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Modelling and predicting wind velocity patterns for windbreak fence design

Se-Woon Hong [a], In-Bok Lee [b,*], Il-Hwan Seo [c,*]

[a] Department of Biosystems, Division M3-BIORES: Measure, Model & Manage Bioresponses, KU Leuven, Kasteelpark Arenberg 30, 3001 Leuven, Belgium
[b] Department of Rural Systems Engineering and Research Institute for Agriculture and Life Sciences, College of Agricultural and Life Sciences, Seoul National University, 599 Gwanangno Gwanakgu, Seoul 151-742, Republic of Korea
[c] Research Institute of Green Eco Engineering, Institute of Green Bio Science and Technology, Seoul National University, 1447 Pyeongchang-daero, Daehwa-myeon, Pyeongchang-gun, Gangwon-do, 232-916, Korea

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ABSTRACT

The use of windbreak fences has become a common practise to reduce wind erosion and dispersion of soil particle or spray-drift in potentially risky areas. For effective and economical use of windbreak fences, this paper introduces regression equations to predict wind speed reduction by windbreak fences based on their screen porosity, fence height and wind speed. The prediction equations provided straightforward procedures to predict the effects of a single fence and multiple-fence arrays. The equations were developed by non-linear regression analysis based on data obtained from computational fluid dynamics simulations, which were validated in advance by wind-tunnel tests and experimental data of literatures. The prediction equations, derived by a genetic algorithm, for a single fence showed good agreement with the simulation results, with $R^2 = 0.99$. The equations for multiple fences were derived from the product of the equations for a single fence and also showed good agreement with the simulation results.

1. Introduction

1.1. Motivation

A windbreak is any structure that provides a shelter effect by decreasing the wind speed near and behind the structure (Santiago et al., 2007). Windbreaks have been used for many years as a wind-erosion control measure against losses of valuable loam and nutrients in agricultural land and dispersion of eroded particles, dust and spray drift to nearby habitation (Alhajraf, 2004; Mercer, 2009; Hong et al., 2014). They have been mostly used in the form of natural vegetative barriers against wind (Cornelis and Gabriels, 2005). However, designing vegetative barriers can be difficult because of the characteristics of vegetation that cannot be easily controlled, such as plant conformation, rigidity, leafiness, leaf and stem shape, and density distribution (Bilbro and Stout, 1999). In addition, plant characteristics are not homogeneously distributed and change with time. Therefore, non-vegetative barriers have also been studied to provide more rapid and reliable shelter effects (Grantz et al., 1998). One applicable non-vegetative barrier is porous fences, which are windscreen fences or windbreak fences defined as artificial barriers, synthetic or mechanical, that obstruct wind flow (Cornelis and Gabriels, 2005). With regard to industrial use, windbreak fences have been used in open coal yards to reduce wind-blown particle emissions to the environment by effectively decreasing the wind force (Cong et al., 2011; Park and Lee, 2002), and in a huge tract of reclaimed land to prevent the generation and diffusion of dust from dry land (Bitog et al., 2009). However, the results of most studies were suited to a specific problem and provide limited information on the various uses of windbreak fences.

1.2. Literature review

The efficiency of windbreak fences in terms of wind speed reduction is determined by various factors, such as fence porosity, porosity distribution, fence height and wind velocity. If more than two fences are installed, the spacing between fences is also an important factor. Fence porosity, defined as the simple ratio between the perforated area and the total area of the fence screen, is generally considered the most influential factor in the flow pattern and wind speed reduction behind a windbreak fence (Perera, 1981; Bitog et al., 2012). A dense screen, i.e., with low porosity, reduces wind speed behind a windbreak fence but creates a strong circulating flow behind the fence. In contrast, a fence with higher porosity, which Perera (1981) and Baltaxe (1967) suggested as 0.30 and 0.35, respectively, is not considered to make

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* Corresponding authors.
E-mail addresses: iblee@snu.ac.kr (I.-B. Lee), ilhwan.seo1228@gmail.com (I.-H. Seo).

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circulating flow zones but reduces the wind speed less. Many studies have been conducted on windbreak flow with respect to the fence porosity through both experiments and numerical simulations and found that porosity between 0.2 and 0.5 generally gave the maximum shelter over the longest leeward distance (Wilson, 1985). Santiago et al. (2007) determined the porosity of 0.35 as an optimum value. Cornelis and Gabriels (2005) concluded that the optimal porosity was from 0.20 to 0.35. Raine and Stevenson (1977) obtained an optimal porosity of 0.2–0.3 through their wind tunnel experiments but suggested a higher porosity of 0.5 when the fence height extended to 3 m high. In some simulation studies using Reynolds-averaged Navier–Stokes (RANS) equations for windbreak modelling, Santiago et al. (2007) proposed to link the fence porosity with resistance coefficients that expressed a pressure drop due to the presence of a porous fence. The relationship $C_{ir} = \left(1/C_d^2\right)(1 - \quad ^2)/ \quad ^2$ can be used to estimate the pressure loss $\left(\quad P = C_{ir}\frac{1}{2} \quad V^2\right)$ by a screen with a porosity of , where C_{ir} is the pressure loss coefficient or inertial resistance coefficient, V is the fluid velocity perpendicular to the screen,   is the fluid density, and C_d is the discharge coefficient for the screen (Perry et al., 1997). Because the discharge coefficient is given as a function of the screen's Reynolds number, the pressure loss due to the screen varies with not only the screen porosity but also with the fluid velocity and cross-sectional shape of the wires (Heisler and Dewalle, 1988). Therefore fences with the equal porosity may have different pressure loss values and the pressure loss coefficient would be a more intuitive and obvious way to represent the aerodynamic characteristics of the porous fences.

The flow patterns behind the windbreak fence are described by the Navier–Stokes equation, whose general form is shown in Eq. (1).

$$\frac{Du}{Dt} = - \quad\quad p + \quad ^2u + \quad f + S_u \tag{1}$$

The terms of Eq. (1) can be changed into non-dimensional forms, such as $u = \frac{u}{U}$, $p = p\frac{1}{\quad U^2}$, $f = f\frac{D}{U^2}$, $\frac{\quad}{t} = \frac{D}{U}\frac{\quad}{t}$, $\quad = D \quad$ and $S_u = \frac{1}{\quad DU}S_u$, and the relationship $\frac{\quad DU}{\quad} = Re$ can be applied to the equation. The non-dimensional form of the Navier–Stokes equation is shown in Eq. (2).

$$\frac{Du}{Dt} = - \quad p + \frac{1}{Re} \quad ^2u + f + S_u \tag{2}$$

In this equation, u is the fluid velocity field (m s^{-1}), p is the pressure field (kg m^{-1} s^{-2}),   is the fluid density (kg m^{-3}),   is the fluid viscosity (kg m^{-1} s^{-1}), t is the time (s), f is the body force per unit mass (m s^{-2}), S_u is the source term (kg m^{-2} s^{-2}) that corresponds to the pressure loss by the screen in this study, Re is the Reynolds number, U is the mean velocity, D is the characteristic length (m) that corresponds to the fence height in this study, and the primes ( ) indicate the non-dimensional form of the properties.

When the body force is neglected ($f = 0$), the non-dimensional flow patterns, which indicate the fluid velocity field and pressure field, u and p, are affected by the Reynolds number and the source term. The source term indicates the effect of fence porosity as mentioned earlier. Therefore, another important factor in the flow pattern and wind speed reduction behind a windbreak fence is the Reynolds number. The fence Reynolds number, which is obtained by substituting the fence height for the characteristic length, is determined by the fence height and wind speed. Therefore, the product of fence height and wind speed is significant to determining the flow pattern. However, there have been some conflicting results on the effect of fence height and wind speed. Fence height was considered to be a scale factor in many studies because the extent of windbreak effects was known to be proportional to the fence height (Plate, 1971). This is theoretically true when the wind speed is properly adjusted. Unless the fence Reynolds numbers of various fence heights (*H*) are considerably different, the flow patterns with respect to the relative distance from the fence (*x*/*H*) are geometrically similar, and a flow pattern using a certain fence height can represent the various flow patterns of various fence heights. In terms of the wind speed, another important factor, the general idea is that wind speed does not affect the windbreak effect as long as the Reynolds number is very high (Heisler and Dewalle, 1988). This is true because the term $\frac{1}{Re}$ is close to zero in Eq. (2) and therefore has a minimal effect. However, some studies showed ambiguous points where changes of the wind speed increased or decreased wind reductions and supposed that the changes in wind reduction occurred because of turbulence and eddy formation near the windbreak (Heisler and Dewalle, 1988). Raine and Stevenson (1977) also showed that the fence leeward flow was dominated by leeward turbulence diffusing into the shelter zone. The turbulence characteristics are included in the term $\frac{Du}{Dt}$ and simplified as the Reynolds stress during derivation of the Reynolds-averaged Navier–Stokes equation. Turbulence in the approach flow is mainly caused by ground roughness and atmospheric stability (Heisler and Dewalle, 1988). The effect of turbulence on wind reduction is quite important factor but still very difficult to be revealed.

The effect of windbreak, i.e., wind reduction, is generally expressed as the mean relative horizontal wind speed downwind and sometimes upwind of the windbreak. For the same concept, Fryrear et al. (2000) used the percent of upwind velocity (PUV) to describe the influence of windbreak fence. The PUV and relative wind speed were primarily measured or calculated at one height between the ground and the fence top. Fryrear et al. (2000) developed a relationship between PUV and downwind distance as an exponential function where the value was close to zero near the fence and 100% as the distance increased. However, in recent studies (Cornelis and Gabriels, 2005; Dong et al., 2007; Santiago et al., 2007), the relationship has been shown with more complex curves rather than in a simple exponential form. The PUV or relative velocity was not zero or minimum near the fence; the maximum reduction was shown at a distance of a few fence heights (*H*) behind the fence. This complex relationship between PUV and downwind distance can be expressed as the sum of two exponential terms that will be introduced in this paper, but more precise equations are always crucial to describing wind speed reductions by fence characteristics and various wind speeds.

1.3. Objective

The objective of this study was to develop a prediction equation to describe wind speed reductions by windbreak fences in an open terrain to provide efficient design suggestions. The three main factors, such as fence porosity, fence height and wind speed, of the non-dimensional Navier–Stokes equation were correlated with vertical and horizontal PUV distributions that were calculated by a commercial computational fluid dynamics (CFD) tool. Turbulence in the approach wind was assumed as a moderate level for neutrally stratified atmospheric boundary layer. For reliable CFD simulations, wind tunnel experiments and experimental data of earlier literatures were used to validate the simulation. This research presents equations to predict PUV distributions according to these three factors for a single fence and then provides equations for multiple fences. For design purposes, the equations in this study will be available to predict wind speed reductions by various arrays of multiple fences with respect to their spacing and fence porosities.