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channelFoamを用いた チャネル乱流の直接数値計算

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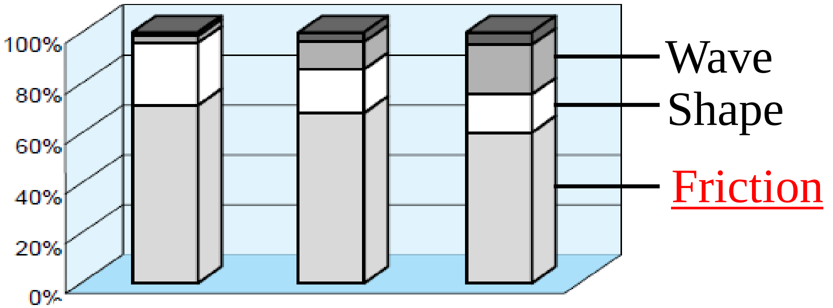
Introduction

Drag reduction for energy saving of ship



Friction coefficient : $C_T = C_S$ (Shape) + C_W (Wave) + C_f (Surface Friction)

Drag reduction techniques

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

Numerical Simulation of wall turbulence

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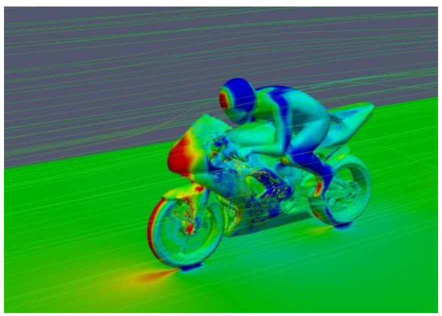
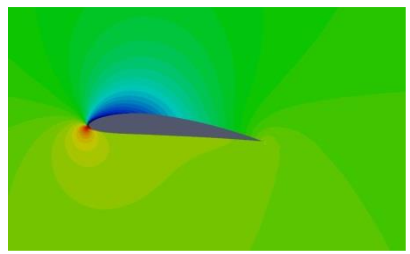
channelFoam ··· incompressible solver for channel flow

Complicated geometry

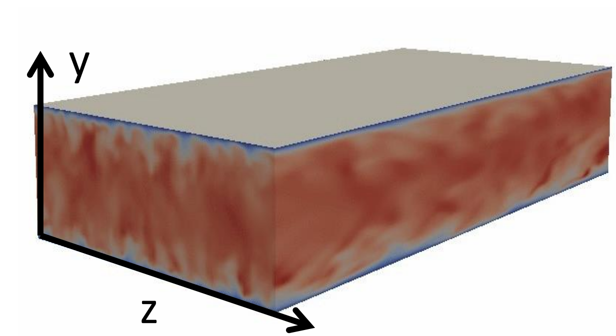
Motor bike case



Wing case



Simple geometry

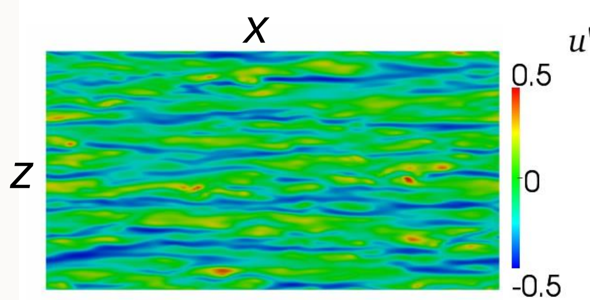


Vortices

Q : standard utility

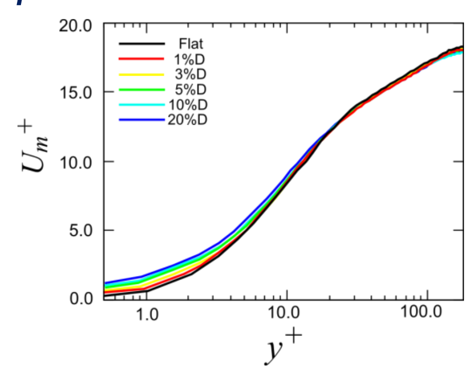
Streaks

Velocity fluctuation :



Turbulent statistics

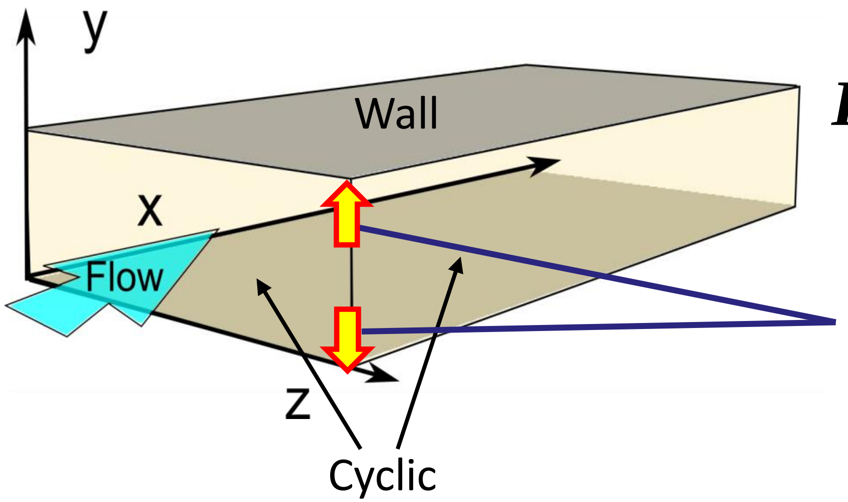
postChannel



Code validation of channelFoam

Code validation

LESModel : *laminar* (No turbulence model)



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

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

Label	Grid number	Method
Kim et al. (1987)[1]	192×129×160	Fourier–spectral
Present study	128×128×128	FVM with OF

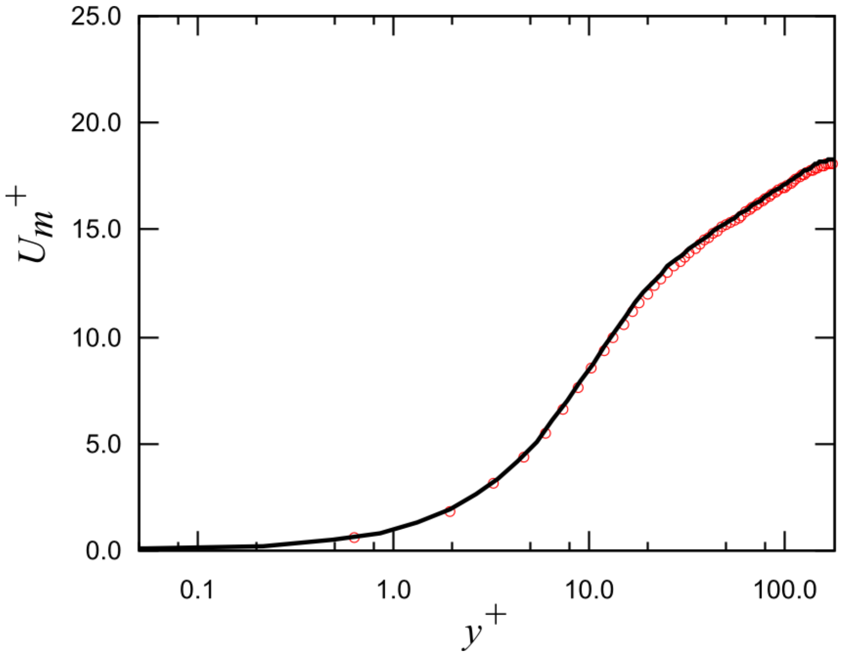
[1] J. Kim *et al., J. Fluid Mech.*, **177**, pp. 133-166 (1987).

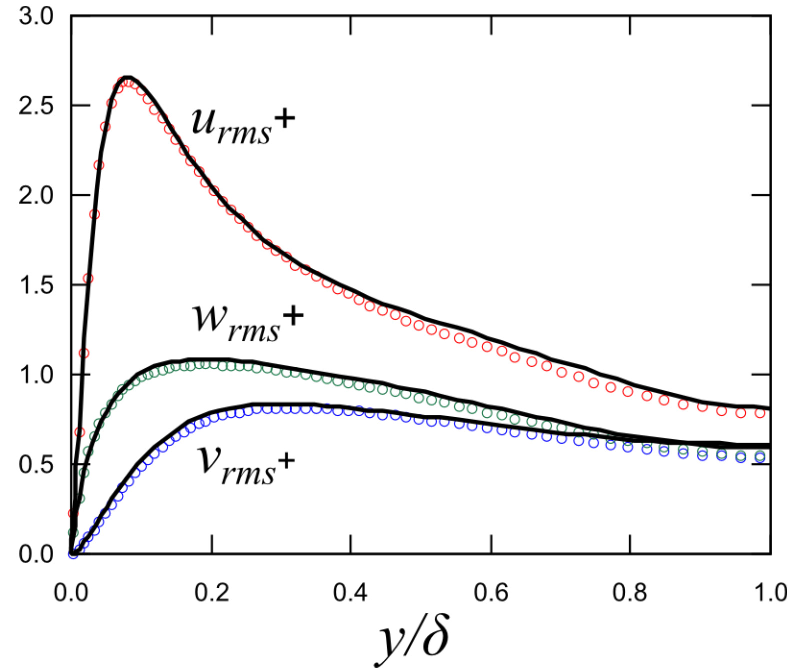
Code validation

Friction coefficient : $C_f = \dfrac{\tau_w}{\rho u_\tau^2}$

Kim et al. (1987) $C_f = 8.18 \times 10^{-3}$

Present study $C_f = 8.07 \times 10^{-3}$





The relative error of friction coefficient was 1.0%

Numerical simulation by channelFoam

- Turbulent channel bounded with wavy walls

- Turbulent channel bounded with porous walls

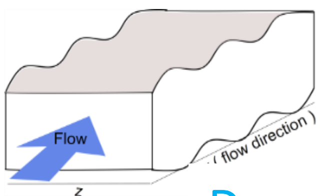
Turbulent channel bounded with wavy walls

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

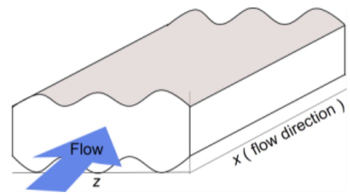
$-\left.\frac{dP}{dx}\right|_{flat}$: mean pressure gradient in a flat channel

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

Case 1



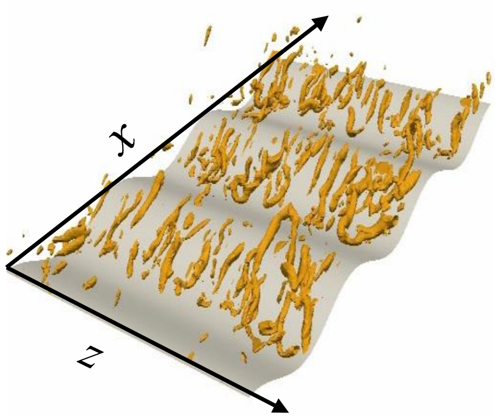
Case 2



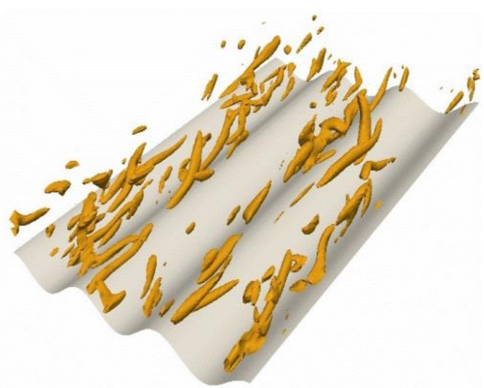
Case 3

Drag increase

DR = -20.4 %

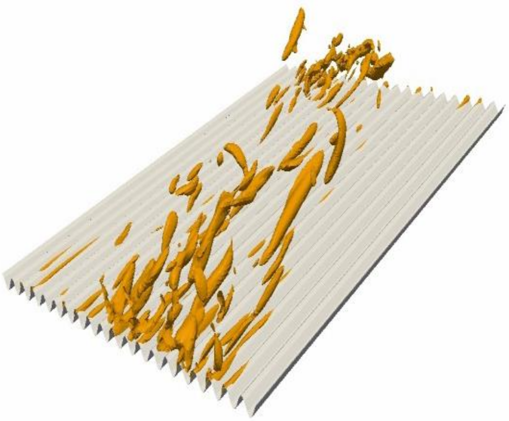


DR = -9.4 %



Drag reduction

DR = +9.3 %



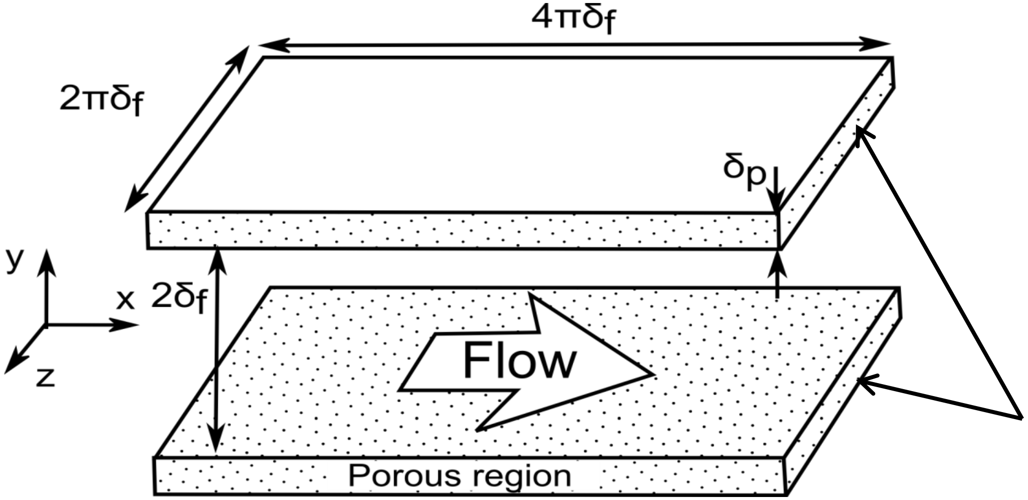
Numerical simulation by channelFoam

- Turbulent channel bounded with **wavy** walls

- Turbulent channel bounded with **porous** walls

Numerical simulation for turbulent channel flow bounded with porous walls

Developped by porous***Foam



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

δ_f : Half-width of fluid region

δ_p : Porous wall thickness

cellZone : porosity

Case	1%D	3%D	5%D	10%D	20%D	Flat
Porous wall thickness δ_p	$0.01\delta_f$	$0.03\delta_f$	$0.05\delta_f$	$0.10\delta_f$	$0.20\delta_f$	—
Total channel width	$2.02\delta_f$	$2.06\delta_f$	$2.10\delta_f$	$2.2\delta_f$	$2.4\delta_f$	$2.0\delta_f$
Number of grid points $N_x, (N_y^f + N_y^p), N_z$	149, (129+10), 129	149, (129+16), 129	149, (129+16), 129	149, (129+20), 129	149, (129+20), 129	129,129,129

DNS of channel flow with porous wall

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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

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

cf. K. Suga *et al* Int. J. *Heat Fluid Flow* (2011)

Results – Drag reduction Ratio

Case	δ_p^+	$C_f \times 10^3$	DR [%]
1%D	2	7.23	+0.3
3%D	5	6.47	+10.6
5%D	9	6.55	+9.6
10%D	18	7.16	+1.2
20%D	37	7.56	-4.3
Flat	-	7.25	-

Drag reduction Ratio

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

C_f^p:Friction coefficient of porous wall

C_f^0:Friction coefficient of flat wall

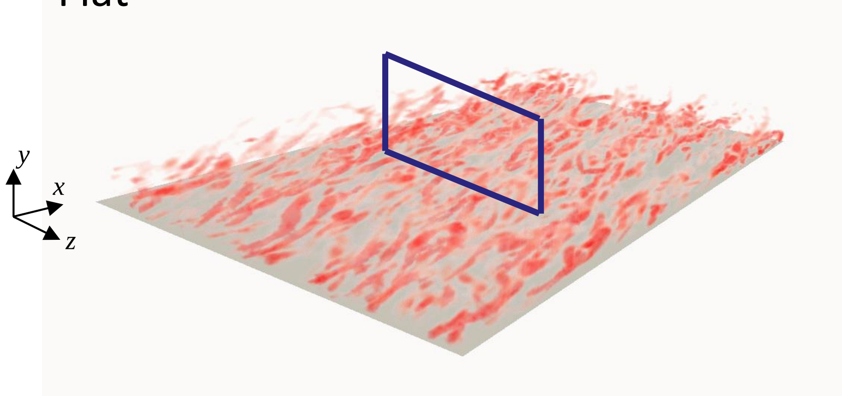
FIK identity for fully developed turbulent channel flow[1]

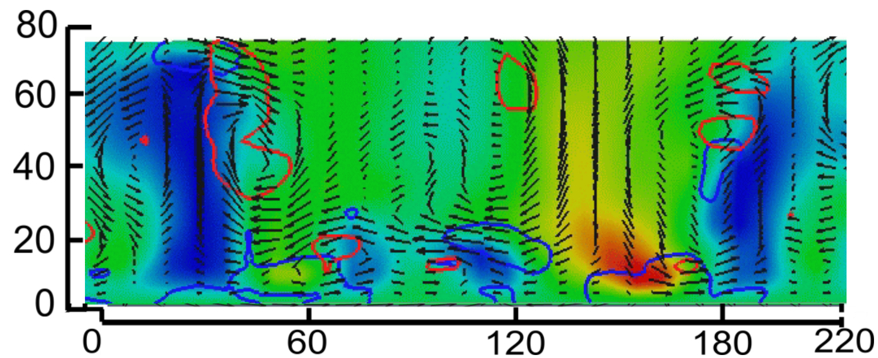
$$C_f = \frac{12}{Re_b} + 12\int_0^1 2(1-y)(\overline{-u'v'})dy$$

Viscous term and Turbulent term

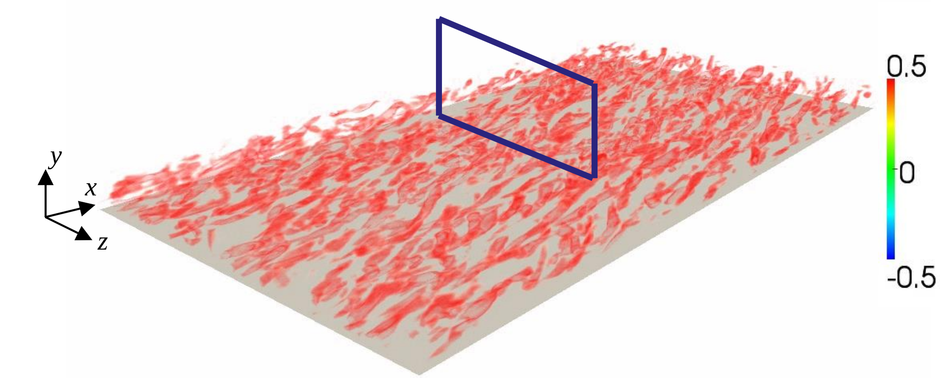
Turbulent structure – Vortex structure

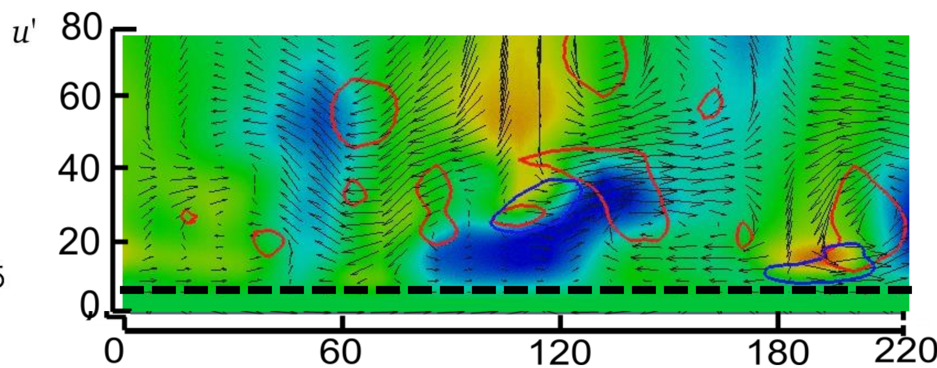
Flat





3%D





Red lines : Iso-contour of $Q^+ = 0.2$

Blue lines : Iso-contour of $\varepsilon^+ = 0.3$

Summary

- The direct numerical simulation of turbulent channel flow by standard incompressible solver *channelFoam.*
- OpenFoam is valid for analysis of turbulent flow, particularly in coupling other numerical model.

BUT

- There are few post utilities for turbulent channel flow analysis.

Future works

Other constitutive equation for porosity model

Biot's consolidation theory

$$\nabla \sigma - \nabla p + \frac{\partial d\boldsymbol{U}}{\partial t} = 0$$

$$\frac{\varphi}{K'}\frac{\partial p}{\partial t} - \frac{K}{\gamma_w}\nabla^2 p + \frac{\partial}{\partial t}(\nabla \cdot d\boldsymbol{U}) = 0$$

σ :Total stress

p :Pore pressure

$d\boldsymbol{U}$:Displacement velocity

γ_w :Specific weight of water

K' :Bulk modulus

K :Permeability

φ :Porosity

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