摩擦抵抗低減効果を持つ機能性船底塗料の数値解析
Numerical simulation for functional painting of ship hull with friction drag reduction effect

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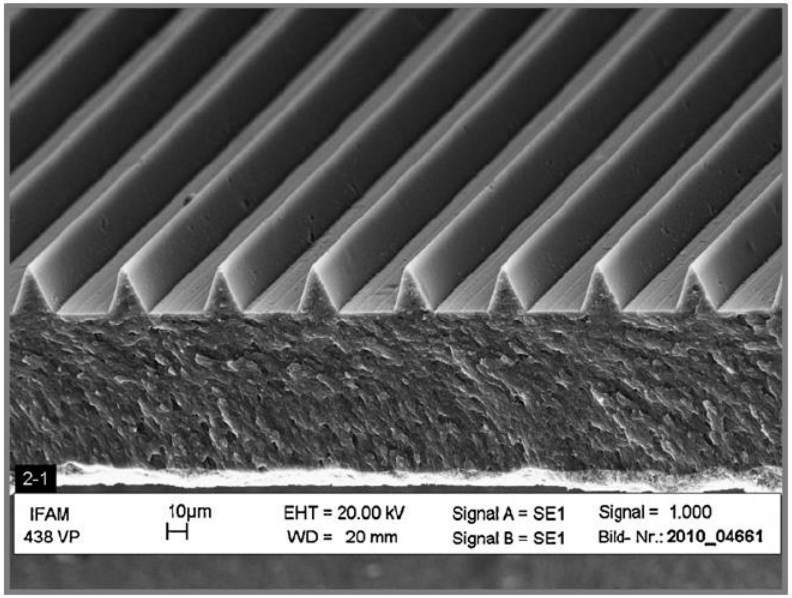
Turbulent drag reduction

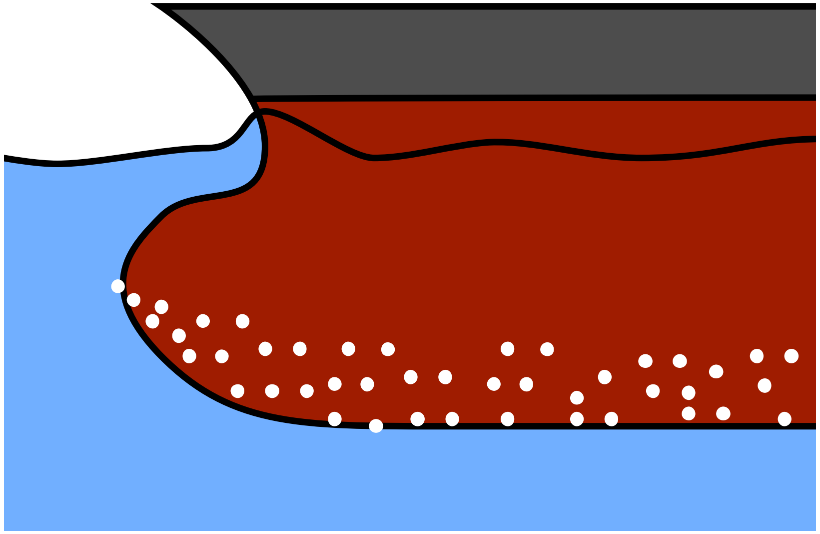
- Applications in wall turbulence

Riblet



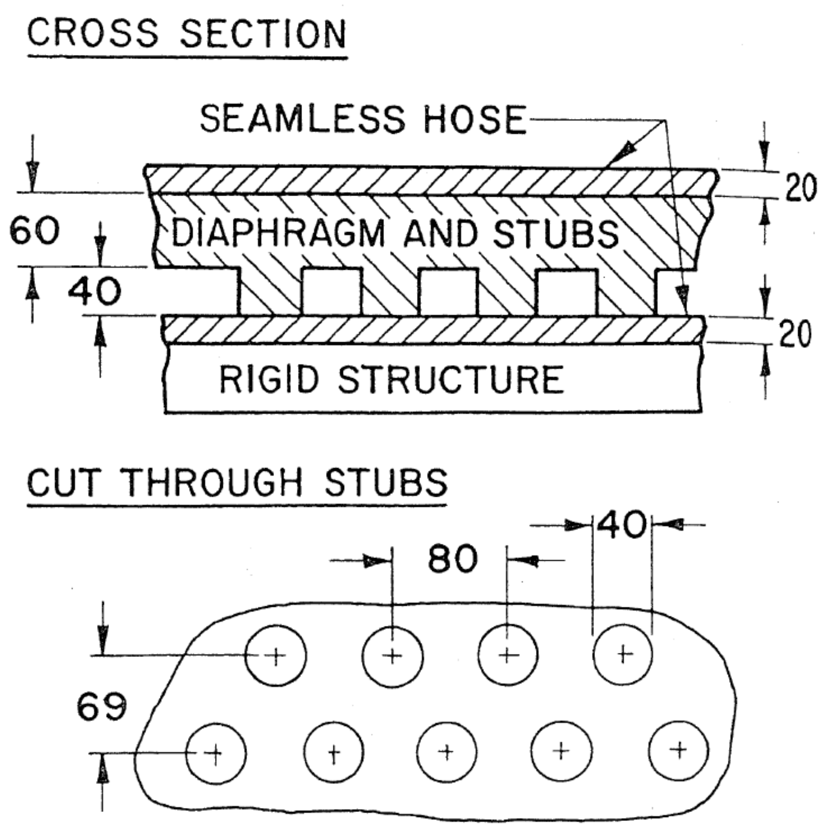
Stenzel *et al*., Prog. Org. Coat. (2011)

Micro bubble



Turbulent drag reduction

Compliant surface



M. O. Kramer, J. American Soc. Naval Eng. (1960)

Requirement for ship hull:

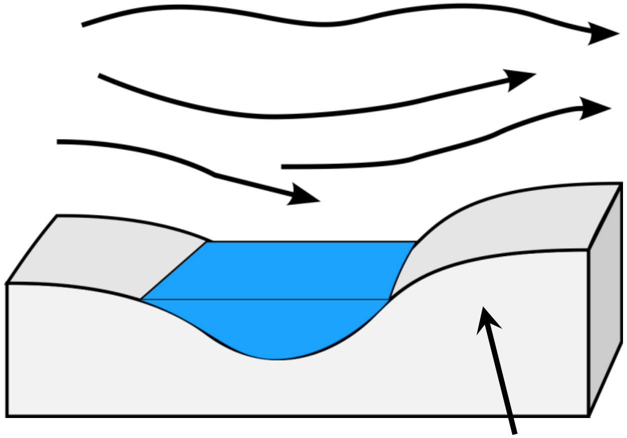
- Easy-to-use
- Durability
- Low cost

Painting is usually used for anti-fouling.

Functional painting with drag reduction effect

Commercial painting

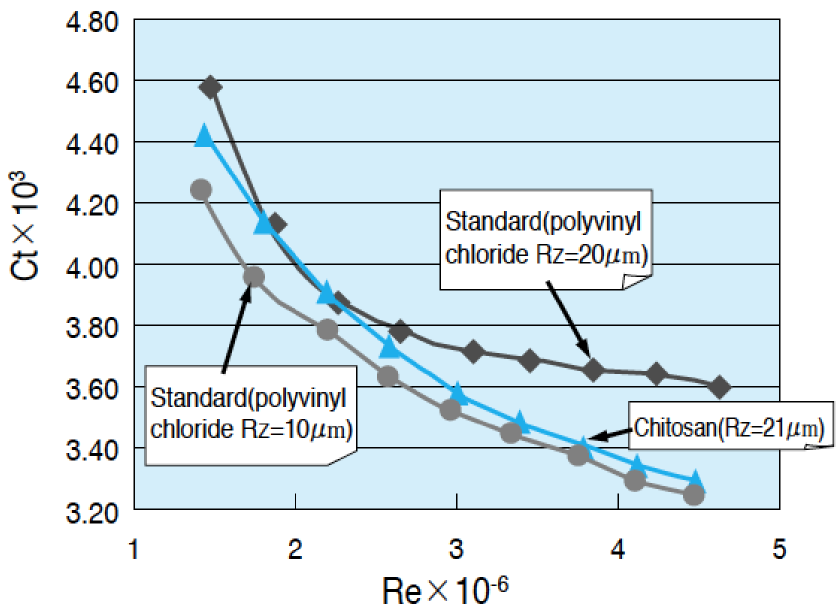
- LF-Sea (Nippon Paint)
  - Hydrogel formation
  - DR ~ 10%
  - Biomimetic
  - Water trapping effect



Water trapped layer

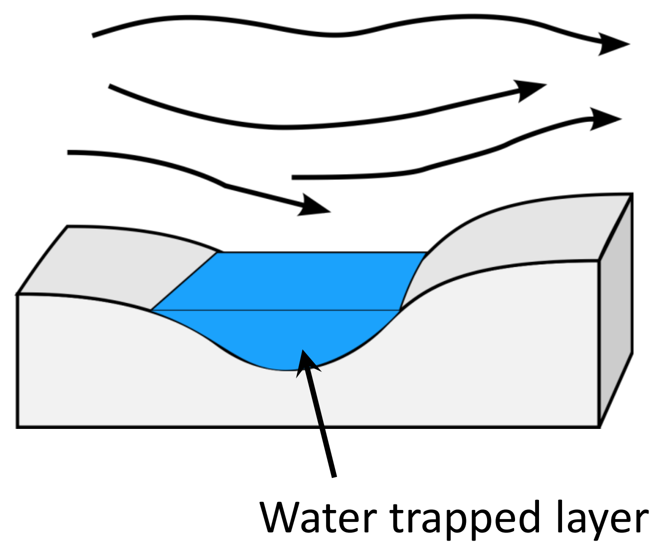
Drag reduction effect with hydrogel

Result of towing tank test



山盛, TECHNO-COSMOS, 2005

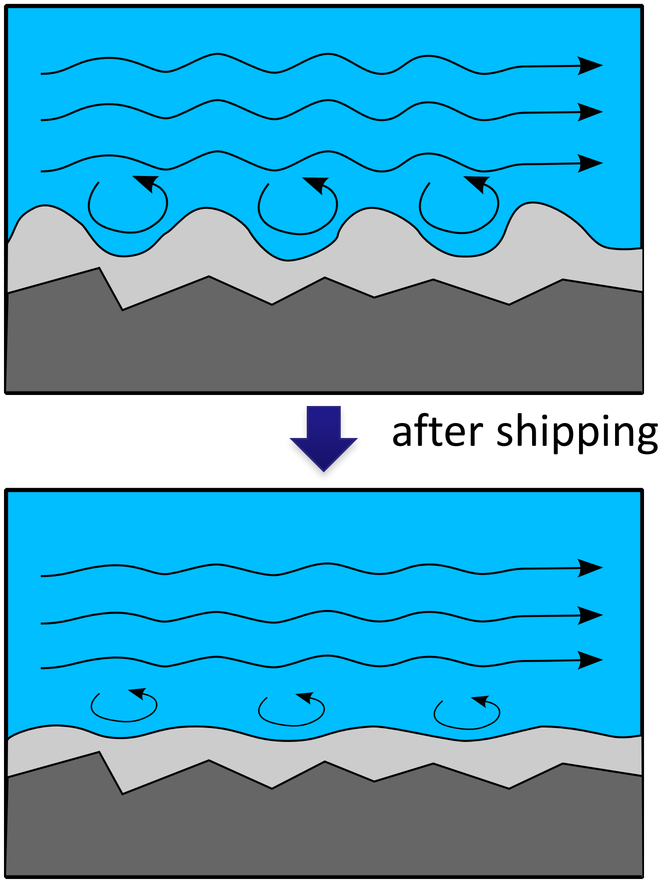
Proposed drag reduction mechanism



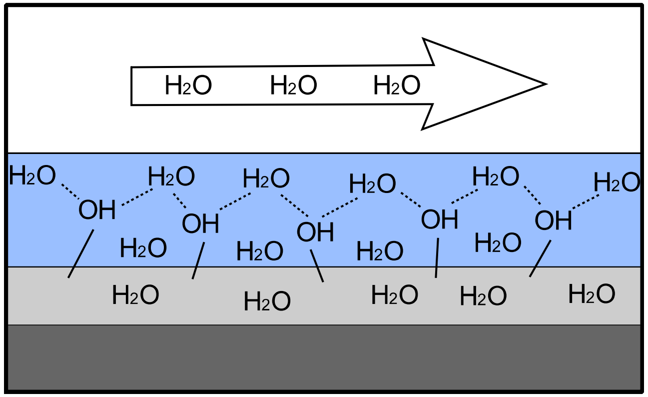
山盛&島田, TECHNO-COSMOS, 2009

Painting condition in sea water

Self-polishing type

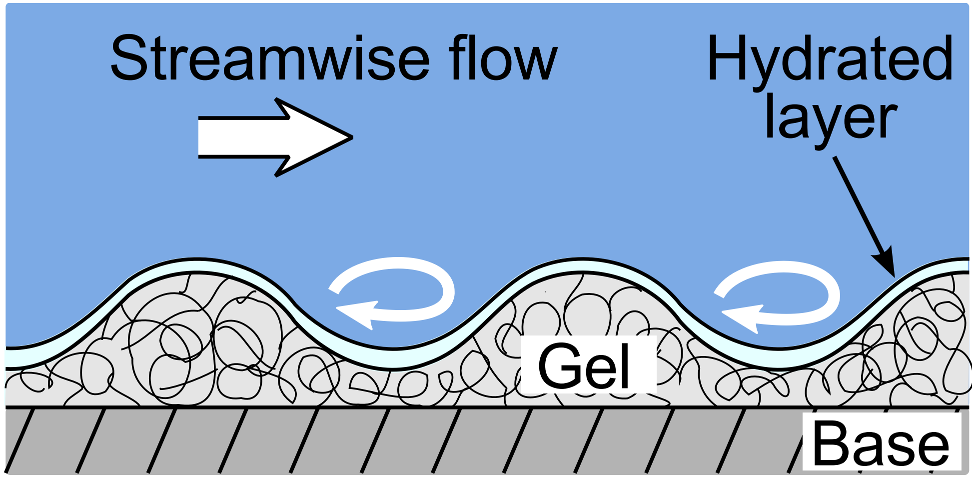


Hydration type



- Green
- Stress relaxation

Structures around hydrogel painting

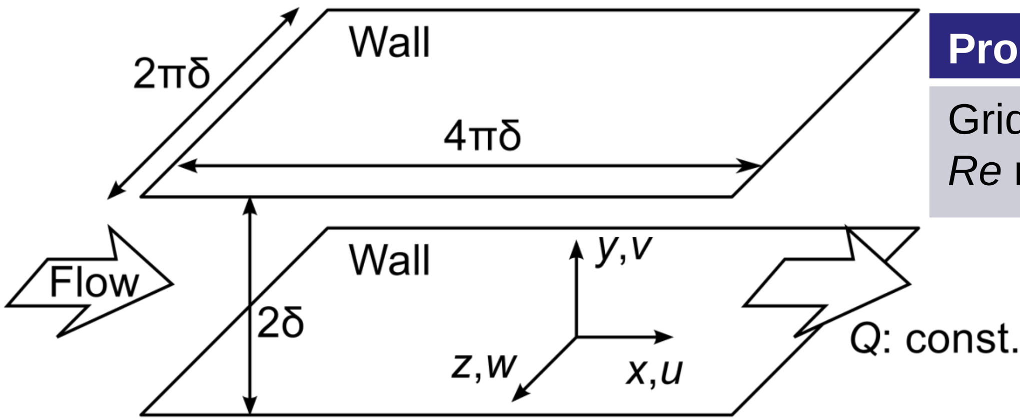


<u>Proposed mechanism for drag reduction</u>

1. Slip velocity due to water trapping
2. Stress relaxation due to compliant gel polymer
3. Surface deformation and roughness
4. Water penetration into hydrated and gel layers (porous-like structure)

1. Slip velocity due to water trapping: numerical modeling in plane channel flow

Direct Numerical Simulation (DNS) of turbulent channel flow



Property	Symbol	Value
Grid number	$N_x \times N_y \times N_z$	$128 \times 151 \times 128$
Re number	Re_C (Re_τ)	4200 (180)

Governing equations

Navier-Stokes equation:

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}}\frac{\partial^2 u_i}{\partial x_j^2}$$

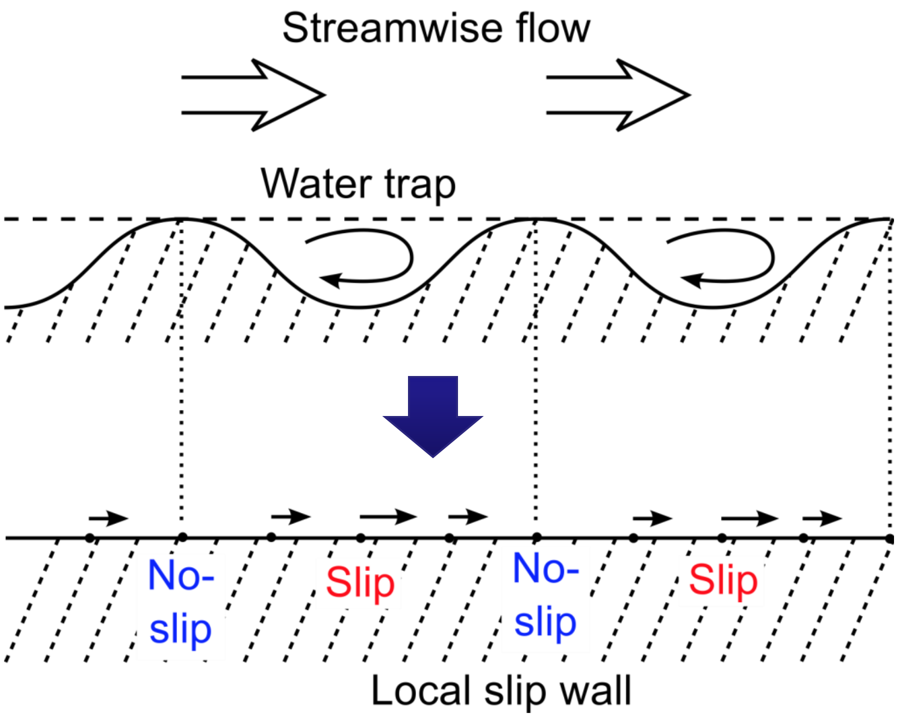
Continuity equation:

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

Numerical scheme

- 2nd-order Finite Difference Method
- Crank Nicholson for viscous term
- 3rd-order Runge-Kuttta
- Poisson eq. in Fourier space was solved by TDMA.

Slip velocity condition



<u>Local slip velocity</u>

$$u_s = l_x \frac{\partial u}{\partial y}, w_s = l_z \frac{\partial w}{\partial y}$$

where

$$l_x, l_z = f_x f_z l_0$$

$$f_x = \frac{1}{2}\left\{1 + \cos\left(\frac{2\pi}{\lambda_x} x\right)\right\},$$

$$f_z = \frac{1}{2}\left\{1 + \cos\left(\frac{2\pi}{\lambda_z} z\right)\right\}$$

Property	Value
Reference slip length (l_0^+)	0.36
Slip wave length:	
x-direction (l_x^+)	275, 368, 550, 735, 1100
z-direction (l_z^+)	50, 100, 183, 367

Validation of simulation code

Drag reduction ratio (DR) under uniform slip velocity condition

Case	Slip length	DR (Min & Kim[1])	DR (Present)
Streamwise slip	$l_x^+ = 0.36,\ l_z^+ = 0$	5%	5.5%
Spanwise slip	$l_x^+ = 0,\ l_z^+ = 0.36$	-3%	-3.6%
Isotropic slip	$l_x^+ = l_z^+ = 0.36$	-1%	-0.6%

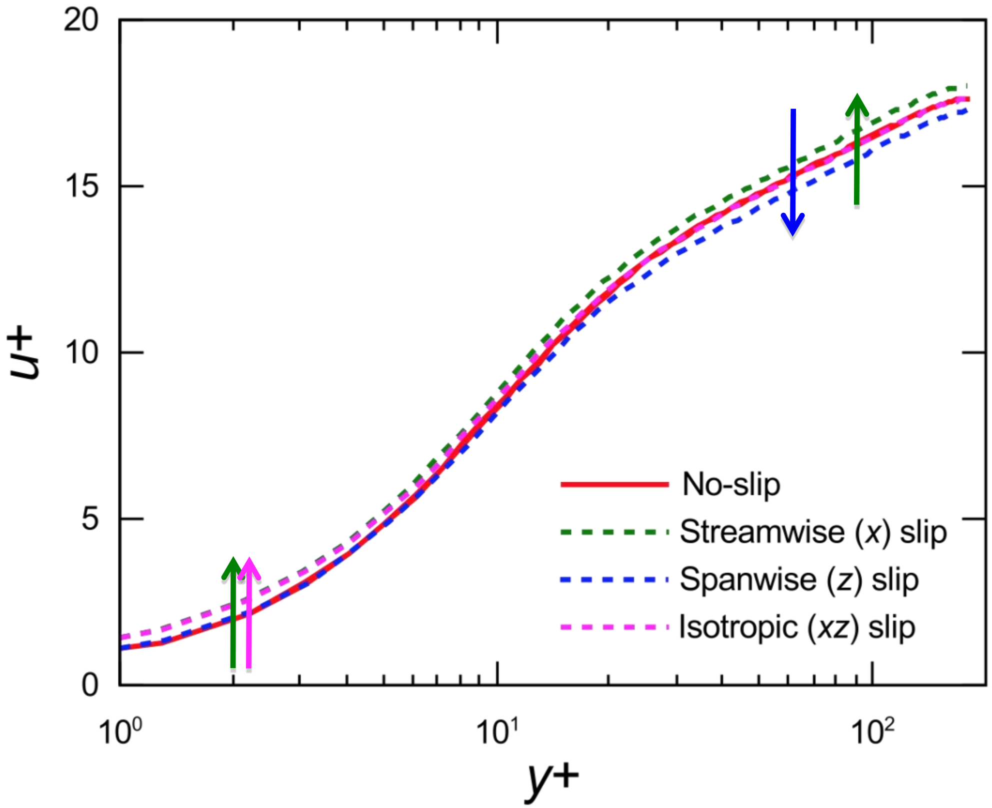
[1] T. Min and J. Kim, Phys. Fluids, 16(7), L55 (2004).

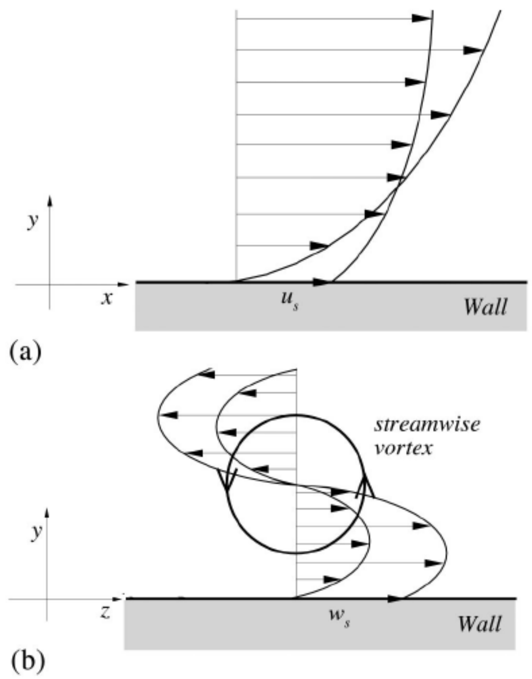
Drag reduction ratio

$$DR[\%] = \frac{\left(-\left.\frac{dp}{dx}\right|_{\text{no-slip}}\right) - \left(-\left.\frac{dp}{dx}\right|_{\text{slip}}\right)}{\left(-\left.\frac{dp}{dx}\right|_{\text{no-slip}}\right)} \times 100$$

Validation of simulation code

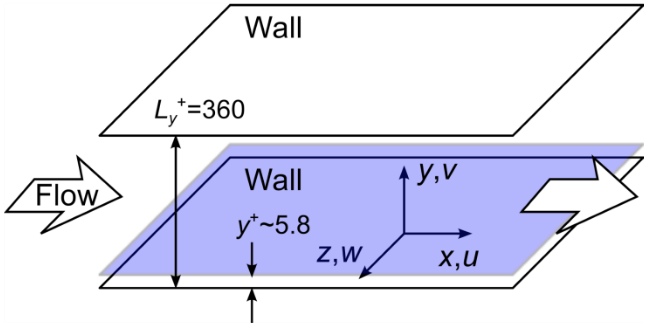
Mean velocity profiles under uniform slip velocity condition





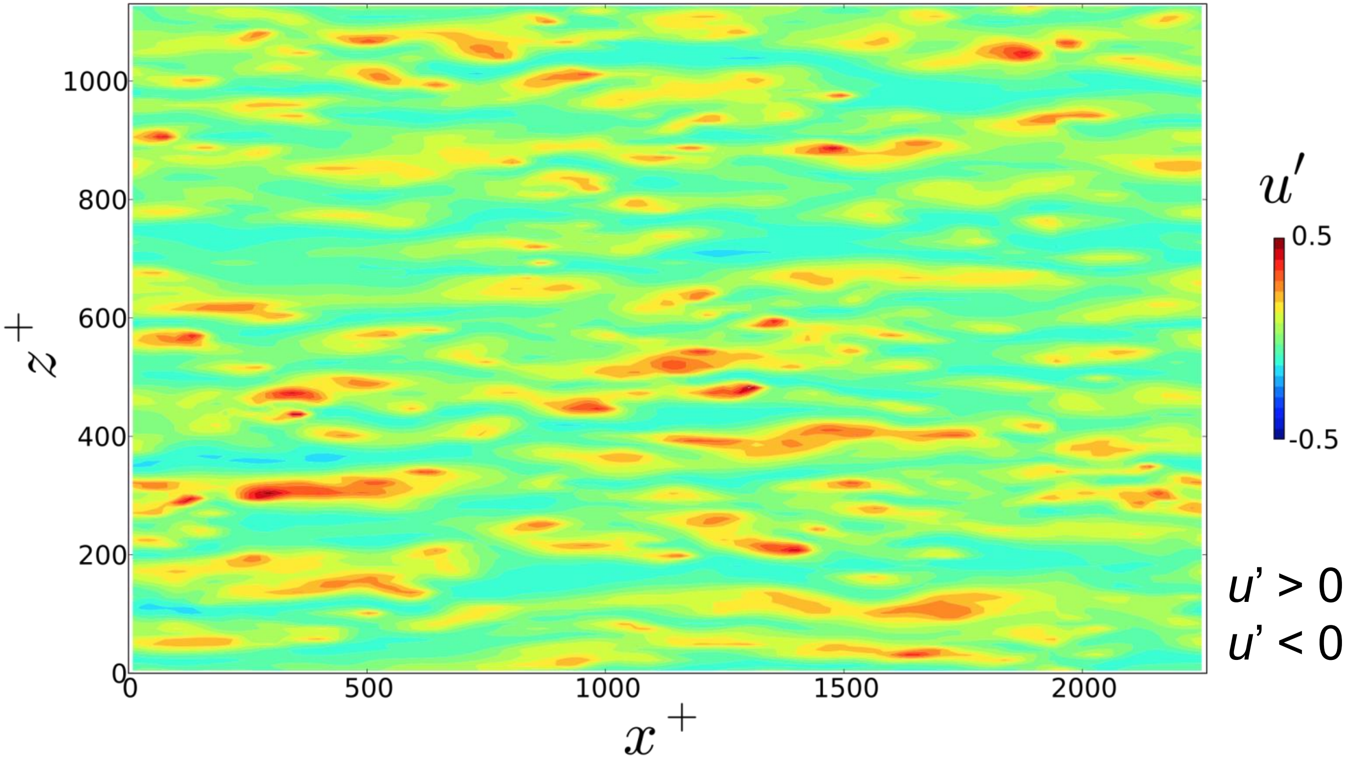
Drag decrease/increase mechanism (Min&Kim, 2004)

Streak structure



Streamwise velocity fluctuation at y^+ ~ 5.8

$$u'(y,t) = u(x,y,z,t) - \langle u(x,y,z,t) \rangle_{xz}$$

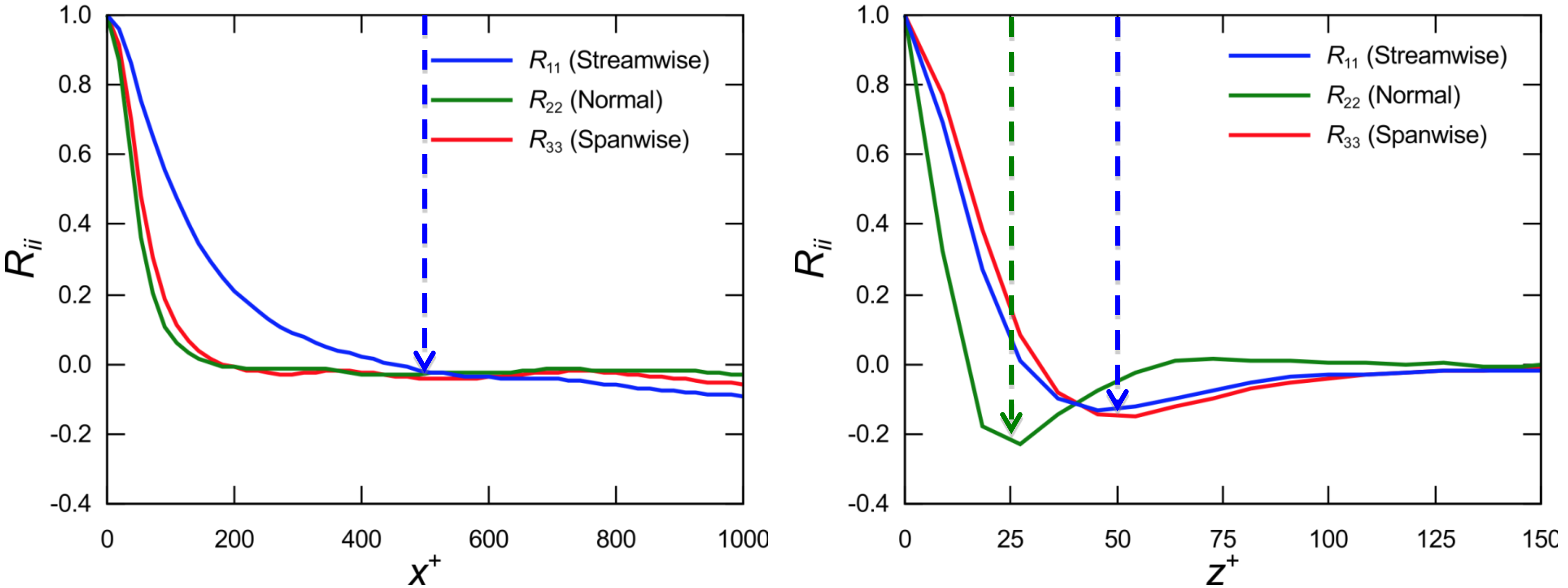


u' > 0: high speed streak
u' < 0: low speed streak

Scale of streak structures

Two-point correlations at $y^+ \sim 5.8$

$$R_{ii}(r_1) = \frac{\langle u_i'(x,y,z)u_i'(x+r_1,y,z)\rangle}{\langle u_i'^2(x,y,z)\rangle}, R_{ii}(r_3) = \frac{\langle u_i'(x,y,z)u_i'(x,y,z+r_3)\rangle}{\langle u_i'^2(x,y,z)\rangle}$$

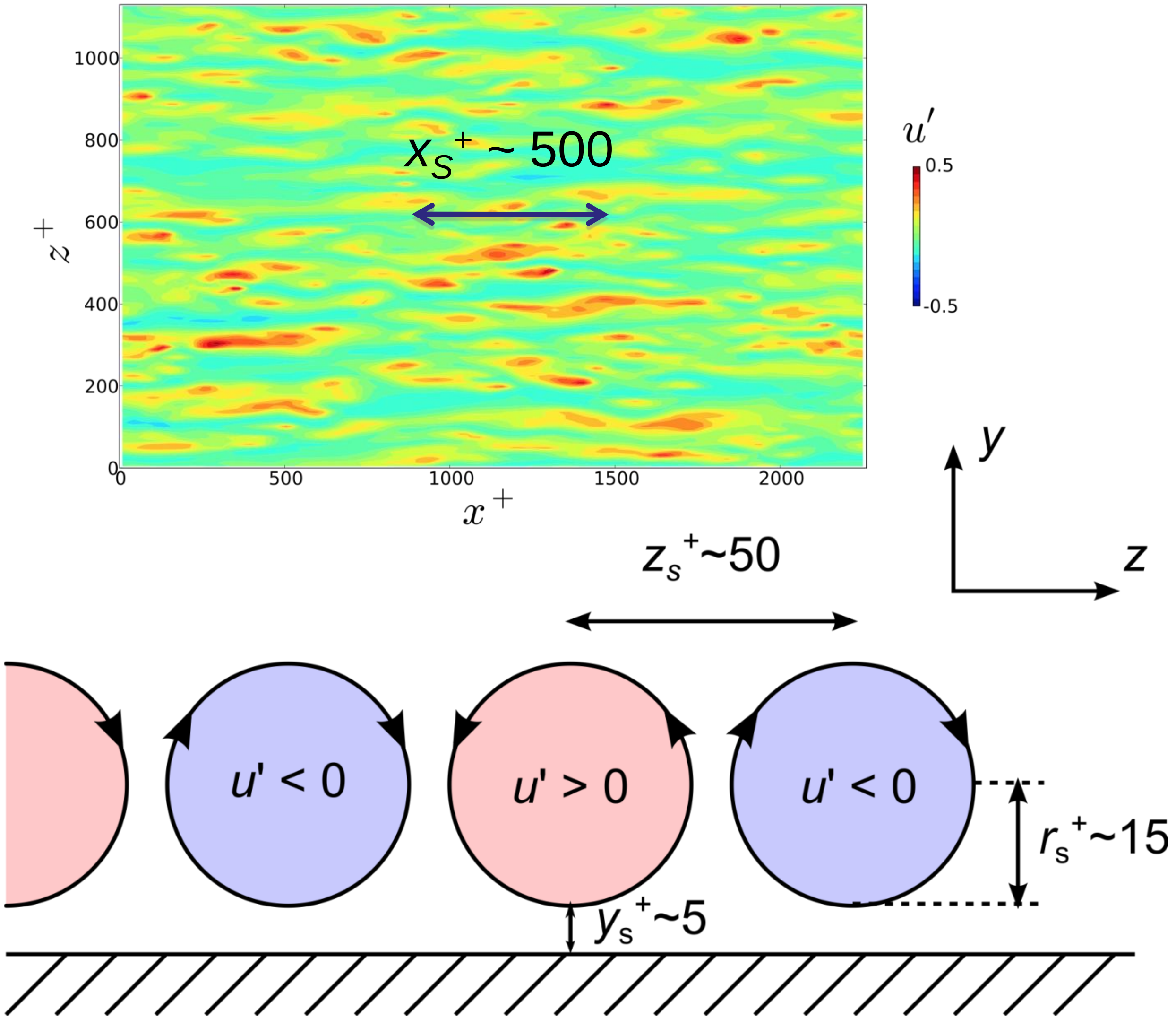


In the streamwise direction

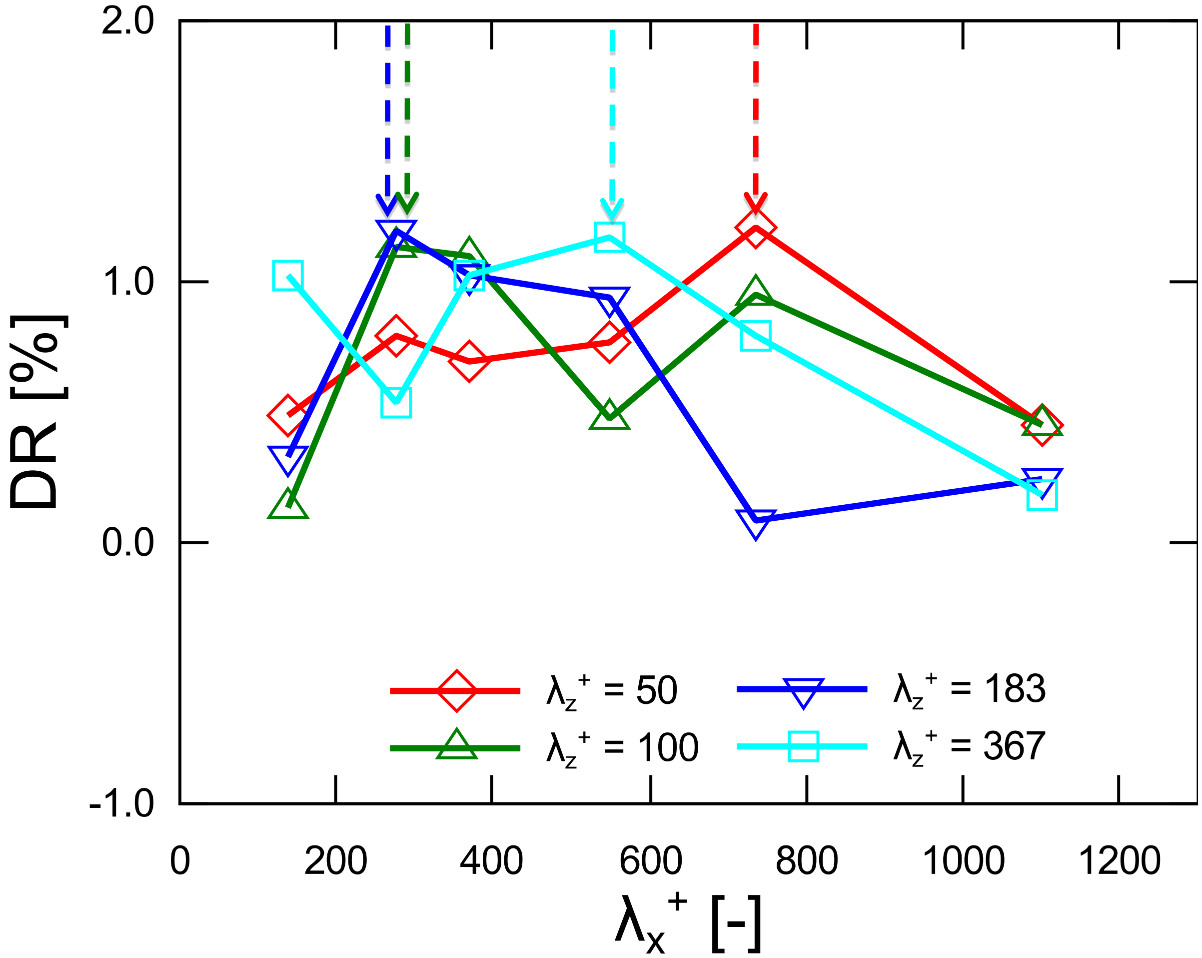
In the spanwise direction

Negative correlation is related with the scale of high/low streaks.

Scale of streak structures



Dependency of local slip velocity

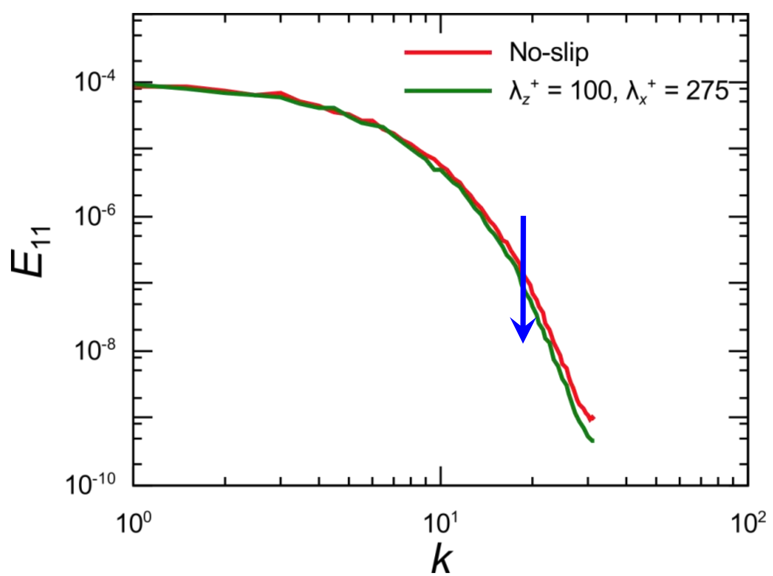


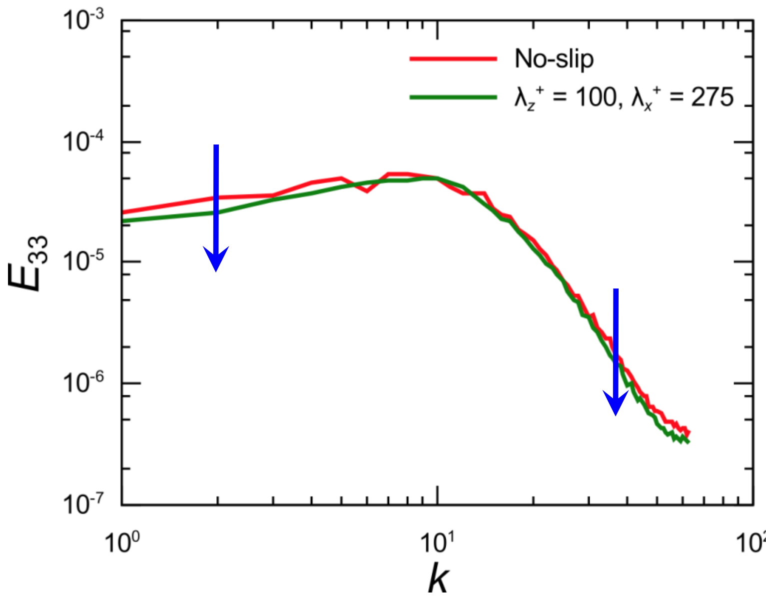
Optimum local slip condition was not specified uniquely.

Suppression of energy dissipation

One-dimensional energy spectra at $y^+ \sim 5.8$

$$E_{11}(k) = \int_{-\infty}^{+\infty} \overline{u_i'(x,y,z)u_i'(x+r,y,z)} e^{-ikr} dr \qquad E_{33}(k) = \int_{-\infty}^{+\infty} \overline{u_i'(x,y,z)u_i'(x,y,z+r)} e^{-ikr} dr$$

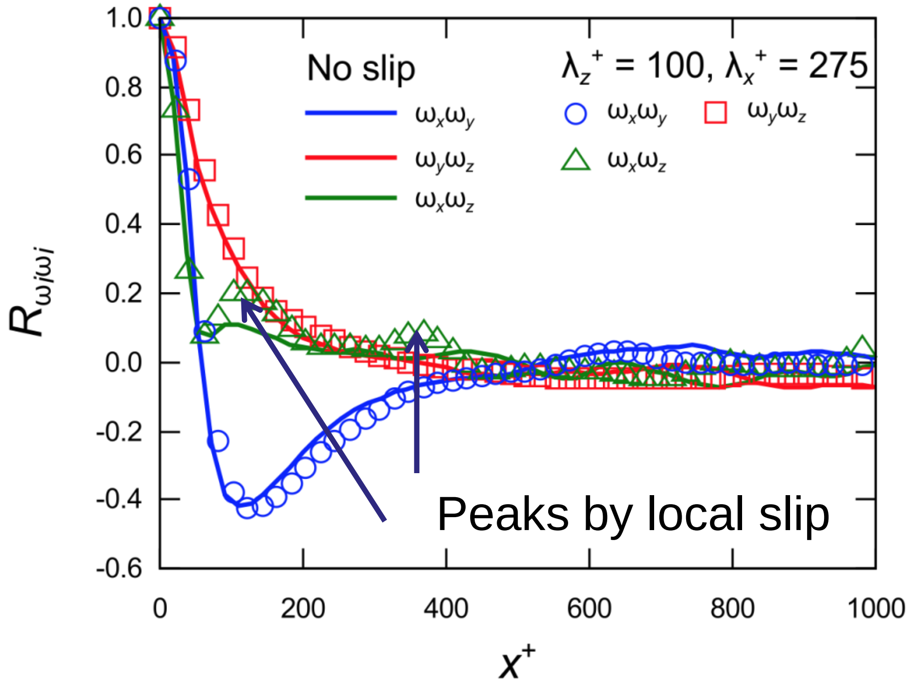




The spanwise intensity of streak structure decreased by local slip.

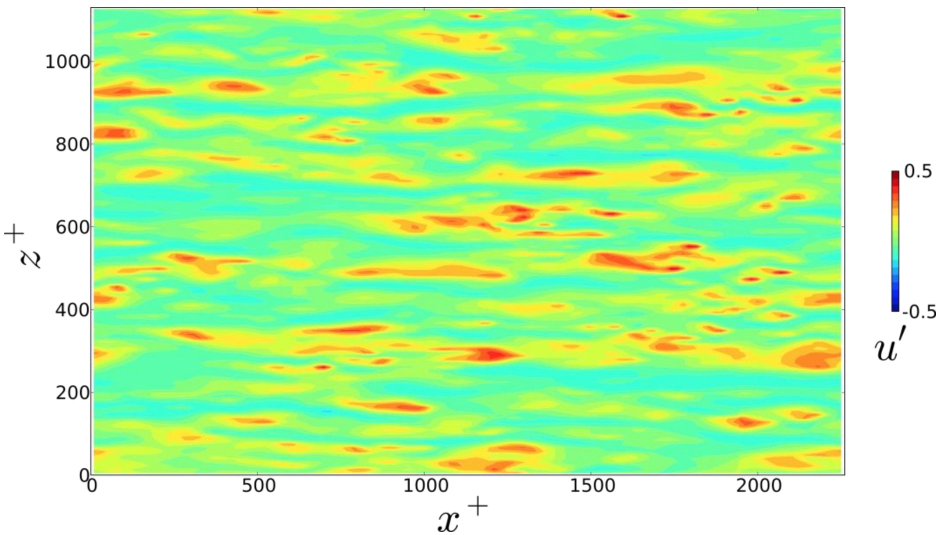
Vortex interaction

Two-point correlation of vorticity



Vortex interaction was seen in the horizontal plane.

Velocity fluctuation (streak structure)



No significant change

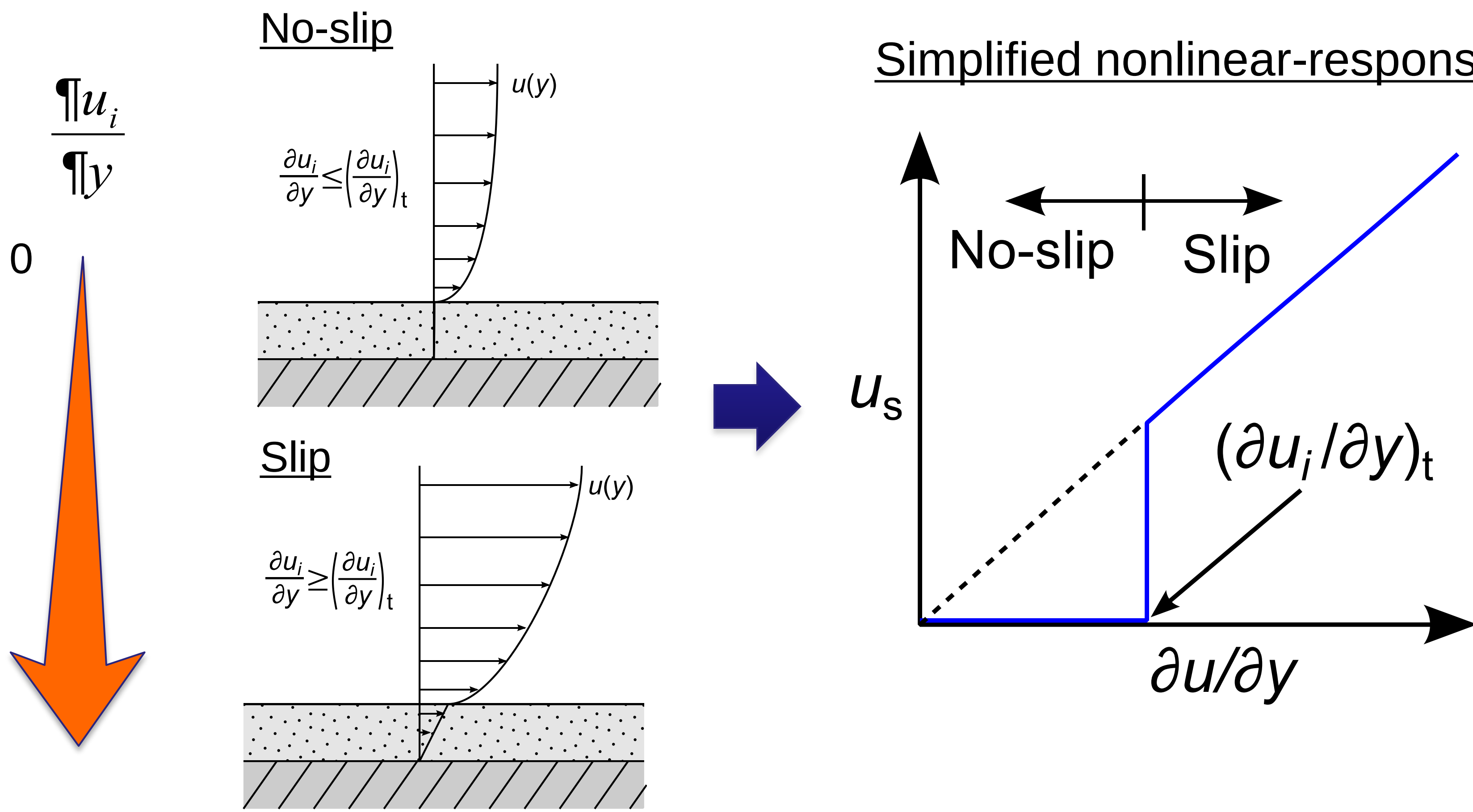
Summary of topic 1

- A turbulent channel flow simulation with local slip velocity was carried out.
- The slip wavelength compared with the size of streak structure was effective for drag reduction.
- The spanwise energy dissipation related with the streak scale was selectively suppressed.
- The vortex interaction was seen in the streamwise and spanwise directions. However, it did not lead to drag increase.

2. Stress relaxation due to compliant gel polymer: Nonlinear response of hydrogel to shear stress

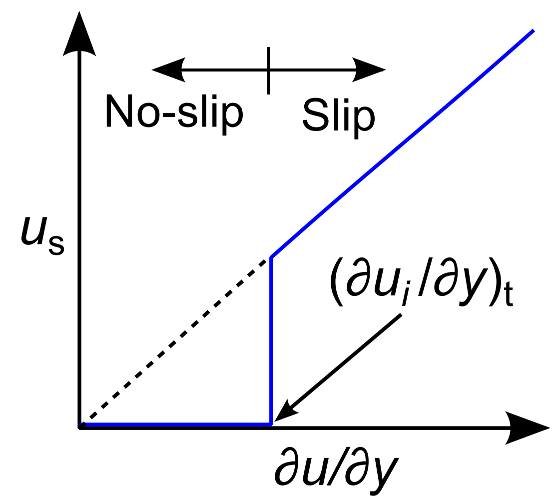
Response to high wall shear stress

- Gel: nonlinear stress response



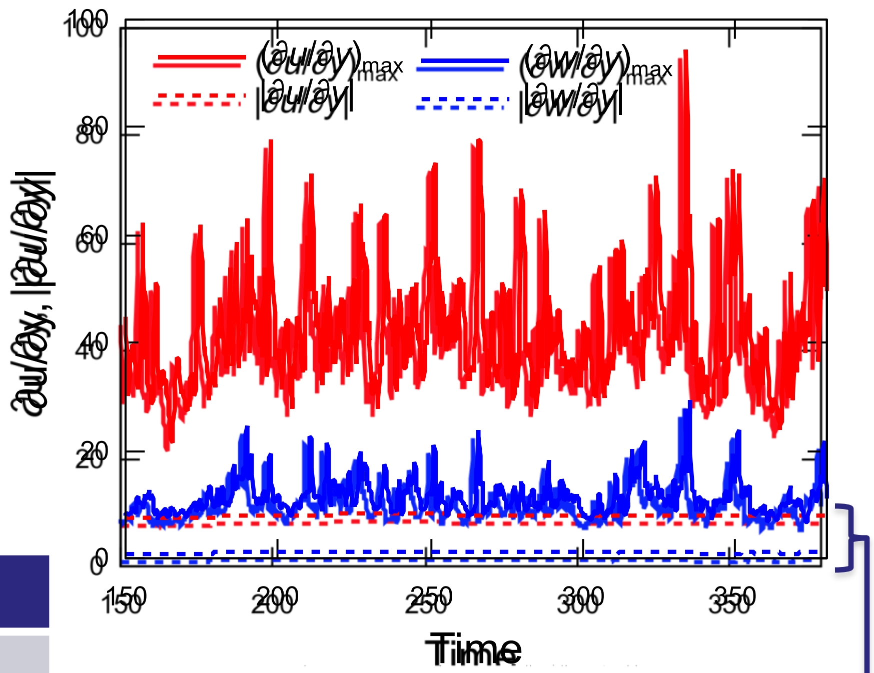
Threshold of slip condition

Nonlinear stress response



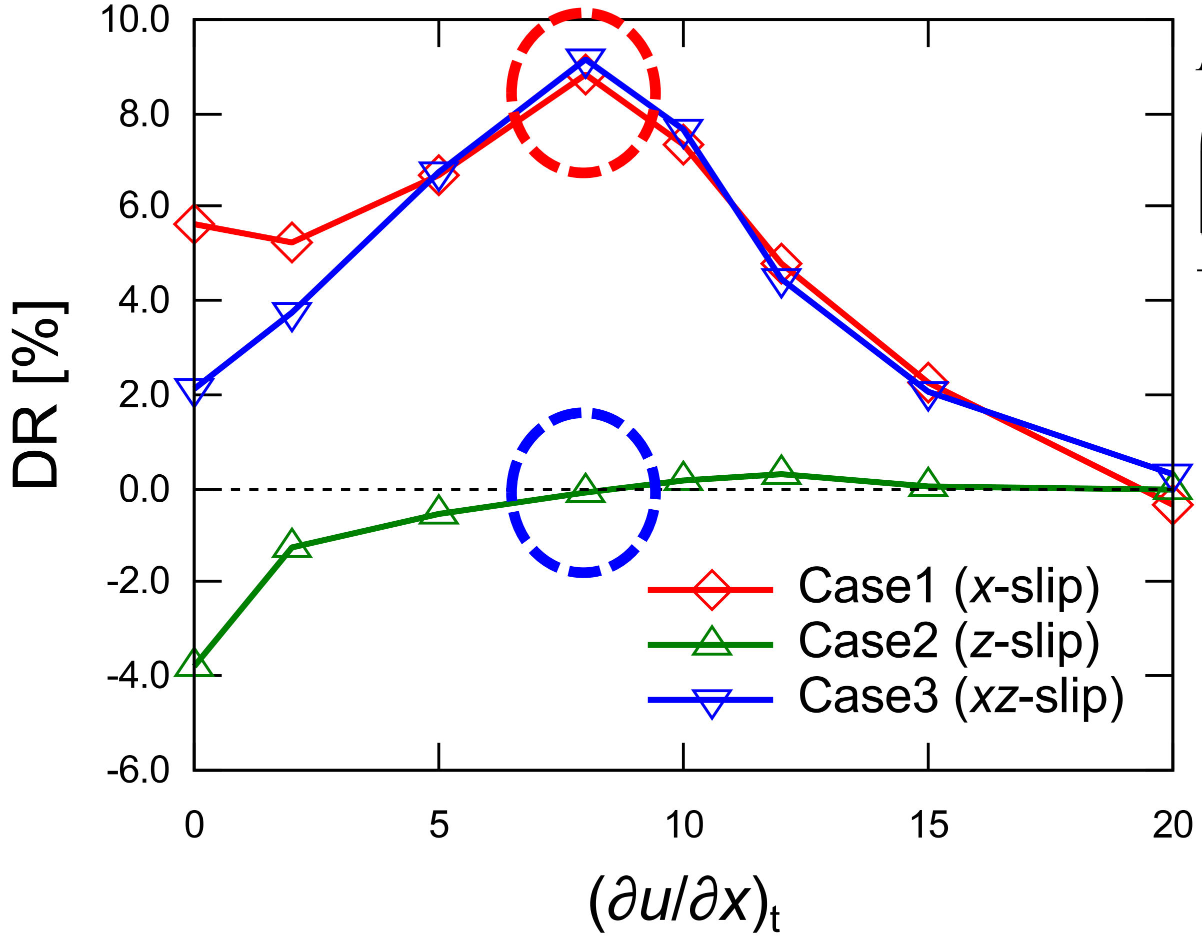
Label	Type	Threshold
Case 1	only x-slip	0 ~ 20
Case 2	only z-slip	
Case 3	isotropic (xz-slip)	

Calculated range of velocity gradient on wall (no-slip case)



$$\left\langle \frac{\partial u}{\partial y} \right\rangle \sim 8, \quad \left\langle \frac{\partial w}{\partial y} \right\rangle \sim 1$$

Dependency of drag reduction



$$DR[\%] = \frac{\left(-\left.\frac{dp}{dx}\right|_{\text{no-slip}}\right) - \left(-\left.\frac{dp}{dx}\right|_{\text{slip}}\right)}{\left(-\left.\frac{dp}{dx}\right|_{\text{no-slip}}\right)} \times 100$$

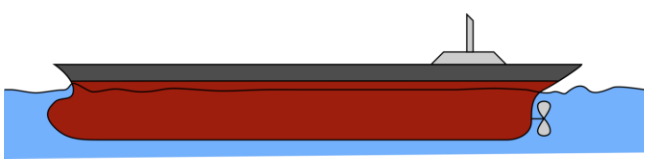
Total slip effect was given by the summation of each contribution.

Summary of topic 2

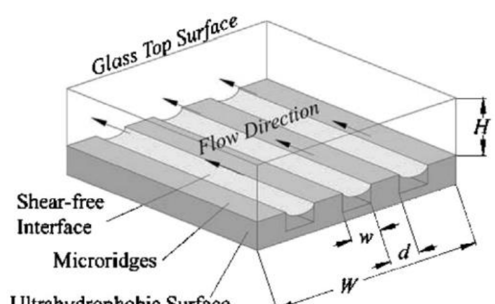
- A three-dimensional simulation considering shear stress response in hydrogel was carried out.
- Although the stress response was isotropic, significant drag reduction effect was achieved.

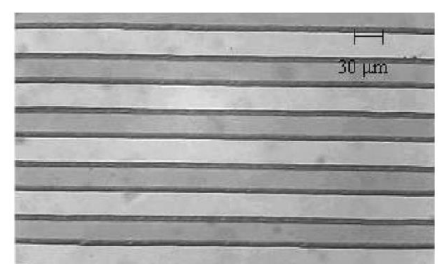
- Isotropic hydrogel painting might be useful for wall turbulence with the change of streamwise direction.

In oblique flow



Super hydrophobic flow





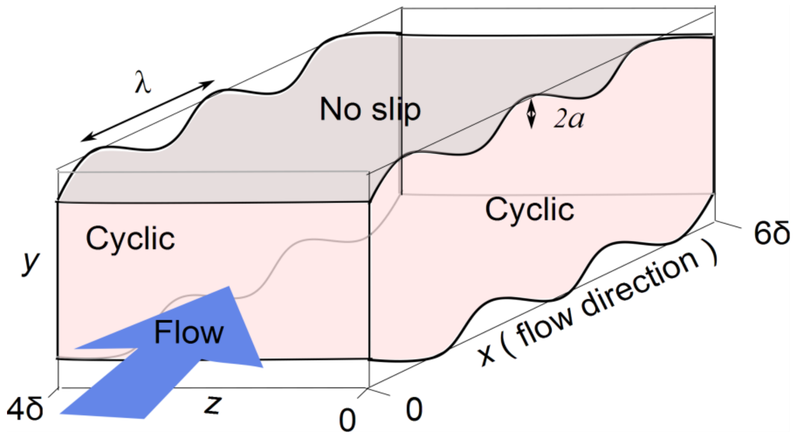
Ou&Rothstein,2005

3. Surface deformation and roughness: wavy channel flow simulation

Numerical condition

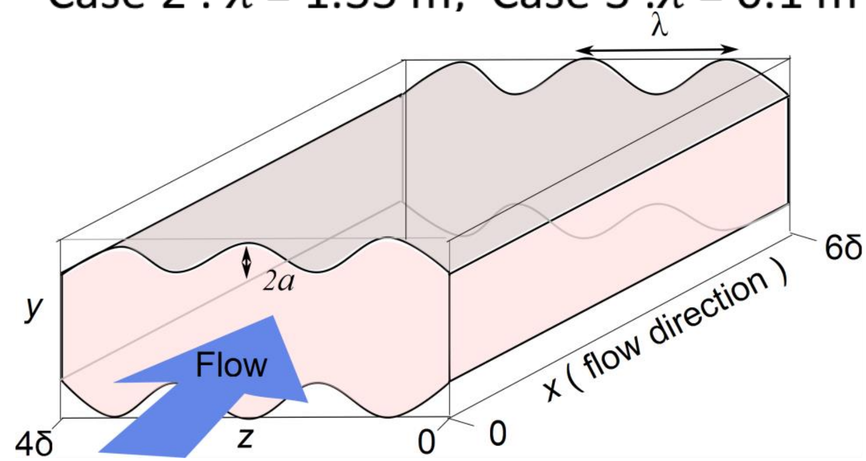
Streamwise wavy channel

Case 1



Spanwise wavy channel

Case 2 : λ = 1.33 m, Case 3 : λ = 0.1 m



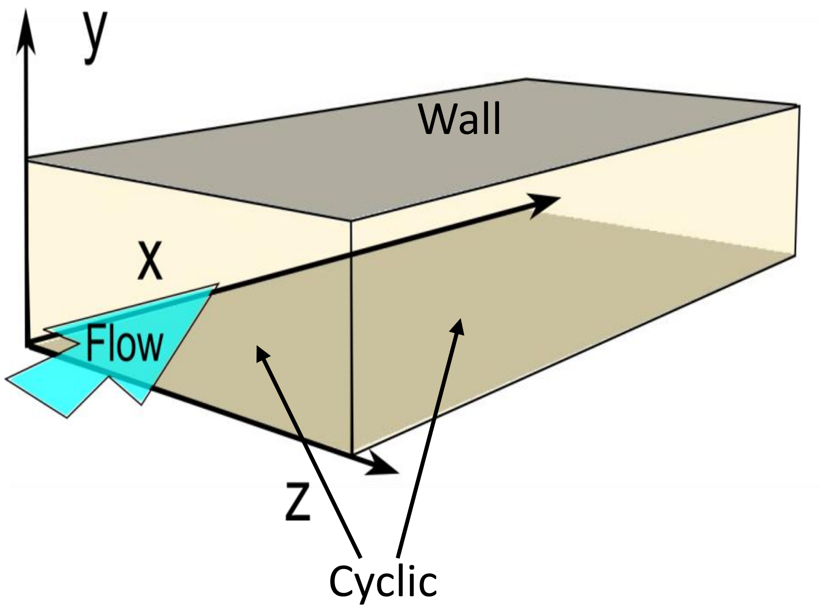
Wave shape of the wall : $y = a\left\{1 + \cos\left(\frac{2\pi}{\lambda}x\right)\right\}$ δ : channel-half width

	Case1	Case2	Case3
Wave type	streamwise	spanwise	
Wave length(λ) [m]	2.0	1.33	0.1
Amplitude(a) [m]	0.1δ	0.1δ	0.1δ
Grid Number(x, y, z)	148,95,128	128,95,148	129,97,241

Code validation

DNS of a turbulent channel flow by using OpenFOAM®

No turbulence model



Label	Grid number	Method
Kim et al. (1987)[1]	192 × 129 × 160	Fourier-spectral
Coarse	64 × 64 × 64	
Middle	96 × 96 × 96	FVM with OF
Fine	128 × 128 × 128	

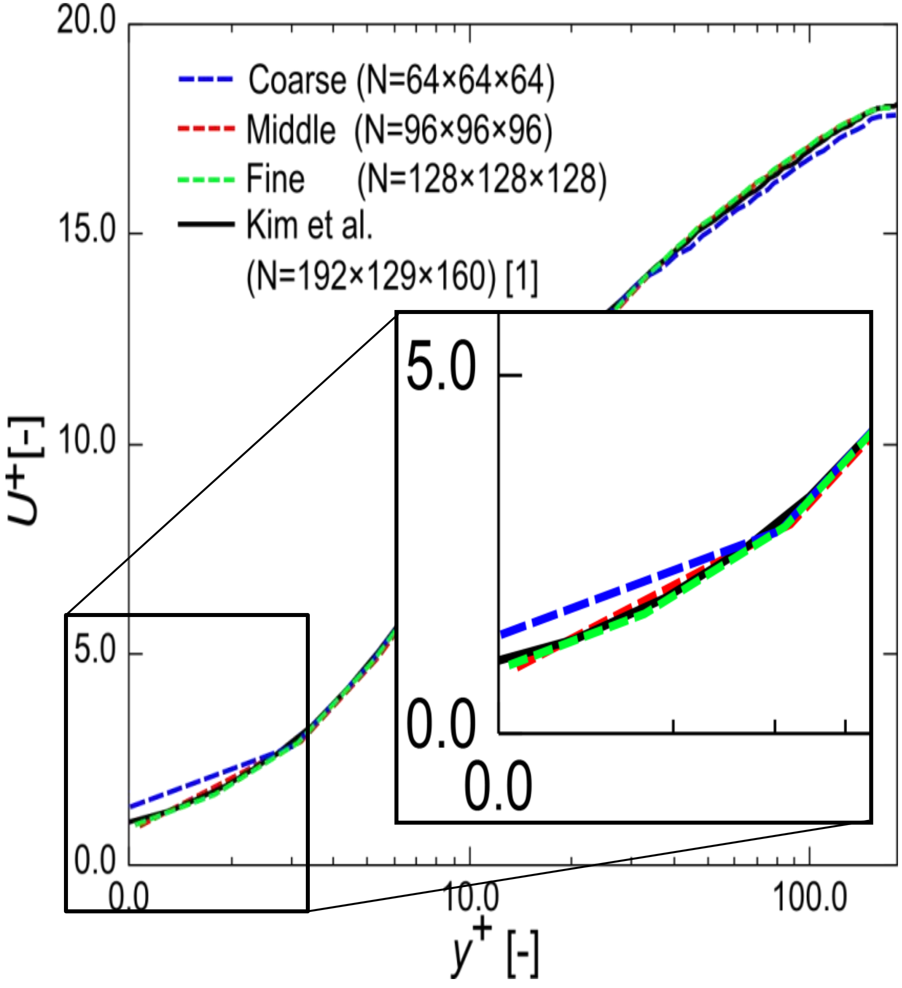
[1] J. Kim *et al.*, *J. Fluid Mech.*, **177**, pp. 133-166 (1987).

$$Re = \frac{2u_m\delta}{\nu} = 5600$$

u_m: mean velocity
δ : channel-half width
ν : kinematic viscosity

Code validation

Mean velocity profiles



	Coarse	Middle	Fine
Averaged y+	0.60	0.51	0.49

Middle and Fine resolution showed good agreements.

OpenFOAM is available for DNS on a turbulent channel flow.

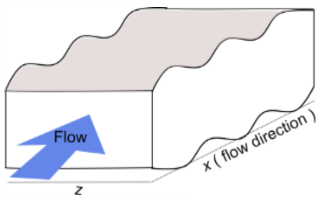
Drag reduction ratio (DR)

$$DR = \frac{\left(-\left.\frac{dP}{dx}\right|_{flat}\right) - \left(-\left.\frac{dP}{dx}\right|_{wavy}\right)}{\left(-\left.\frac{dP}{dx}\right|_{flat}\right)}$$

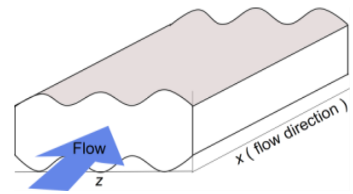
$-\left.\frac{dP}{dx}\right|_{flat}$: mean pressure gradient in a flat channel

$-\left.\frac{dP}{dx}\right|_{wavy}$: mean pressure gradient in a wavy channel

Case 1



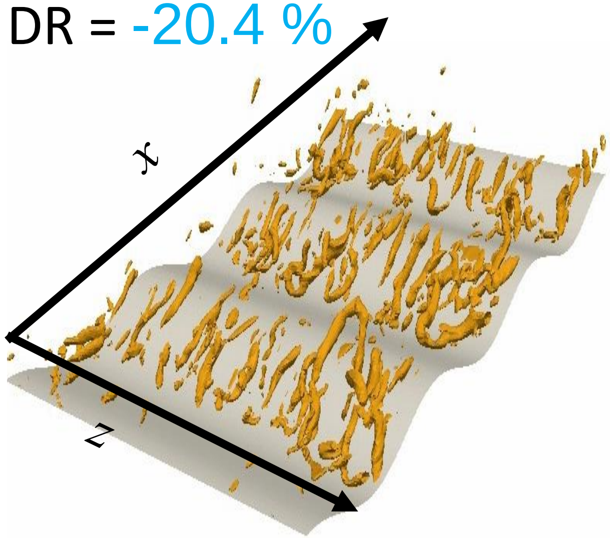
Case 2



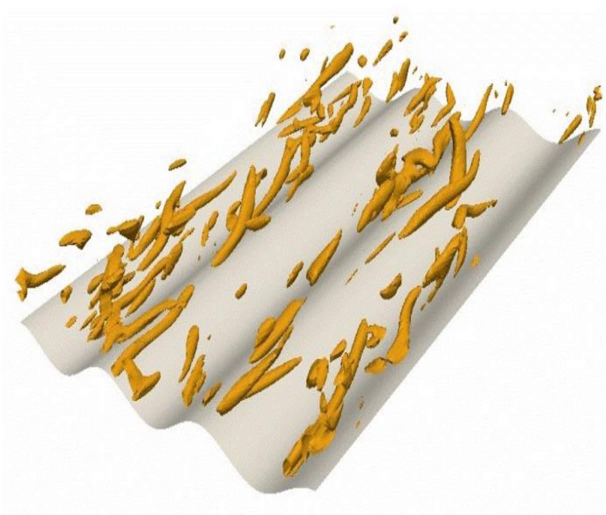
Case 3

Drag increase

DR = -20.4 %

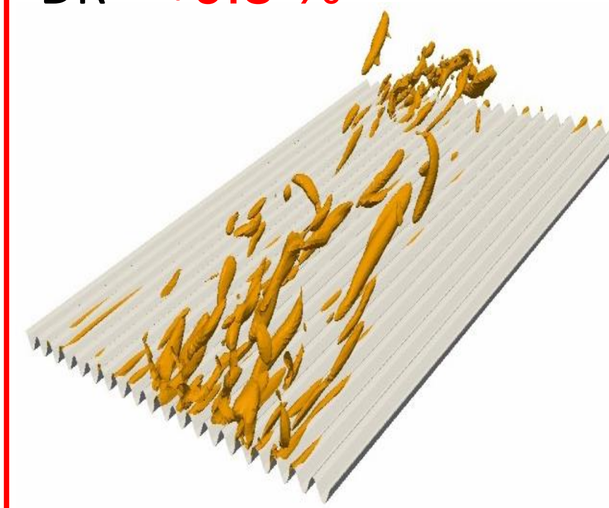


DR = -9.4 %

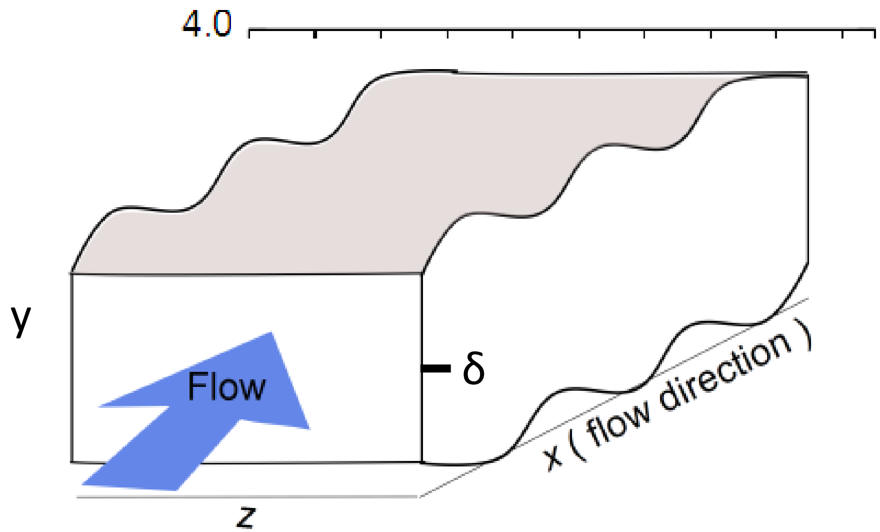


Drag reduction

DR = +9.3 %



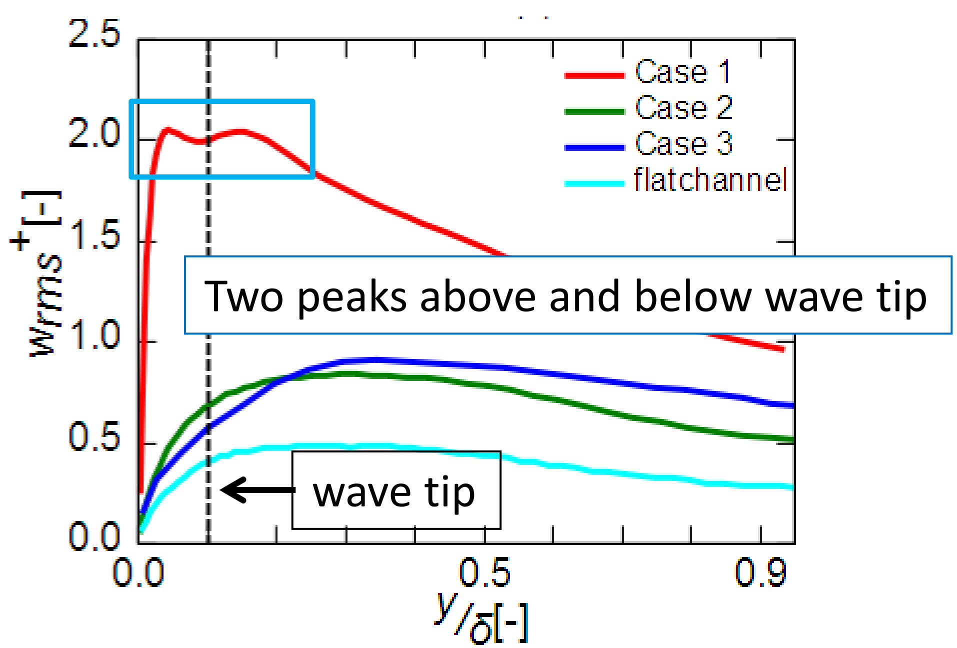
Discussion — Case1 : streamwise wavy channel

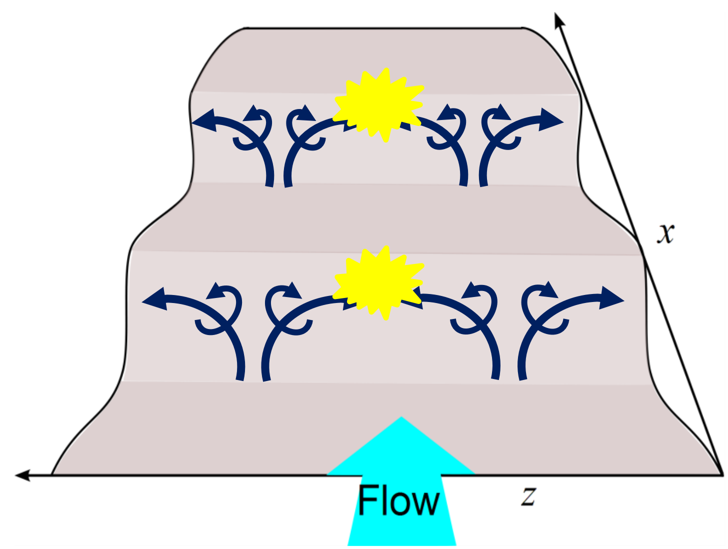


The peak of RMS value profile

➡ Most random flow region

δ : channel-half width

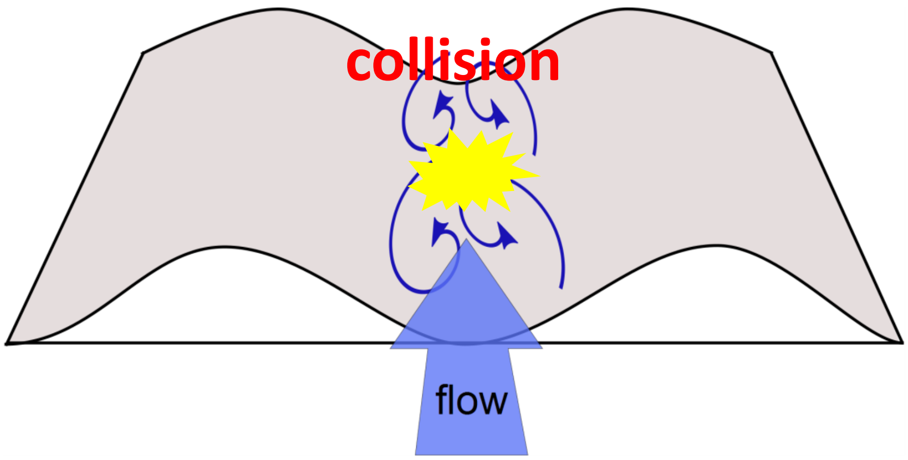




Case2 and Case 3 : spanwise wavy channel

Case 2

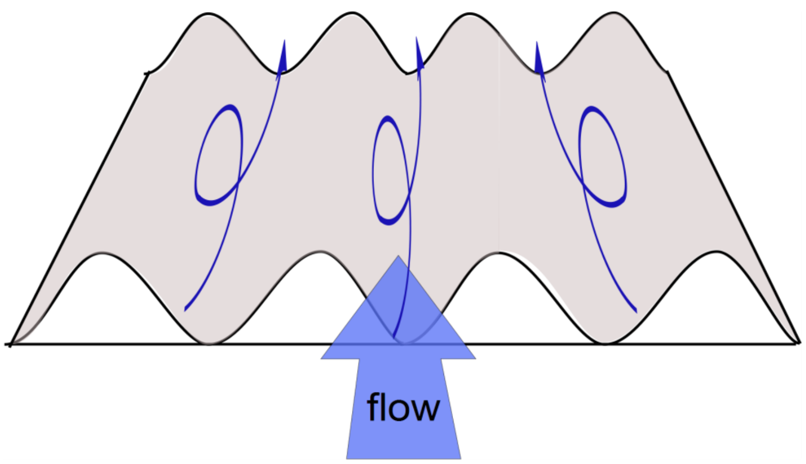
Some vortices in one wave



Advance the dissipation

Case 3

Unit vortex in one wave



Drag reduction

Median diameter of eddies

	Case1	Case 2	Case 3	Flat channel
Median diameter [m]	0.184	0.272	0.09	0.240
Spanwise wave spacing[m]	—	1.333	0.1	—
DR [%]	-20.4	-9.4	+9.3	0

Summary of topic 3

- Drag reduction effect was shown when collision of vortices was suppressed by wall shape.
- Dissipation was advanced by collision of several vortices in one wave .

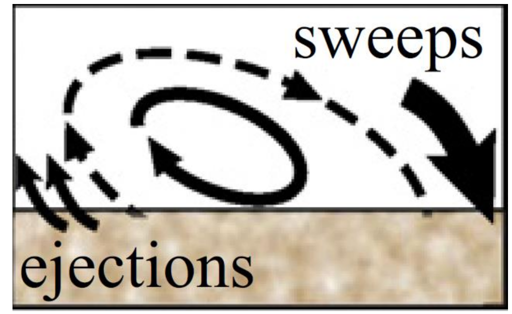
	Case1	Case2	Case 3
Wave type	Streamwise	Spanwise	
Wave length(λ)	2.0	1.33	0.1
Median diameter	0.184	0.272	0.09
DR [%]	-20.4	-9.4	9.3

Soft matter, Hydrogel, has advantage for drag reduction on ships bottom surface

4. Water penetration into hydrated and gel layers (porous-like structure): channel flow with porous wall

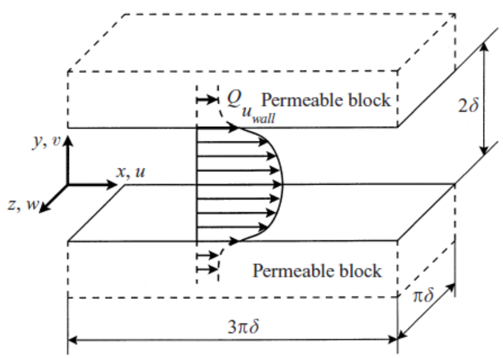
Approaches for fluid flow through porous structure

- Experimental research
  - Observation of sweep/ejection near wall[1)]



- Numerical research

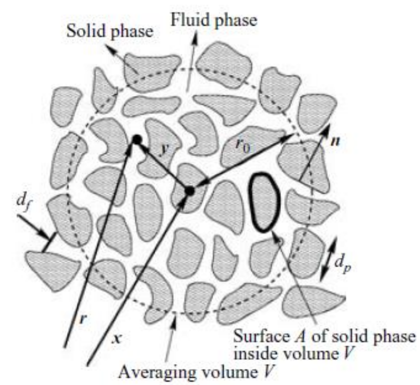
Boundary condition approach[2)]



Increase of turbulent drag

?

Continuum approach[3)]

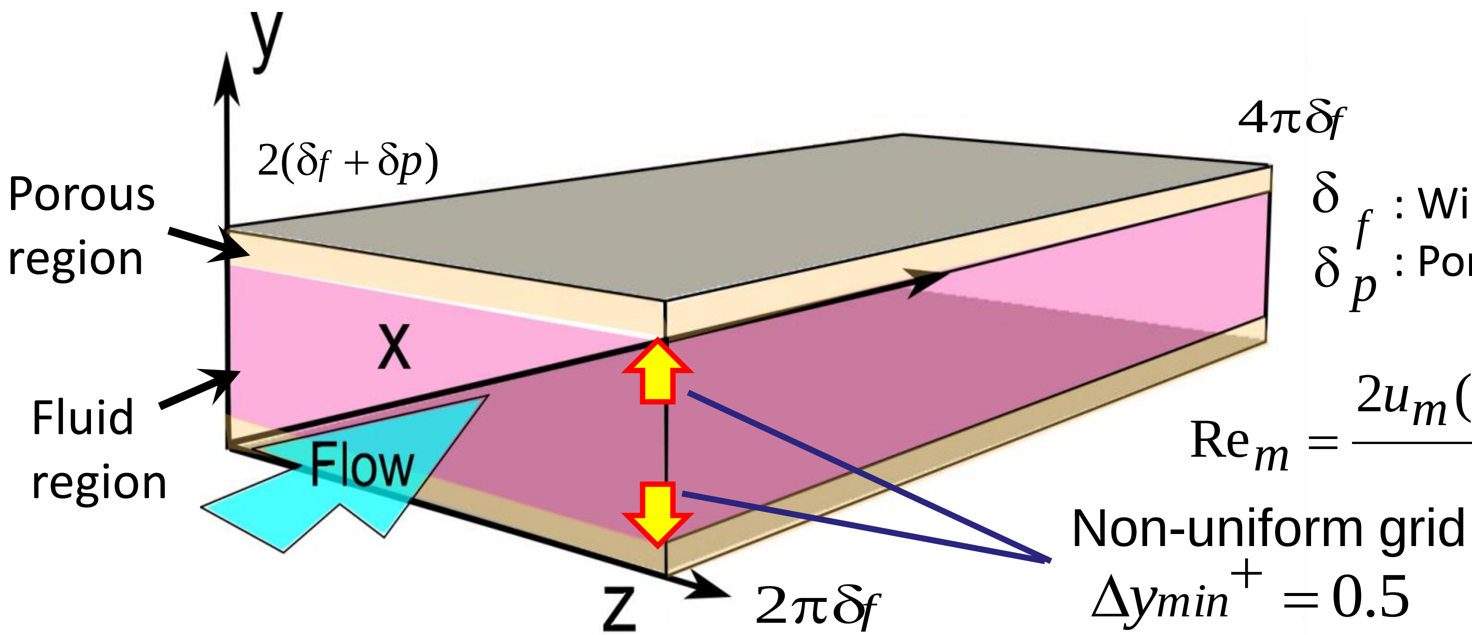


Decrease of skin friction due to **slip velocity**

1) K. Suga et al., *Int. J. Heat Fluid Flow*, 32, 586-595 (2011)
2) S. Hahn *et al*., *J. Fluids Mech.* vol. 450, pp. 259- 285(2002)
3) W. P. Breugem *et al*., *J. Fluids Mech.* vol. 562, pp. 35-72 (2006)

Numerical conditions

Case	5%D	10%D	20%D	Flat
Porous media thickness δ_p	$0.05\ \delta_f$	$0.10\ \delta_f$	$0.20\ \delta_f$	—
Total channel width	$2.1\ \delta_f$	$2.2\ \delta_f$	$2.4\ \delta_f$	$2.0\ \delta_f$
Number of grid points $N_x, (N_y^f + N_y^p), N_z$	149,(129+16),129	149,(129+20),129	149,(129+20),129	129,129,129



δ_f : Width of fluid region
δ_p : Porous wall thickness

$$Re_m = \frac{2u_m(\delta_f + \delta_p)}{\nu} = 5600$$

DNS of turbulent channel flow

Governing equations

Continuity equation

$$\nabla \cdot \boldsymbol{u} = 0$$

Momentum equation

$$\frac{D\boldsymbol{u}}{Dt} = -\nabla p' + \nu \nabla^2 \boldsymbol{u} + (1-\varphi)\boldsymbol{S}$$

Numerical scheme

- **Spatial discretization scheme**
  Finite Volume Method
- **Time advancement**
  Implicit Euler method (1 st)
- **Poisson equation**
  PISO algorithm

OpenFOAM®

Porous model

Darcy-Forchheimer equation

$$\boldsymbol{S} = -\frac{\nu}{K}\boldsymbol{u_m} - 2\frac{c_f}{\sqrt{K}}|\boldsymbol{u_m}|\boldsymbol{u_m}$$

φ	: Porosity	0.80
K	: Permeability	0.02 [mm^2]
c_f	: Forcheheimer coefficient	0.17

Drag reduction ratio

$$DR[\%] = \left(1 - \frac{C_f^p}{C_f^0}\right) \times 100$$

C_f^p : Friction coefficient over porous wall
C_f^0 : Friction coefficient over flat wall

FIK identity[1]

$$C_f = \frac{12}{Re_b} + 12\int_0^1 2(1-y)(\overline{-u'v'})dy$$

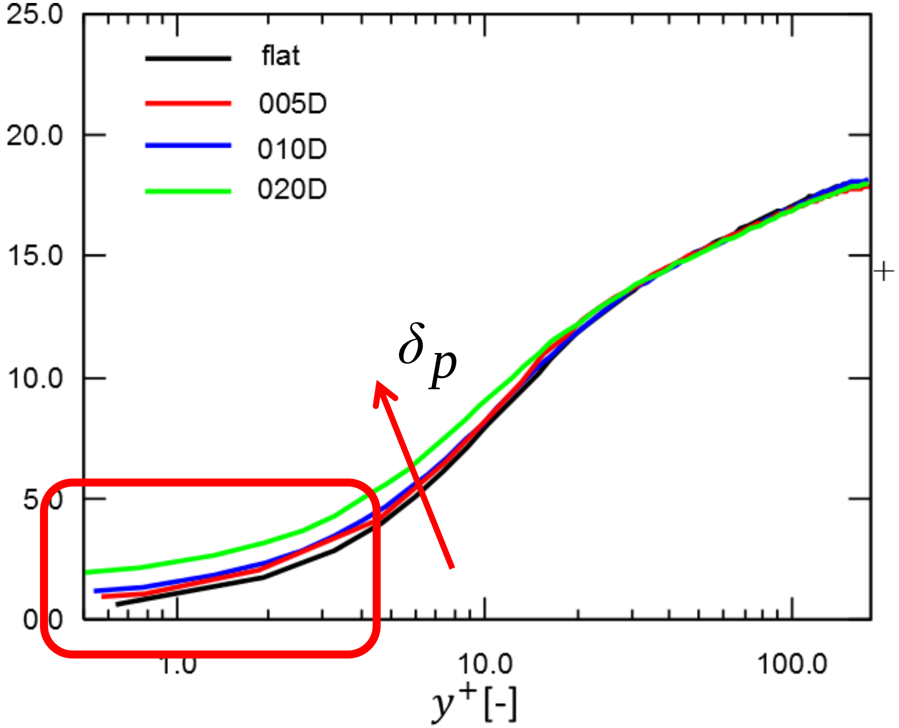
Viscous term and Turbulent term

Case	$C_f \times 10^3$	DR [%]	δ_p^+
5%D	6.55	+9.6	9
10%D	7.16	+1.3	18
20%D	7.56	-4.3	37
Flat	7.25		

[1]Fukagata, K., Iwamoto, K. and Kasagi, N., Phys. Fluids, 14 (2002), pp.73-76

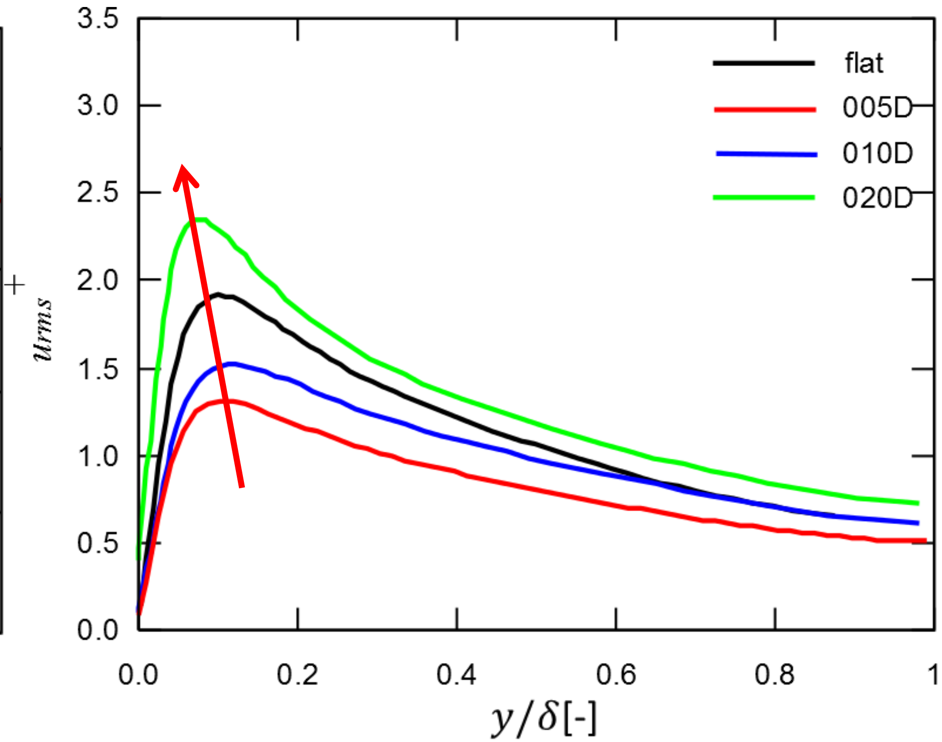
Turbulent statistics

Mean velocity profiles



Slip velocity occurred over porous walls.

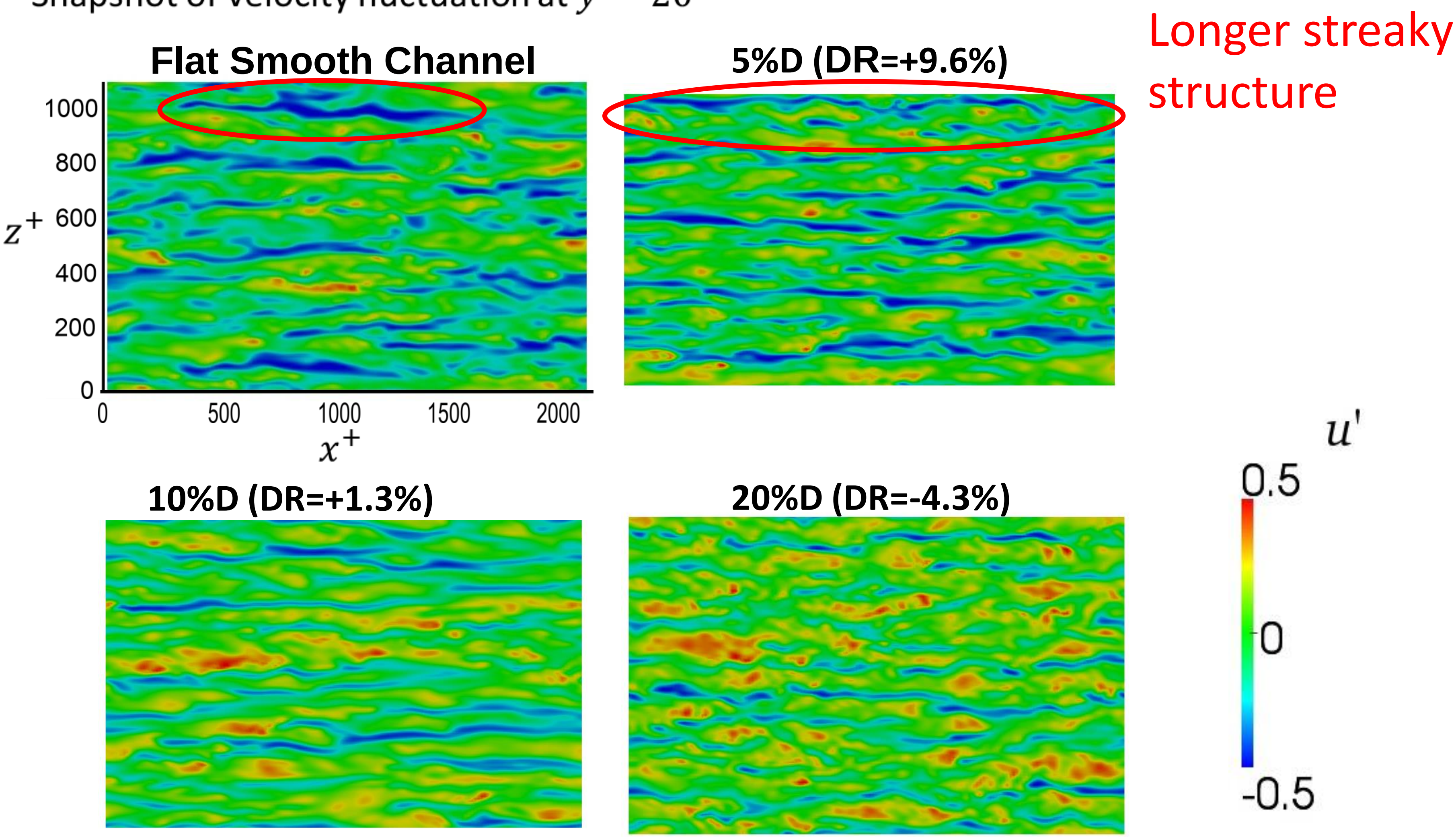
Turbulence intensity



Turbulent intensity became stronger.

Turbulent structure – Streak structure

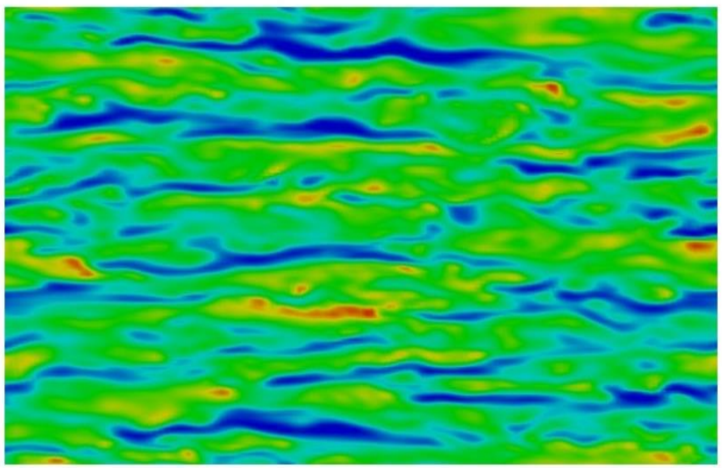
Snapshot of velocity fluctuation at $y^+ \sim 20$



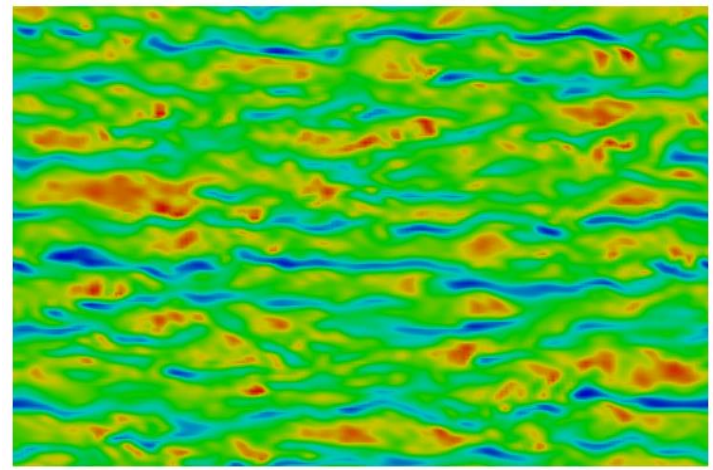
Effect of wall thickness

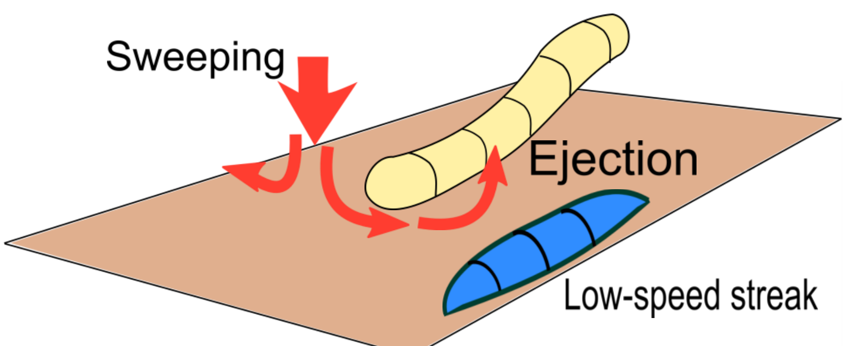
The mechanism of vortex generation

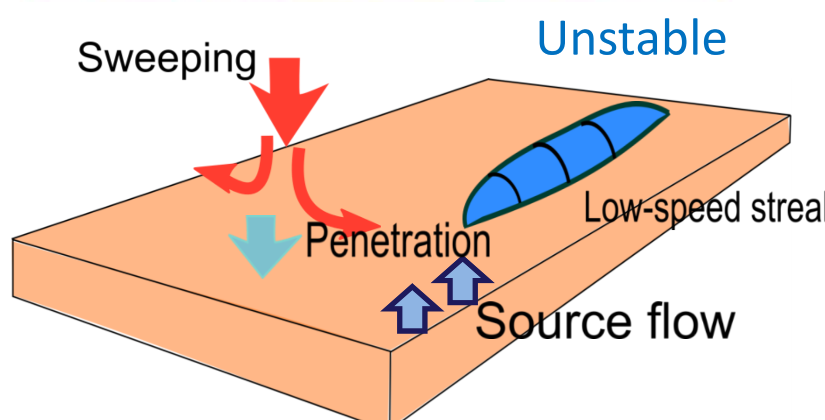
Flat wall



Porous wall



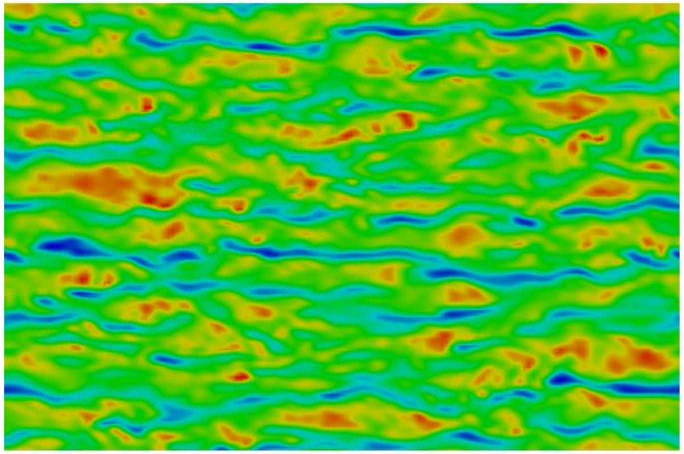


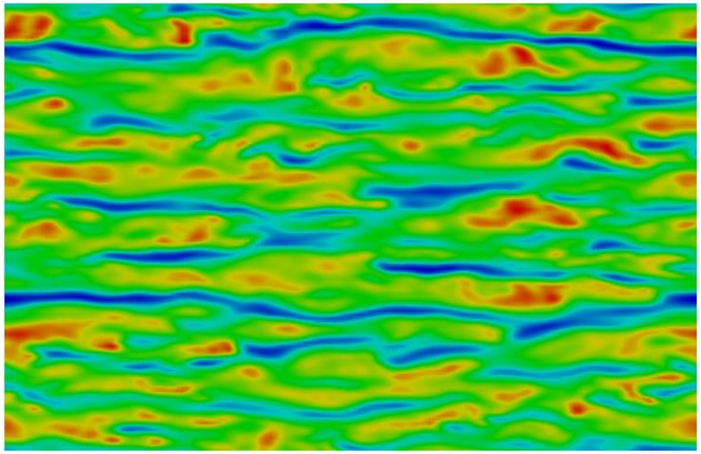


Effect of wall thickness

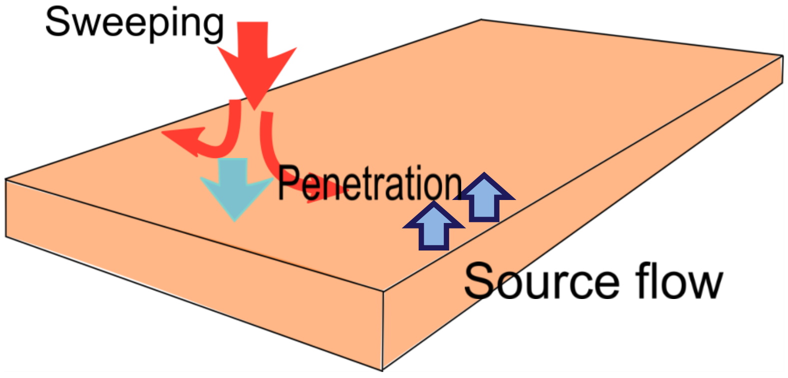
The mechanism of vortex generation and decaying

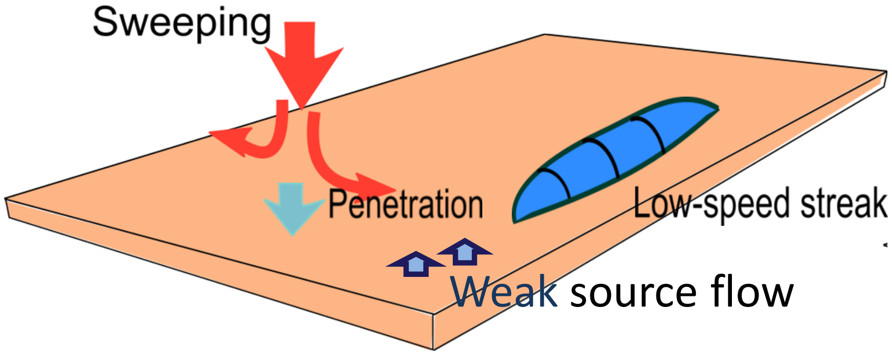
Thick Porous wall (Drag increasing) Thin porous wall (Drag reducing)





Unstable

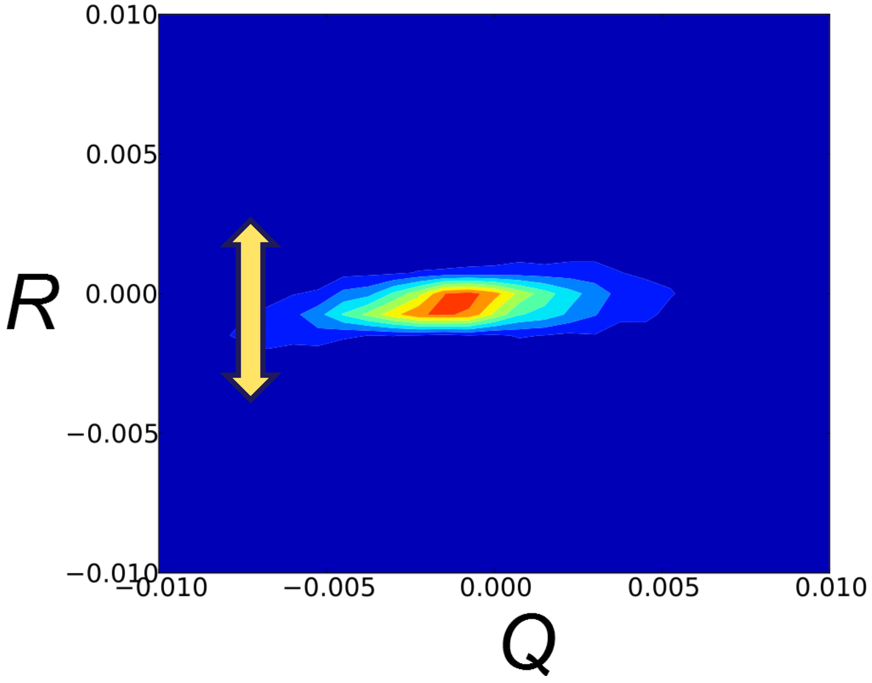




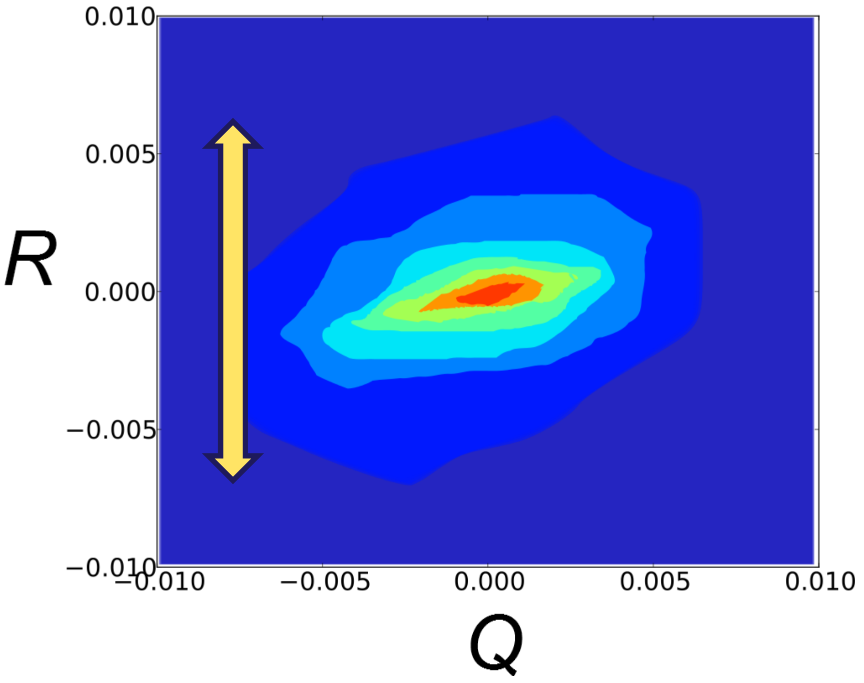
Joint Probability Density Function (JPDF)

The mechanism of vortex generation and decaying

Thin porous wall 5%D (Drag reducing)



Thick Porous wall 20%D (Drag increasing)



Summary of topic 4

- The direct numerical simulation on a channel with porous walls which had varying wall thickness were carried out.

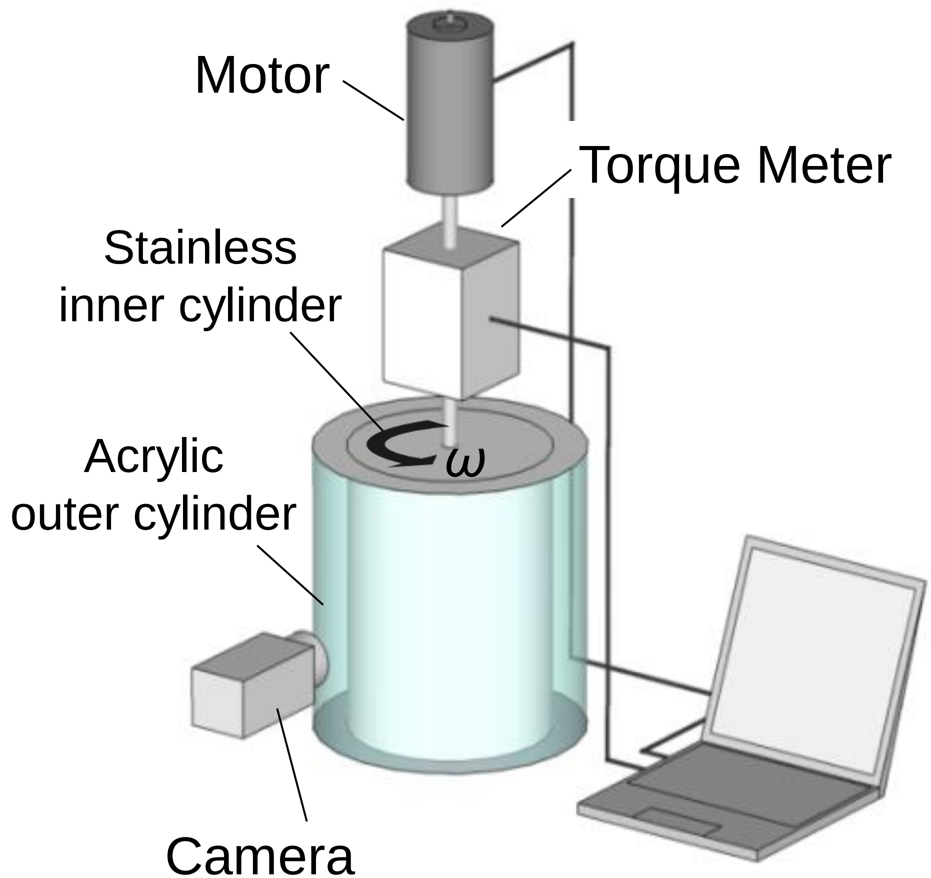
- The drag reduction was achieved over the thinnest porous wall, and in that case, turbulent intensity became weaker.

- The turbulent structures suggested that the relationship between the intensity of sweep (or ejection) and the thickness of porous wall was an important factor for drag reduction.

5. Experimental evaluation of drag reduction: Taylor-Couette flow

Experimental setup

Rotating cylinder facility



r_i: radius of inner cylinder [m]
r_o: radius of outer cylinder [m]
L: height [m]
ω: angular velocity [m]
d: gap between the cylinders [m]
ν: kinetic viscosity [m^2/s]
ρ: density [kg/m^3]
T: toque of inner cylinder [Nm]

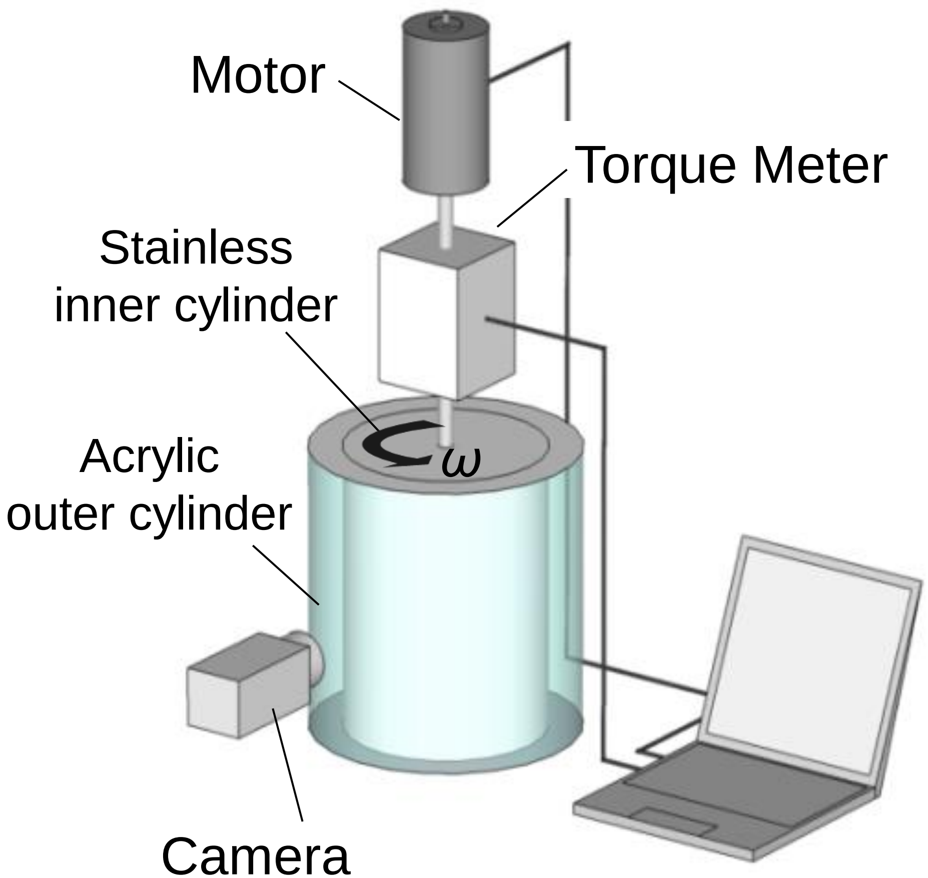
r_i = 48 mm
r_o = 64 mm
L = 128 mm

Reynolds number: $$Re = \frac{r_i \omega d}{\nu}$$

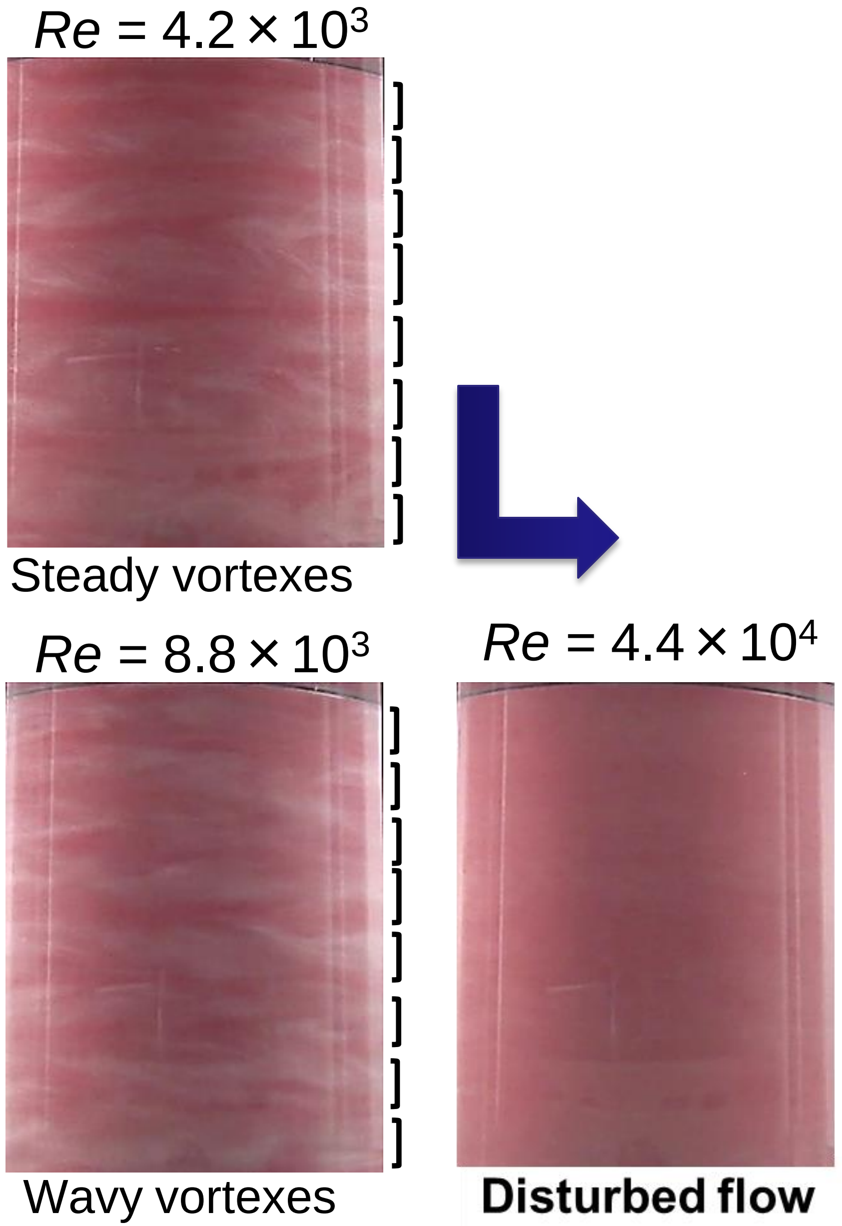
Nondimensionalized torque: $$G \equiv \frac{T}{\rho \nu^2 L}$$

Flow pattern

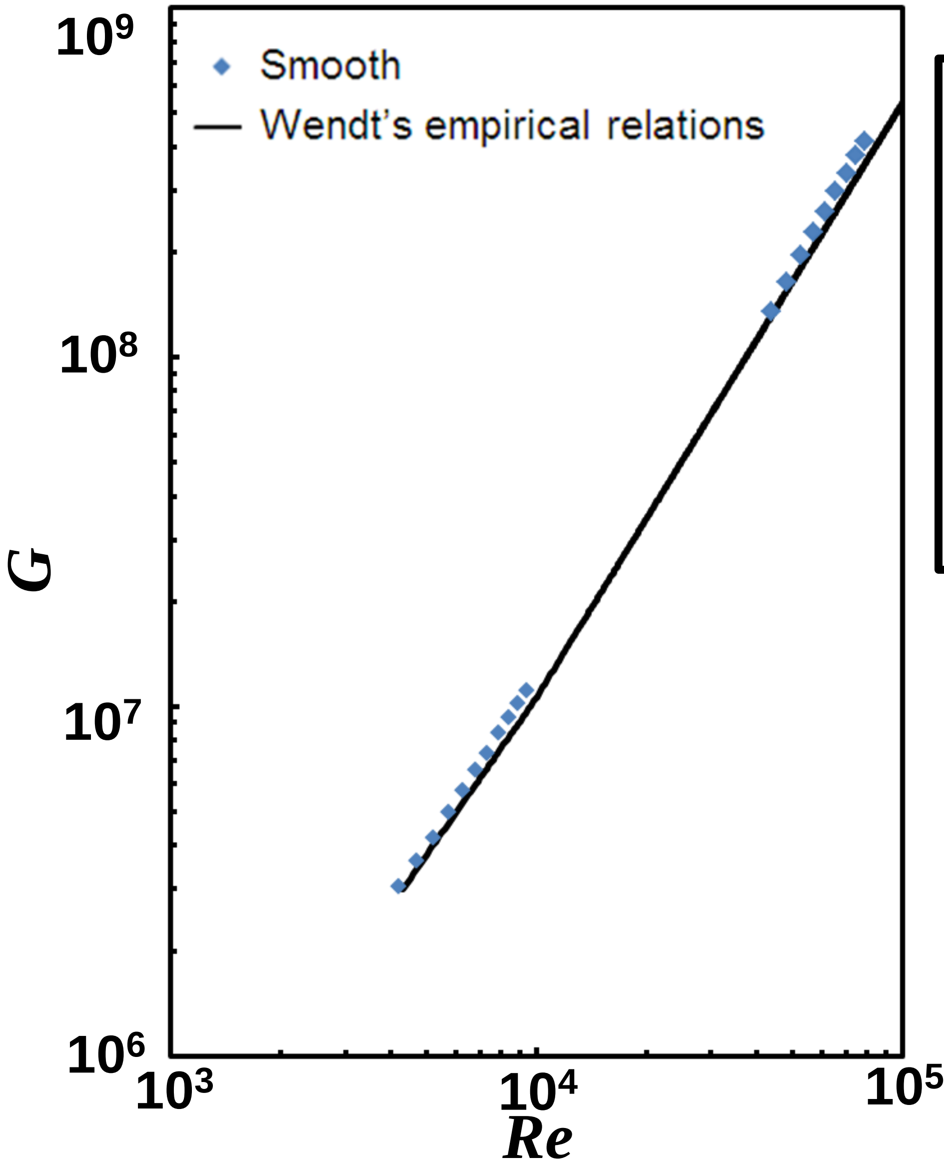
Rotating cylinder facility



Reynolds number: $Re = \dfrac{r_i \, \omega \, d}{\nu}$



Validity of measurement



Wendt's empirical relations

$$G = \begin{cases} 1.45 \dfrac{\eta^{3/2}}{(1-\eta)^{7/4}} \mathrm{Re}^{1.5} & for\ 4\times10^{2} < \mathrm{Re} < 10^{4} \\ 0.23 \dfrac{\eta^{3/2}}{(1-\eta)^{7/4}} \mathrm{Re}^{1.7} & for\ 10^{4} < \mathrm{Re} < 10^{5} \end{cases}$$

$\eta : radius \quad ratio \quad r_i / r_o$

F. Wendt, Ingenieur-Archiv. **4**, 577 (1933).

Experimental conditions

Test cylinders

Smooth　　Cured　　Hydrogel

Thickness of primer

Total : 220 μm

- 1st layer : 140 μm
- 2nd layer : 80 μm

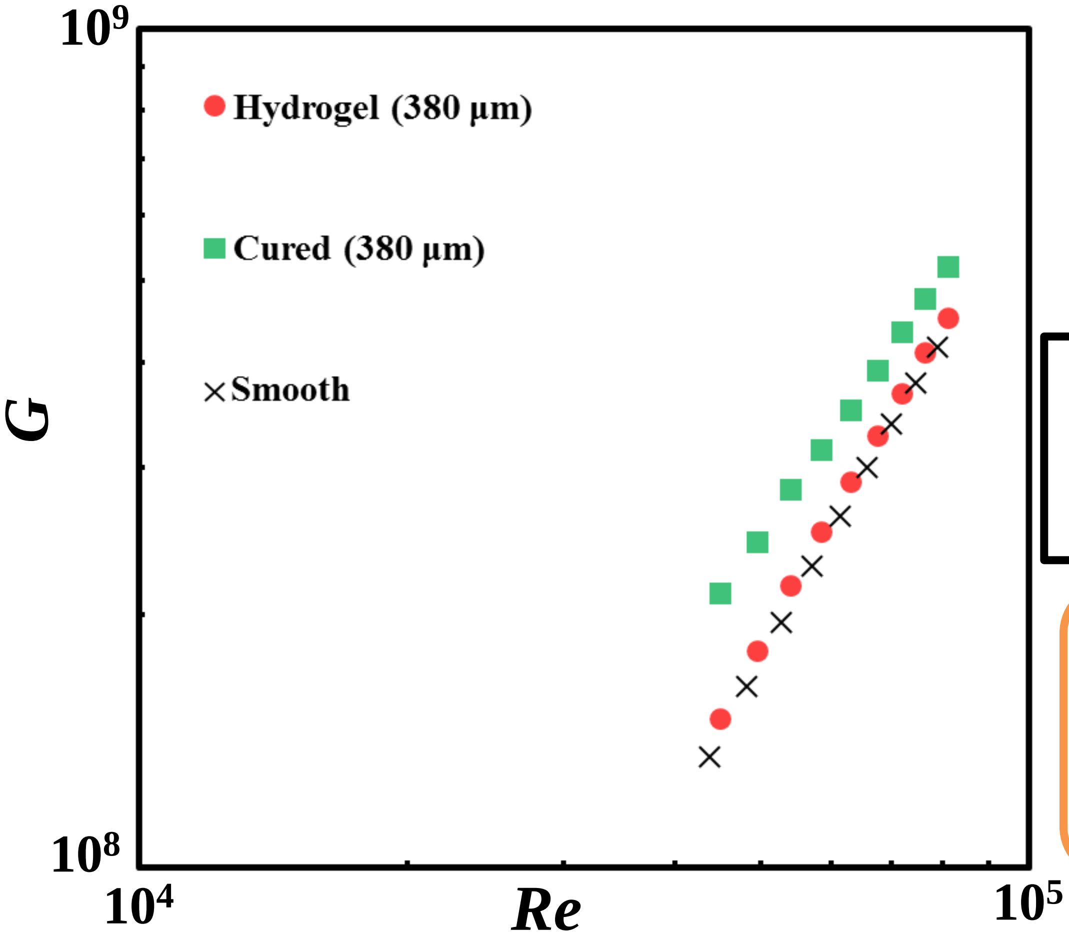
Thickness of coating

	Thick	Thin
Cured	380 μm	240 μm
Hydrogel	380 μm	240 μm

Range of *Re*

$$4.4 \times 10^4 < Re < 8.1 \times 10^4$$

Drag reduction effect



Reynolds number

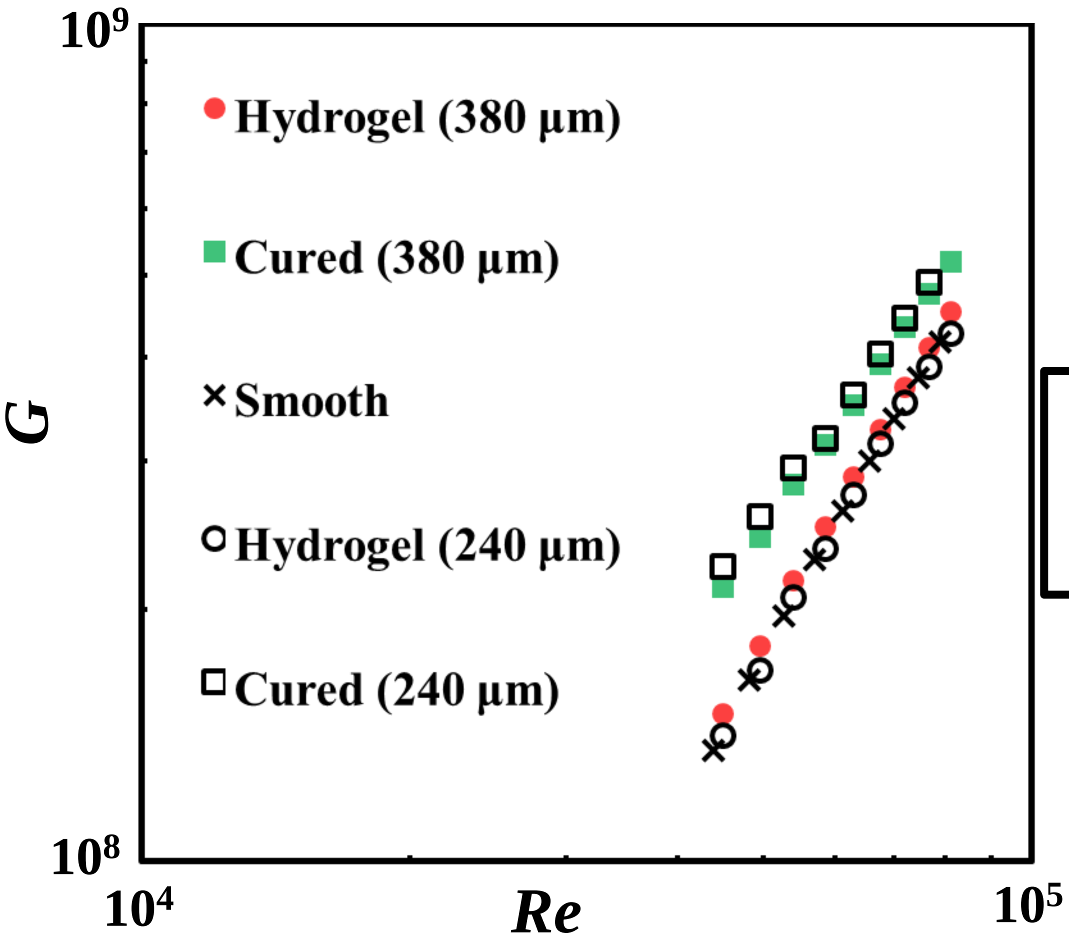
$$Re = \frac{r_i \omega d}{\nu}$$

Nondimensionalized torque

$$G \equiv \frac{T}{\rho \nu^2 L}$$

Torque *G* of hydrogel coating was smaller than that of Cured coating.

Drag reduction effect



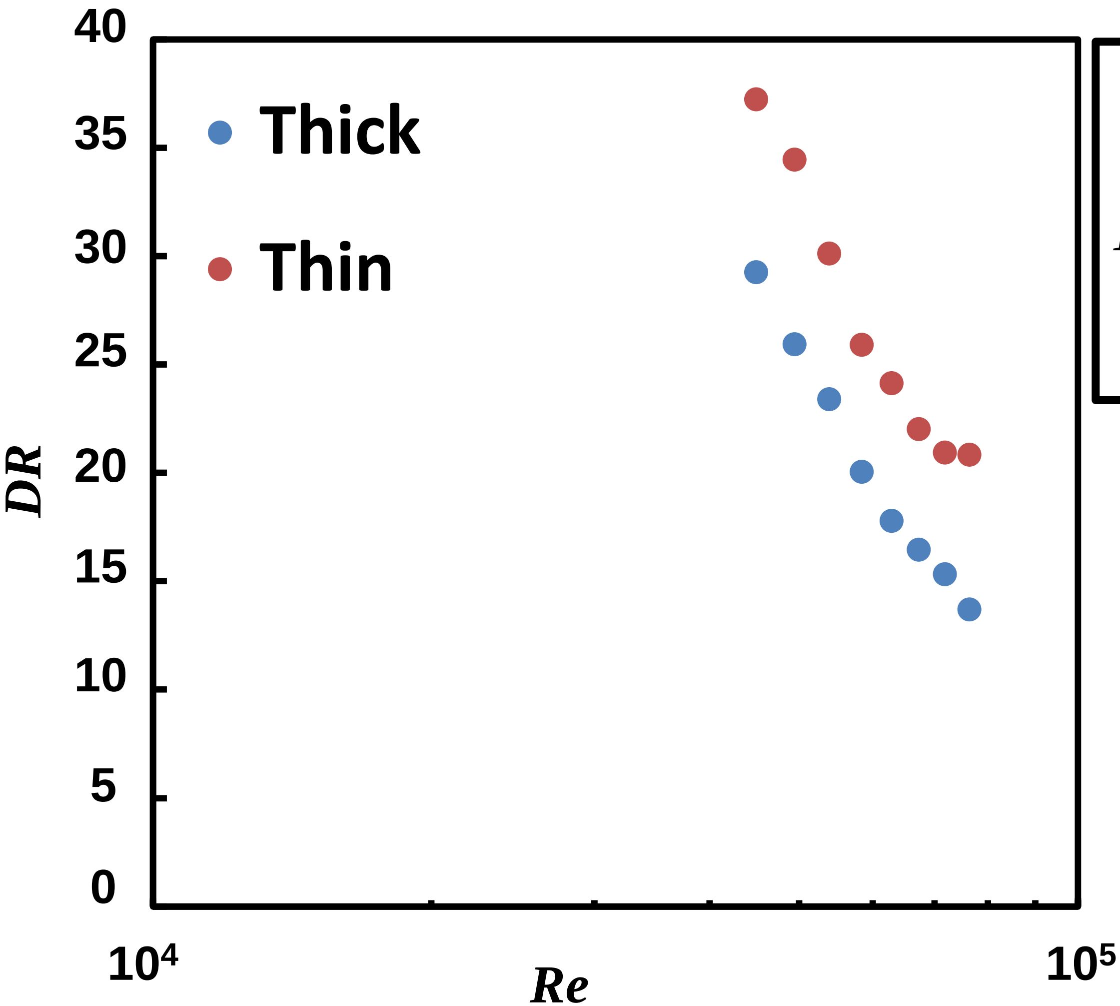
Reynolds number

$$Re = \frac{r_i \omega d}{\nu}$$

Nondimensionalized torque

$$G \equiv \frac{T}{\rho \nu^2 L}$$

Relation with DR and Re



Drag Reduction Ratio

$$DR = \frac{G_{Cured} - G_{Hydrogel}}{G_{Cured}} \times 100$$

$\Delta DR \sim 7\%$

Drag reduction effect of thin hydrogel was larger than thick one.