

Reevaluation of Control Performance for Turbulent Skin Friction Drag Reduction in terms of Energy Saving and Convenience

Money versus Time

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Skin Friction Drag Reduction Technology



□ Key Aspects of Practical Fluid Transport Systems

- **✓** Convenience
 - flow rate in pipeline
 - travel speed of vehicle





✓ Energy Saving

- energy consumption to achieve certain "Convenience"

- **■** Evaluation of Control Performance in Fundamental Studies
- ✓ Constant Flow Rate (CFR): wall friction is changed by control <u>Successful Control</u>

Reduction of wall friction (reduction of pumping power)

✓ Constant Pressure Gradient (CPG): wall friction is kept constant by design <u>Successful Control</u>

Increase of flow rate (increase of pumping power)

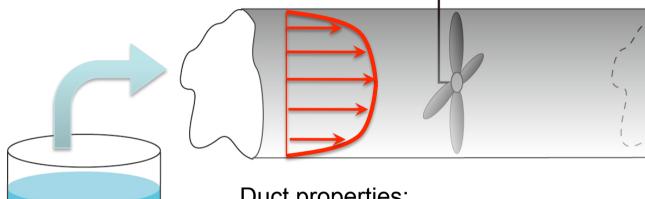


Internal Flow



Flow rate U_h







Mass: M = rV

Duct properties:

- Cross sectional area : A
- Wetted perimter: C
- Hydraulic diameter: D = 4A/C
- ✓ Fluid travel time per unit length: $1/U_h$
- ✓ Pumping energy per unit wetted area:

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



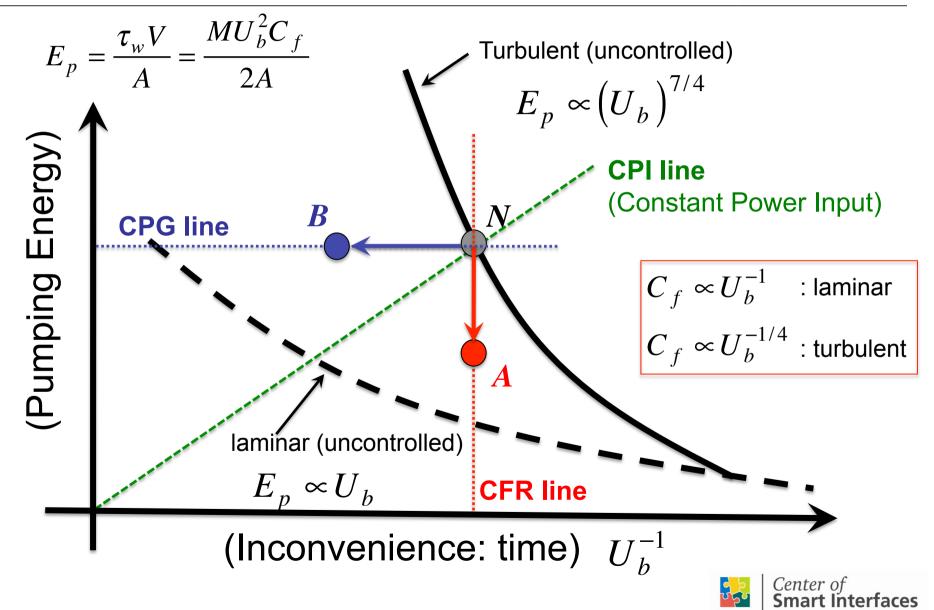
$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U_b^2}$$





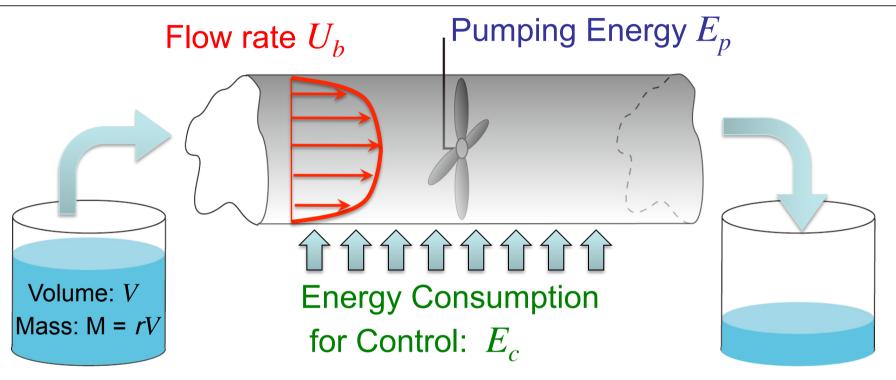
Energy Saving vs Convenience





Active Control of Internal Flow



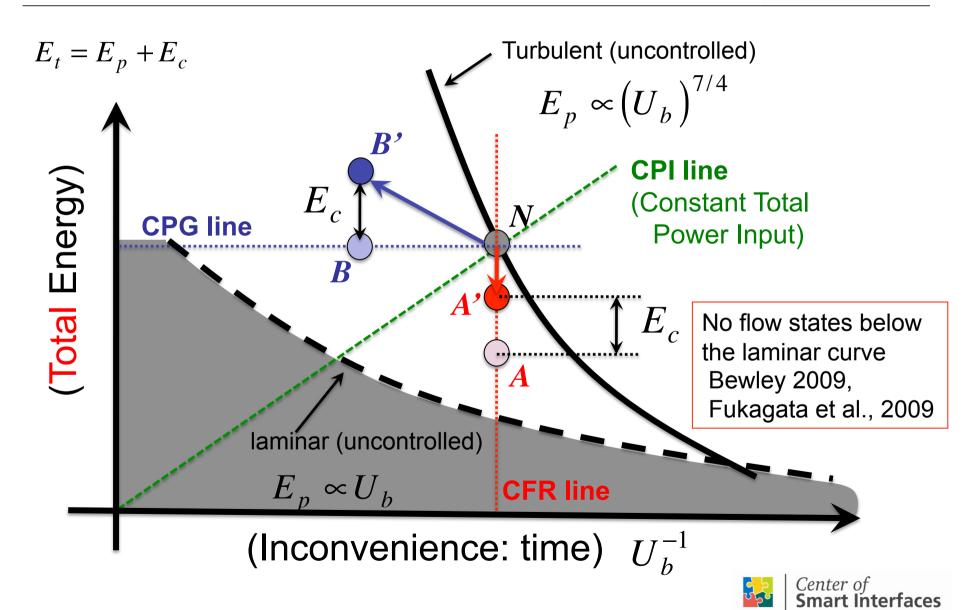


- \checkmark Fluid travel time per unit length: $1/U_b$
- ✓ Total energy consumption per unit wetted area:

$$E_t = E_p + E_c$$
 Control energy

Energy Saving vs Convenience

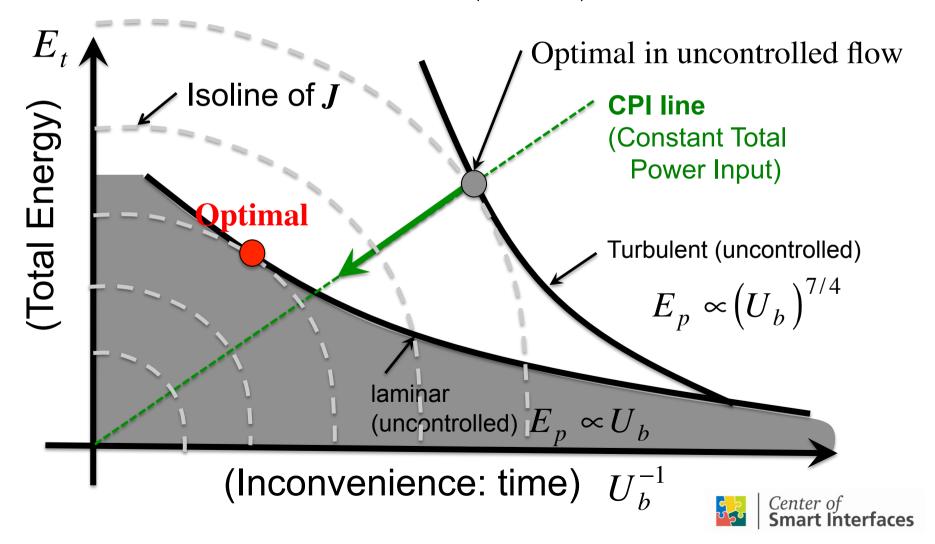




Example



Cost function:
$$J = E_t^2 + (1/U_b)^2$$



Non-dimensionalization



□ Convenience (Fluid travel time per unit length)

$$T_c = 1/U_b$$

$$\left(\frac{1}{U_b}\right)\left(\frac{v}{D}\right) = \frac{v}{U_b D} = \text{Re}_b^{-1}$$

□ Energy Expenditure

✓ Pumping Energy

$$E_p = \frac{MU_b^2 C_f}{2A} \qquad C_f = E_p \left(\frac{2A}{MU_b^2}\right) \qquad C_f \operatorname{Re}_b^2 = E_p \left(\frac{2AD^2}{Mv^2}\right)$$

✓ Total Energy (Pumping + Control)

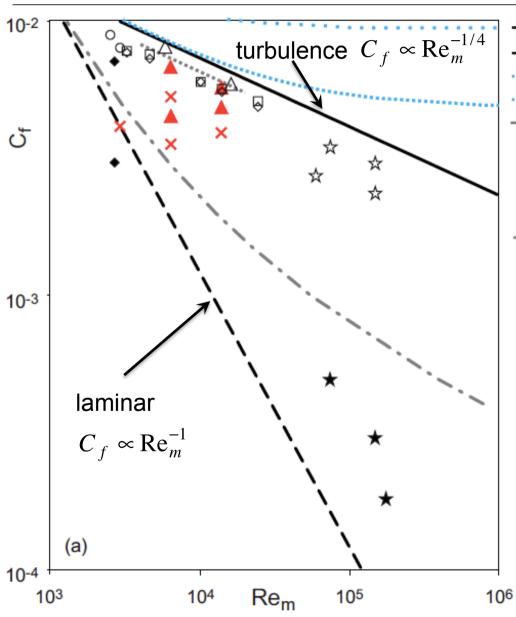
Effective wall friction

$$\tau_w^e = \frac{P_p + P_c}{U_b} = \tau_w + \frac{P_c}{U_b} \qquad C_f^e \operatorname{Re}_b^2 = E_t \left(\frac{2AD^2}{Mv^2}\right)$$



Conventional C_f - Re_b Plot



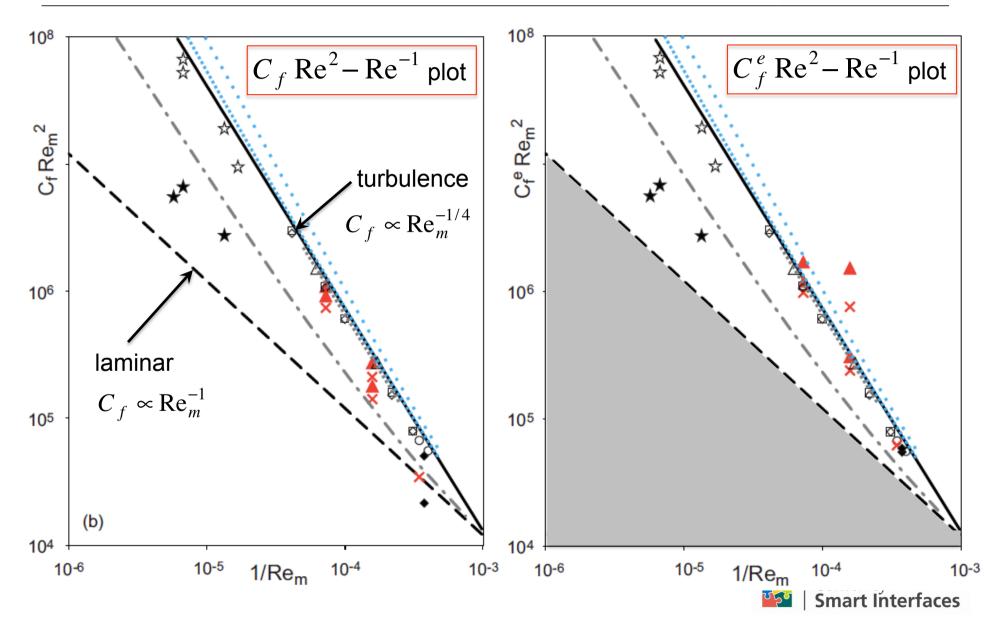


- **–** laminar
- turbulent
- rough pipe D/k=1000 (Colebrook 1939)
- rough pipe D/k=100 (Colebrook 1939)
- - polymers (MDR asymptote) (Virk et al., 1974)
- ★ polymers + surfactants (Lee et al., 1974)
- ☆ fibers (Delfos et al. 2011)
- △ riblets (Gruneberger & Hage, 2011)
- micro grooves (Frohnapfel et al., 2007)
- seal fur (Itoh et al., 2006)
- ▲ spanwise wall oscillation (Quadrio & Ricco, 2004)
- streamwise travelling wave (Quadrio et al., 2009)
- opposition control (Iwamoto et al., 2002)
- suboptimal control (lwamoto et al., 2002)
- upstream travelling wave (Min et al., 2006)
 - ✓ The value of C_f does not represent energy consumption, e.g.,
 - C_f decreases with increasing Re
 - ✓ Comparison of C_f at different Re does not make sense



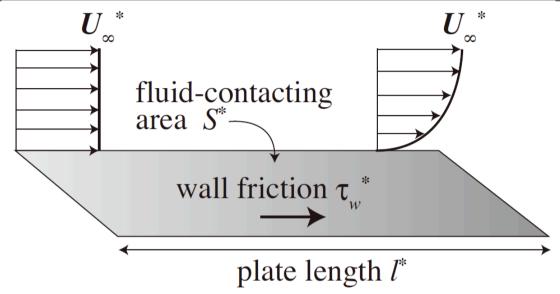
New Plot (Energy vs Convenience Plot)





Application to External Flow





□ Convenience (traveling time per unit distance)

$$(U_{\infty})^{-1} \longrightarrow v/(U_{\infty}l) = \mathbb{R}e_l^{-1}$$

□ Propulsion energy per unit fluid-contacting area and unit distance

$$E_p = \frac{1}{2} \rho U_{\infty}^2 \overline{C_f} \qquad \qquad \boxed{\overline{C_f} \operatorname{Re}_l^2} = E_p \left(\frac{\rho v^2}{2l^2} \right)$$

 C_fRe^2 - Re^{-1} plot can also be used for external flows ter of interfaces



Conclusions



- □ In real applications, a compromise between *Convenience* (Time) and *Energy expenditure* (Money) has to be reached so as to accomplish a goal which in general depends on a specific application.
- Based on this idea, we propose a new evaluation plane (money-time plane), which can be viewed as an improved version of the conventional Cf-Re plot.
- The new plane consists of two dimensionless parameters Re^{-1} and C_fRe^2 which represent the flow rate (convenience) and the energy expenditure required to achieve that flow rate, respectively.
- □ The new evaluation plane is useful to seek the optimal control strategy for minimizing the application-dependent cost function.
- **□** The above considerations can be easily extended to external flows.

Reference:

Frohnapfel, Hasegawa & Quadrio, "Money versus Time", JFM Vol. 700, pp.406-418, 2012

