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Estimate of turbulent dissipation in a decaying grid turbulent flow

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ABSTRACT

The dissipation rate of kinetic energy is a key quantity in turbulent flows. The number of measured components and the resolution of the measurement techniques limit dissipation rate estimates; thus, they are derived by surrogates of dissipation. We examine the validity and accuracy of these estimates by investigating decaying grid turbulence using particle image velocimetry and laser Doppler velocimetry. Dissipation rates are computed and compared via three different methods (i) using the decay rate of turbulent kinetic energy, (ii) direct calculation using measured velocity gradients, and (iii) using second and third order structure functions. Discrepancies have been found between the surrogate methods; specifically, the structure function method requires correction terms. The known factors leading to bias are viscous correction which is significant at low Reynolds numbers and inhomogeneity of the decaying flow. Furthermore, we demonstrate inaccuracy in calculations of the third order structure function which are related to inter-scale dependencies. Test procedures are suggested for decaying and inhomogeneous flows to determine susceptibility to these sources of error.

1. Introduction

The dissipation rate of the turbulent kinetic energy ($\varepsilon \equiv 2\nu s_{ij}s_{ij}$, hereinafter is called dissipation for the sake of brevity, s_{ij} is the rate of strain tensor) is a fundamental quantity in the characterization of turbulence. It is essential to estimate or calculate the total dissipation accurately as it represents the total amount of energy loss in a given system. In turbulent flows, the fluctuating part of the dissipation rate is larger than the dissipation rate stemming from the mean flow by several orders of magnitude [1]. The dissipation rate, as it appears in the turbulent kinetic energy equation, is three dimensional, regardless of the quasi-two-dimensional approximation of the mean flow (in flows such as boundary layers, planar jets and wakes, decaying grid turbulence, etc.). There are numerous procedures to estimate turbulent dissipation using experimental tools, which have been extensively reviewed in the handbook of experimental fluid mechanics [2] and in the recent books on turbulence (e.g. [3,4]).

Among the experimental methods the ones of note are those that access turbulent dissipation rate via all of its components, following the definition: $\varepsilon \equiv 2\nu s_{ij}s_{ij}$. These include the three-dimensional hot-wire arrays, e.g. [5,6], and optical methods such as 3D particle tracking velocimetry (PTV) [7], tomographic particle image velocimetry (PIV) [8], holographic PIV [9], scalar imaging [10], among others, e.g. [2]. However, some techniques are limited to moderate Reynolds number (e.g. PTV) or limited due to the lack of spatial resolution (such as the hot-wire technique which is also an intrusive method).

Thus, the majority of experimental data are obtained using tools that are typically limited by resolution either in time or in space or only enable the measurement of partial components of velocity and velocity derivatives. Dissipation rate estimates based on a limited number of components are commonly known as surrogates of dissipation rate; i.e, expressions derived from a set of assumptions relating to the magnitude of the missing components.

Inhomogeneity in turbulent flow has been known to bias estimates of dissipation. For instance, Folz and Wallace [11] measured all of the components of the velocity gradients in the atmospheric boundary layer. The authors estimated various contributions to dissipation rate using multi-hot-wire sensor data and compared three surrogates: (i) $\varepsilon \sim 2\nu\sum_i\sum_j(\partial u_i/\partial x_j)^2$, which ignores inhomogeneous cross products of velocity derivatives, (ii) $\varepsilon \sim 1/\nu\omega_i\omega_j$ and (iii) $\varepsilon \sim 15\nu(\partial u/\partial x)^2$, the isotropic surrogate, where x, u is the streamwise coordinate/velocity respectively, and u_i, x_j are 3D vectors, i.e. $i,j = 1, 2, 3$. The three surrogates were compared to the direct measure of $2\nu s_{ij}s_{ij}$, which showed relatively large discrepancies between the different techniques, pointing out the importance of the inhomogeneous components. Browne et al. [12] used hot-wires to measure squared gradient terms in the cylinder wake. The terms were found to be anisotropic and the isotropic estimate $\varepsilon \approx 15\nu\left(\frac{\partial u}{\partial x}\right)^2$ underestimated the mean dissipation rate by 45 to 80 percent. Balint et al [13] using a nine-sensor hot-wire probe, found that the isotropic estimate is lower by 85–60% in the near

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wall region of the boundary layer, at $y^+ = 11$ and $y^+ = 72$, respectively. Without cross-product terms, values were underestimated by 25% and 10%, respectively. It is noteworthy that the largest error is in the near wall region of boundary layers, close to the viscous sublayer, i.e. a low Reynolds number turbulent flow. This is an important notion for analysis of decaying flows or for flows near solid boundaries, where low velocities are prominent.

De Jong et al. [14] reviewed five (direct and indirect) methods to estimate dissipation in a zero-mean turbulent flow apparatus. The authors recommended use of the second order structure function method, which was found to be most robust and accurate. Direct methods are typically discarded as not accurate and prone to discretization and resolution errors. Lavoie et al. [15] compared PIV results with Hot Wire Anemometry, (HWA) results in decaying grid turbulence at the same range of Reynolds numbers as presented in this manuscript. Their comparison has shown that HWA is more accurate in terms of resolution but with proper corrections, PIV can provide a comparable second order structure function values to meet the ones obtain by the HWA. The immediate output for the end-user is to use PIV with the corrections suggested by the authors [14–16], among others and apply second order structure functions for the estimation of dissipation. The present work adds to this point of view with terms that allow for correction of the bias in inhomogeneous shear flows.

We report on a similar experiment in which a grid turbulence decays in a water channel. We measured the flow using PIV, estimated dissipation using direct and indirect methods and compared with LDV measurements. Our results show that, in order to define dissipation properly, one has to measure the decay of turbulent kinetic energy at several locations and use the power law of decay for the estimation of dissipation rate as a function of streamwise coordinate. Although the direct method compares favorably with the LDV and indirect methods, in high Reynolds number turbulent flows, PIV resolution becomes insufficient and we expect the errors due to interrogation window size and differentiation to become significant. The two-point statistics, such as second-order and third-order structure functions are useful to estimate these types of errors. By applying the kinematic relations (defined by Hosokawa [17]) and conditional averaging, we demonstrate that the results are dependent on the large scale flow. The bias is therefore non-linear and changes with the streamwise distance from the grid, according to the growth of spatial turbulent scales ($L \propto x$) where L is the integral length scale and the decay of turbulent velocity ($u \propto 1/x$).

The objective of this manuscript is to investigate new tools available for the assessment of key quantities in measured turbulent flows, mainly the so-called 'kinematic relations'. In the flow under investigation, we demonstrate that at typical Reynolds number used in water channels past a grid (e.g. Ref. [18]) the flow conditions should not be oversimplified. The presence of both large and small scale dynamics in turbulent flows such as grid turbulence is shown using the kinematic relations. The paper does not solve the problem but presents an additional method to assess the turbulent flow characteristics.

The paper is organized as follows. The experimental facility and methods are outlined in the following Section 2. We present the results regarding the turbulent quantities in the decaying turbulent flow past a grid in Section 3. The analysis of various components and the sources of errors are continued in the framework of kinematic relations in Section 4. Finally, we summarize the main findings and draw some conclusions regarding the applicability of the surrogates in various turbulent flows.

2. Experimental method

Experiments were performed in the water tunnel at the Boundary Layer Wind Tunnel Laboratory of the University of Western Ontario shown in Fig. 1. The facility consists of an inlet reservoir, where water is introduced into the tunnel, followed by a settling chamber consisting of a honeycomb and screens, an 8:1 contraction, the test section, and a 90 degree turn to return the water to the sump through a control valve. The present set-up allows a maximum flow rate of 0.036 m^3/s, with a uniform mean velocity profile (within 1%) and a turbulence intensity of less than 1% in the test section. The length of the test section was chosen to be 10 times the height. The width, W, and height, H, of the test section are 600 mm and 300 mm, respectively.

Measurements were carried out in turbulent flow generated by a square mesh grid interwoven with stainless steel rods of 6.35 mm diameter and a spacing of $M = 25.4$ mm, placed perpendicular to the flow at the beginning of the test section. (The solidity ratio of the grid was 64%). Measurements were made at five locations downstream of the grid (i.e. $x = 100$, 500, 600, 800 and 900 mm) with a mean flow velocity of 0.20 m/s. The flow behind the grid evolves from a highly non-homogeneous velocity field close to the grid where it is generated, to a state where it becomes homogeneous and isotropic (within a close approximation). The dissipation rate estimate at the closest measurement point, $x = 100$ mm, is in the developing region and we disregard it from the analysis in the following sections. All the results will be presented for the streamwise locations associated with the developed decaying grid flow, namely at 500, 600, 800 and 900 mm.

Measurements were conducted using Particle Image Velocimetry (PIV). The measured field of view was in the center of the water tunnel, in the streamwise-wall normal plane, where for each streamwise location, the system was traversed. The PIV system used for the current study makes use of a double pulse Nd:YAG laser operating at 15 Hz with energy of 120 mJ/pulse that produces a sheet of light at a wavelength of 532 nm illuminating a flow field that is seeded with Silicon Carbide particles with an average diameter of 2 μm and a density of 3200 kg/m^3. Despite the density difference, the particles are small enough to follow the water flow, fulfilling the requirements suggested by Melling [19]. The scattered light from the particles is collected into a CCD camera located 90 degrees to the light sheet. The CCD has a pixel array of $1600 \times 1200$with a dynamic range of 12 bits operating in double exposure mode. The time interval between two sequential images was set to be 2.5×10^{-3} sec. During each PIV experiment 4000 images were acquired per batch resulting in 2000 vector maps. The cross-correlation analysis was performed using OpenPIV (http://www.openpiv.net, Taylor et al. [20]) for interrogation windows of 32×32 pixels with a 50% overlap. Special filters such as mean, standard deviation and local median, removed the erroneous vectors. In total, about 5% of the vectors were removed.

To complement the PIV results and verify the estimate of the dissipation rate, we have used a single component Laser Doppler Velocimetry (LDV) system operated in back-scatter mode. The transmitting lens had a focal length of 350 mm in air, resulting in a measuring volume diameter and length of 0.046 mm and 1.2 mm, respectively. A two-axis motor, driving the traversing unit, was used to move the LDV probe in two directions. The flow was seeded using the same particles as for the PIV.

3. Results

3.1. Dissipation estimate based on energy decay

This section describes the various estimates of the dissipation rate in the decaying turbulent flow past a grid. The results are given at the four streamwise locations ($x = 500$, 600, 800 and 900 mm from the grid).

The equation of turbulent kinetic energy transport as derived from the Navier–Stokes equations is (see e.g. [1]):