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Cardiac-cycle inspired turbulent drag reduction

Jose M. López[1], Davide Scarselli[2], Atul Varshney[3], and Bjoern Hof[2]

jose.lopez@uma.es

[1]Departamento de Ingeniería Mecánica, Térmicas y de Fluidos, Universidad de Málaga, Spain
[2]Institute of Science and Technology, Austria
[3]School of Physical Sciences NISER Bhubaneswar, India

Flows through pipes and channels are in practice almost always turbulent and the eddying motion is responsible for the major part of the encountered friction losses and pumping costs. Conversely, for pulsatile flows, in particular for aortic blood flow, turbulence levels remain surprisingly low, despite relatively large peak velocities. Indeed, in this latter case high turbulence levels are intolerable as they would damage the shear sensitive endothelial cell layer. We here show that turbulence in ordinary pipe flow is diminished if the flow is driven in a pulsatile mode that incorporates all the key features of the cardiac waveform. At Reynolds numbers comparable to aortic blood flow, turbulence is largely inhibited, whereas at much higher speeds, the turbulent drag is reduced by more than 25%. This specific operation mode is considerably more efficient when compared to steady driving, which is the status quo for virtually all fluid transport processes ranging from heating circuits to water, gas and oil pipelines.

1 Introduction

Turbulent flows are associated with large friction levels and high pumping costs when compared to laminar conditions. Available estimates show that around 10% of global electric power is consumed for pumping fluids (Frenning , 2001). In addition to the excessive drag levels, fluctuations and alternating shear stresses can also have adverse effects in many enginnering applications. Hence, much effort has been dedicated to develop techniques for turbulence intensity reduction. However, despite many novel and innovative approaches (Brunton , 2015), so far a broadly applicable method remains elusive. Active control techniques require complex actuation devices and in experimental realizations the costs often far exceed the gains. Passive approaches equally suffer from high implementation costs and typically have a limited operation range. Available control techniques are hence problem specific and intrusive, requiring either manipulation of fluid properties or costly and often impractical implementations. Conversely, aortic flow provides an example where a specific propulsion scheme, consisting of impulsive bursts separated by quiescent intervals, appears to hold turbulence at bay despite relatively large peak velocities. Based on this observation, we propose an alternative approach to turbulence control, where drag reduction is achieved using unsteady, pulsatile driving, specifically mimicking the cardiac cycle, and show that the applicability of this method extends to Reynolds numbers well beyond those at which the human heart operates.

2 Methodology and results

We have conducted laboratory experiments and direct numerical simulations on turbulent pipe flow to investigate the drag reduction associated with a pulsatile operation mode under different conditions. In initial experiments and simulations, we tested a cycle consisting of a series of linear flow rate ramps smoothly joined together, corresponding to Re oscillating between $Re_{\min} = 3\,200$ and $Re_{\max} = 18\,800$ with a period $T = 4.5$ s, see Fig. 1 **a**. However, the drag measured in these experiments turned out to be 3% larger than for steady flow, showing that pulsation does not necessarily lead to drag reduction. Inspired by the diastolic phase found in the aortic flow and the low turbulence levels present in these flows, we designed a new cycle where a region of constant Re (rest phase) is inserted that effectively decouples the deceleration from the consecutive acceleration phase (Fig. 1 **b**). Remarkably, the flow responds with considerably lower values of wall shear stress during acceleration, as well as during part of the deceleration phase (Fig. 1 **e**). In this case we obtain a net drag reduction of 22%. However, the additional energy input required to accelerate the flow exceeds the energy savings due to drag reduction. There was however an important difference between this waveform and that of the aortic flow: the studied waveform is characterized by slower deceleration and faster acceleration rates, whereas the opposite holds for velocity waveforms in the aorta (Burk , 2012). Correcting for this, we chose the waveform displayed in Fig. 1 **c**, with a higher acceleration rate, while the rest phase is left unchanged. With this adjustment, drag reduction reaches 27%, while producing a net energy saving of $\sim 8\%$ compared to steadily driven pipe flow.

We have also investigated how changing the acceleration and rest phase affects drag reduction and power savings. To this end, we have carried out a total of 540 experiments spanning different rest phase and acceleration durations, while keeping minimum and maximum *Re* and the period constant. It is found that shorter acceleration times consistently lead to higher power savings, hence suggesting the importance of a brief, intense acceleration followed up by a longer, more gentle deceleration. A non zero rest phase is always required to save power. However, there is an optimal rest phase and longer rest phases are counterproductive. The optimal value of rest phase depends weakly on the acceleration rate and it is approximately equal to half the period. Remarkably, the rest phase in aortic blood flow also matches this criterion.

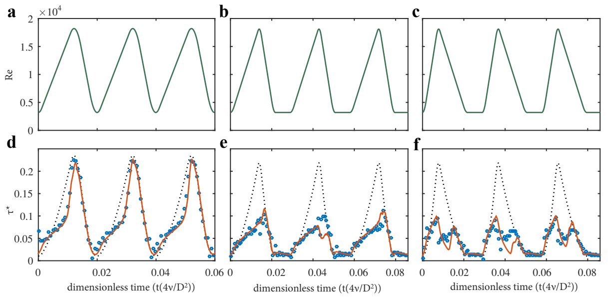

Figure 1: Friction reduction in pulsating flow. Effect of three different cycles on the wall shear stress. **a**, **b** and **c**, Reynolds number modulation imposed in experiments and DNS. **d**, **e** and **f**, corresponding friction dimensionless wall shear stress τ^* for experiments (blue circles) and DNS (red line). For comparison, the friction associated with the quasi–steady flow is shown in the black dotted line given by $\tau_{\text{qs}}(t) = 0.079 Re(t)^{-0.25} U_m(t)^2/U_{\text{min}}^2$ (where the Blasius friction scaling is assumed).

3 Conclusions

We demonstrate that the existence of a rest phase (the diastolic phase) in the waveform of the cardiac cycle is crucial to diminish the wall shear stress and keep it at levels tolerable for the blood vessels' endothelial cell layer. This rest phase has to be optimally timed and combined with a subsquent rapid flow acceleration to not only reduce the flow drag, but to also optimize its efficiency and minimize power consumption. We also show that applying the same waveform to a turbulent pipe flow at significantly larger Reynolds numbers than those at which the cardiac cycle operates also produces significant drag reduction and net power saving. These findings unveil the potential of using a pulsatile operation mode as a drag reduction strategy in pipeline flows.

References

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