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Energy transfer rates in turbulent channels with drag reduction at constant power input

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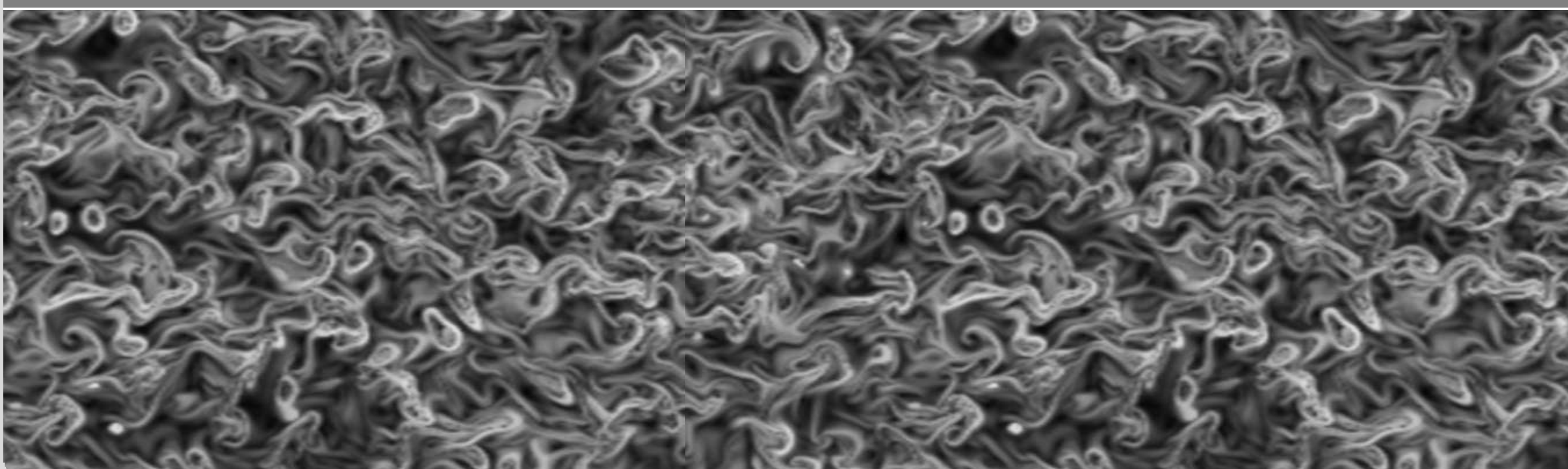
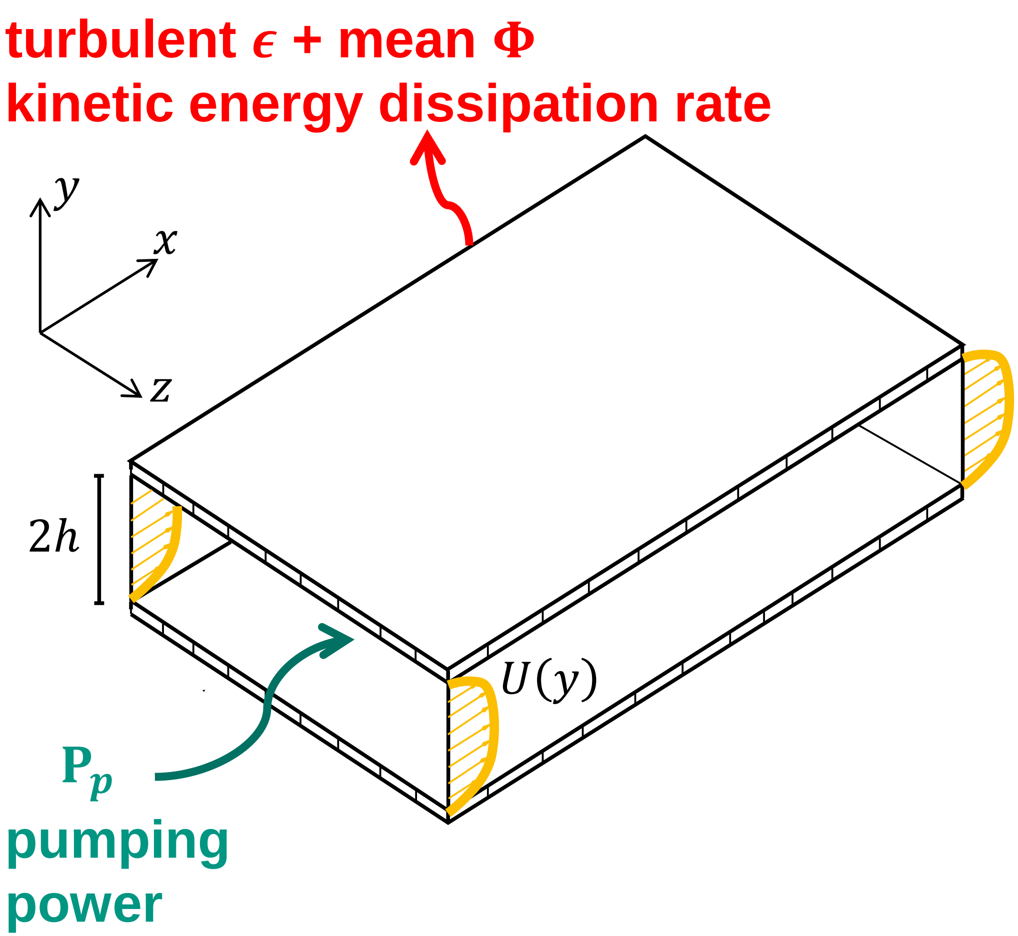
EDRFCM 2017, Villa Mondragone, Monte Porzio Catone



The drag reduction experiment



bulk velocity: U_b

pressure gradient:

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

skin-friction coefficient:

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

pumping power (per unit area):

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

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:

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

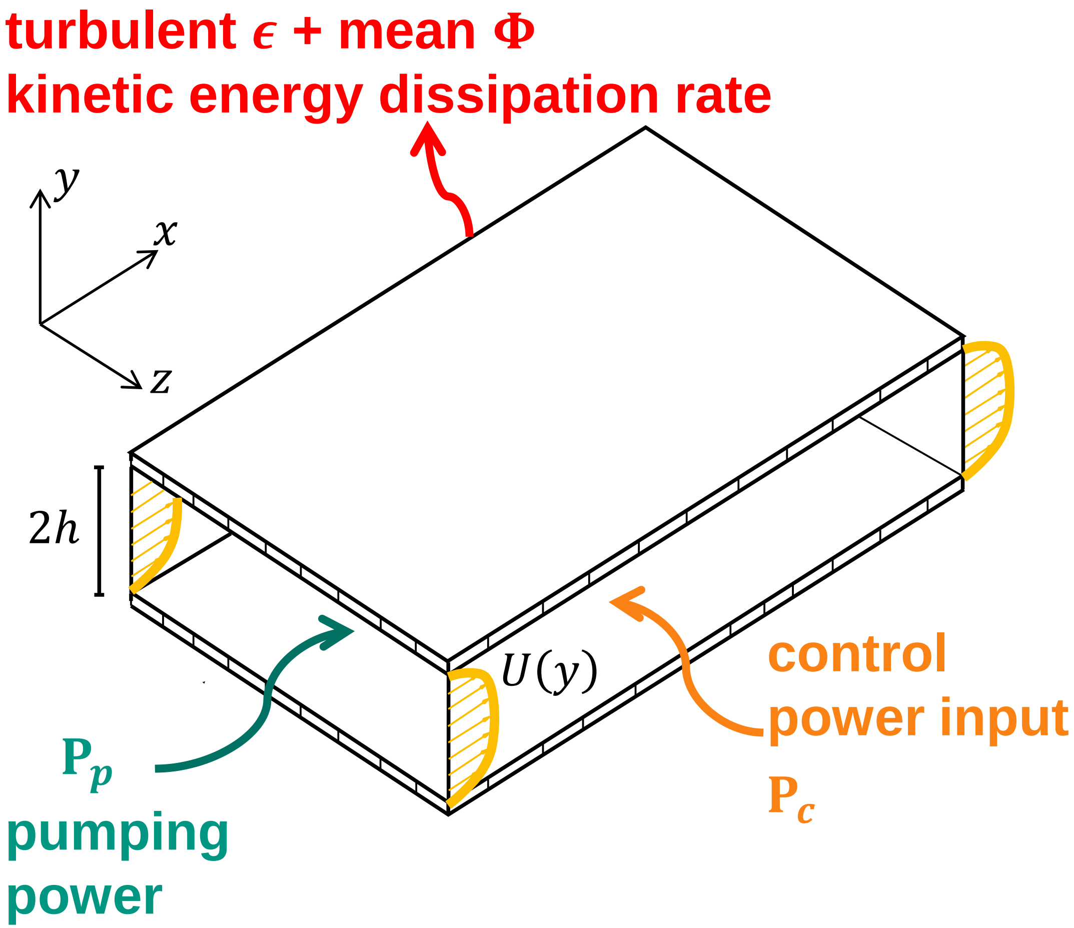
$\frac{1}{2}\rho\overline{u'^2}$ turbulent kinetic energy (TKE) budget:

$$P_{uv} = \boldsymbol{\epsilon}$$

global energy budget:

$$\boldsymbol{P_p} = \boldsymbol{\Phi} + \boldsymbol{\epsilon}$$

The drag reduction experiment



at (statistical) steady state:

$$\mathbf{P_t} = \mathbf{P_p} + \mathbf{P}_c = \boldsymbol{\epsilon} + \boldsymbol{\Phi}$$

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:

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

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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**

Goal

We investigate how skin-friction drag reduction
affects energy-transfer rates in turbulent channels

- do different control strategies behave similarly?
- do universal relationships $\epsilon = \epsilon(R)$ or $\Phi = \Phi(R)$ exist?
- can we predict changes of ϵ or Φ?

by producing a direct numerical simulation (DNS) database
of turbulent channels
modified by several drag reduction techniques

Comparing energy transfer rates correctly

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

	U_b	$-\frac{\mathrm{d}p}{\mathrm{d}x}$	$\mathbf{P_p} = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$	$\mathbf{P_t} = \mathbf{P_p} + \mathbf{P_c}$	$\boldsymbol{C_f}$
CPG	↑	$=$	↑	↑	↓
CFR	$=$	↓	↓	$?$	↓

P_p and P_t change between controlled and natural flow!!

Hasegawa et al., JFM (2014) propose alternative forcing methods:

CPI	↑	↓	↓	$=$	↓

The DNS database at CPI

- Box size $\left(L_x, L_y, L_z\right) = (4\pi h, 2h, 2\pi h)$
- Resolution $(\Delta x^+, \Delta y^+, \Delta z^+) = (9.8, 0.47 - 2.59, 4.9)$
- Average over 25000 viscous time units

Viscous "+" units:

$$u_\tau = \sqrt{\tau_w/\rho}$$

$$\delta_\nu = \nu/u_\tau$$

$$t_\nu = \nu/u_\tau^2$$

Constant total Power Input (CPI):

$$Re_\Pi = \frac{U_\Pi \delta}{\nu} = 6500$$

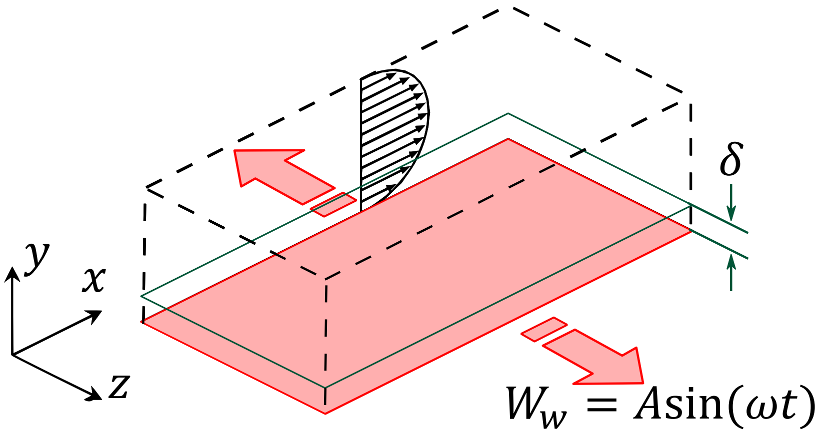
$$U_\Pi = \sqrt{\frac{\mathrm{P}_t h}{3\mu}}$$

$\boldsymbol{P_t} = P_p + P_c$ **is** kept **constant** to $\dfrac{P_t}{\rho U_\Pi^3} = \dfrac{3}{Re_\Pi}$

control power fraction $\gamma = \dfrac{P_c}{P_t}$, so that $P_p = (1-\gamma) P_t = \dfrac{3(1-\gamma)}{Re_\Pi}$

Control strategies

Spanwise wall oscillations



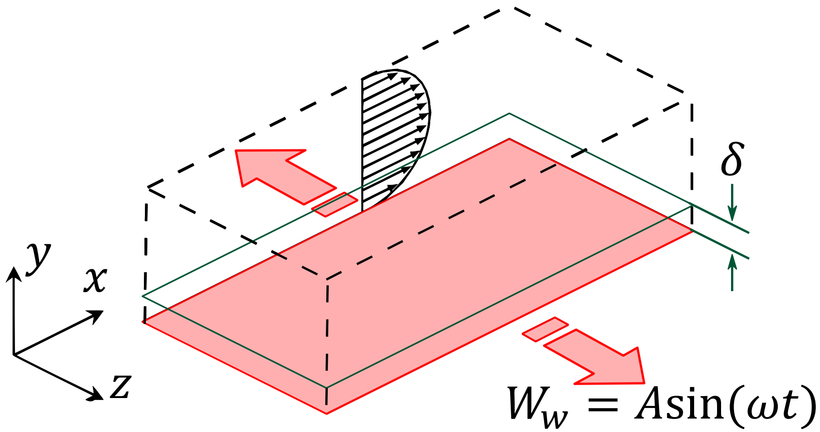
drag reduction $R = 1 - {C_f}/{C_{f,0}} = 17.1\%$

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

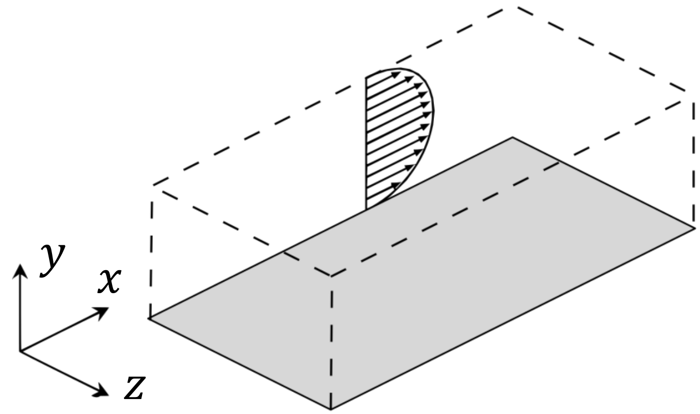
$$\frac{U_b}{U_{b,ref}} = 1.028$$

Control strategies

Spanwise wall oscillations



Opposition control



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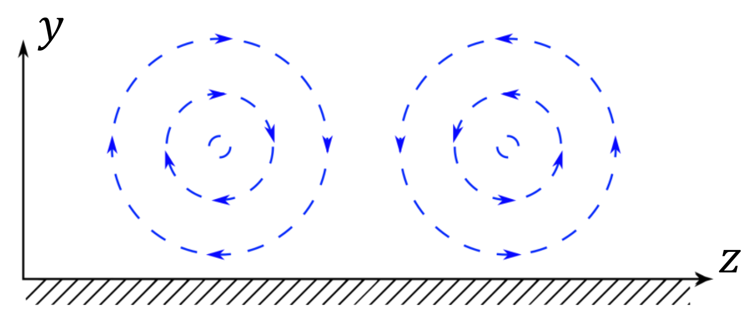
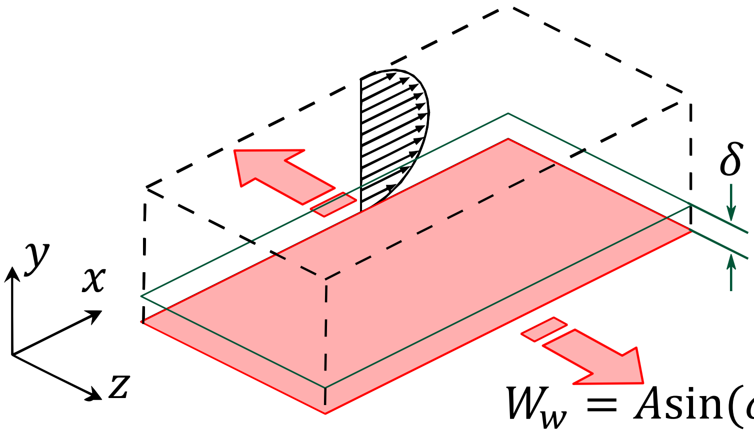


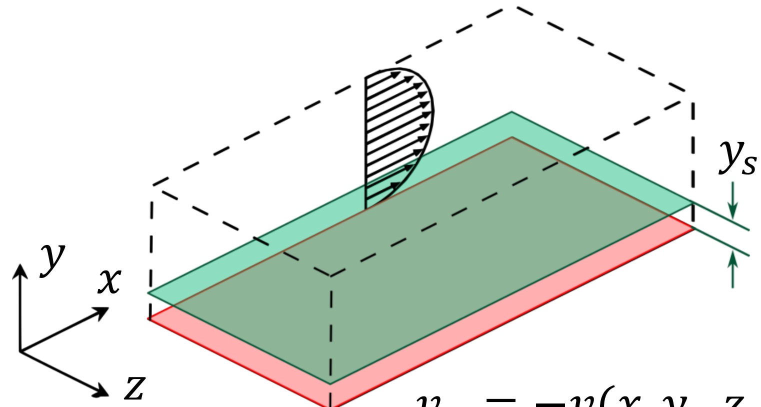
Control strategies

Spanwise wall oscillations



$$W_w = A \sin(\omega t)$$

Opposition control

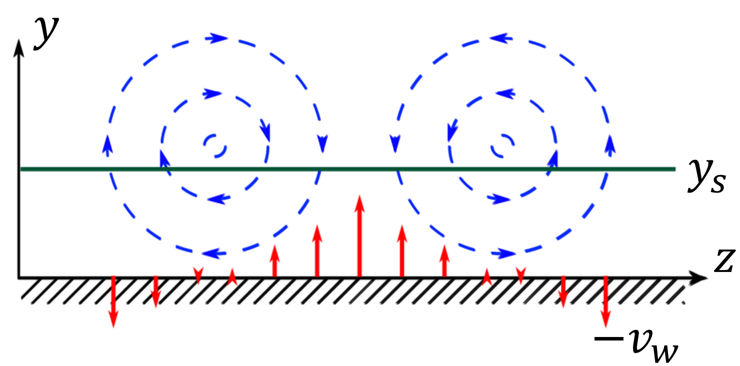


$$v_w = -v(x, y_s, z, t)$$

drag reduction $R = 1 - {C_f}/{C_{f,0}} = 17.1\%$

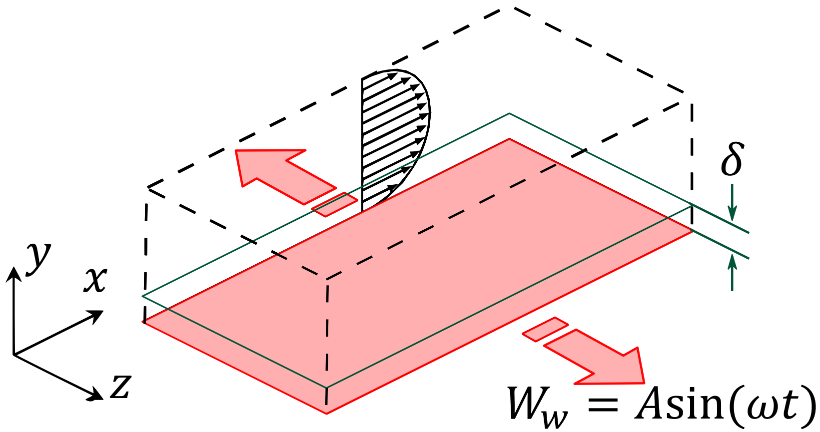
control power fraction $\gamma = {P_c}/{P_t} = 0.098$

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

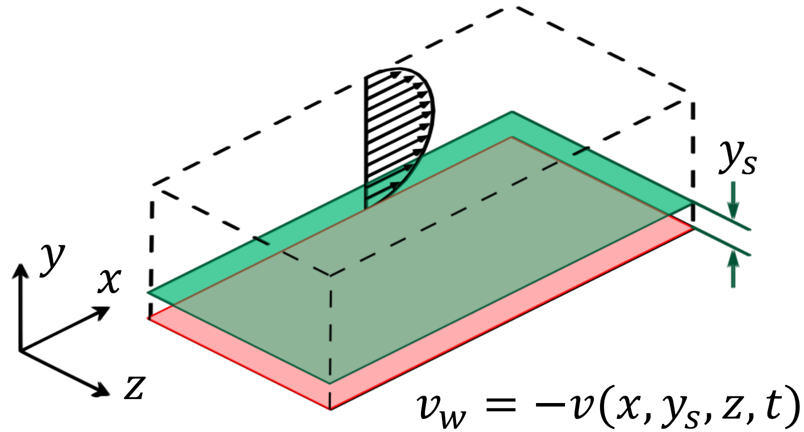


Control strategies

Spanwise wall oscillations



Opposition control



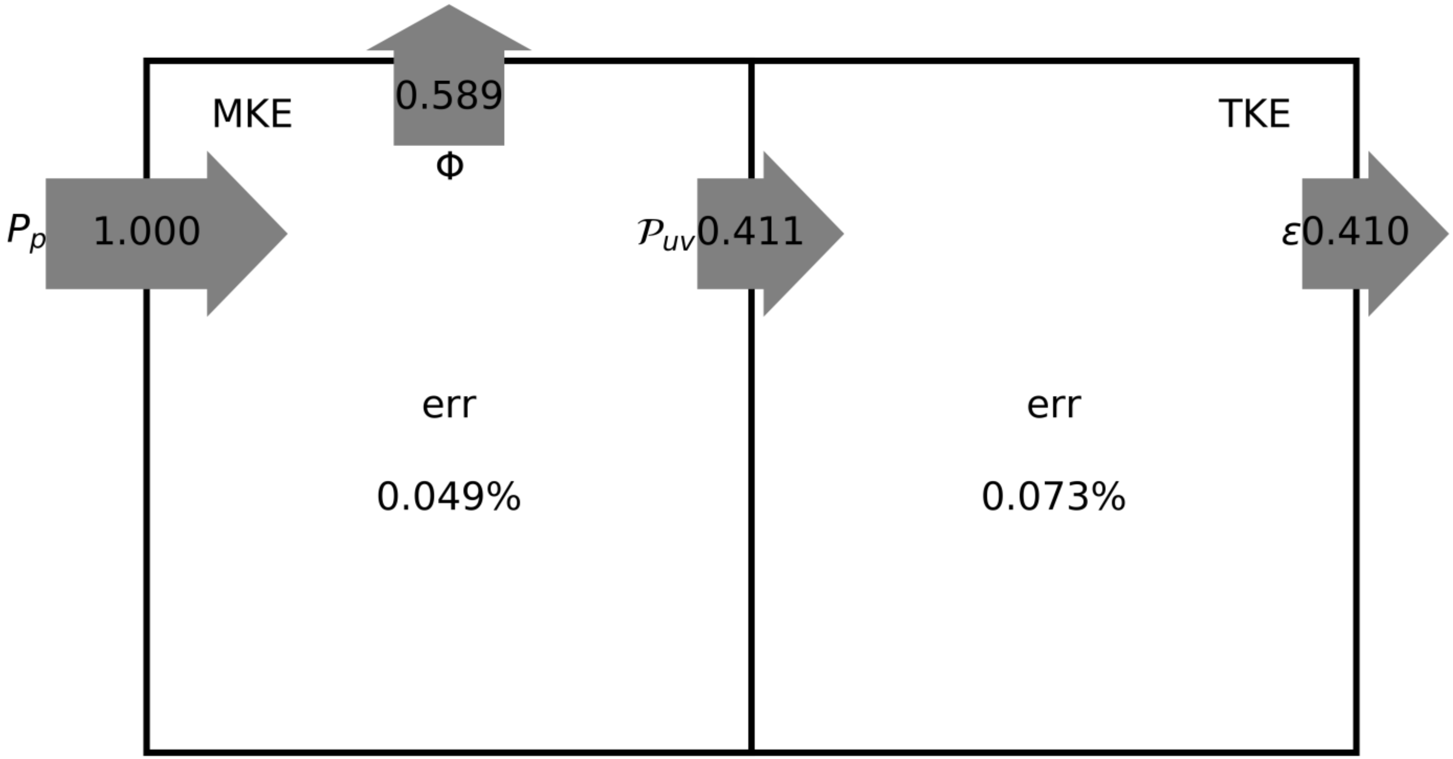
drag reduction $R = 1 - {C_f}/{C_{f,0}} = 17.1\%$ $\qquad$ $R = 23.9\%$

control power fraction $\gamma = {P_c}/{P_t} = 0.098$ $\qquad$ $\gamma = 0.0035$

$$\frac{U_b}{U_{b,ref}} = 1.028 \qquad \frac{U_b}{U_{b,ref}} = 1.094$$

The energy box

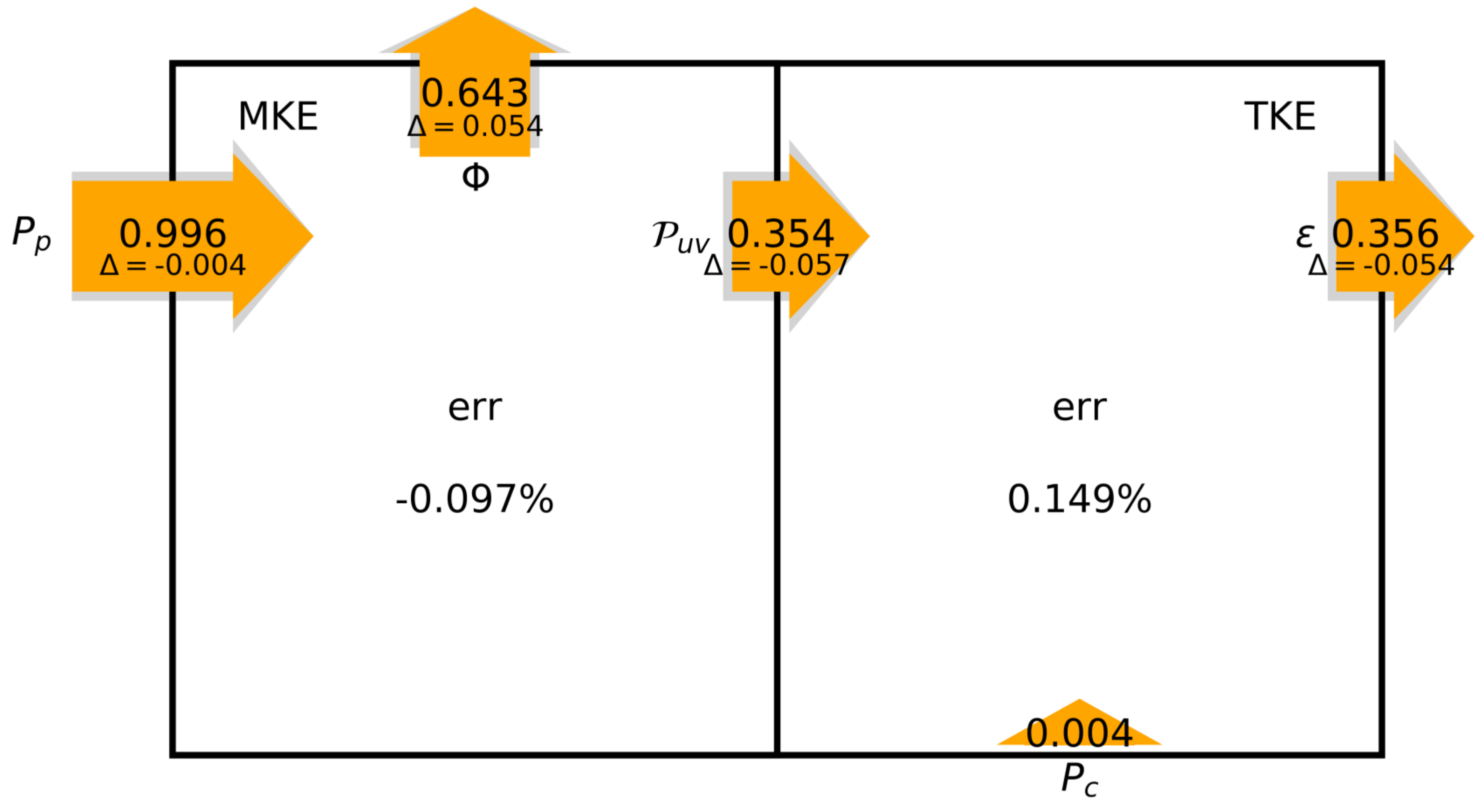
reference flow $Re_b = 3177$ $Re_\tau = 199.7$



The energy box

opposition control

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

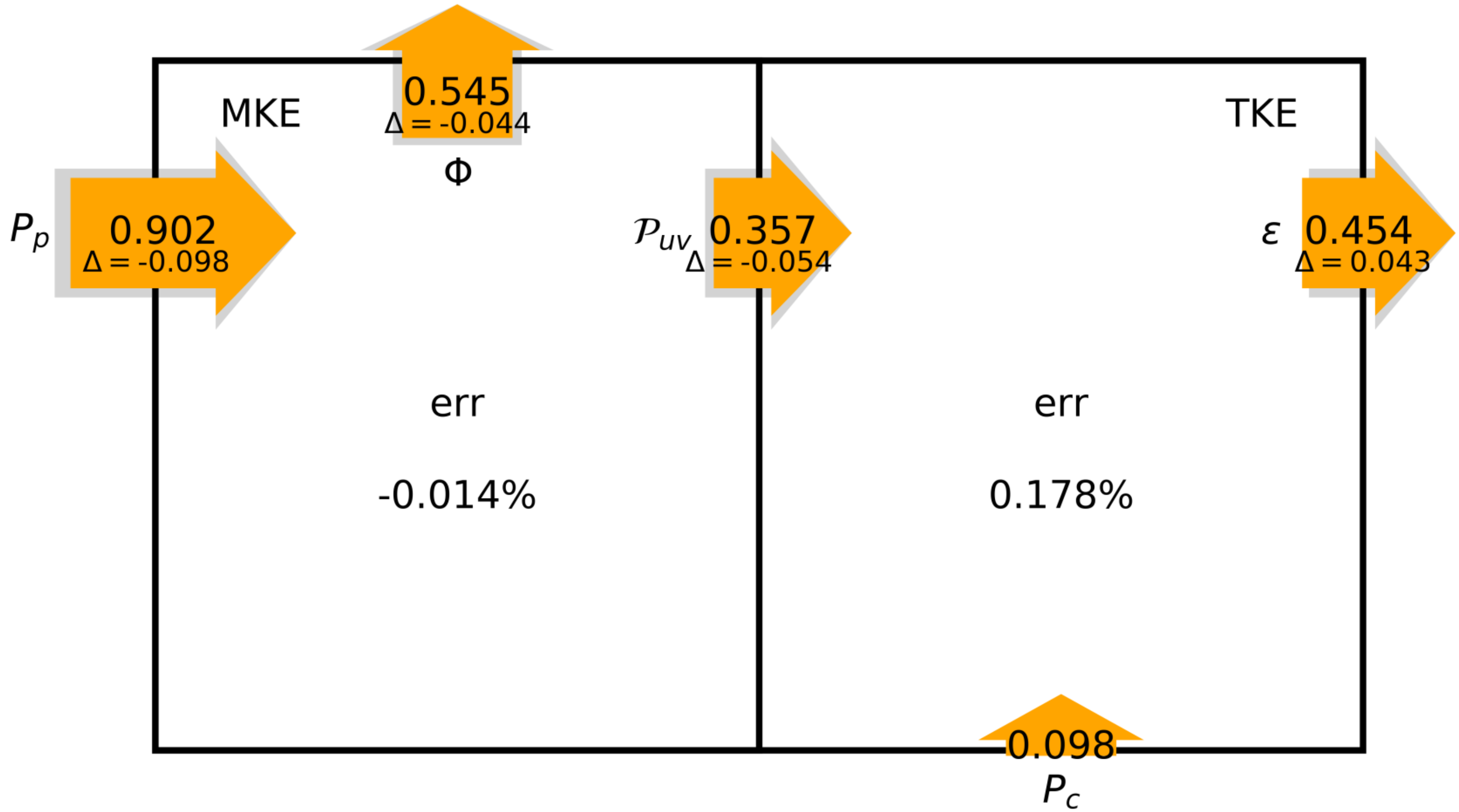


MKE dissipation rate Φ increases

TKE production rate P_{uv} and dissipation rate ϵ decrease

The energy box

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



Both MKE dissipation Φ and TKE production P_{uv} rates decrease, U_b increases!

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

P_c surprisingly good alternative to pumping with wall oscillations!

By accounting for the physics of the control and
separating the contribution of P_c to ϵ, it is also true that:

Drag reduction $\Leftrightarrow$ reduction of TKE dissipation rate ϵ

Predicting $\epsilon(R)$ for $R \approx 0$ (1)

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The dissipation ϵ in power units is linked to ϵ^+ in viscous units by the following:

$$\epsilon = \epsilon^+ \left(\frac{Re_\tau}{Re_\Pi} \right)^3$$

Re_τ can be substituted with Re_b with the following relationship:

$$\mathrm{P}_p = -\frac{\mathrm{d}p}{\mathrm{d}x} h U_b$$, which in nondimensional form reads $Re_\tau^2 Re_b = 3(1-\gamma) Re_\Pi^2$

this yields

$$\epsilon = \epsilon^+ \left(\frac{3(1-\gamma)}{Re_\mathrm{b}} \right)^{3/2}$$

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Predicting $\epsilon(R)$ for $R \approx 0$ (2)

The following relation holds for both controlled and reference flow

$$\epsilon = \epsilon^+ \left(\frac{3(1-\gamma)}{Re_\mathrm{b}}\right)^{3/2}$$

by taking the ratio in the controlled and reference channel we obtain

$$\frac{\epsilon}{\epsilon_0} = \frac{\epsilon^+}{\epsilon_0^+}\left[(1-\gamma)\frac{Re_{b.0}}{Re_b}\right]^{3/2}$$

for a reference channel flow it is known that the ϵ^+ is a mild function of Re_τ

$$\epsilon^+ = 2.54 \ln Re_\tau - 6.72$$

Abe & Antonia, JFM (2016)

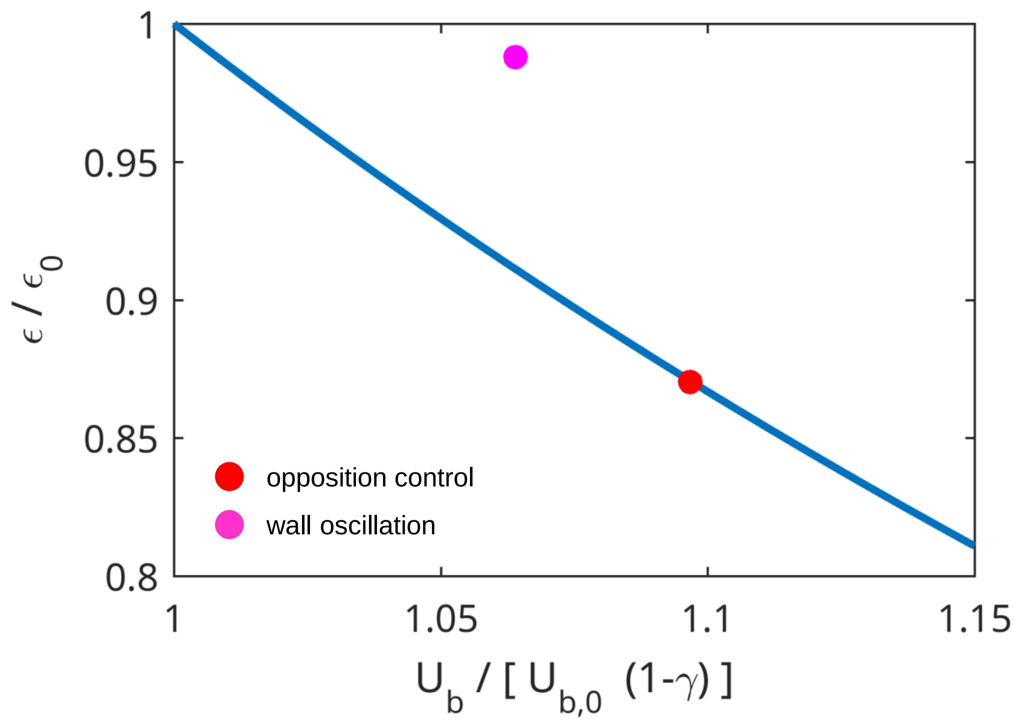
Hypothesis: if $R \approx 0$ then $Re_\tau \approx Re_{\tau,0}$, so we assume $\left(\frac{\epsilon^+}{\epsilon_0^+}\right) \approx 1$

Predicting $\epsilon(R)$ for $R \approx 0$ (3)

The relation reduces eventually to:

$$\frac{\epsilon}{\epsilon_0} = \left[(1-\gamma)\,\frac{Re_{b.0}}{Re_b}\right]^{3/2}$$

no general statement on ϵ^+ without considering the physics of the control!



Conclusions

- CPI approach is essential to assess energy transfer rates in drag-reduced flows

- Energy box analysis yields two statements

  Drag reduction $\Leftrightarrow$ reduction of TKE dissipation rate ϵ

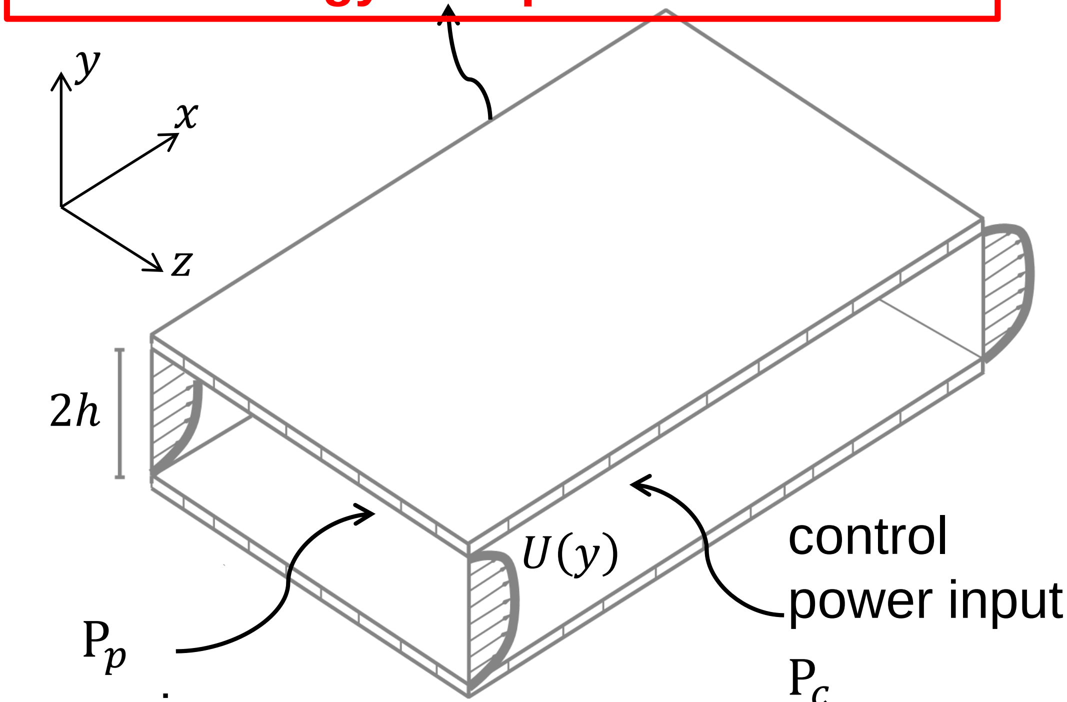
  Drag reduction $\neq$ increase of MKE dissipation rate Φ

- No universal relationship between R and ϵ could be found

  without considering the physics of the control

The drag reduction experiment

turbulent ϵ + mean Φ
kinetic energy dissipation rate



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drag reduction rate:

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

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THANKS

for your kind attention!

for questions, complaints, ideas:

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