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COMPARING VARIOUS DRAG-REDUCTION TECHNIQUES IN THE MONEY-VS-TIME FRAMEWORK

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Up to now, various drag-reducing techniques, applied to the canonical turbulent channel or pipe flows, have been explored either through Direct Numerical Simulation (DNS) of the Navier–Stokes equations, or by laboratory experiments. In DNS, their control performance has been evaluated while keeping constant in time either the flow rate (CFR) or – less often – the pressure gradient (CPG).

Under the CFR condition, a successful drag-reducing technique effectively reduces friction drag, which immediately translates into a reduction of the pumping energy. One important drawback of imposing the CFR constraint, however, is that the wall shear stress, which is a important factor in near-wall turbulence dynamics, changes due to the applied control, so that it becomes difficult to understand the essential effects of the control input owing to superimposed Reynolds number effects. When the CPG condition is used, on the other hand, friction drag is indeed unchanged by design, and 'drag reduction' manifests itself through an increase of the flow rate, which implies an increase in the power required to drive the flow.

We have recently proposed [1] a conceptual framework where an unequivocal assessment of (non necessarily active) flow control techniques against whatever application-dependent value-for-money considerations is made possible. A new evaluation plane is proposed in which both quantities, i.e. energy consumption and convenience, are simultaneously and explicitly considered. This new plane can be viewed as an improved version of the familiar $C_f - Re$ plane, which describes in a dimensionless way how the flow rate and the pressure gradient required to achieve that flow rate are related. In the new plane, an analogous non-dimensional description relates the flow rate and the energy expenditure required to achieve that flow rate, possibly including control energy.

We shall consider a given fluid volume V_f^* which has to be transported through a duct by means of a pressure gradient. The asterisk represents dimensional quantities throughout this paper. The flow is assumed to be fully developed. The cross sectional area A^* and the wetted perimeter C^* of the duct do not vary along the streamwise direction x. The hydraulic diameter is defined as $D^* = 4A^*/C^*$.

A simple analysis leads to the following relationship for the pumping energy per unit wetted area:

$$E_p^* = \tau_w^* \frac{V_f^*}{A^*} = \frac{M^* {U_b^*}^2 C_f}{2A^*}, \tag{1}$$

where τ_w^*, U_b^*, ρ and $M^* = \rho^* V_f^*$ are the wall-shear-stress, the bulk mean velocity, the fluid density and the total mass of the transported fluid, respectively. The dimensionless friction coefficient C_f is defined as

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

If the flow control technique is of the active type and thus requires energy to operate, its energy input E_c^* must enter the picture, and the total energy $E_t^* = E_p^* + E_c^*$ is used on the vertical axis. The solid and broken lines in Fig. 1 indicate non-controlled turbulent and laminar flows. The paths for a controlled flow state under CFR and CPG are shown by the arrows NA' and NB'. The additional control energy input E_c^* is reflected in Fig. 1 by the shift of points A and B in the vertical direction to A' and B', respectively. The total energy consumption at a given flow rate is minimized when the flow becomes laminar. Therefore, no flow state can be located below the laminar curve, i.e., in the grey region in Fig. 1.

From Fig. 1 it becomes readily evident that there are multiple ways of bringing a flow towards the laminar state, and that starting from the non-controlled state N multiple target laminar states can be defined according to which quantity one decides to minimize. The money-vs-time framework highlights that a choice from the designer is required to identify which quantity is best valued in a particular application. The CFR and the CPG strategies are only two extreme cases where the designer values just energy alone (money) or just performance alone (time).

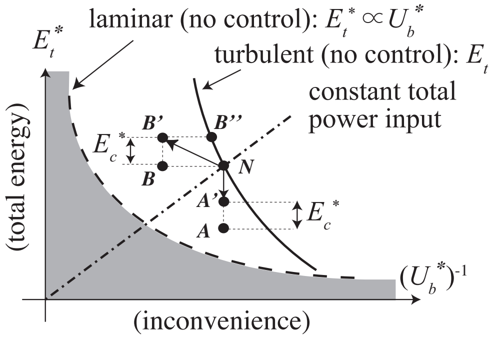

Figure 1: Total energy E_t^* versus the inverse of the bulk mean velocity U_b^*. Starting from the non-controlled flow state N, successful flow control under CFR shifts it to A, whereas successful flow control under CPG shifts it to B. The vertical shifts from A and B to A' and B' represent the energy consumption E_c^* for the control.

At the meeting, we will exemplify how the money-vs-time framework can be effectively used to compare the energetic performances of some known skin-friction drag reduction techniques. To this purpose, a dimensionless version of the previous Fig. 1 is used, where the horizontal axis is made dimensionless by using $\nu^*/(U_b^* D^*) = Re_D^{-1}$, where Re_D is the diameter-based Reynolds number and ν^* is the fluid kinematic viscosity. To deal with the vertical axis, the following dimensionless quantity is used [1]:

$$C_f^e Re_D^2 = \frac{2A^* E_t^*}{M^* (\nu^*/D^*)^2}, \tag{3}$$

so that E_t^* is non-dimensionalized by the fluid viscosity and geometrical properties of the duct only. Here, $C_f^e = (2A^* E_t^*)/(M^* {U_b^*}^2)$ is the effective friction coefficient based on the total energy consumption E_t^*.

We will consider a fully developed turbulent channel flow, where the Reynolds number Re_m is defined based on the bulk mean velocity and the channel height at $Re_\tau = 200$. As for a control technique, we consider so-called spanwise forcing, an open-loop scheme that offers a large amount of available control results. Specifically, the data for spanwise wall oscillation (SWO) [2] [3] under the CFR and CPG conditions respectively, and for streamwise traveling wave of spanwise wall velocity (StTW) [4] under CFR will be considered, and differences and implications for flow control will be discussed.

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