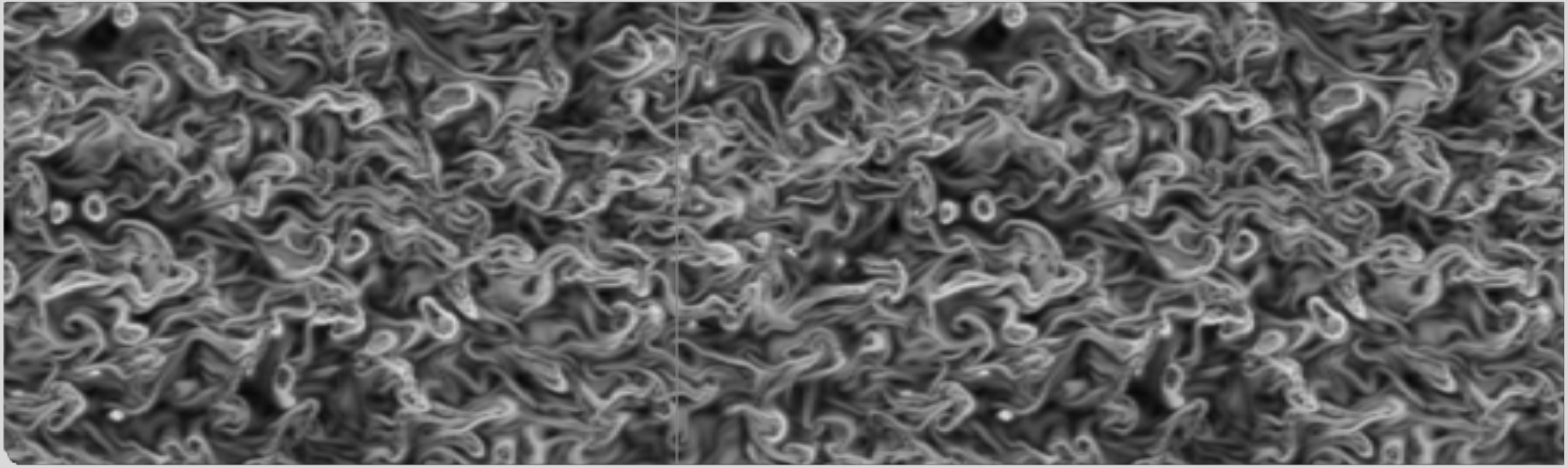
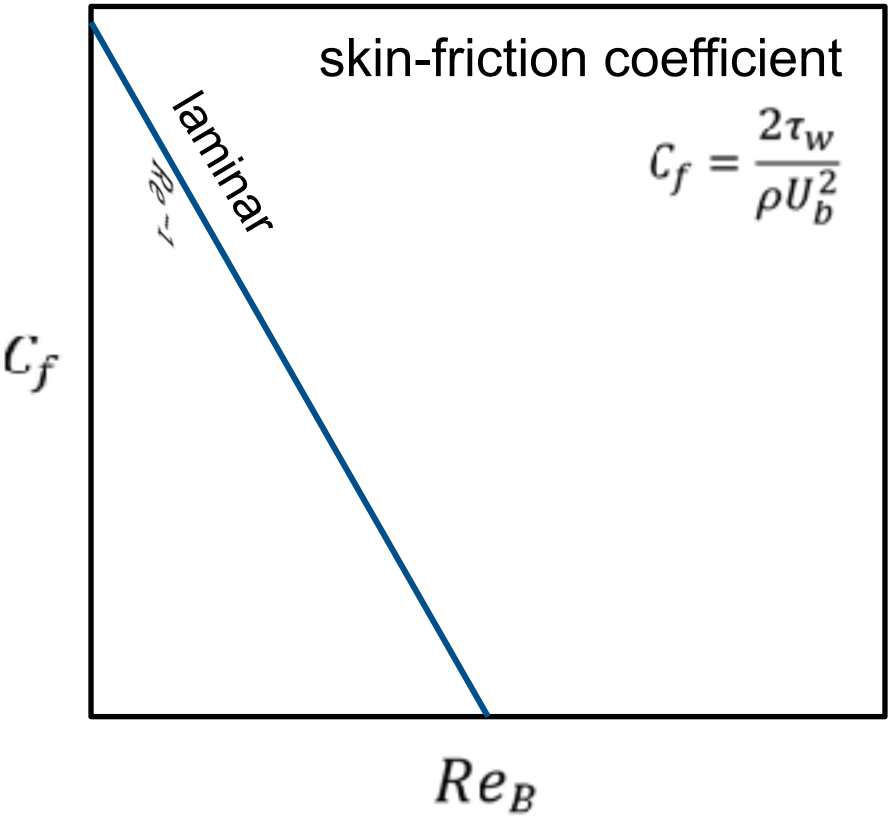
Turbulent skin-friction drag reduction from the energetic viewpoint

Davide Gatti

Fluids and Structures: Interaction and Modeling 2017, Naples, Itally

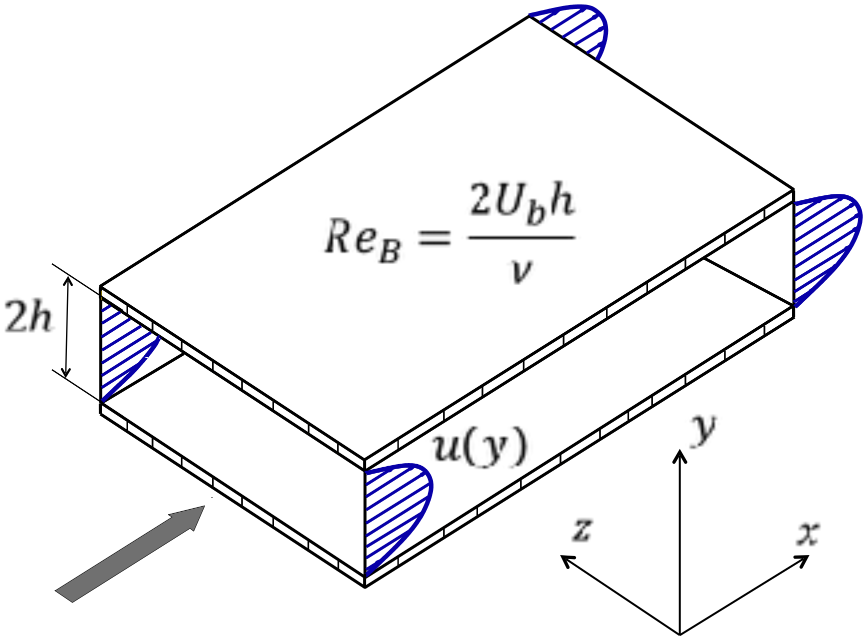


Skin-friction drag

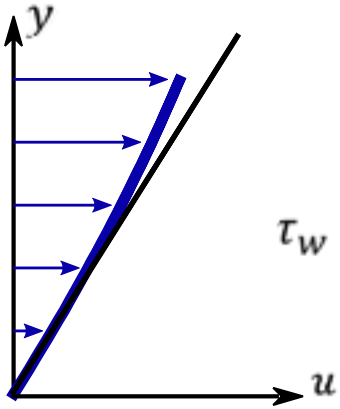


skin-friction coefficient

$$C_f = \frac{2\tau_w}{\rho U_b^2}$$

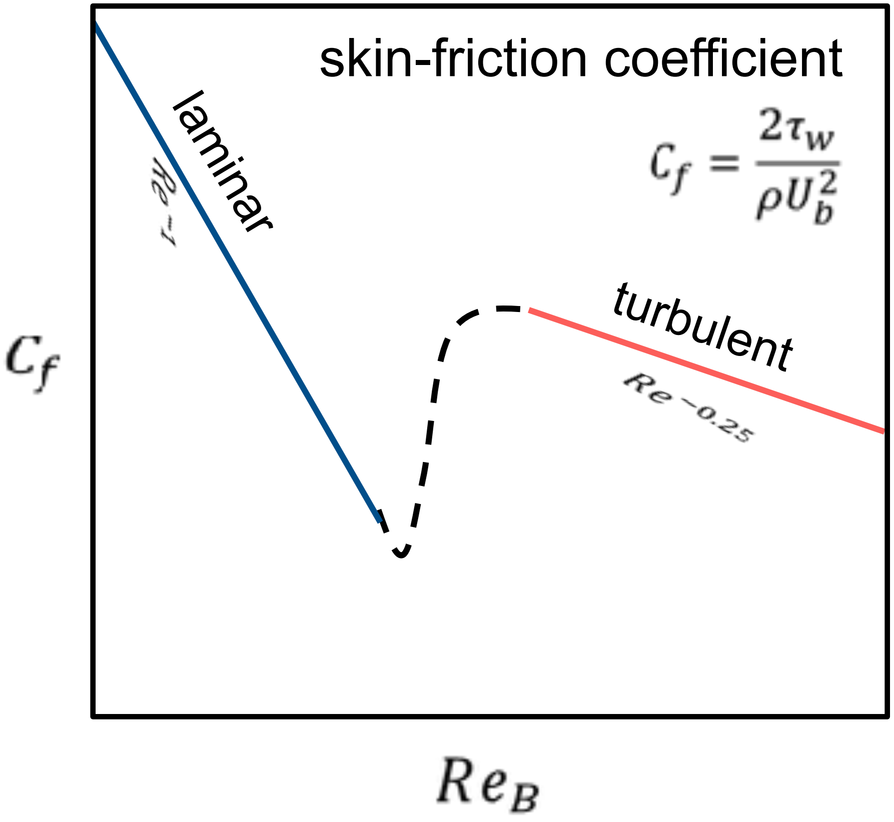


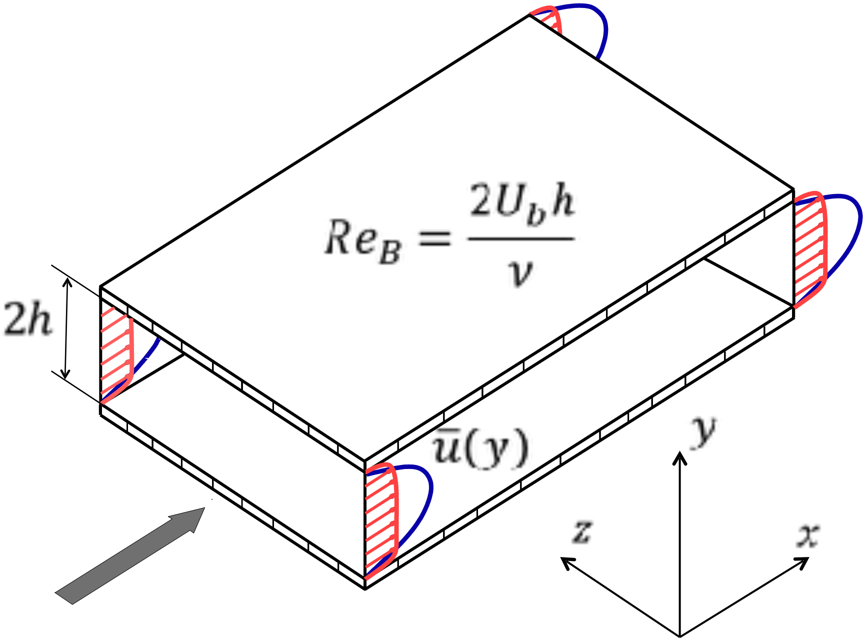
$$Re_B = \frac{2U_b h}{\nu}$$

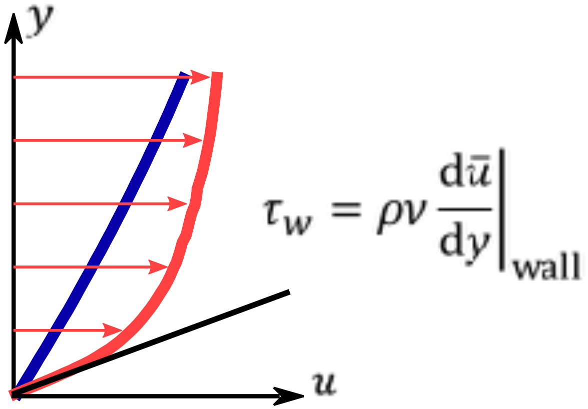


$$\tau_w = \rho\nu \left.\frac{\mathrm{d}u}{\mathrm{d}y}\right|_{\text{wall}}$$

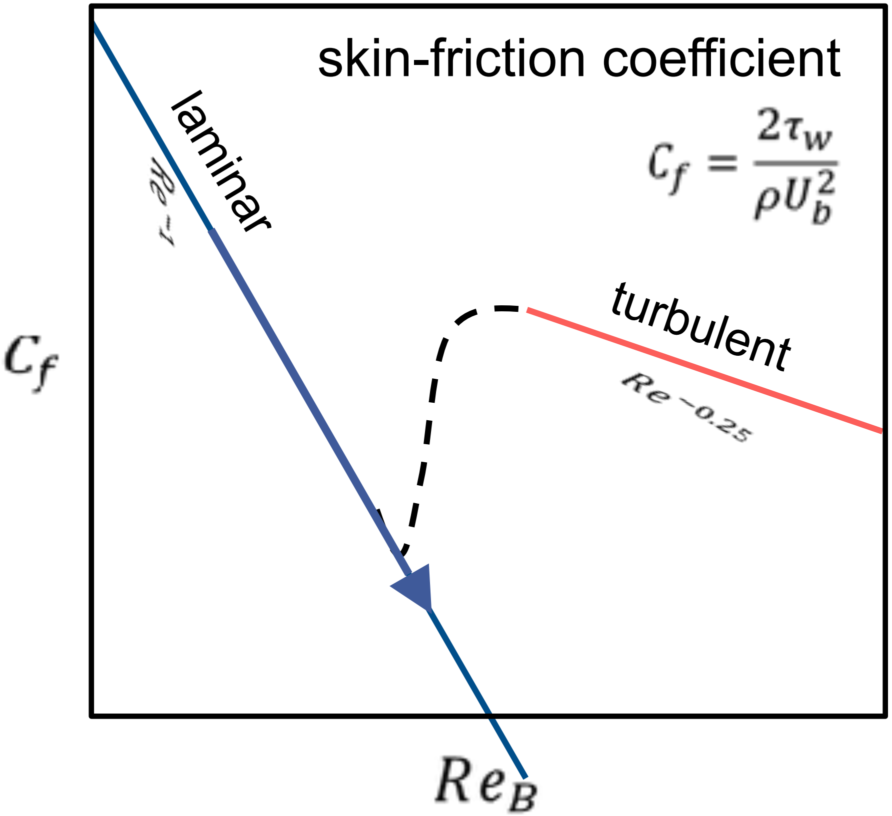
Turbulent skin-friction drag







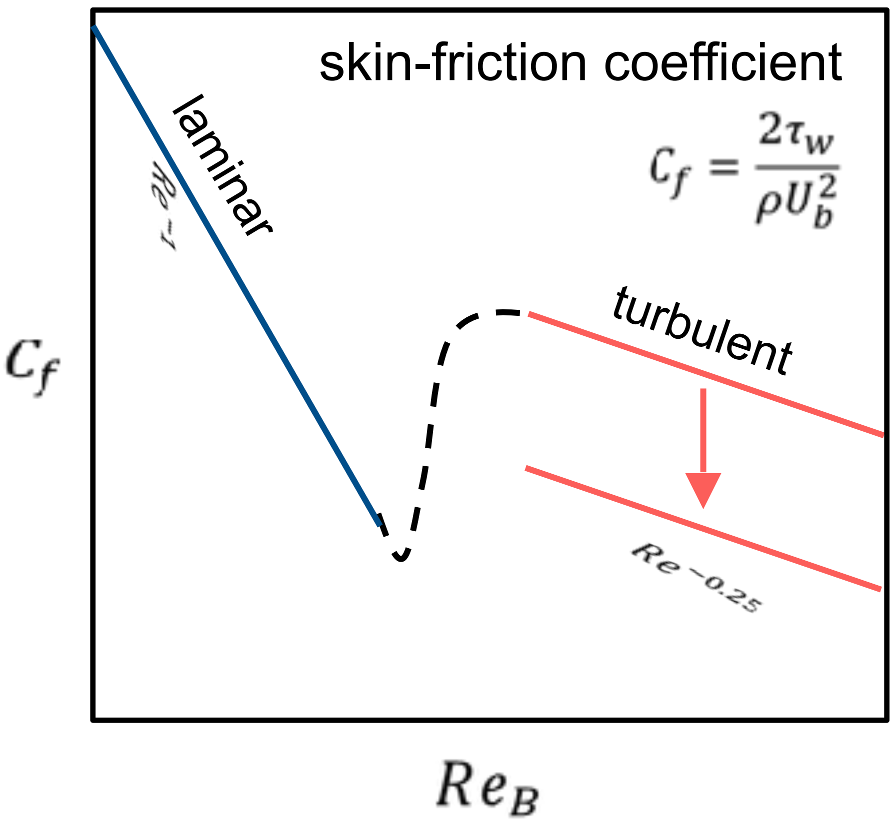
Turbulent skin-friction drag reduction!



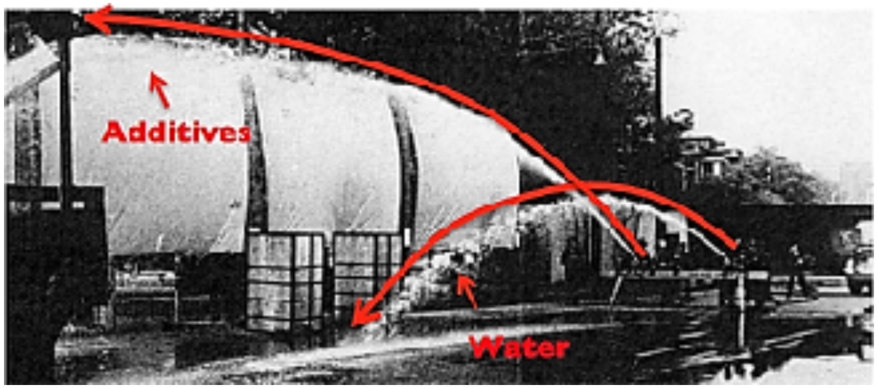
- Transition delay

[Source: Alex Duchmann, SLA]

Turbulent skin-friction drag reduction!

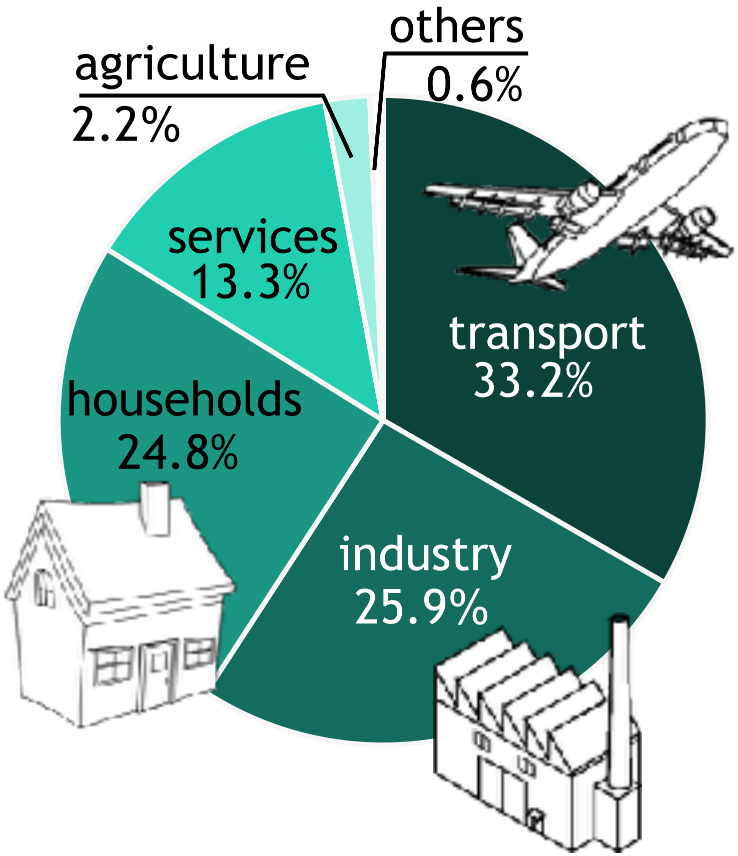


- Transition delay
- Turbulent drag reduction



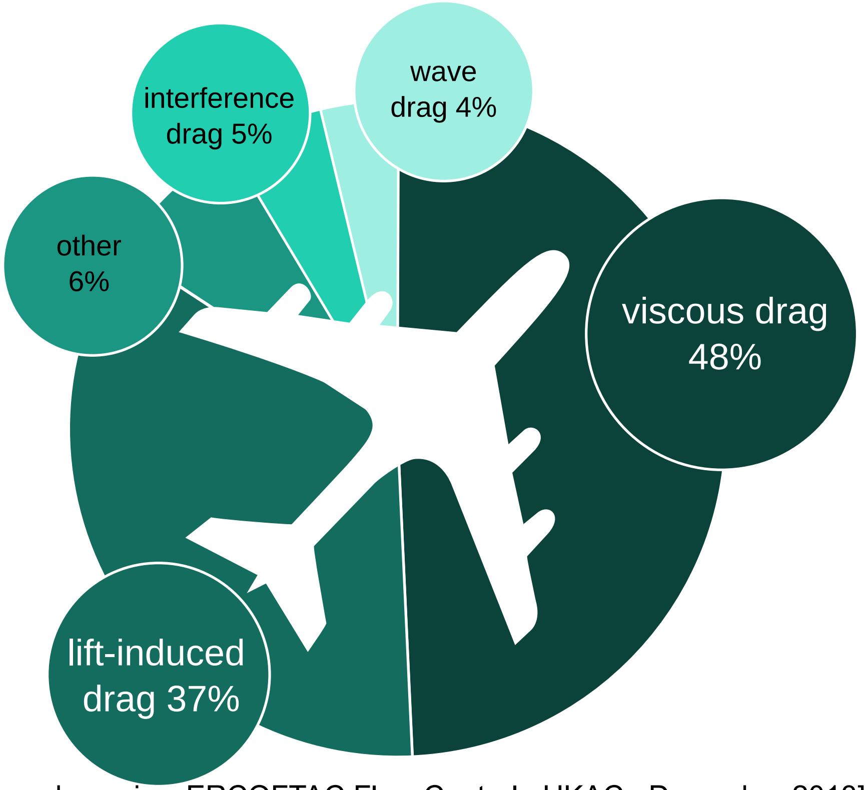
[E. Blume, RAND document 1969]

Motivation for skin-friction drag reduction



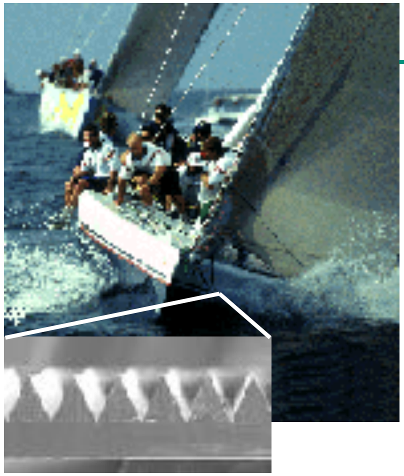
[Eurostat (2016) European Commission]

- Reduced energy consumption
  → Reduced emissions
- Increased throughput



[UK Aerodynamics, ERCOFTAC Flow Control , UKAC, December 2013]

Different control approaches



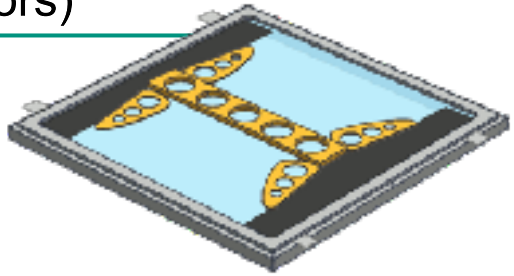
NASA.gov (1993)

Passive: no power required by control

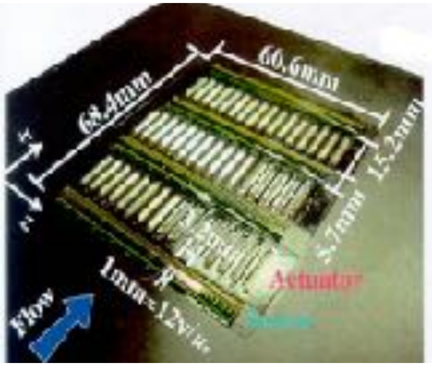
additives
morphology
slip

Active, predetermined (only actuators)

wall movements
wall blowing and suction
body force



Gatti et al. (EXIF), 2015

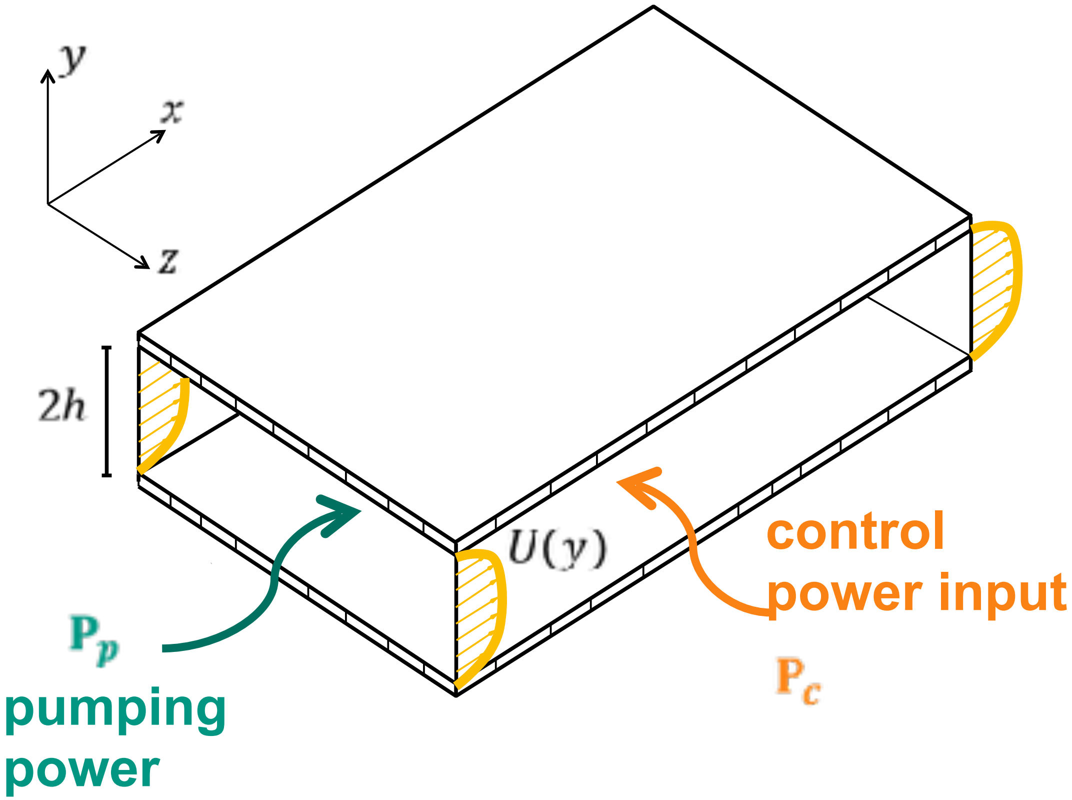


Kasagi et al. (Ann. Rev. Fluid Mech.), 2009

Active, reactive (sensors and actuators)

optimal control theory
feed-back control
feed-forward control

The drag reduction experiment



bulk velocity: U_b

pressure gradient:

$$-\frac{\mathrm{d}p}{\mathrm{d}x} = \frac{\tau_w}{h}$$

skin-friction coefficient:

$$C_f = \frac{2\tau_w}{\rho U_b^2}$$

pumping power (per unit area):

$$\mathbf{P}_p = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$$

drag reduction rate:

$$\boldsymbol{R} = 1 - \frac{C_f}{C_{f,0}}$$

The choice of flow condition (1)

- Navier-Stokes equations alone do not pump fluid through the duct
- **Forcing term needed** to mimic pump

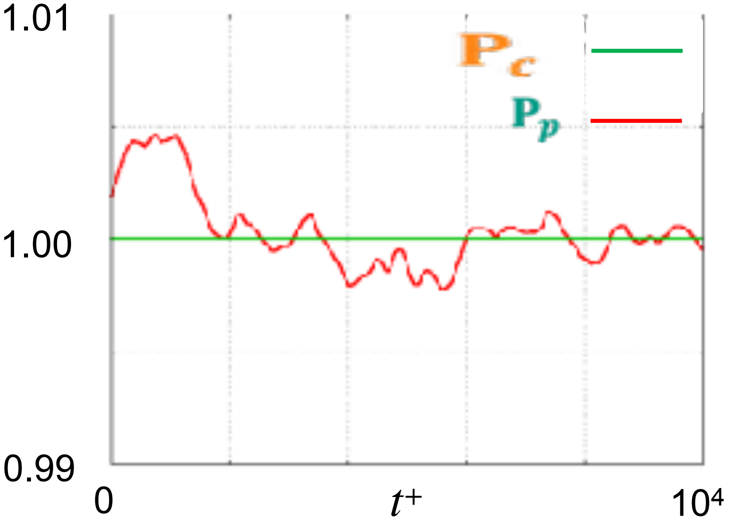
- Many **arbitrary choices** possible
- Often equivalent on physical grounds
- Different on practical grounds
- Different realizations, same statistics

The choice of flow condition (2)

Constant Pressure Gradient
(CPG)

↓

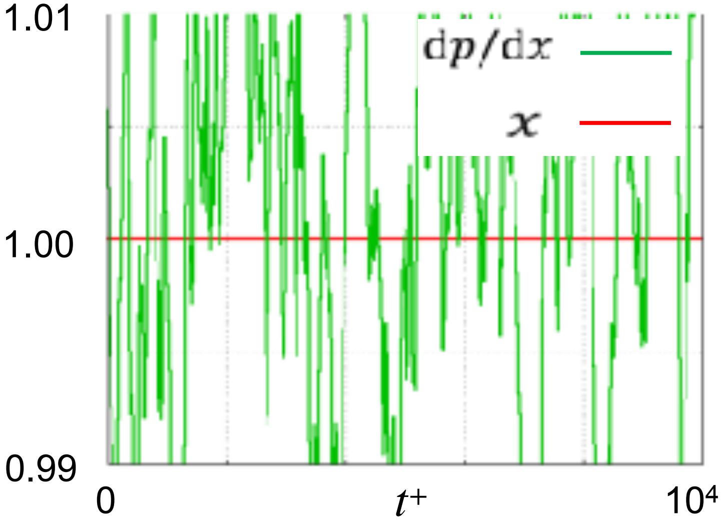
Flow rate fluctuates in time



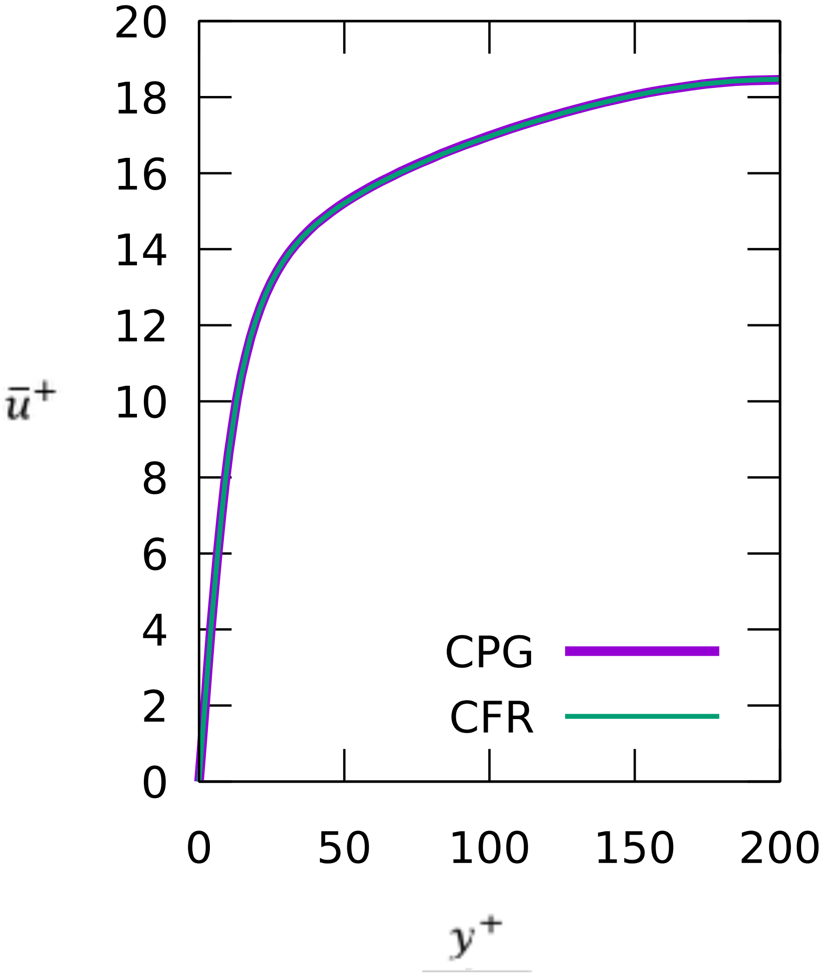
Constant Flow Rate
(CFR)

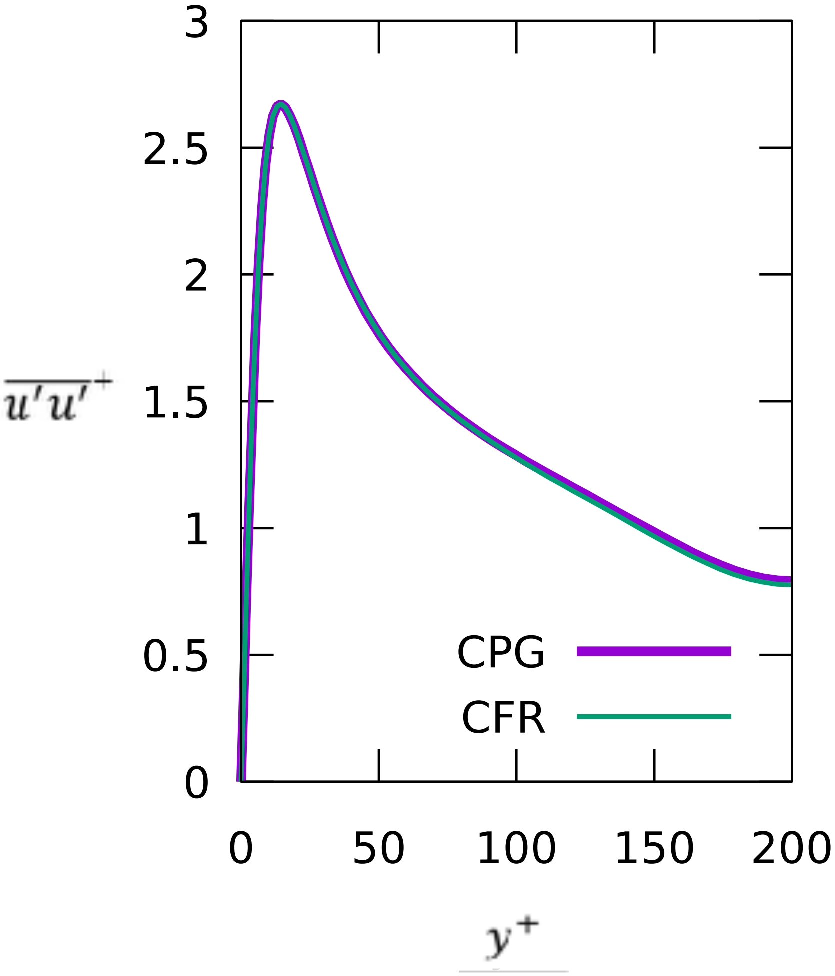
↓

Pressure gradient
fluctuates in time



Unimportant choice for uncontrolled flows





Important choice in flow control!

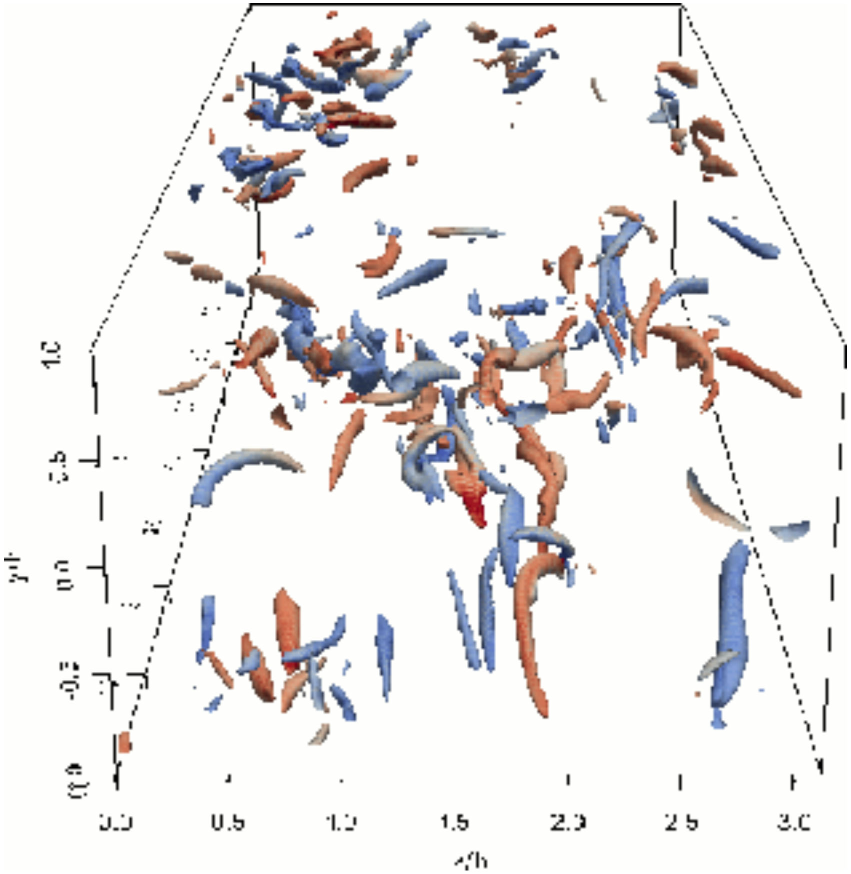
"Turbulent fluctuations are destroyed"

<u>Spanwise wall oscillations</u>

Constant Flow Rate (CFR)

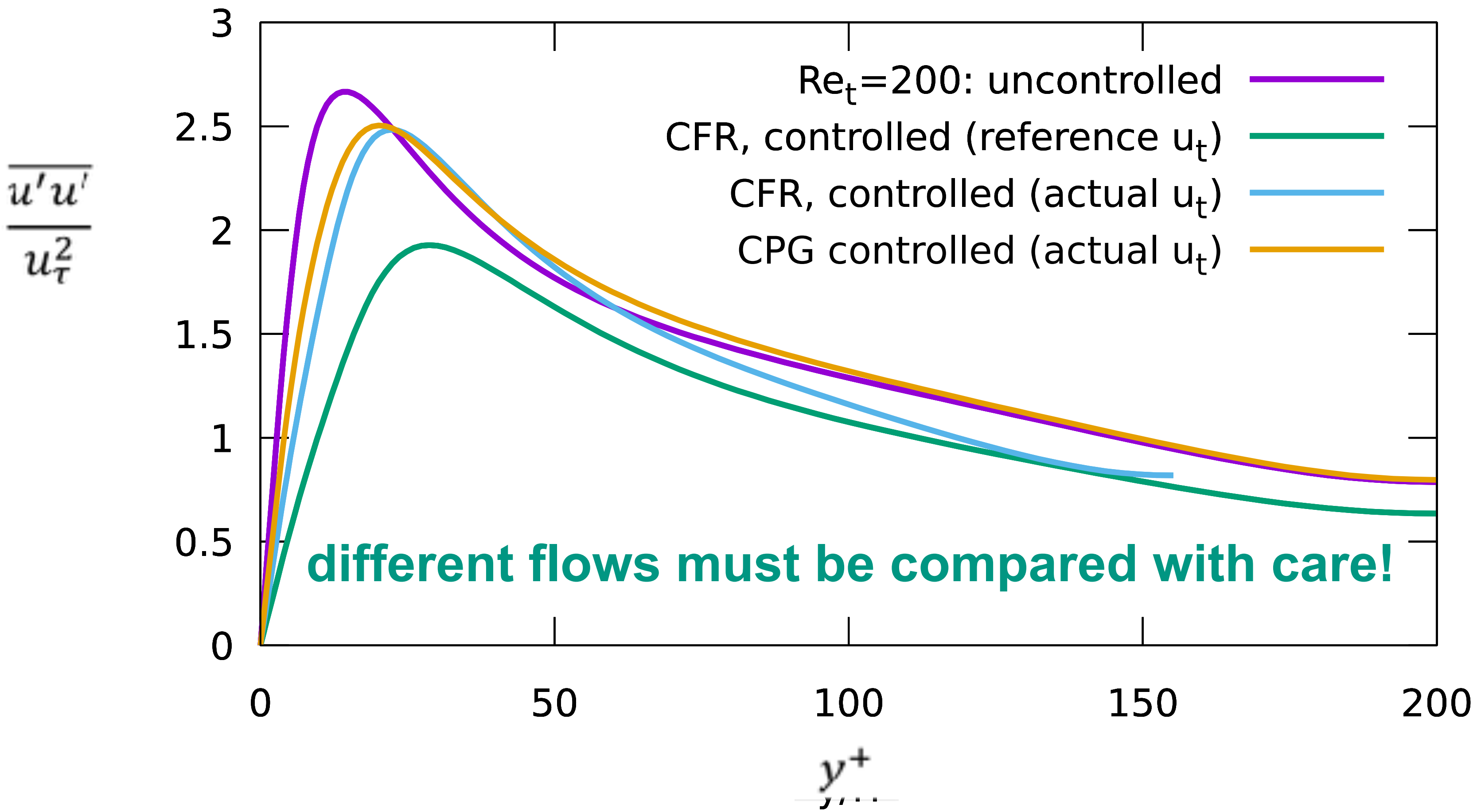
$Re_b = 6400$

$R \approx 30\%$



Important choice in flow control!

“Turbulent fluctuations are destroyed”?

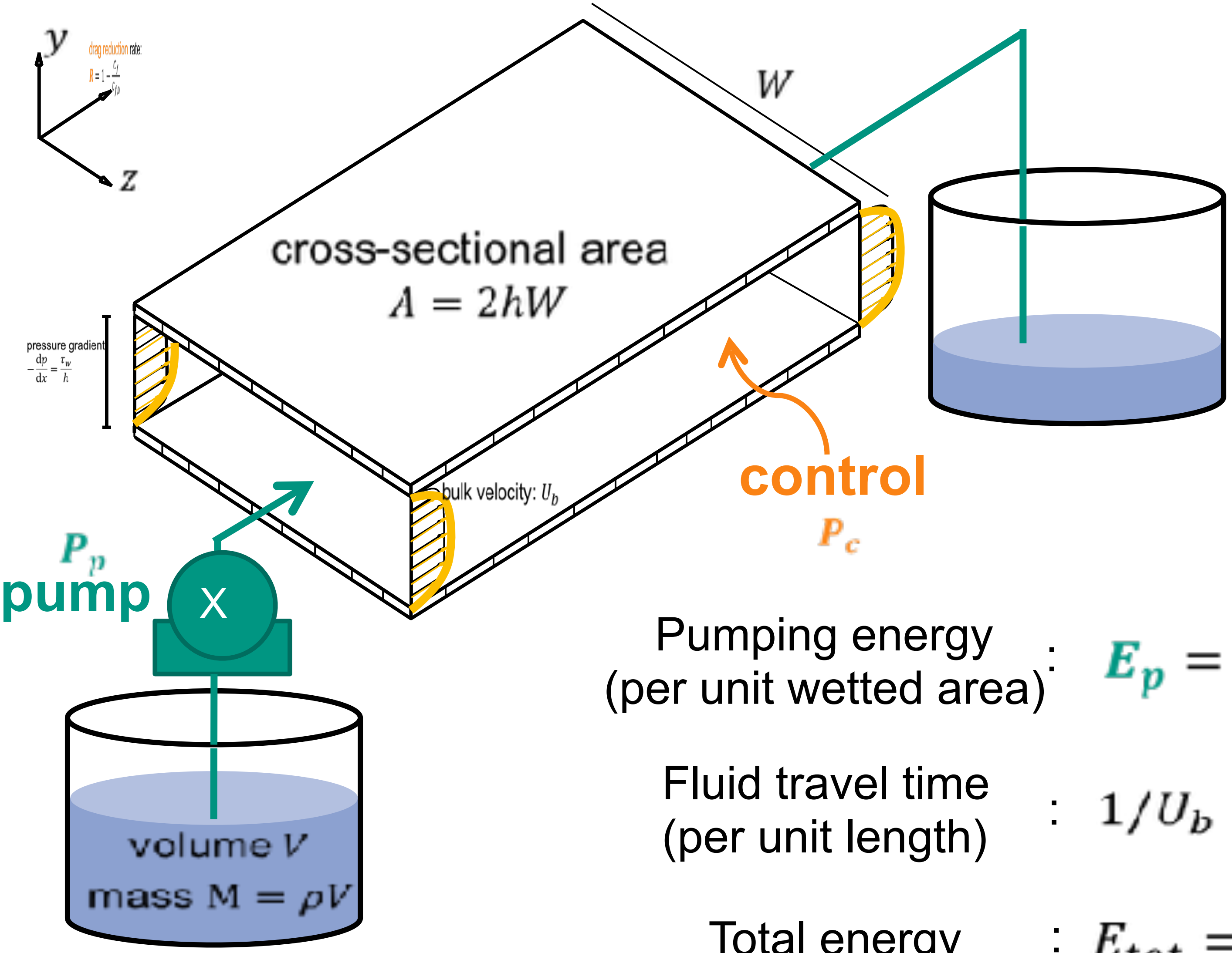


Important choice in flow control!

successful control $\boldsymbol{R} = 1 - \frac{C_f}{C_{f,0}} > 0$ manifests differently

- With control: either different Re_τ or different Re_B
- $C_f \neq P_p$: successful control can increase pumping power!

The Drag Reduction Experiment



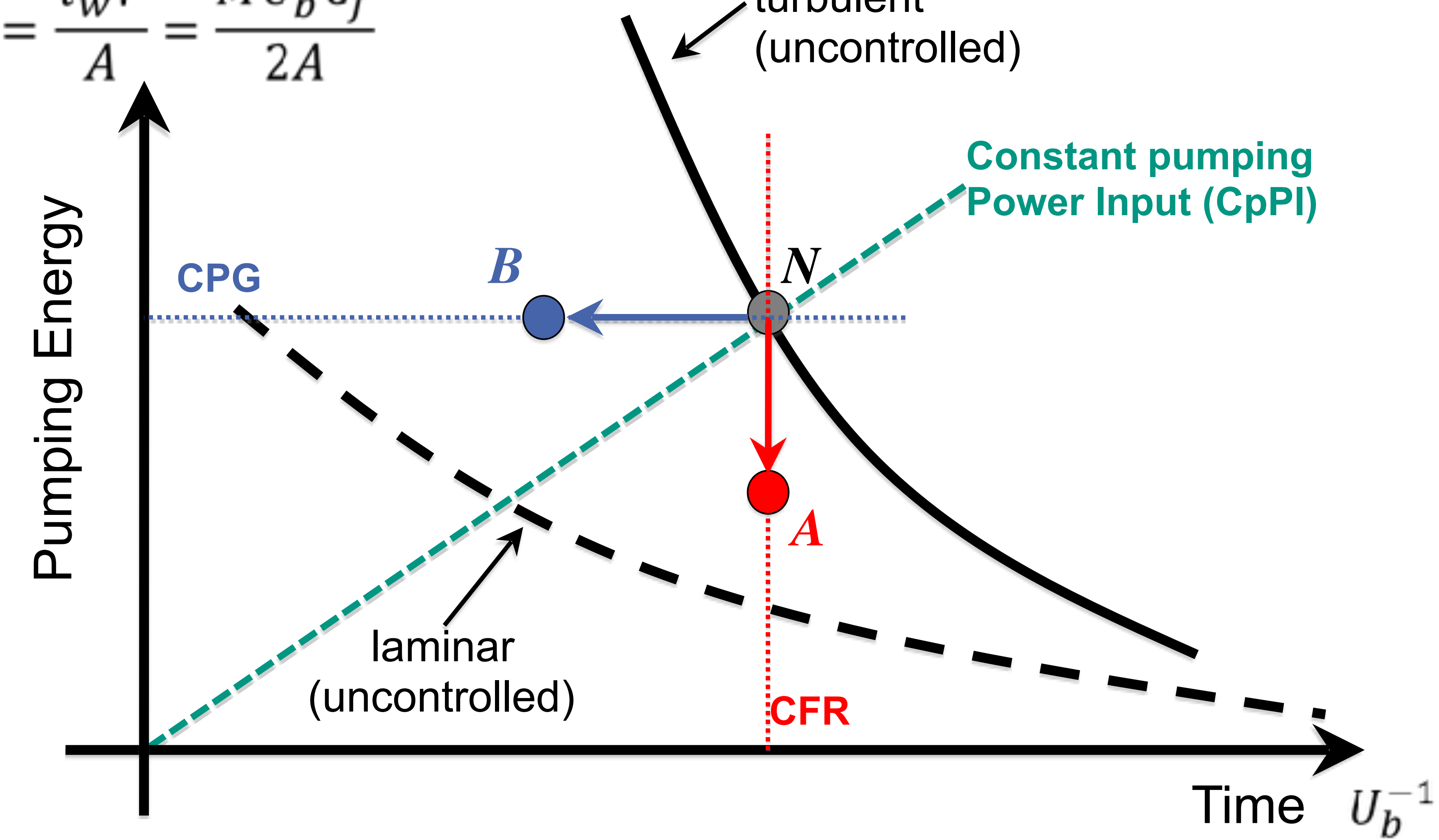
Pumping energy (per unit wetted area) : $E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$

Fluid travel time (per unit length) : $1/U_b$

Total energy : $E_{tot} = E_p + E_c$

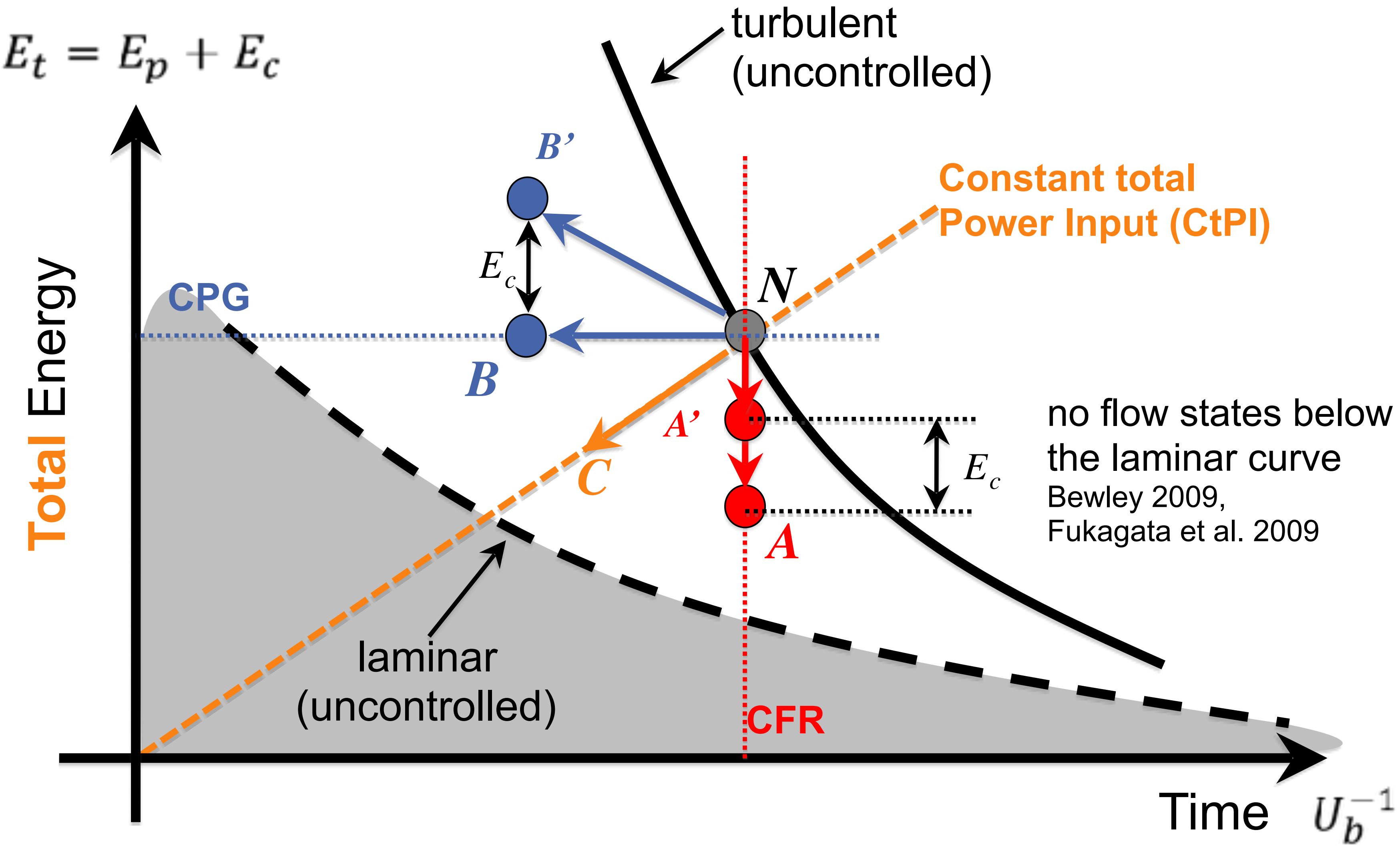
Energy (cost) vs. Time

$$E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$$



Frohnapfel, Hasegawa, Quadrio, JFM 2012

Total Energy (cost) vs. Time



Frohnapfel, Hasegawa, Quadrio, JFM 2012

Comparison of different flow conditions

successful control $R = 1 - \frac{c_f}{c_{f,0}} > 0$ manifests differently

CPG	⇧		⇧	⇧	⇩
CFR		⇩	⇩		⇩
CPI	⇧	⇩			⇩

Checkpoint: what you should not forget

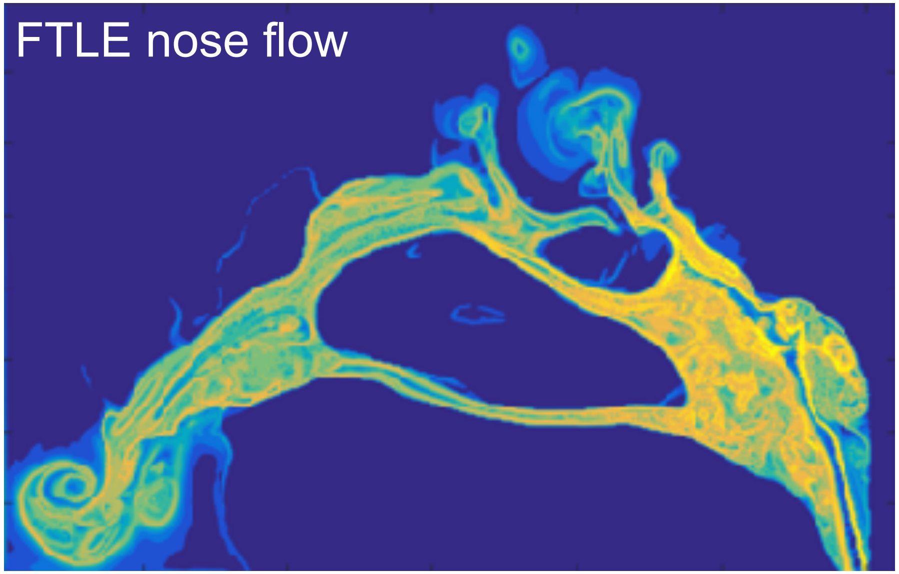
How to drive the flow (CFR, CPG, CPI)?

- necessary and important choice
- affects the results and their interpretations
- different manifestations of “drag reduction”

Constant Power Input

- possible choice close to real conditions (pump)
- power input (energy transfer rate) is kept constant
- relevant for various applications

Checkpoint: what you should not forget

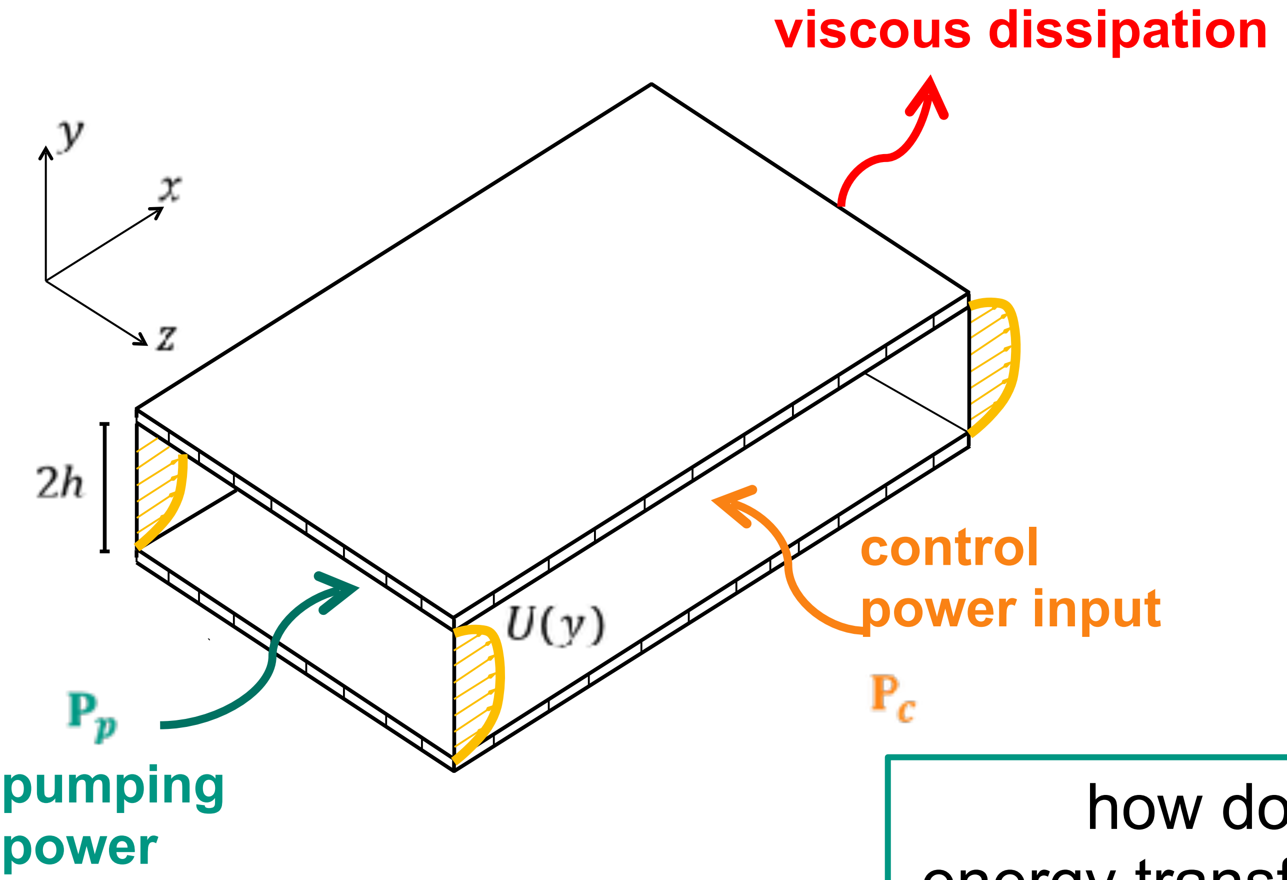


Constant Power Input

- possible choice close to real conditions (pump)
- power input (energy transfer rate) is kept constant
- relevant for various applications

The drag reduction experiment from the energetic viewpoint

CPI ideal framework to study energy transfer rates



how does control affect energy transfer phenomena?

Integral energy budget

Reynolds decomposition:

$$u(x,y,z,t) = \bar{u}(y) + u'(x,y,z,t)$$

$\frac{1}{2}\rho\bar{u}^2$ mean kinetic energy (MKE) budget:

$$P_p = P_{uv} + \Phi$$

$\frac{1}{2}\rho\overline{u'^2}$ turbulent kinetic energy (TKE) budget:

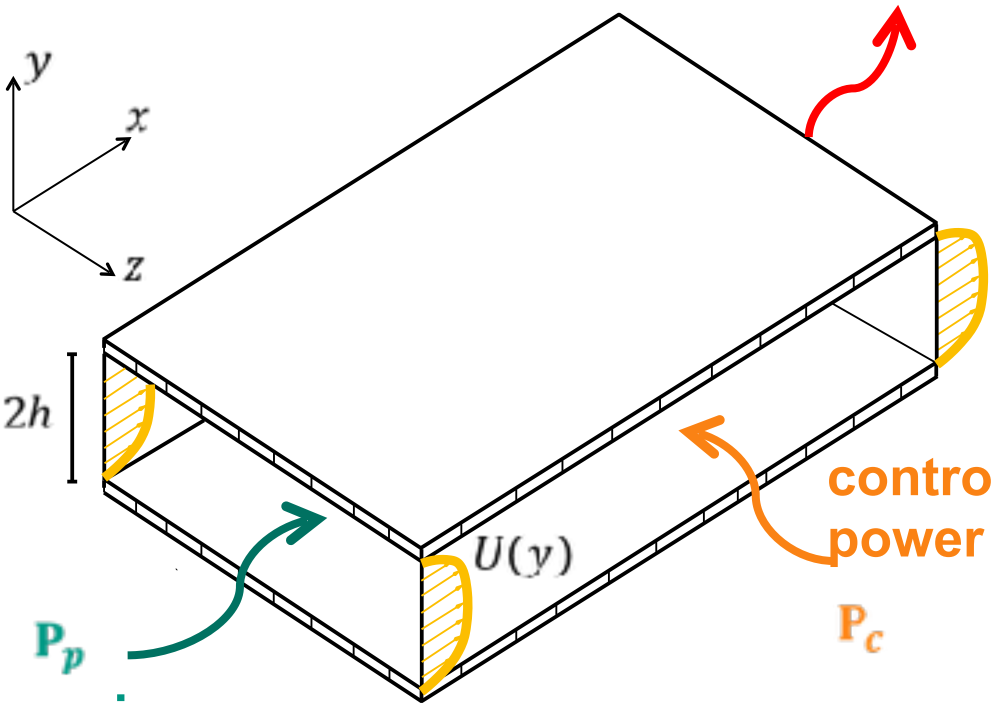
$$P_{uv} = \epsilon$$

global energy budget:

$$P_p = \Phi + \epsilon$$

The drag reduction experiment from the energetic viewpoint

CPI ideal framework to study energy transfer rates



turbulent ϵ + mean Φ
kinetic energy dissipation rate

control
power input
P_c

P_p
pumping
power

at (statistical) steady state:

$$P_t = P_p + P_c = \epsilon + \Phi$$

how does control affect energy transfer rates?

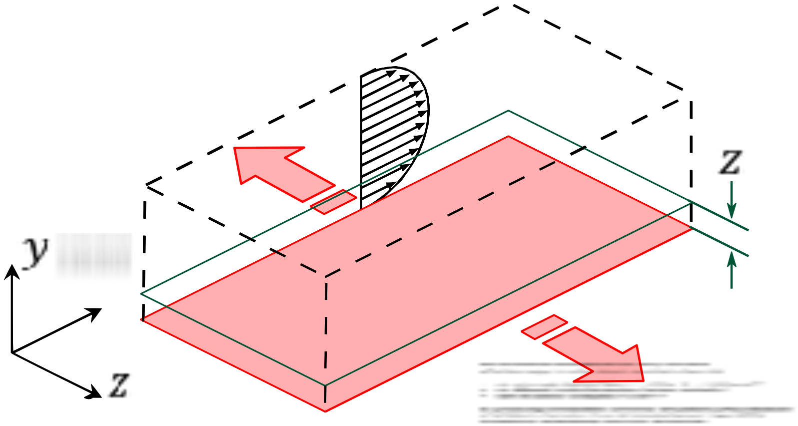
How does drag reduction affect energy transfer rates?

a (seemingly) trivial question with a non trivial answer

- Ricco et al., JFM (2012):
  substantial **increase of ϵ** caused by control with spanwise wall motions
- Frohnapfel et al., (2007):
  ϵ needs to be reduced to achieve drag reduction
- Martinelli, F., (2009):
  drag reduction obtained via feedback control aimed at **minimizing ϵ**

Control strategies

Spanwise wall oscillations



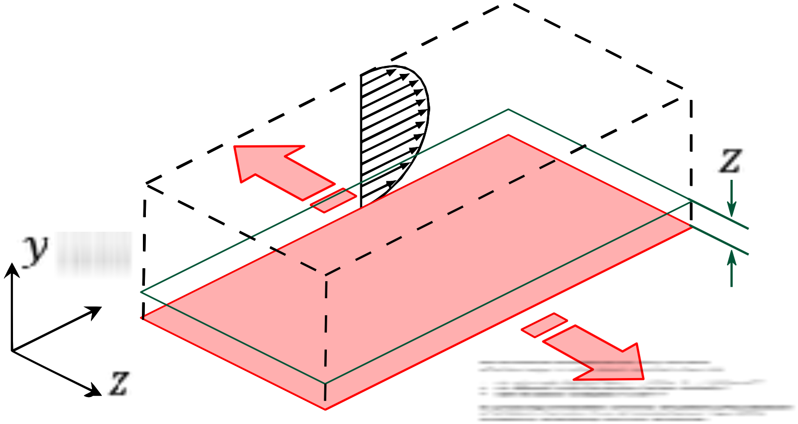
drag reduction $1/U_b$

control power fraction $\gamma = {}^{P_c}/_{P_t} = 0.098$

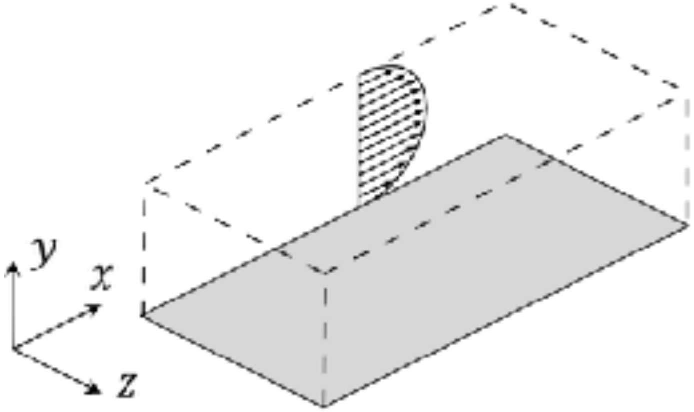
$$\frac{U_b}{U_{b,ref}} = 1.028$$

Control strategies

Spanwise wall oscillations



Opposition control



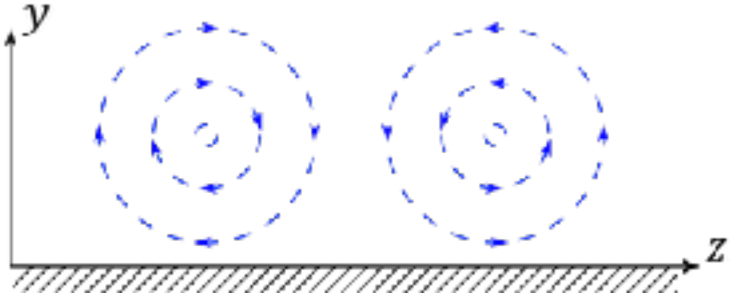
drag reduction

$$2h$$

control power fraction

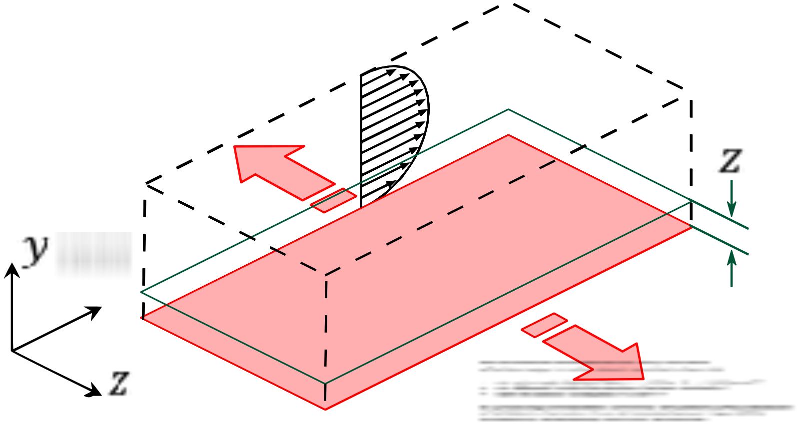
$$\gamma = {}^{P_c}/_{P_t} = 0.098$$

$$\frac{U_b}{U_{b,ref}} = 1.028$$

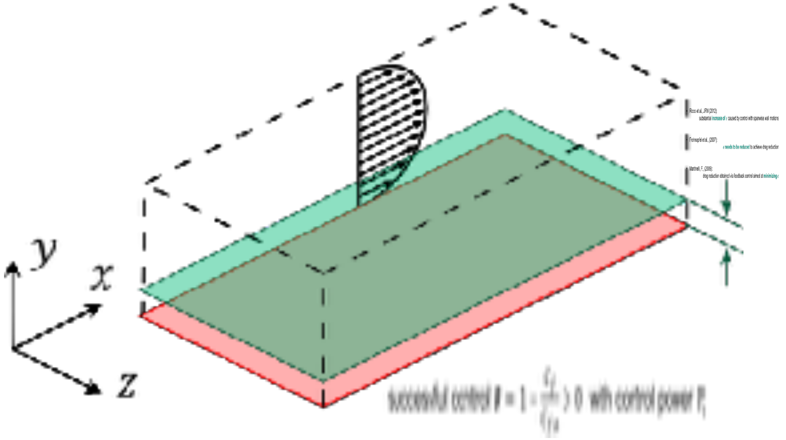


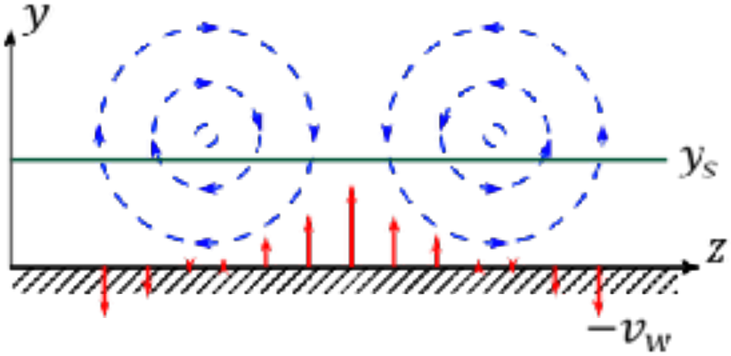
Control strategies

Spanwise wall oscillations



Opposition control





drag reduction

$2h$

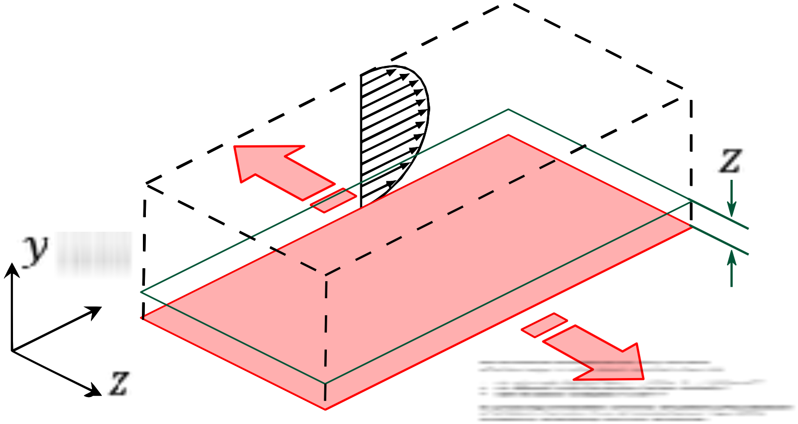
control power fraction

$$\gamma = {}^{P_c}/_{P_t} = 0.098$$

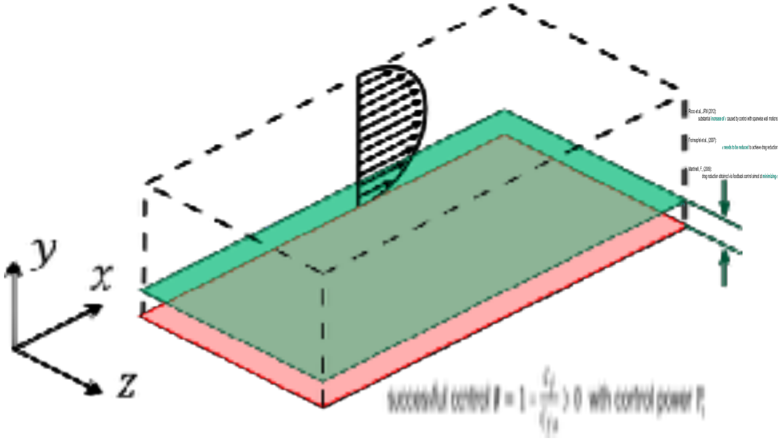
$$\frac{U_b}{U_{b,ref}} = 1.028$$

Control strategies

Spanwise wall oscillations



Opposition control



successful control $R = 1 - \frac{C_f}{C_{f,0}} > 0$ with control power P_c

drag reduction $2h$ $R = 23.9\%$

control power fraction $\gamma = {}^{P_c}/_{P_t} = 0.098$

turbulent + mean kinetic energy dissipation rate

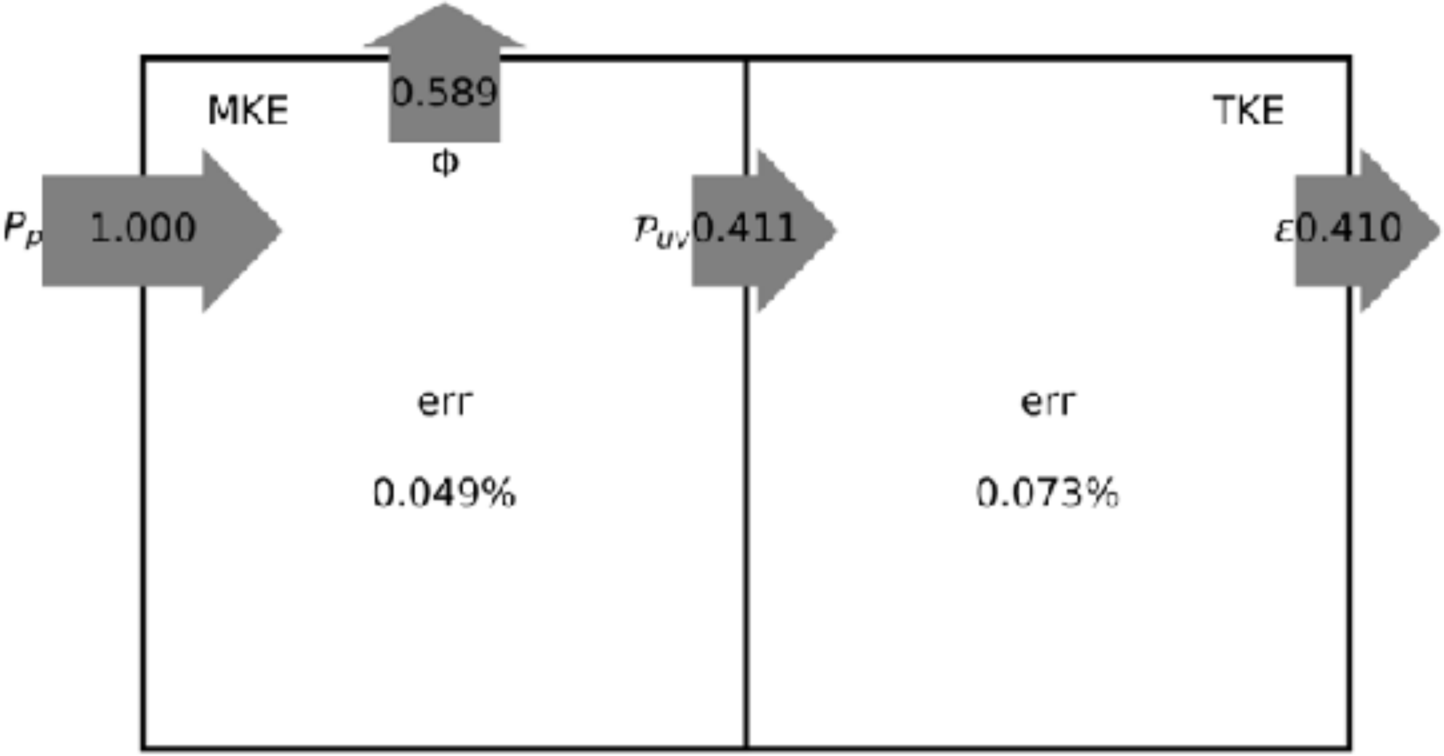
$$\frac{U_b}{U_{b,ref}} = 1.028$$

$$\frac{U_b}{U_{b,ref}} = 1.094$$

The energy box

reference flow

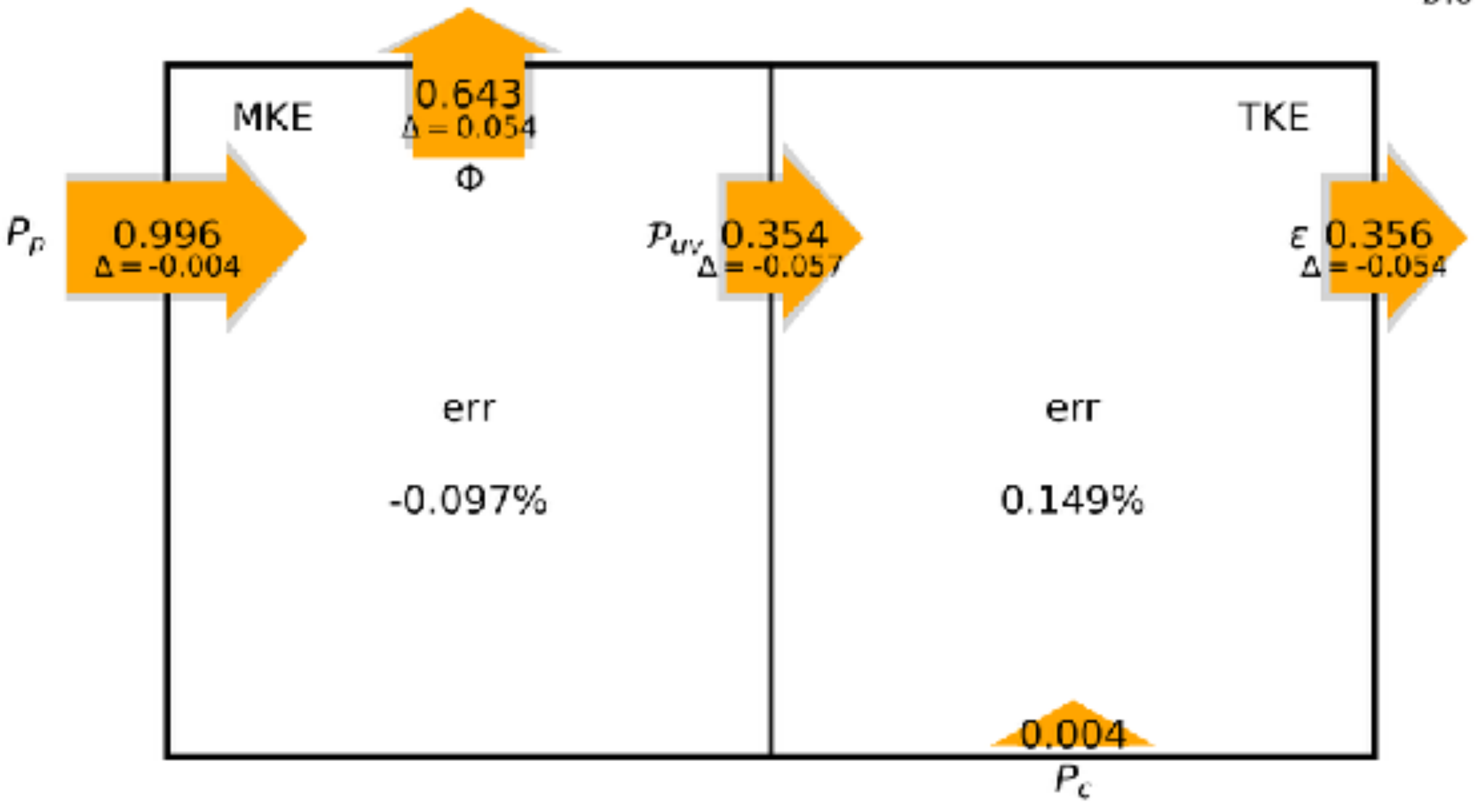
$Re_b = 3177 \qquad Re_\tau = 199.7$



The energy box

opposition control

$Re_b = 3474$ $Re_\tau = 190.5$ $\frac{U_b}{U_{b.0}} = 1.094$



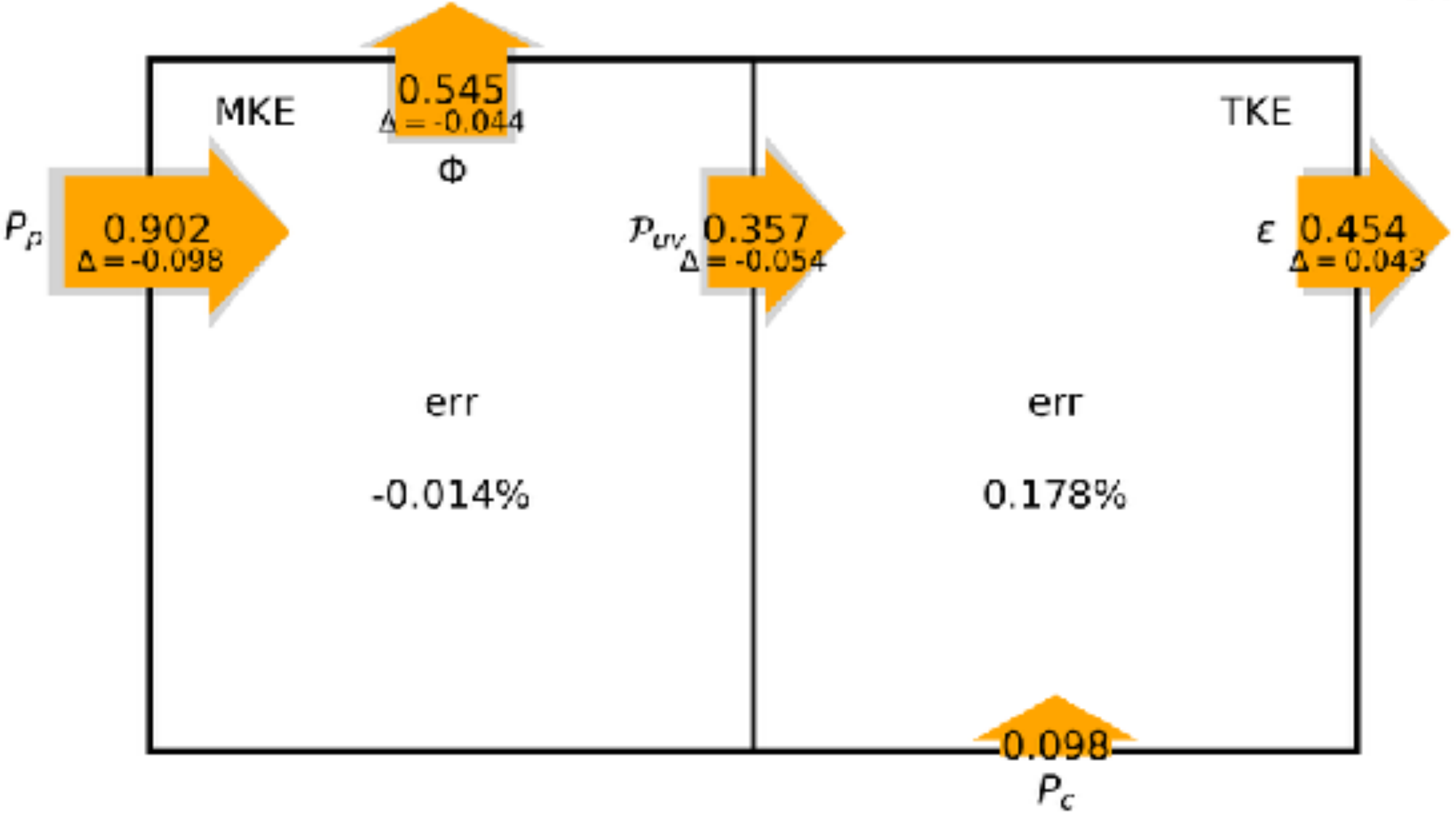
mass $M = \rho V$

cross-sectional area
$A = 2hW$

The energy box

oscillating wall

$Re_b = 3267$ $Re_\tau = 186.9$ $\frac{U_b}{U_{b.0}} = 1.028$



MKE

TKE

Φ 0.545 $\Delta = -0.044$

P_p 0.902 $\Delta = -0.098$

$\mathcal{P}_{uv}$ 0.357 $\Delta = -0.054$

ε 0.454 $\Delta = 0.043$

err -0.014%

err 0.178%

P_c 0.098

$$E_p = \frac{\tau_w V}{A} = \frac{M U_b^2 C_f}{2A}$$

TKE dissipation rate ε increases

The energy box: lesson

Drag reduction $\Leftrightarrow$ reduction of TKE production rate P_{uv}

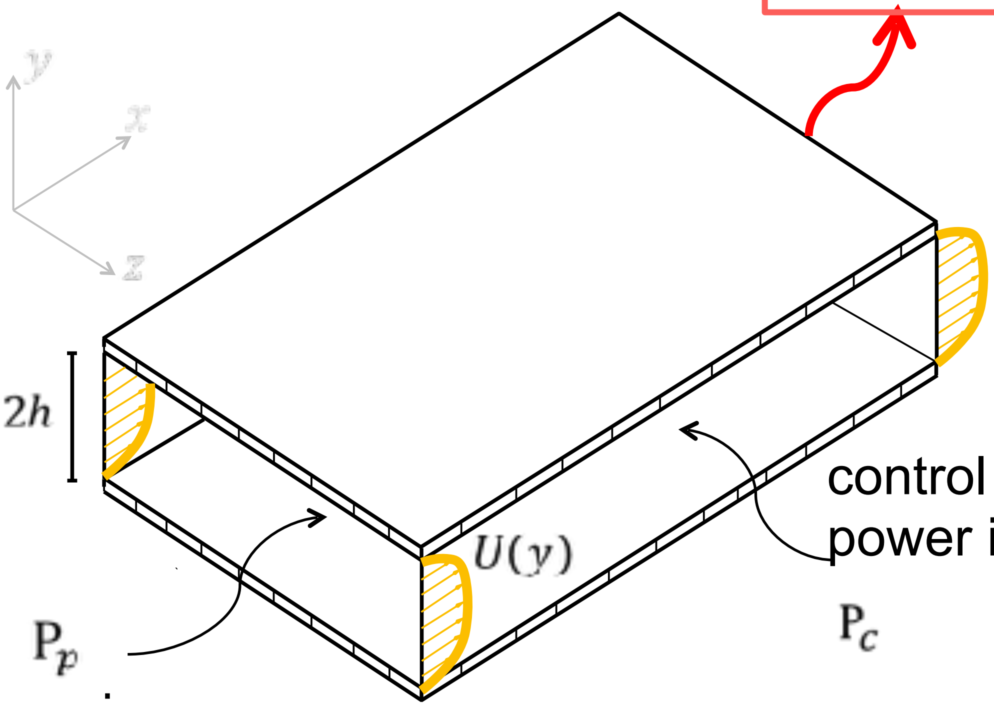
Drag reduction $\neq$ increase of MKE dissipation rate Φ

At CPI effect of control on energy transfer rates unveiled!!

Sometimes Π_c is a good alternative to Π_p

We made another (probably) unaware choice!

The drag reduction experiment from the energetic viewpoint



turbulent ϵ + mean Φ
kinetic energy dissipation rate

control
power input

pumping
power

at (statistical) steady state:

$$P_t = P_p + P_c = \epsilon + \Phi$$

Conclusions

How to drive the flow?

- is an **important** and necessary **choice**
- **CPI is** a **possible** alternative…
- …necessary to study systems energetically

Drag reduction from the **energetic viewpoint**

- **requires CPI** to highlight nontrivial behaviours
- ‘Reynolds’ decomposition of dissipation
  is also an arbitrary choice!

THANKS

for your kind attention!

for questions, complaints, ideas:

davide.gatti@kit.edu