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Experimental investigation of wake flow field and wind comfort characteristics of fractal wind fences

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ABSTRACT

Wind fences are frequently utilized in many areas from agriculture to traffic safety in order to provide a sheltered region behind. The conventional geometry of wind fences are usually porous with circular or rectangular holes. Recent studies on fractal/multiscale grid geometries, i.e. a geometry that consists of smaller scales that are copies of the whole, show interesting results, indicating a potential towards using these types of grids as wind fences. Thus, the main purpose of this study is to investigate the performance of fractal grids as wind fences. For this purpose, four different types of wind fences, three of which have fractal grids, all having the same porosity ratio of 40%, are tested in a wind tunnel. Results of the two-dimensional PIV measurements downstream of each fence are presented. Comparisons of the details of the wake flow structure as well as quantitative comparisons of wind comfort and shelter characteristics up to 10H downstream of fences, where H is the fence height, are also presented. Results show that the jet-wake-wall interactions within the near wake of the fences have a major impact on wind comfort characteristics further downstream. These interactions can potentially be manipulated by custom designing fractal grid fences based on given wind comfort requirements in order to obtain required mean flow and sheltering characteristics.

1. Introduction

Any natural or artificial obstructions that result in a reduction of wind velocity and provide a sheltered region behind are defined as wind barriers or fences. Wind fences are frequently utilized in many different areas. In agriculture, for example, wind fences are used for controlling wind conditions at specific areas in order to produce an appropriate microclimate (Baltaxe, 1967), (Hagen et al., 1981). Likewise, in coal or aggregate piles, wind fences can help to decrease the amount of wind-blown particles (Lee and Kim, 1999; Santiago et al., 2007). Traffic safety is another area where the use of wind fences is crucial. They not only reduce the sand or snow drifting in highways (Dong et al., 2004; Dong et al., 2007), but also improve traffic safety by reducing the transverse wind velocity at bridges and viaducts (Charuvisit et al., 2004; Kozmar et al., 2014; Wium, 2005).

From an aerodynamic point of view, the mechanism of the sheltering effect is straight forward for wind fences (RaineStevenson, 1977). According to Raine and Stevenson (Heisler and Dewalle, 1988), the sheltering effect is due to the drag force exerted by wind fences, which causes a loss of momentum in the flow. Although the working principle is simple, the resultant flow patterns can be quite complicated due to the turbulent wake downstream of the fences. When the range of Reynolds number is considered for a typical wind fence under daily wind conditions, the most important parameter which dominates the characteristics of the wake flow as well as the efficiency of the fence is the porosity ratio, i.e. ratio of the open area to the total area of a wind fence (Heisler and Dewalle, 1988; Perera, 1981). When there is no porosity, in other words when the fence is solid, the sheltered area behind the fence rapidly diminishes even though solid fences perform better than porous fences in terms of wind speed reduction. (Dong et al., 2007; RaineStevenson, 1977; Wilson, 1987; Wu et al., 2013). Moreover, sand accumulation at the windward side of the fences can be considered as another problem for solid fences (Dong et al., 2006). Because of these reasons, the majority of the studies on wind fences focus on porous ones.

The shape of holes and porosity ratio alter the behavior of the flow at the leeward zone of the fence. The optimum porosity ratio of a wind fence can differ depending on the requirements of the application area. If the main purpose of the wind fence is wind speed reduction within a long

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Nomenclature

CSG	Conventional Square Grid
D_f	Fractal dimension
FSG	Fractal Square Grid
FIG	Fractal I Grid
FRIG	Fractal Reverse-I Grid
H	Height of the wind fence
k	Turbulent kinetic energy
L_0	Maximum bar length in fractal grid (bar length of the 1st iteration)
L_1	Bar length of the 2nd iteration in fractal grid
L_2	Minimum bar length in fractal grid (bar length of the 3rd iteration)
N	Number of successive iterations
PIV	Particle Image Velocimetry
$Rc_{\Delta x,y}$	Wind speed reduction coefficient
R_L	Ratio of successive bar lengths
R_t	Ratio of successive bar thickness
t_0	Maximum bar thickness in fractal grid (bar thickness of the 1st iteration)
t_1	Bar thickness of the 2nd iteration in fractal grid
t_2	Minimum bar thickness in fractal grid (bar thickness of the 3rd iteration)
t_r	Ratio of thickest to thinnest bar thickness
t_p	Thickness of perimeter
$u_{\Delta x,y}$	Time-average wind speed in the disturbed flow caused by the fence
$u_{0\Delta x,y}$	Time-average wind speed in the absence of fence
U_0	Mean streamwise velocity in the absence of fence
U_∞	Free-stream wind velocity
u	Mean streamwise velocity (along x direction)
v	Mean transverse velocity (along y direction)
β	Porosity Ratio (%)
δ	Boundary layer thickness
Ψ	Shelter parameter
Ω_Z	Mean out-of-plane vorticity

region in the leeward zone, the porosity ratio of the fence can be in the range of 20%–35% (Cornelis and Gabriels, 2005). Porosity ratio between 30% and 40% effectively reduces the wind induced erosion as presented in (Dong et al., 2006). Lee and Kim (1999) showed that a fence with 40% porosity ratio revealed desired wind flow characteristics in terms of wind speed reduction and level of turbulence intensity.

In the literature, majority of studies examined porous wind fences with conventional geometries with square, rectangular or circular holes. On the other hand, recent studies on fractal/multiscale grids show interesting results, which indicate a sign of potential towards using these types of grids as wind fences. Here, fractal geometry implies a geometry that consists of small scales or copies of the whole. Fractal objects are being intensively studied because they allow the control of turbulence generation by just altering their geometrical properties (Staicu et al., 2003; Hurst and Vassilicos, 2007; Gomes-Fernandes et al., 2012). One important characteristics of the fractal grid generated turbulence is that it introduces a variety of length scales to the flow (Nedić et al., 2012). While regular grids create uniform wake patterns and scales, fractal grids create different scales of wakes which meet at different downstream distances (Laizet and Vassilicos, 2012). This causes an increase in turbulence intensities and a rapid recovery of pressure in the case of regular grid turbulence. For space filling fractal square grids, on the other hand, there exists a much longer pressure recovery and a much slower turbulence decay (Laizet and Vassilicos, 2012).

In a study by Hurst and Vassilicos (2007) three different types of fractal grids with cross, I, and square patterns were examined. The study revealed that such fractal grids can be designed to generate flows with high pressure drop and low turbulence intensity or just the opposite (Hurst and Vassilicos, 2007; Laizet and Vassilicos, 2009; Gomes-Fernandes et al., 2012). Fractal geometries that generate high turbulence intensity are mainly used for increasing the efficiency of mixing and burning in combustion chambers (Soulopoulos et al., 2013; Sponfeldner et al., 2015), whereas fractal grids designed to have low turbulence intensity are mainly used for decreasing acoustic noise in spoilers (Nedić et al., 2012) and fractal wind fences (Keylock et al., 2012; Mcclure, 2016).

Aforementioned characteristics of fractal grids offer many advantages to be also used as wind fences. Keylock et al. (2012), investigated the wake flow of 1D multiscale fractal fences and compared the results with the conventional ones with the same porosity ratio. They stated that in addition to height, bottom gap, and porosity ratio, the arrangement of the fractal struts have an important effect on the turbulence characteristics of the wake flow behind the wind fences. McClure (Keylock et al., 2012) conducted an experimental study on turbulent flow induced by two different fractal wind fences one of which is the replica of the 1D fractal fence used in Keylock's study and the other one is a 2D multiscale fence very similar to the cross fractal grid presented in Vassilicos's study (Hurst and Vassilicos, 2007). McClure showed that 2D fractal fence was the most

(a) (b)

Fig. 1. Wind tunnel facility used in the experiments.

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