GLOBAL AND LOCAL ENERGY DISSIPATION IN TURBULENT VON KÁRMÁN FLOW

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Abstract We use PIV measurements to study local and global energy transfer in a Von Kármán flow. First, we use a Large Eddy Simulation (LES) approximation to model and compute the injected and dissipated power. This procedure involves a free parameter that is calibrated using angular momentum balance [4]. We then estimate the local and global mean injected and dissipated power for several types of impellers, for various Reynolds numbers and for various flow topologies. These PIV-estimates are then compared with direct injected power estimates, provided by torque measurements at the impellers. The agreement between PIV-estimates and direct measurements depends on the flow topology. In symmetric situations, our estimates capture 30 to 70% of the actual energy dissipation. However, our results become increasingly inaccurate as the shear layer responsible for most of the dissipation is approaching one of the impeller, where it cannot be resolved by our PIV set-up. Finally, we show that a very good agreement between PIV-estimates and direct estimates of the dissipated power is obtained using a new method based on the work of Duchon and Robert [1] that generalizes Kármán-Horwath equation to non-isotropic, non homogeneous flows. This method provides parameter-free estimates of the energy dissipation as long as the smallest resolved scale lies in the inertial range.

Understanding how energy is dissipated in turbulent flows has been a great challenge for many years, and would have important implications in many areas such as fundamental research, aeronautics or industry. In the latter, for instance, turbulent flows are used due to their increased mixing properties, and it is important to be able to estimate the global dissipation rate of the flow as well as the local one. Particle Image Velocimetry (PIV) is a powerful tool to achieve these goals. Its interest stems from its ability to measure the instantaneous flow field at many points of a plane (or of a volume) at the same time. From these measurements, estimations of the derivatives of the velocity components $u^i(x^j)$ at these points can be made. As a consequence, PIV allows the computation of tensors such as the large scale rate of strain tensor $S_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i)$, or quantities built from these tensors such as the local dissipation rate $\epsilon = 2\nu S_{ij} S_{ij}$. These features of PIV have allowed it to supersede the two most important methods of point-wise velocimetry, hot-wire anemometry (HWA) and laser-Doppler velocimetry (LDV), and to become the currently dominant method for measuring velocity [8]. Therefore, PIV has been largely used for the past thirty years, and has allowed us to achieve a lot, especially in turbulent flow researches. For instance, the analysis of coherent trailing flow structures of a 1:48 model of the Airbus A340-300 has been carried out in [5], the first experimental observation of nonlinear traveling waves in a turbulent pipe flow was reported in [2], and first spatially and temporally fully resolved data of a flow in a volumetric domain were obtained around a decade ago using time-resolved PIV (see for instance [3]). The implementation of tomographic PIV, which gives us access to the instantaneous 3D velocity field, has revealed that this method is very promising. Indeed, it allows the computation of the nine components of the gradient tensor in the 3D measurement domain, and therefore quantitative estimates of ϵ can be made without having to use any symmetry assumptions. In [7], Tokgoz et al. look into the subject to see whether tomographic PIV measurements allow a good estimation of the energy dissipation rate. They observe that while the laminar flow and Taylor vortex flow regimes appear to be fully resolved, the turbulent flow regime is increasingly under-resolved with the Reynolds number (Re). The explanation is that PIV measurements strongly depend on the finite resolution of the cameras which are used. Indeed, when thinking about a turbulent flow, one has in mind the Richardson cascade of energy picture. Large unstable eddies break up into smaller eddies down to the Kolmogorov length scale $\eta = (\frac{\nu^3}{\epsilon})^{\frac{1}{4}}$ where viscous effects become important and energy is dissipated into heat. As a consequence, if one computes ϵ for various Re, one observes that the accuracy of the computation strongly decreases as Re increases. This is due to the finite resolution of the cameras which does not allow the investigation of small structures down to η. In order to make up for that, techniques borrowed from Large-Eddy-Simulation (LES) are used. This allows us to model the subgrid scales (SGS) in terms of the large scale velocity fields [7, 6].

In this contribution, we use PIV measurements to study local and global energy transfer in a Von Kármán flow. This kind of measurements gives us access to the effective velocity field on a grid that does not resolve the dissipative scale. Therefore, we use a LES approximation to model the influence of unresolved scales. This procedure involves a free parameter which has to be calibrated for our set-up. This is achieved by imposing angular momentum balance at the resolved scale [4]. After deriving an energy balance equation at a fixed scale λ, we proceed to estimate four quantities from our PIV measurements: the local and global mean power injected by the propellers and the local and global mean dissipated power. This computation is performed for several types of impellers, for various Reynolds numbers and for various flow topologies. These PIV-estimates are then compared with direct injected power estimates, provided by torque measurements at the impellers. The agreement between PIV-estimates and direct measurements depends on the flow topology. In symmetric situations, we capture 30 to 70% of the actual energy dissipation. However, our results become increasingly inaccurate as the shear layer responsible for most of the dissipation is approaching one of the impeller, where it cannot be resolved by our PIV set-up. Finally, we explore a new method for PIV estimate of the energy dissipation, based on the work of Duchon and Robert [1] that generalizes Karman-Horwath equation to anisotropic, inhomogeneous turbulence. This method provides parameter-free estimates of the energy dissipation as long as the smallest resolved scale lies in the inertial range. In our set-up, we then obtain a very good agreement between PIV-estimates and direct measurements.

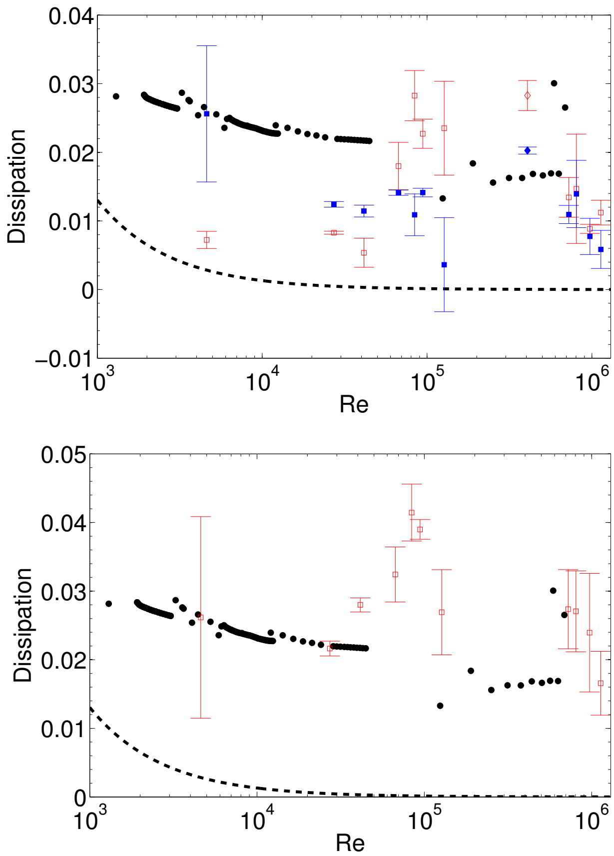

Figure 1. Results obtained by modeling the SGS with LES techniques (top) and by following the work of Duchon and Robert (bottom). On the top, we compare PIV based estimates of energy injection (red symbols) and dissipation (blue symbols) with direct measurements of energy injection obtained using torque measurements (black circles), at various Reynolds numbers, for TM60 (+) (squares) and TP87(+) (diamonds) impellers. The dotted line represents the "laminar fit" $\epsilon = 10Re^{-1}$. On the bottom, we compare the averaged local dissipation $\overline{D_\lambda(\vec{u})}$ (red squares) at scale $\lambda = 0.15$ with direct measurements of the injected power (filled black circles) for TM60(+) for various Reynolds numbers. The estimates are computed based on at least 600 instantaneous velocity snapshots. The error bars are computed using 2 to 15 different realizations of the experiment.

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