Effect of finite size rigid fiber in turbulence drag reduction

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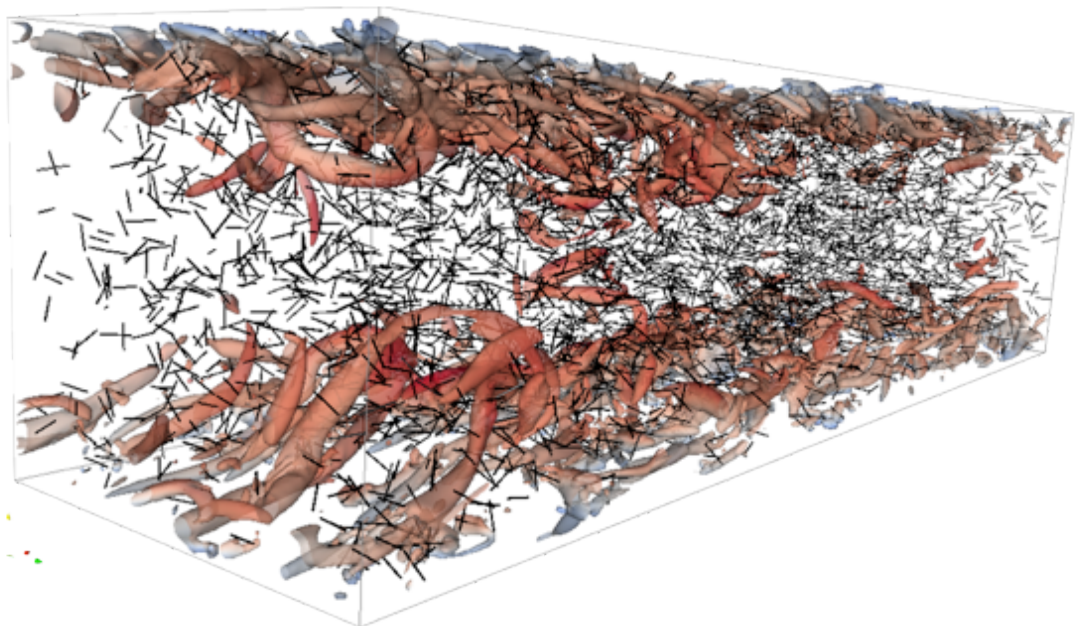
Suspension turbulent channel flow

- Simulation:
  - An isotropic grid, 26 million cells
  - Wall unit $\Delta^+ = 2$
- Channel high ~ 2 cm, Re_τ ~ 180.
- Fiber length ~ 0.15÷1.5mm (L^+=3.2÷24)
- Density ratio = 1.2 (cellulose vs. water)
- Volume fraction = 0.1÷0.4% (dilute regime)
- No gravity effect.

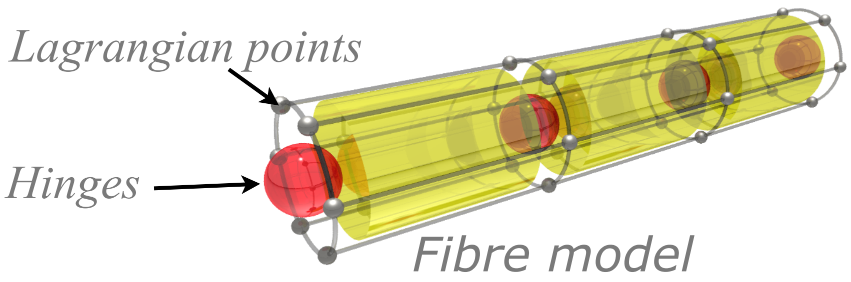


Two phase flow model

- Turbulent flow is model by Entropy Lattice Boltzmann method. (Keating 2007)

- The no-slip boundary condition on the moving particle boundary is handled by an external boundary force method (Wu & Aidun 2010)

  - Including the contact and lubrication force models for fibre-fibre and fibre-wall interactions (four ways coupling).
  - Fiber model "could" take into account the fiber bending, twisting by apply the bending and twisting moments on each hinge.



Two phase flow model

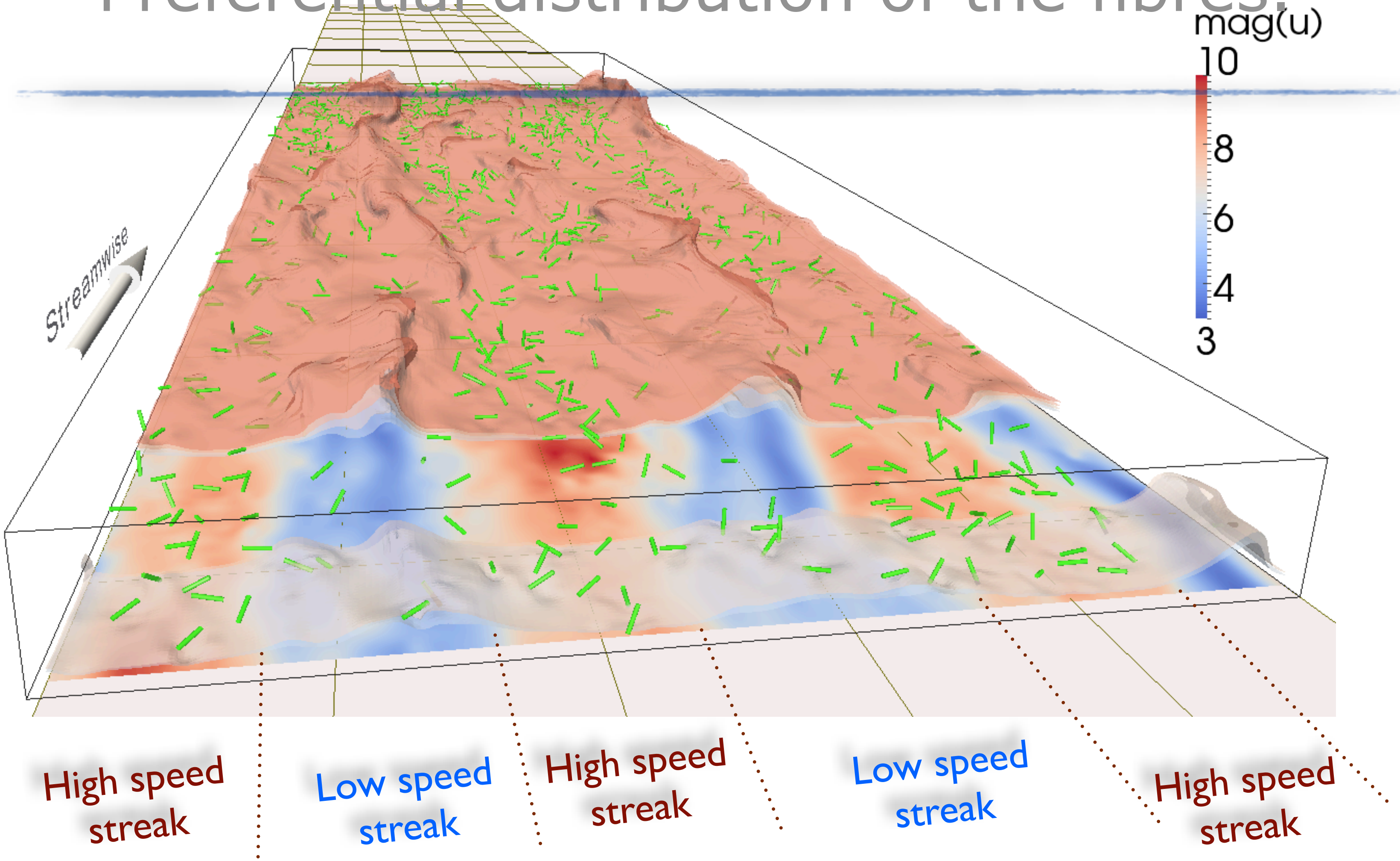
- Small Stokes number
- Small inertial effects because the fibres are almost (or exactly) neutrally buoyant, r_ρ=1.2 or 1.0
- No gravity.

$$\tau_p = \frac{2\rho_f}{9\rho_l \nu} \frac{L^2}{a_p} \frac{\ln(a_p + \sqrt{a_p^2 - 1})}{\sqrt{a_p^2 - 1}},$$

$$St = \frac{\tau_p}{\tau_f}, \quad St^+ = \frac{\tau_p}{\tau^+}.$$

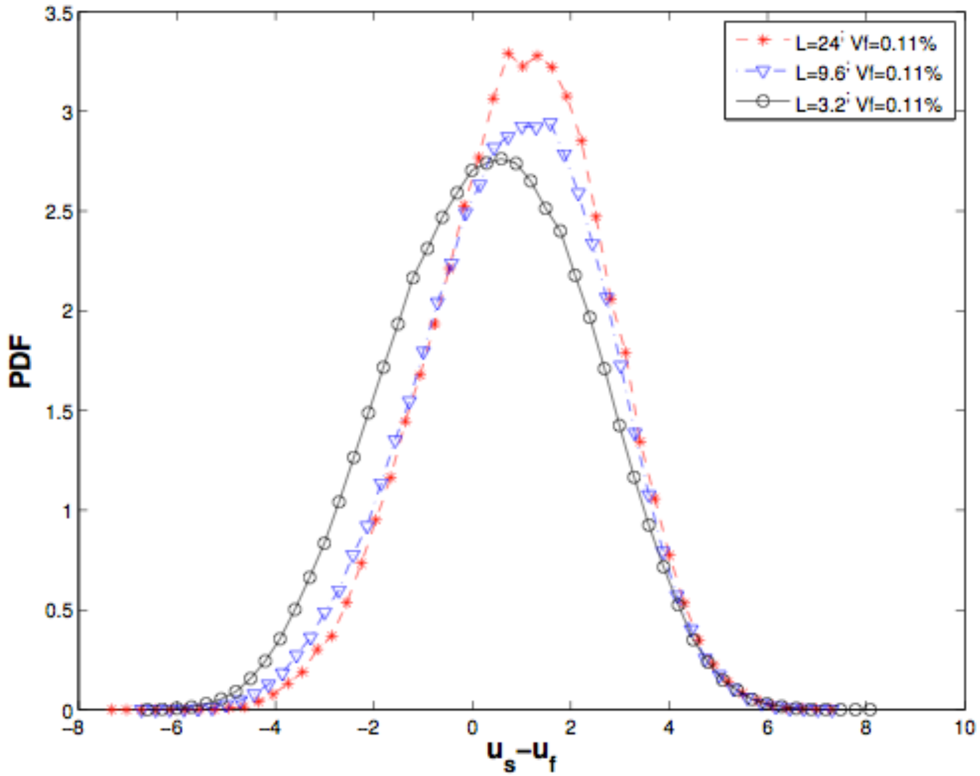
Case	N_p	r_ρ	L	V_f	$n_p L^3$	St	St^+
#1	4752	1.2	24	0.11%	0.325	0.245	2.326
#2	11800	1.2	9.6	0.11%	0.052	0.181	1.716
#3	35640	1.2	3.2	0.11%	0.006	0.110	1.038
#5	35640	1.0	3.2	0.11%	0.006	0.091	0.865

Preferential distribution of the fibres.



Three dimensional view, fibre length $L^+ = 9.6$, $v_f = 0.44\%$. The fibre plotted here are fibres within ($y^+ < 16$). The dimensions of the outlined box are 1420, 64 and 396 wall units in the x, y and z dimensions, respectively.

Preferential distribution of the fibres.



Fiber number density distribution as a function of fluctuating streamwise velocity. The data is collected for a region (4 < y+ < 16) and a duration time t = 30t*. Number of bins = 100.

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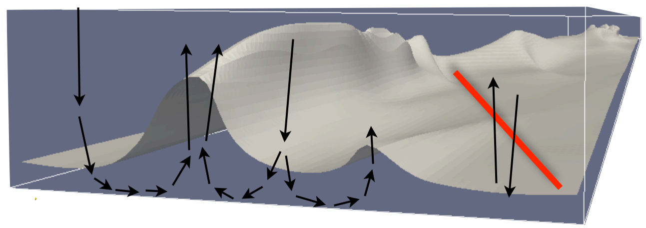
Time history of a fibre moving in the vicinity of the wall

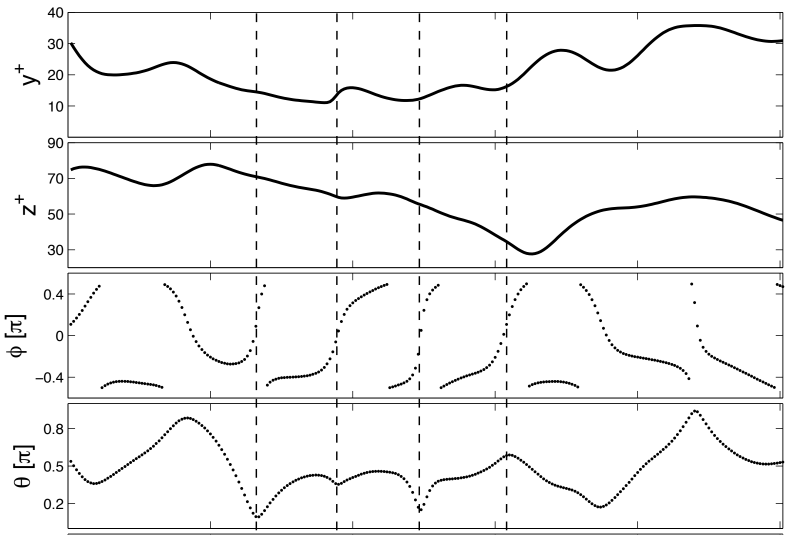
Fibre stay in the high speed streak longer than in low speed streak



Schematic of fluid flow between streaks

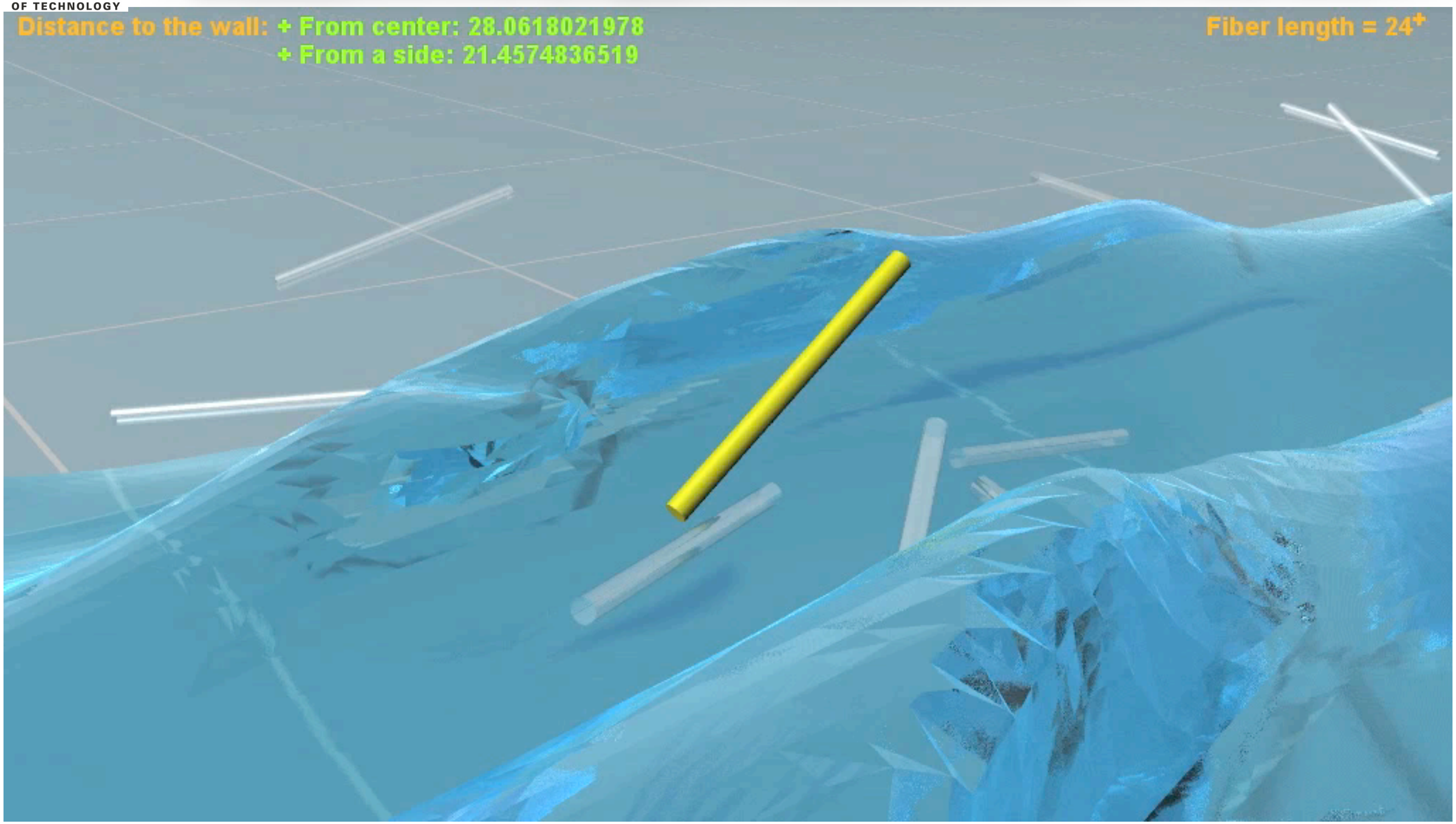
Location of the fibre

Orientation



Fibre length $L^+=24$

A fibre moving in the vicinity of the wall



ρ_s/ρ_f=1.2ρ_f; Re_τ=180; R=0.8$^+$, aspect ratio=15 ; Volume fraction = 0.11%

RED color: fiber is go away from the wall; GREEN color is go to the wall.

Fibers have higher mean velocity than the fluid near the wall

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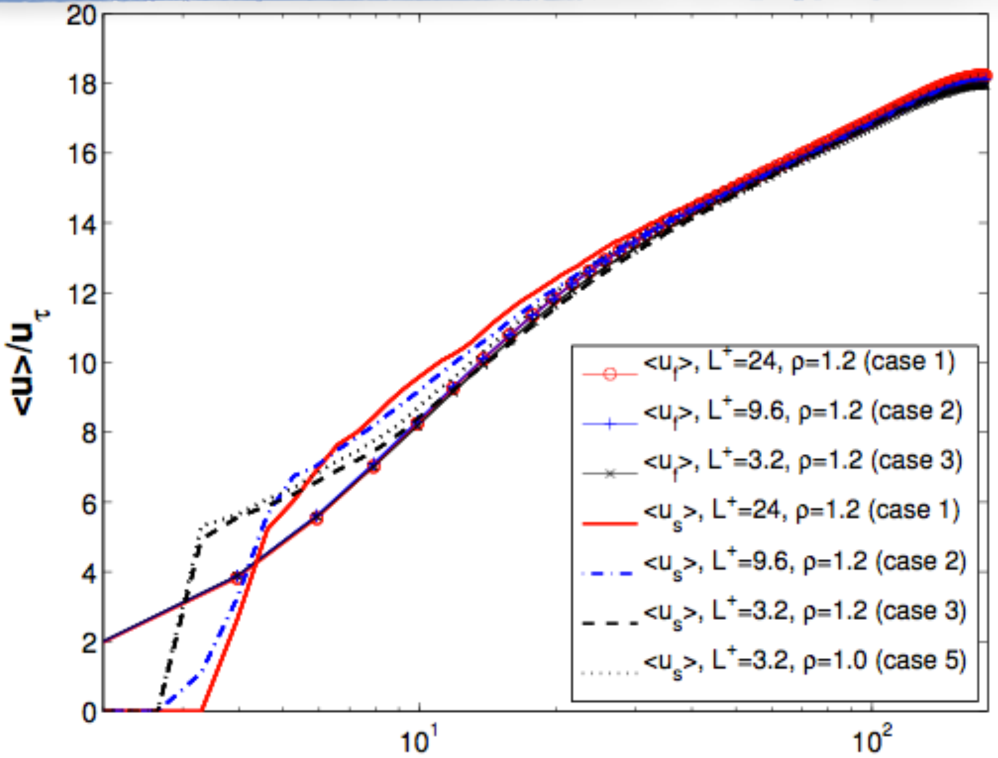
The higher velocity not due to the inertial as point particle !



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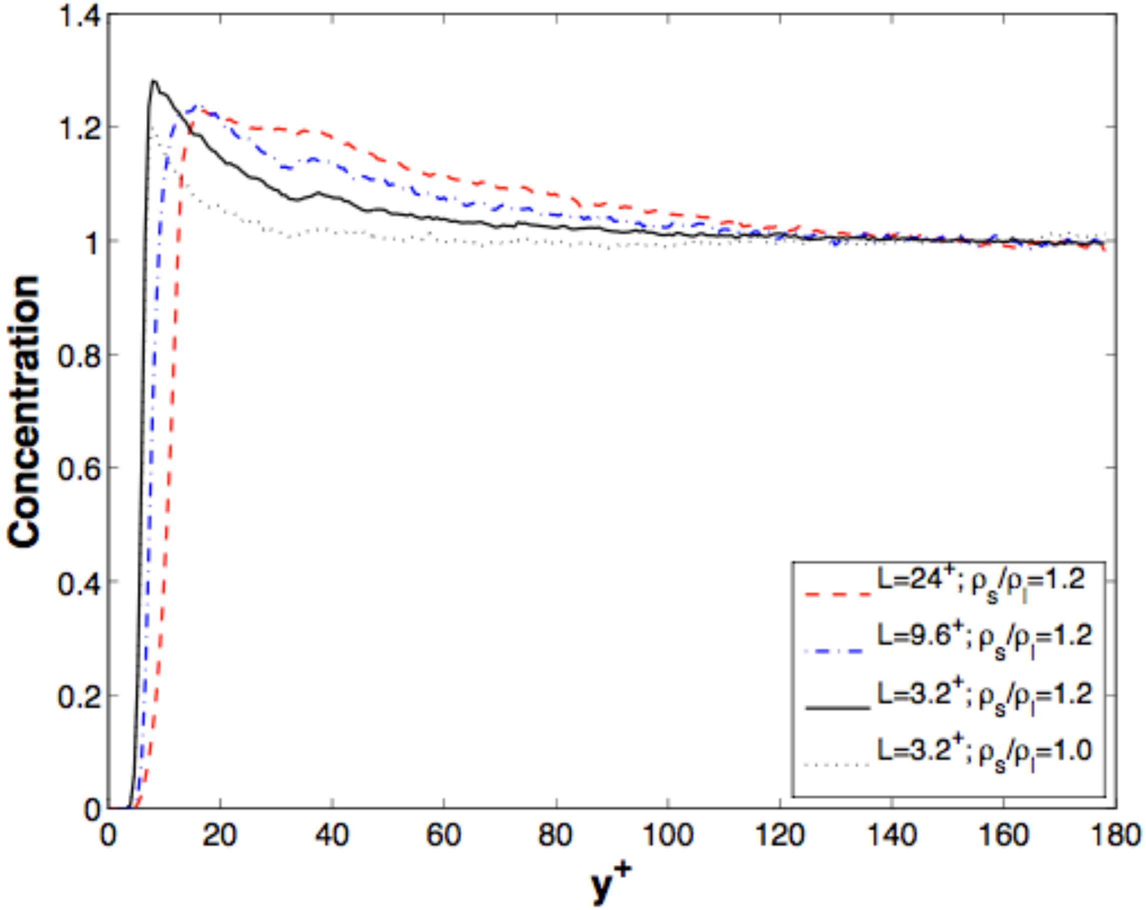
Preferential concentration



Preferential concentration due to fibre-wall interaction

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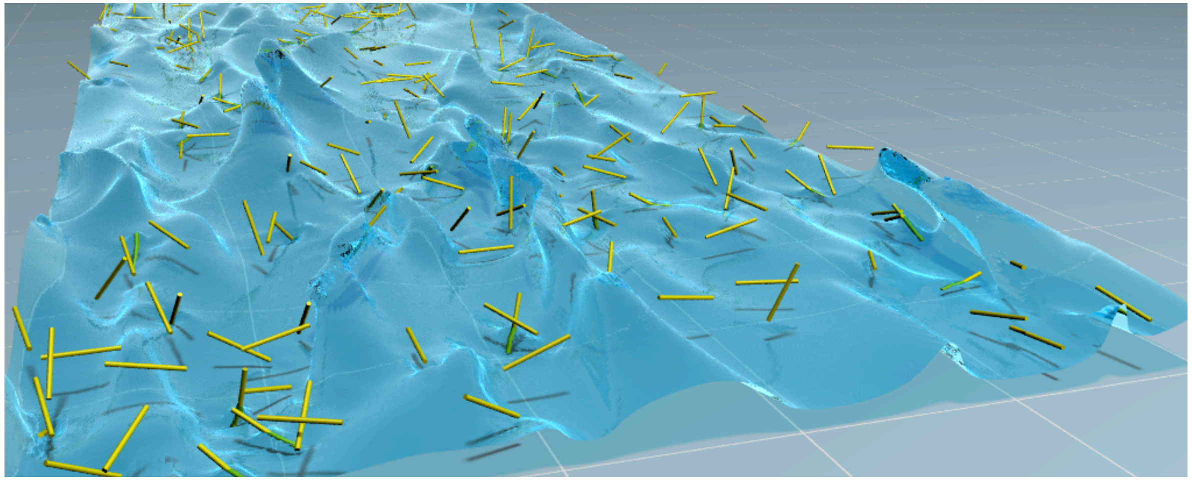
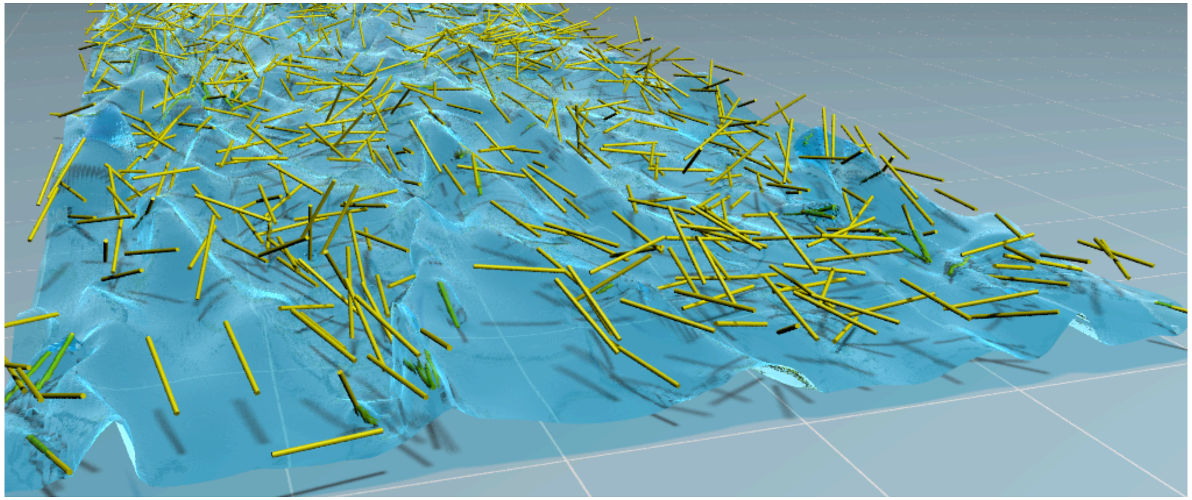


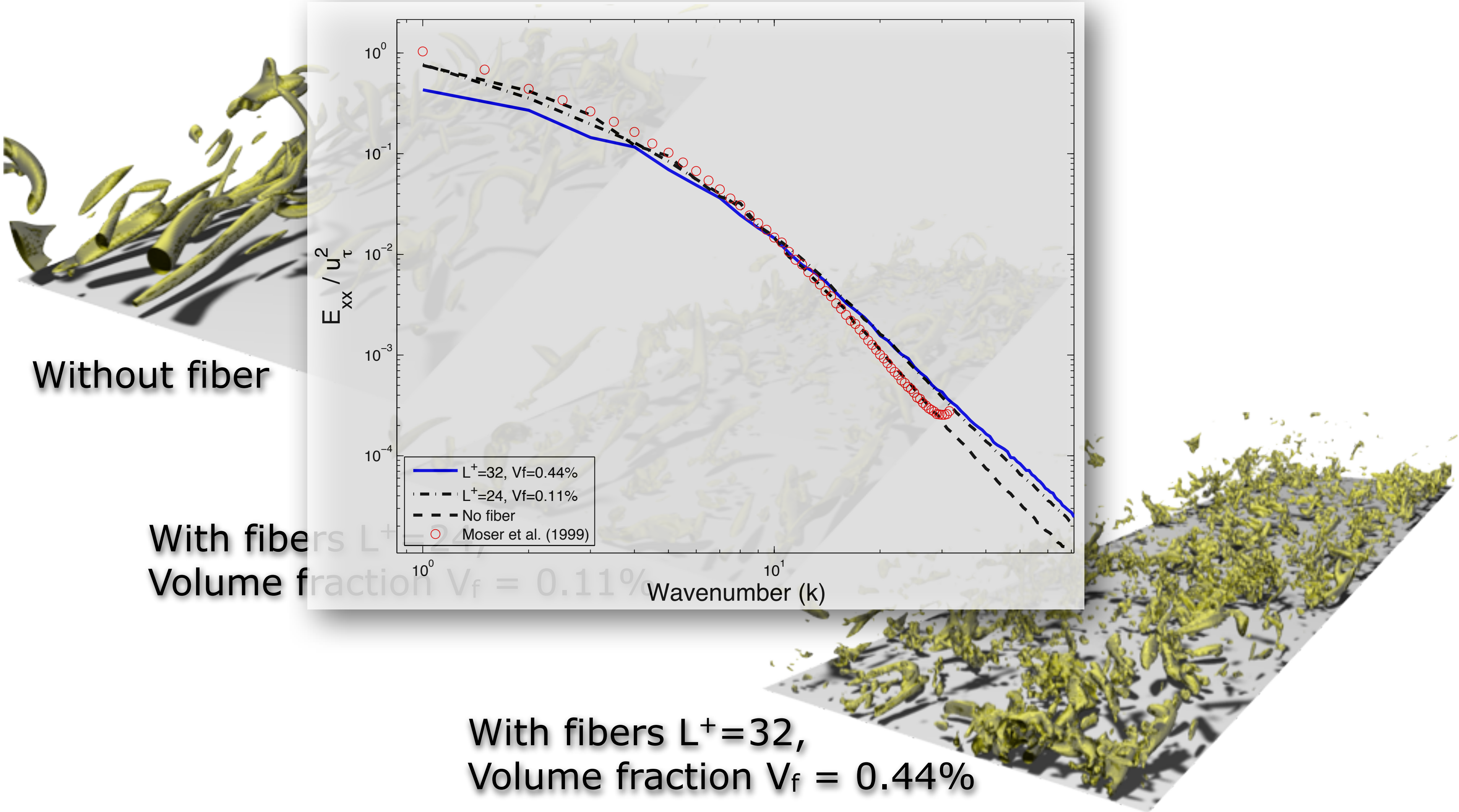
aspect ratio=15 ;
Volume fraction = 0.11%



aspect ratio=20 ;
Volume fraction = 0.44%

$\rho_s/\rho_f=1.2\rho_f$; $Re_\tau=180$; $R=0.8^+$

Turbulent vortices in the flow field. The second invariant Q_2



Without fiber

With fibers $L^+=24$,
Volume fraction $V_f = 0.11\%$

With fibers $L^+=32$,
Volume fraction $V_f = 0.44\%$

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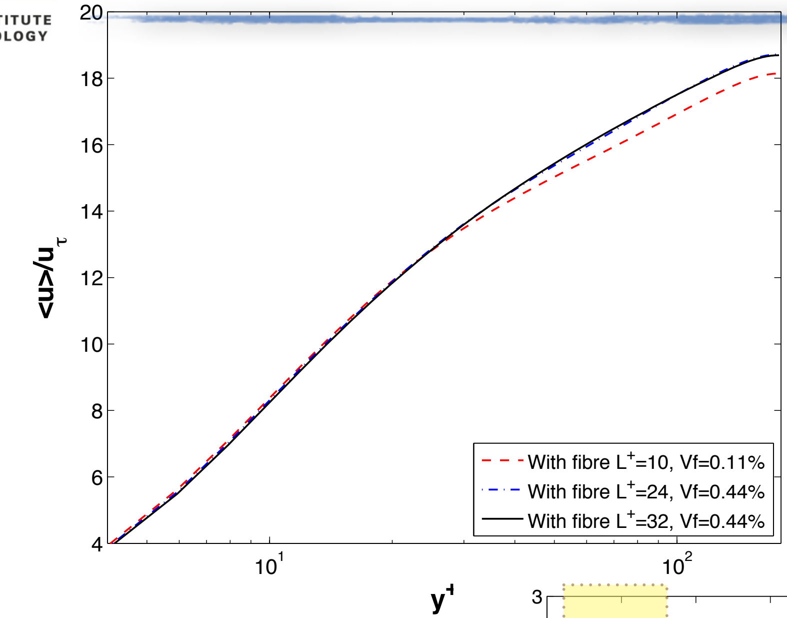
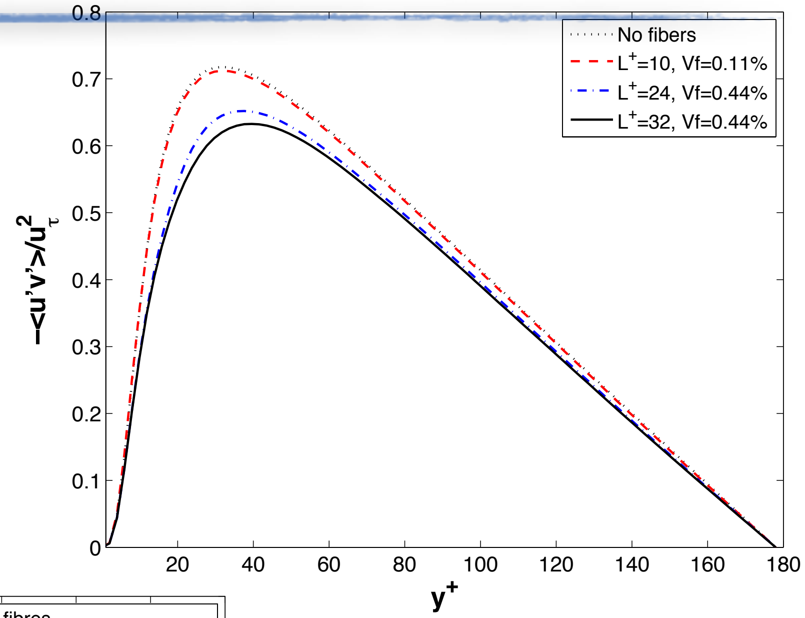
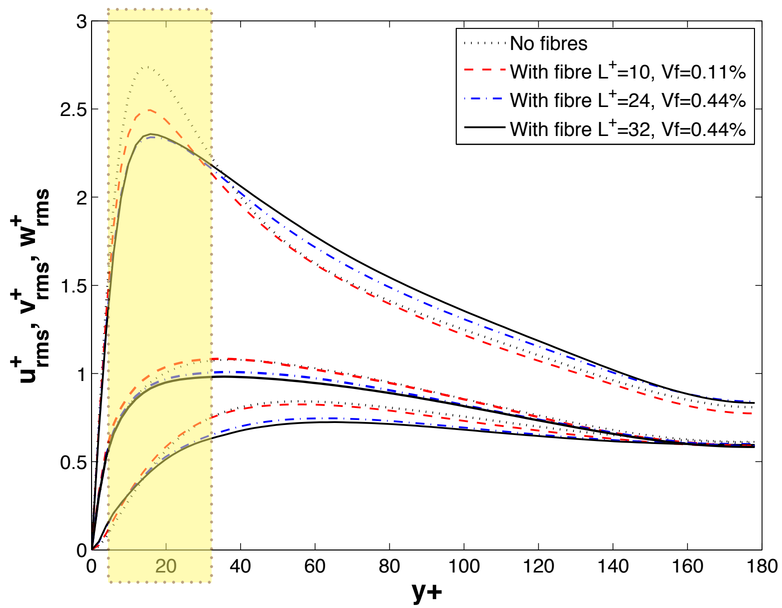
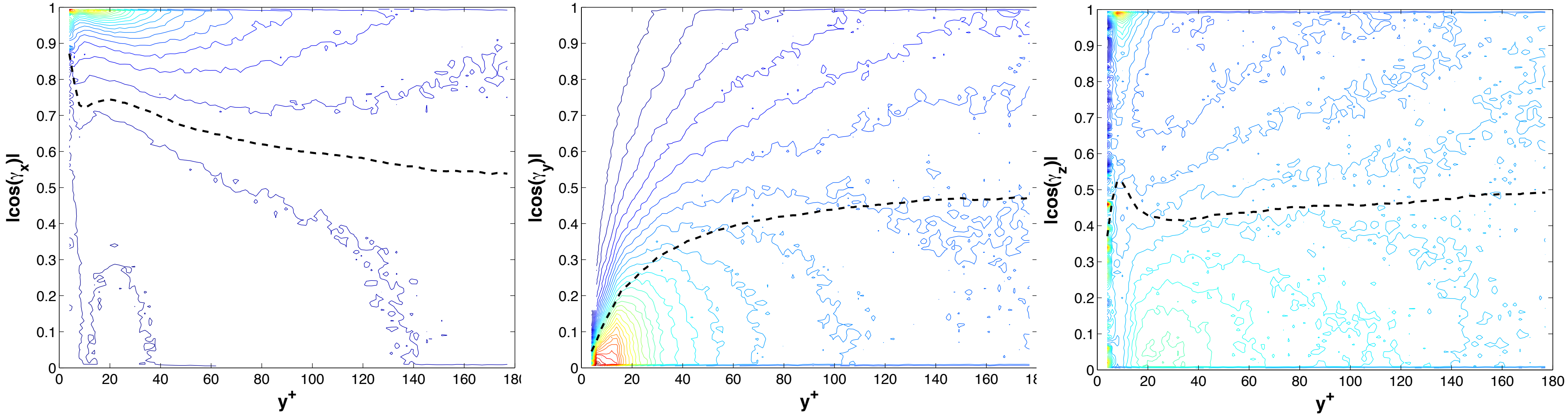
Turbulent drag reduction by rigid fibres







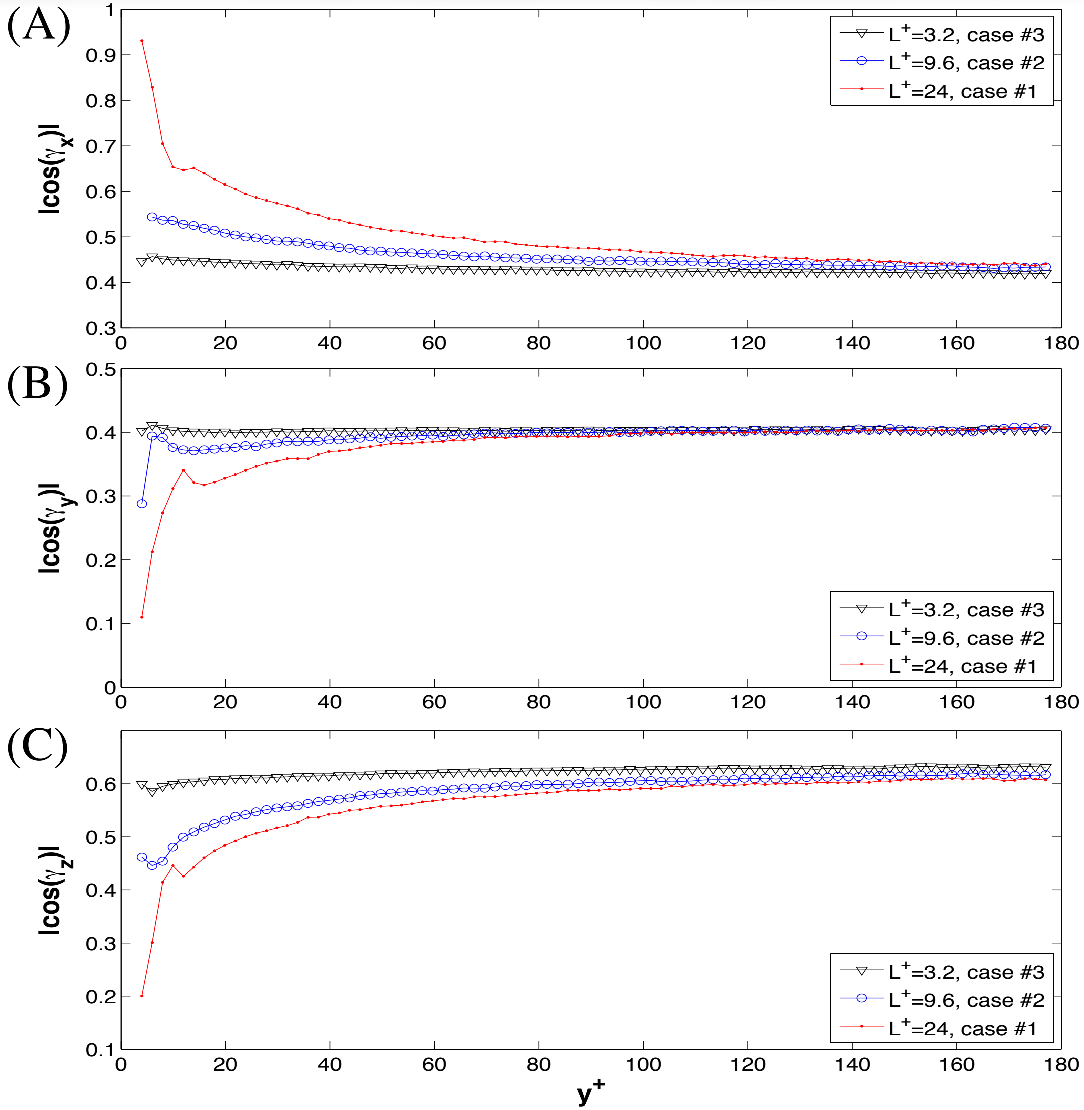
Mean values of direction cosines

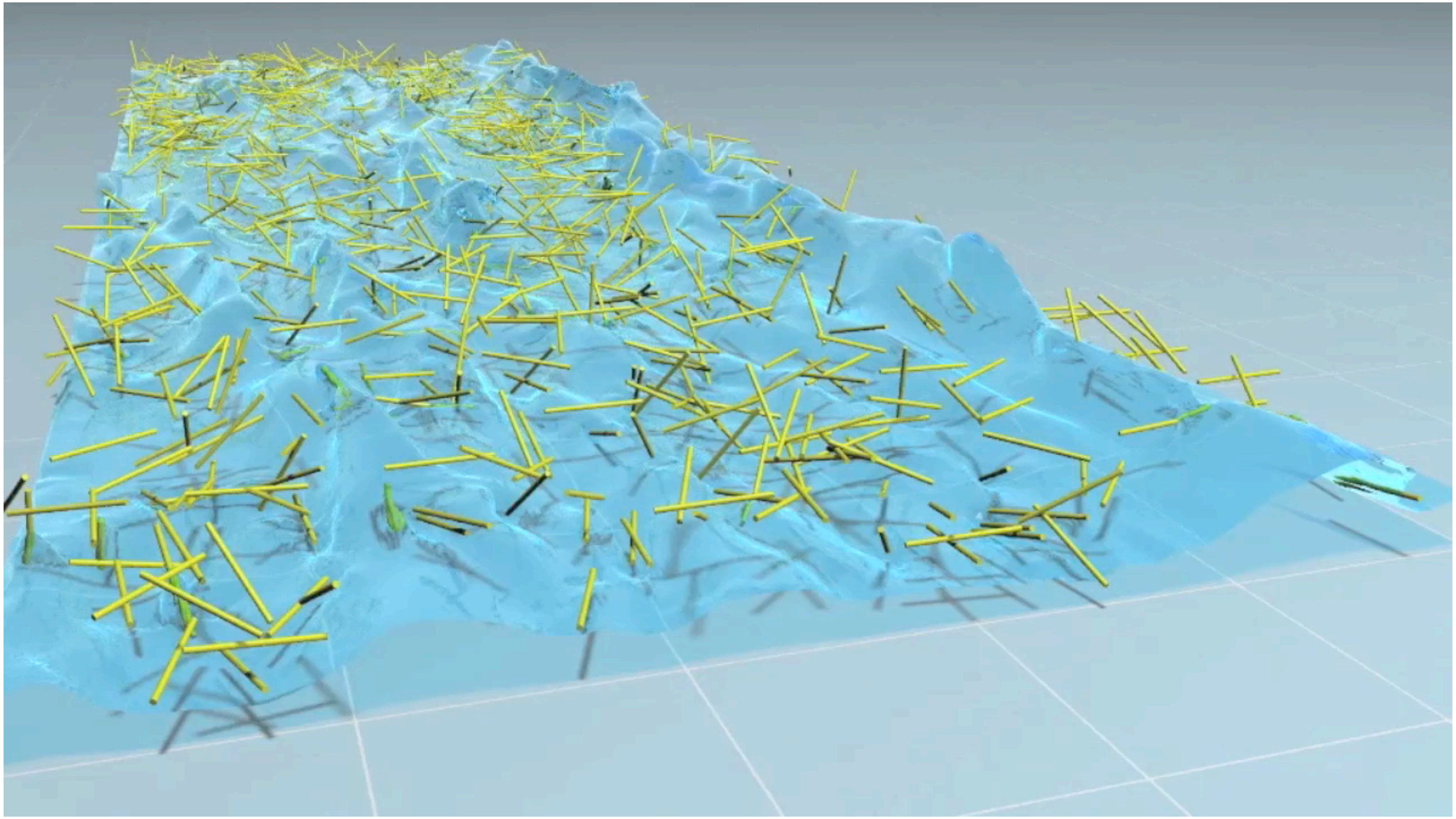


Streamwise   Wall-normal   Spanwise

ρ_s/ρ_f=1.2ρ_f; Re_τ=180; R=0.8$^+$, aspect ratio=20 ; Volume fraction = 0.44%

Mean values of direction cosines





ρ_s/ρ_f=1.2ρ_f; Re_τ=180; R=0.8$^+$, aspect ratio=20 ; Volume fraction = 0.44%

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Conclusions

- The finite size leads to fibre-turbulence interactions that are significantly different from earlier published results for point-like particles (e.g. elongated ellipsoids smaller than the Kolmogorov scale).
  - An effect that becomes increasingly accentuated with fibre length is an accumulation in high-speed regions near the wall, resulting in a mean fibre velocity that is higher than the mean fluid velocity.
  - There is also a resulting preferential concentration near the wall, which was shown to persist even for neutrally buoyant fibres.
- The finite length was also shown to influence the orientation of the fibres in the near-wall region,
  - Short fibres preferentially rotating around the spanwise direction.
  - Long fibres preferentially rotating in the shear (xz) plane and reducing the turbulence intensities in the buffer region (increasing in the bulk).

Acknowledgment

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