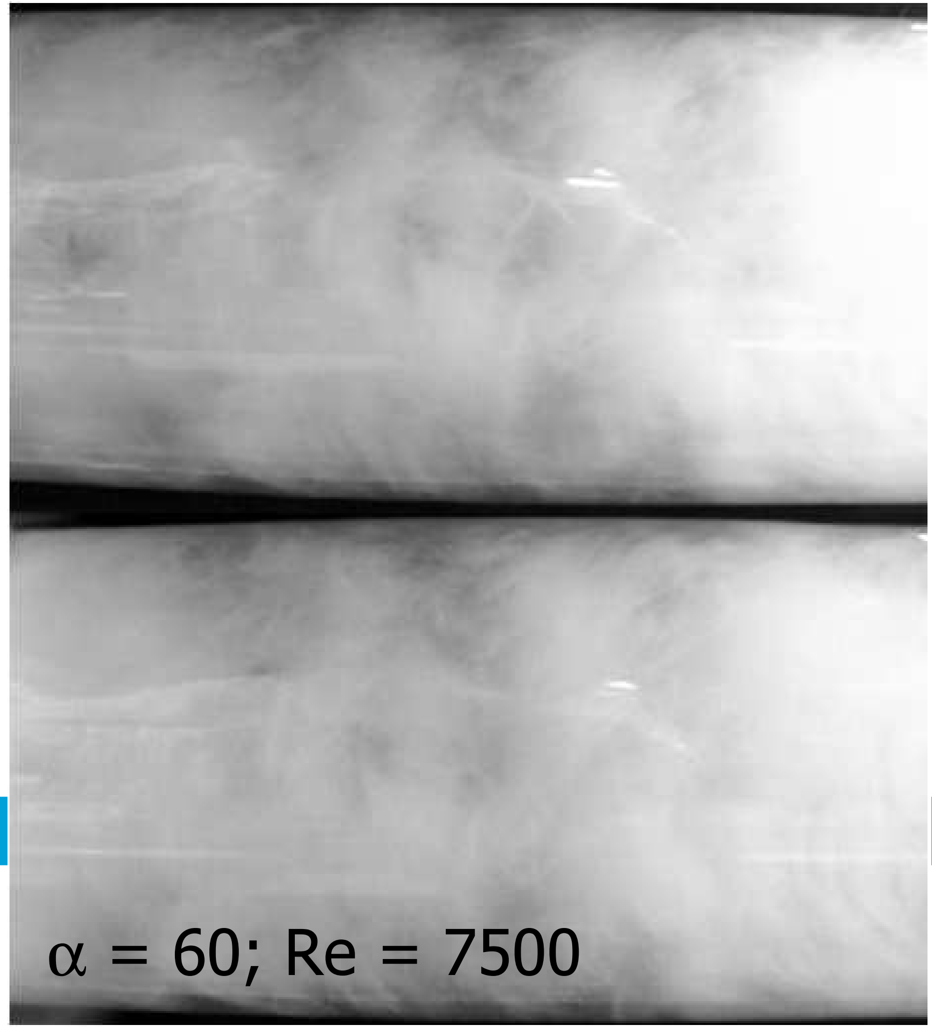
Visualisation

Sliding camera; moving with the mean flow

Fibres 4 mm x 10 μm

‘turbulent flow’ vs. ‘plug flow’





Conclusions

- Drag reduction with fibres comparable in magnitude to that with polymers, but only for a narrow range in Re_B
- Drag reduction increases quadratic in fibre concentration
- Fibres are most effective at $L^+ = 75$
- Efficiency increases with Re, as long as fibers are short!
- At $\alpha = cr^2/(\ln(r)-0.8) = 40$ we get a 'solidified plug', surrounded by probably turbulent 'lubrication film'
-

Future experiments

- Measure <u>inside tube</u>

➢ We built a fully index-matched pipe (including pipe wall)

➢ Fibre orientation and velocities; simultaneous with liquid velocities?

➢ Measure in lubrication film between plug and wall

- Experiments with gas!
- Thinner fibres or larger pipe diameter

Higher Reynolds numbers?

Vertical pipe?

And modelling and simulation, of course...

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