Nonequilibrium dissipation scaling in fan–array–generated uniform and uniform-shear turbulence

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We investigate dissipation scaling in fan-array-generated turbulence under controlled mean-flow conditions. Experiments are performed using a wind generator driven by an 8×8 array of 64 counter-rotating fans with row-wise pulse-width modulation (PWM) control, which enables repeatable realization of two canonical configurations: nominally uniform mean flow and nominally uniform shear flow. Hot-wire anemometry is used to obtain turbulence statistics, including the Taylor-scale Reynolds number Re_λ and the nondimensional dissipation rate C_ε. To go beyond global long-time-averaged measures, we apply a short-time local analysis to the velocity records and evaluate C_ε within local subensembles. When the streamwise root-mean-square (r.m.s.) velocity fluctuation is used as the velocity scale, the global and local results in both configurations exhibit decreasing trends of C_ε with increasing Re_λ that are broadly consistent with an inverse-Reynolds-number dependence. In the nominally uniform-flow configuration, this local tendency is more apparent upstream and weakens downstream, whereas in the nominally uniform shear-flow configuration it shows weaker streamwise variation. For the shear flow, however, an additional normalization based on the approximate turbulent kinetic energy produces a similar decreasing global trend but a substantially weaker local dependence on Re_λ. These results show that fan-array forcing enables systematic comparison of dissipation behavior across mean-flow configurations, while also demonstrating that local conditional scaling in anisotropic shear turbulence can be sensitive to the velocity scale used for normalization.

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I. INTRODUCTION

Turbulence is ubiquitous in both engineered and natural environments, from the flow around ground vehicles to riverine and atmospheric motions. Tightening energy-efficiency requirements in transportation and the rapid growth of small unmanned aerial vehicles (e.g., drones) have further increased the demand for predictive, quantitative descriptions of turbulent flows.

Wind-tunnel experiments remain a cornerstone for meeting this demand because they offer repeatability and well-controlled boundary inputs. A common route to laboratory turbulence is to place a passive grid in the flow; however, classical grid turbulence provides limited control over the achievable turbulence intensity and integral length scale. To broaden the accessible parameter space, several actively forced generators have been developed. Gad-el-Hak and Corrsin[1] enhanced turbulence production by injecting streamwise jets from the grid elements, and Makita[2] introduced an active grid capable of producing substantially larger intensities and scales. Besides grid-based generators, alternative concepts have also been explored. A notable early example is the multiple-jet "Porcupine" turbulence generator proposed by Betchov,[3] which generated approximately homogeneous turbulence through the interaction of many small jets. Unlike this fixed-jet configuration, modern fan-array facilities allow the output of each actuator to be controlled independently, enabling both the mean-flow profile and the turbulence characteristics to be prescribed. Building on these concepts, a complementary family of facilities drives the flow itself using arrays of jets or fans, including multijet wind tunnels[4–6] and multifan wind tunnels and wind generators.[7–15] These independently controlled systems offer two key advantages for turbulence research: they can prescribe the mean flow (e.g., nominally uniform or nominally uniform shear profiles) while simultaneously tuning the spatio-temporal characteristics of the imposed forcing. Data-driven control strategies have recently been shown to enable fan-array wind tunnels to reproduce prescribed target flow fields with high fidelity, thereby expanding their applicability beyond conventional turbulence generation.[16] Fan-array wind generators have also been increasingly employed to generate flows with prescribed spatial and temporal variations through independent fan control and have demonstrated their capability for advanced aerodynamic and turbulence studies.[11–17] These advances highlight the rapid evolution of fan-array facilities into versatile platforms for turbulence generation, flow control, and aerodynamic testing.[18]

From the viewpoint of turbulence measurements, a practical concern in fan-driven facilities is the swirl and secondary motion imparted by the rotors, which can distort the mean flow and introduce additional inhomogeneity. In the present generator, we adopt counter-rotating fan units (front and rear rotors rotating in opposite directions)[14,15] as a hardware-level mitigation. Although the degree of swirl reduction depends on operating conditions and array interactions, counter-rotation is expected to reduce the net angular-momentum content of the discharged flow and to promote a more rectilinear mean streamwise motion. This provides a cleaner baseline for turbulence measurements and enables more direct comparisons of how turbulence statistics respond to changes in mean-flow configuration and actuation protocol.

Motivated by this capability, we focus on a central quantity in turbulence phenomenology and modeling: the viscous dissipation rate and its scaling. We consider the nondimensional dissipation rate

$$C_\varepsilon = \frac{\varepsilon L}{u_{\mathrm{rms}}^3}, \tag{1}$$

where ε is the viscous dissipation rate of turbulent kinetic energy, u_{rms} is the root-mean-square (r.m.s.) velocity fluctuation, and L is a large-eddy length scale, taken here as an integral length scale. Under the equilibrium hypothesis that the interscale energy flux balances viscous dissipation, C_ε is expected to be approximately constant at sufficiently large Reynolds numbers.[19–21] Wind-tunnel experiments, however, have shown that this constancy can break down in spatially developing turbulence, yielding nonequilibrium regions where C_ε varies systematically.[22–25] In particular, grid-generated turbulence in the initial decay region often follows the empirical scaling

$$C_\varepsilon \propto \frac{Re_0^{m_p/2}}{Re_\lambda^{n_p}}, \tag{2}$$

where both m_p and n_p are approximately unity. Here, Re_0 is a Reynolds number set by the inlet/initial conditions, and $Re_\lambda = u_{\mathrm{rms}}\lambda/\nu$ is the Taylor-scale Reynolds number, where λ is the Taylor microscale and ν is the kinematic viscosity. Recent developments further emphasize that nonequilibrium behavior may be obscured by global averaging: Zheng *et al.*[26,27] showed that *local* (short-time-averaged) estimates of C_ε from hot-wire records can exhibit nonequilibrium scaling even when the *global* (long-time-averaged) C_ε appears nearly independent of Re_λ. This finding has also been confirmed by direct numerical simulation

(DNS) of temporally developing grid turbulence[28] and compressible homogeneous isotropic turbulence.[29]

These findings raise a key question: how robust are nonequilibrium dissipation laws when the mean-flow configuration and turbulence-production mechanism are altered? Multifan facilities are well suited to address this question because they enable systematic changes in imposed mean flow and actuation protocol within a single facility while maintaining comparable measurement conditions.[7,8] In the present work, we build an unsteady multi-fan wind generator and first establish its baseline performance in steady operation. We then realize two canonical steady configurations—a nominally uniform flow and a nominally uniform shear flow—and measure turbulence statistics by hot-wire anemometry. Building on these data, we evaluate ε and examine the scaling of C_ε, with particular attention to nonequilibrium behavior reported for grid turbulence[22,23] and to the local-analysis framework of Zheng *et al.*[26,27] By comparing the streamwise evolution of C_ε evaluated globally and locally for the two configurations, we assess whether nonequilibrium dissipation scaling is universal or flow-dependent in a multifan-generated environment. Finally, we outline how the same facility can be operated with explicitly unsteady actuation to examine how imposed mean-flow unsteadiness further modifies dissipation scaling.

The remainder of the paper is organized as follows: Sec. II describes the multiple-fan wind generator, operating protocols, and measurement and data-reduction procedures; Sec. III presents the mean-flow characterization, turbulence statistics, energy spectra, and the global and local analyses of dissipation scaling; and Sec. IV summarizes the principal conclusions and outlines directions for future work.

II. EXPERIMENTS

The multiple-fan wind generator comprises 64 counter-rotating fans arranged in an 8×8 array. Each fan is a SANYO DENKI 9CRA0812P8G001 unit with outer dimensions of $80 \times 80 \times 80$ mm^3. The center-to-center distance between adjacent fan rotation axes is 0.10 m; following the conventional notation used in grid-generated turbulence, we denote this characteristic fan-to-fan spacing by M. The coordinate system is defined as shown in Fig. 1(a): x denotes the streamwise direction, y the spanwise direction, and z the vertical direction. The origin of x is located at the fan outlet plane, and the origins of y and z are