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Turbulent wake of a fractal square grid: effects of the fractal iteration

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Abstract

Fractal square grids, consisted of the basic square pattern, have been used as a passive flow control strategy for enhancing fluid mixing and convective heat transfer. While previous studies have established that the largest scale being dominant in affecting the turbulence enhancement, effects of the smaller scales and the interaction of the range of scales on the generated turbulent flow remain unclear. This work is to determine the relationship between the fractal iteration N and the turbulence statistics of the wake using water-tunnel experiments. Systematic measurements of velocity fields of the wake generated by fractal square grids with increasing number of scales (N = 1, 2, 3, and 4) are obtained by a planar Particle Image Velocimetry (PIV) at the Reynolds number of 3400. Results reveal fundamental flow structure that are of importance to enhance turbulence level. Multiple scales, including the smaller fractal scales, play significant role in this process.

1 Introduction

A fractal consists of self-similar patterns superimposed at different length scales (Debnath 2006). The length scale is often reduced by a fixed ratio from the parent to the child generation, thus maintaining self-similarity. Many multi-scale objects of a complex appearance, such as branching pulmonary network and corals in biology, river network, a tree, and cumulus clouds in geophysics, as well as large-scale structure of the universe in astronomy, are either fractals or fractal-like. While having multiple length scales, several fractals can be fully described by simple recursive mathematical expressions (Hurst and Vassilicos, 2007), making them elegant tools for fundamental studies.

Fractal grids have been adopted as a passive flow control strategy to enhance fluid mixing and convective heat transfer, which remains a topic of great interest due to the high demand for effective and efficient flow-control devices. The fractility of such grids generates vortices of different sizes that interact at different locations downstream of the grid. Furthermore, the set of geometric parameters of the fractal grid can be purposely tuned to alter the location and magnitude of the peak turbulence intensity (Mazellier et al. 2010), thus making the fractal grids attractive for highly controlled mixing and heat transfer. Fractal grids have been recently used to renovate the design of wind fences, heat exchanger fins, and low-swirl combustion chambers (Goh et al. 2013, Verbeek et al. 2015, McClure et al. 2017).

Extensive experiments and numerical simulations have been carried out over the last decade to understand the fractal grid-generated turbulence. It is well recognized that the location and magnitude of the peak turbulence intensity, closely related to the largest bar length L_0 and largest bar thickness t_0. However, it is still unclear how significant the additional scales in modifying the fractal grid-induced turbulence. The present research aims to understand how the multiple scales of a fractal square grid influence the flow structure, turbulence statistics using a set of fractal square grids (with iterations N = 1, 2, 3 and 4), with the largest bar dimension being constant. This allows for the effects of additional fractal scales associated with successive fractal iteration to be evaluated.

2 Experiments

A set of fractal grids (FGs) are examined in this study: a single square grid FG1 (N = 1), a fractal square grid of four iterations FG4 (N = 4), and intermediate configuration FG2 and FG3 (N = 2, 3), as shown in Figure 1. Measurements of the turbulent flow induced by a fractal square grid are conducted using a two-dimensional two-component (2D2C) planar PIV system (Lavision, Göttingen, Germany). Experiments were performed in a recirculating water tunnel with a test section of 0.3 m (W) x 0.3 m (H) x 2.0 m (L) at the Mechanical Engineering Department, Cleveland State University.

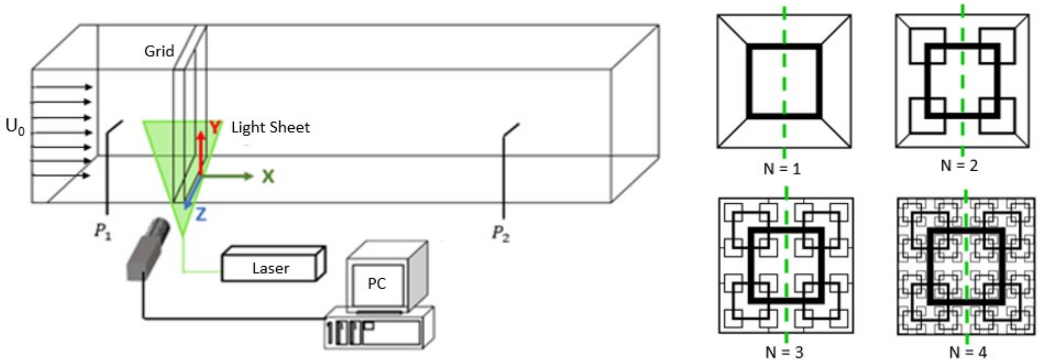

Figure 1: Experimental setup (left) to measure the wake behind the four fractal square grids (right). The green vertical line marks the measurement plane of PIV tests.

3 Results

The instantaneous velocity fields of turbulent wake shows a characteristics of jet flow in the center plane, of which the length scale is associated to the largest bar (Fig. 2). Several typical flow regions are identified: jet, wake (reversed flow), and shear layers in between. The distribution of each flow feature is directly related to the number of length scales of the grid, with a bar causing a wake and an opening (space between the bars) causing a jet. The high-velocity jet region is extended as the fractal iteration increases from 1 to 4. Figure 2 also show that the division between the major jet flow and two adjacent wakes becomes more visible as additional fractal scales are added (from FG1 to FG4). A shear layer of steep velocity gradient occurs between the jet and wake region, which drives a significant increase in the momentum transport between these regions.

The change in the flow structure by the addition of multiple scales highlights the significance of interaction of the multiple scales, which is expected to affect the turbulence statistics, responsible for enhanced turbulent mixing and heat transfer rate. Clear differences are observed in the turbulence intensities, including smaller scales gradually by systematically changing the iteration N (Fig. 3). The high T_u immediately behind the grid displays an elongated trend as smaller scales present and interaction of multiple scales occur. Most distinctly, the centerline T_u increases downstream of the grid at a different rate: at X/H = 1, sharing a very similar T_u level of 5% but at X/H = 3 the T_u reaches different level of 12.5% (FG1), 13.5% (FG2) and 20% (FG4).

A proper orthogonal decomposition or POD analysis is carried out for the 1500 snapshots of the streamwise velocity fields. The first spatial mode, as shown in Figs. 4 and 5, indicates that high energy content exists very close to the grid for FG1, but shifts downstream for multi-scale fractal grids. Especially, tremendous amount of energy appear at X/H = 3-5 for both FG3 and FG4. In the case of the

FG4, the lowest contribution to the total energy is in the near wake while the contribution downstream at positions 4 - 7 is much higher. This is well aligned with the contour distribution of the streamwise turbulence intensity, shown in Fig. 3, of low level of turbulence close to the grid and the progressive intensifying of the turbulence further downstream, owing to the interaction of the multi-scale wakes.

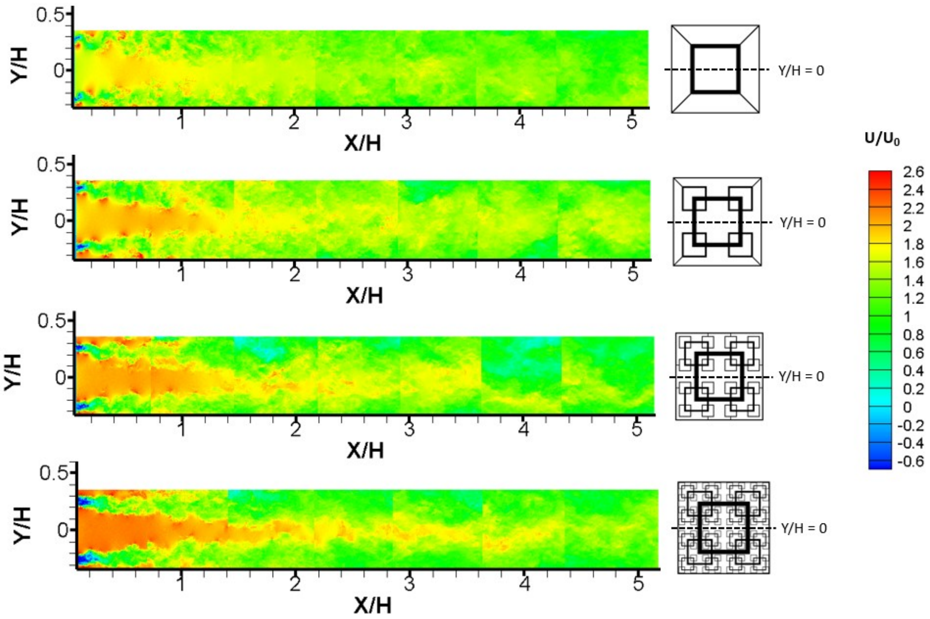

Figure 2: The instantaneous stream-wise velocity contours downstream of a fractal square grid in the center plane. FG1, FG2, FG3 and FG4 from top to bottom.

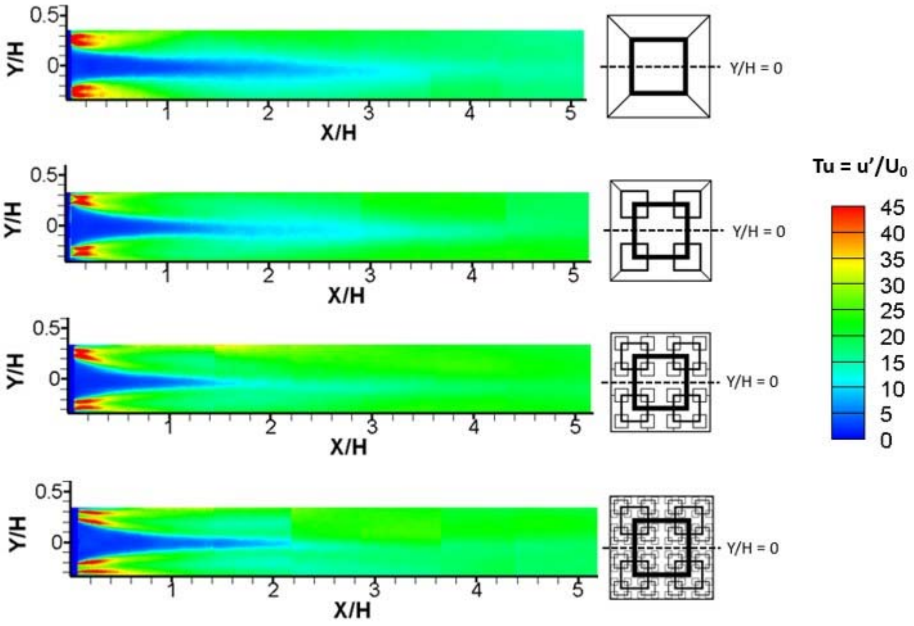

Figure 3: Streamwise turbulence intensity T_u (%) downstream of a fractal square grid at Re = 3400. FG1, FG2, FG3 and FG4 from top to bottom.

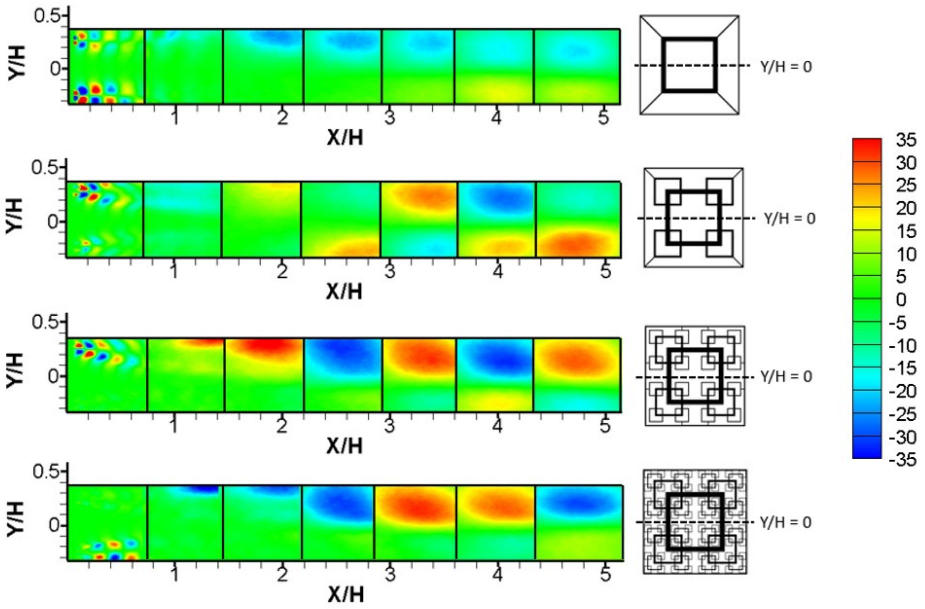

Figure 4: First spatial mode of the streamwise velocity fluctuations at Re = 3400. FG1, FG2, FG3 and FG4 from top to bottom.

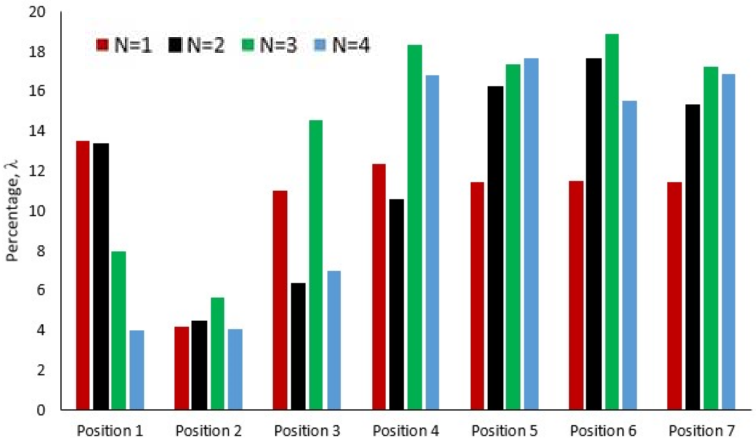

Figure 5: Energy variance of mode 1 of the streamwise velocity fluctuations at Re = 3400. FG1, FG2, FG3 and FG4 from top to bottom.

4 Conclusion

A set of fractal square grids are tested in water-tunnel experiments at Re = 3400, to determine the effects of the multiple fractal scales. Detailed flow fields reveal the multiple jets, wakes and the shear layers in between, produced by the multiple scales of bars, are the fundamental flow physics that promote momentum transport in the fractal grid generated turbulence. The spatial distribution of turbulence intensities and the POD analysis suggest important effects of the additional fractal scales along with the largest scale. Further work will intent to incorporate the scale effects into analytical models, such as the wake interaction length scale model. Understanding the role that multiple length scales have in momentum and energy transport is essential for effective utilization of fractal grids in a wide variety of engineering applications. Owing to the high demand of flow control strategy, this work can potentially benefit a wide variety of applications where energy efficient mixing or convective heat transfer is a key process.

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