

ON DISSIPATIVE STRUCTURES OF STIRRING-GRIDS TURBULENCE

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Summary The spatiotemporal scalar and kinetic energy dissipation rates were measured in a stationary near-isotropic turbulence generated by a pair of vertically stirring grids in a water tank. Results reveal the complexity of dissipative scales containing line, blob, and sheet-like structures at which essentially all dissipations are concentrated. These fine structures are found ranging in scale from 0.4 to 5 Kolmogorov scale, η , with a mean of about 1 and 3 η for scalar and kinetic energy dissipative structures, respectively.

INTRODUCTION

Isotropic turbulence is the simplest turbulence that has long been used in theoretical treatments of turbulence, as a crucial building block for understanding more complex, real turbulent flows [1]. Most experimental studies on isotropic turbulence were conducted in wind and water tunnels, where a mean flow was passed through a grid and turbulence was in a rapidly decaying state. An alternative to water- or wind-tunnel decaying isotropic turbulence was a vibrating-grid turbulence (VGT) created in a water tank by a pair of vertically vibrating-grids, in which a near-isotropic stationary turbulence may be generated in the core region between the two grids [2]. This work presents measurements of kinetic energy (KE) and scalar dissipation rates in VGT flow using a four-dimensional particle image velocimetry (PIV) and a full spatial laser-induced fluorescence technique, so that fine-scale structures can be investigated. Fine-scale turbulence is central to the understanding of turbulent mixing [3]. Ever since 1948, Burgers and Townsend independently proposed three canonical structures of the dissipative scales for the vorticity field in turbulence, the line-like, sheet-like, and blob-like elements, respectively. The line-like and/or sheet-like structures have respectively one major dimension much greater and/or smaller than the other two. There is still no consensus on which canonical structure dominates fine-scale turbulence. For instance, some experiments found that finest scales were more to be line-like than sheet-like in a fully turbulent flow [4], while some reported that the sheet-like structure was the only underlying canonical element of for turbulent flows [5]. Furthermore, direct numerical simulations [6] concluded that the highest values of the vorticity were concentrated in line-like structures in homogenous isotropic turbulence. Hence, there is a need to further study the true dissipative structures, in particular, the full spatial KE dissipation rate field in statistically stationary isotropic turbulence, as the one presented here. We will show and compare the probability density functions of the sizes of both KE and scalar dissipative structures in the VGT flow for the first time.

EXPERIMENTAL

Figure 1 presents the experimental setup, including the VGT apparatus and the associated 4-D PIV arrangements. Vertically vibrating a pair of horizontally-oriented grids in a water tank of an inside dimension of 15x15x30 cm height can generate near-isotropic stationary turbulence in the core region between the two grids, please see [2] for details. The experimental conditions are: the distance between the two grids is fixed to be 10.56 ± 2 cm and the grid stroke, mesh size, and oscillation frequency are set to be $S=2$ cm, $M=3$ cm, and $f=6$ Hz, respectively, yielding a grid turbulent Reynolds number $Re_g=fSM/\nu=3,600$. The method uses a high-speed successive sweeping 5-W Argon-ion laser sheet and two synchronous high-speed stereo CCD cameras (up to 8,000 frames/s) combined with a fast image processing system, so that the underlying full spatial velocity field in near-isotropic region of the VGT flow can be extracted (see Fig. 1), where the seeding particles used are polyethylene with a mean diameter of 15 μm and with a density of 1.03 g/cm^3 . Each measuring image ($1.4 \times 1.2 \text{ cm}^2$) contains 480×420 pixels in which the resolution reaches beyond the local Kolmogorov scale and may resolve the local strain-limited molecular diffusion scale of turbulence. Note that in this work the temporal separation between successive data planes is 4 ms and the spatial resolution is about 29 μm , which are respectively much smaller than the estimated Kolmogorov time (42 ms) and length (0.21 mm) scales. The resulting four-dimensional data can be thus differentiated directly in all three space dimensions and in time to extract the true dissipation rates. Due to the space limit, the reader is directed to [7] for a detailed treatment concerning measurements of the scalar dissipation rate in the same VGT flow.

RESULTS AND DISCUSSION

Figure 1 also shows three typical 3-D velocity maps at three different z positions, where the axes are normalized by the local strain-limited viscous diffusion scale $\lambda_v \approx 5.9 \eta$, the color bar represents the magnitude and direction of z -component velocity, and the reference arrow of 1.44 cm/s that is the energy-weighted r.m.s. turbulent intensity for the VGT flow at $f=6$ Hz [2] is also plotted. Thus, the true KE dissipation rate field can be determined by differentiation of these data planes in all three directions. Figure 2a displays a typical example of a fully resolved three-dimensional ($420^2 \times 210$ pixels) spatial data volume, revealing the kinetic energy dissipation rate field $\epsilon(\mathbf{x}, t) = 2 \nu \mathbf{s} : \mathbf{s}$, where $\mathbf{s} = 0.5(\partial u_i / \partial x_j + \partial u_j / \partial x_i)$ is the strain rate tensor in index notation. A typical scalar dissipation rate field, $\chi = \nabla \zeta \cdot \nabla \zeta$,

is shown on Fig. 2b, where the experimental conditions are the same as Fig. 2a, ζ is the conserved scalar, and ζ_m is the mean value in such data plane. It is found that fine-scale mixing occurs in both sheet-like layers and line-like tubes (roughly circular) for the present VGT flow. The distribution of the dissipation rate field is a highly intermittent phenomenon, in which high dissipation rates occur very infrequently, similar to that found by Sreenivasan & Antonia [3]. Regions of high kinetic energy dissipation rate are well correlated with regions of high principal strain rate. We found that the fine structures of the kinetic energy dissipation rate field in the present VGT flow are complex, containing sheet-like, line-like, and blob-like structures at which all dissipations are concentrated. This result is different from [5] in which only the sheet-like structure is observed in a free shear turbulent jet flow, probably due to different types of turbulence applied. In order to estimate the sizes of these fine structures, we plot only highest values of KE dissipation rate data for $\log_{10} \varepsilon / \langle \varepsilon \rangle \geq 0.66$ (less than 2 % of volume fraction). As can be seen from Fig. 2c, these fine structures are found ranging in scale from 0.4 to 5η with a mean of about 1 and 3η for scalar and kinetic energy dissipative structures, respectively. The important scaling properties of 3-D velocity data are also discussed.

References

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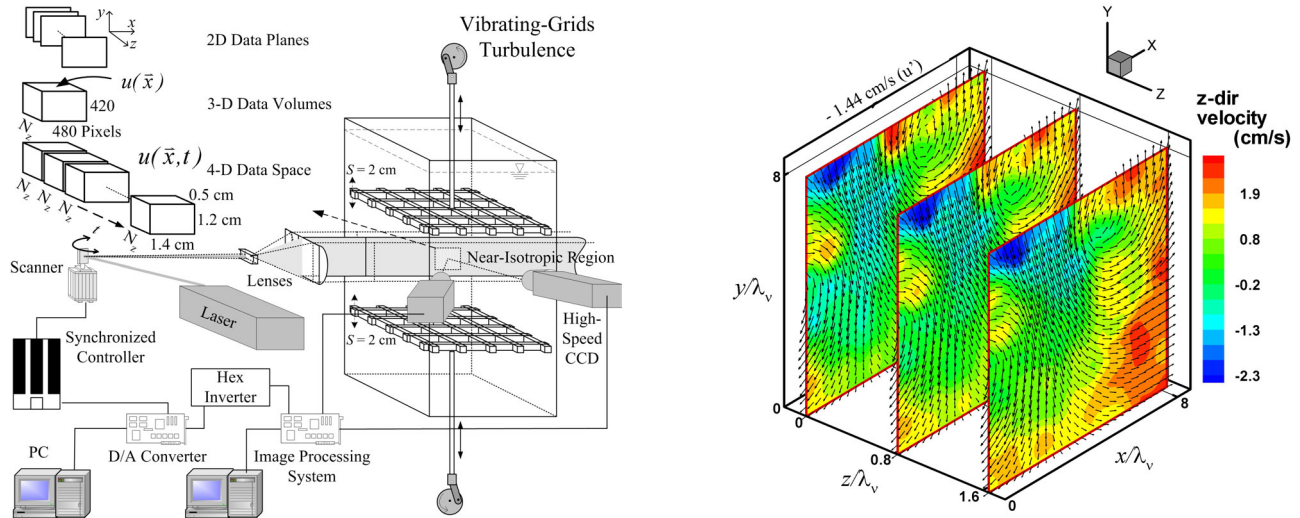


Fig. 1. Schematic of the setup and 3-D velocity maps, where the local strain-limited viscous diffusion scale $\lambda_v \approx 5.9 \eta$ (the Kolmogorov length scale).

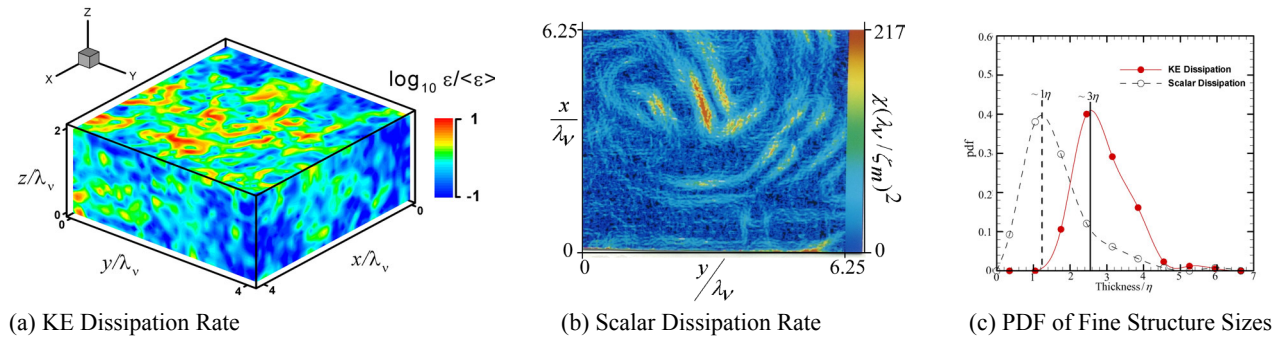


Fig. 2. (a) Typical logarithmic plot of kinetic energy dissipation rate field, where $\langle \varepsilon \rangle$ is the mean kinetic energy dissipation rate averaged from the corresponding data volume. (b) Typical scalar dissipation rate field $\chi = \nabla \zeta \cdot \nabla \zeta$, where ζ is the conserved scalar and ζ_m is the mean value in such data plane. (c) The probability density function of the thickness of both scalar and kinetic energy dissipative structures.