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Research Paper

Numerical simulation study of a tree windbreak

Jessie P. Bitog [a,b], *In-Bok Lee* [a,*], *Hyun-Seob Hwang* [a], *Myeong-Ho Shin* [c], *Se-Woon Hong* [a], *Il-Hwan Seo* [a], *Kyeong-Seok Kwon* [a], *Ehab Mostafa* [a,d], *Zhenzhen Pang* [a,e]

[a] *Department of Rural Systems Engineering and Research Institute for Agriculture and Life Sciences, College of Agriculture and Life Sciences, Seoul National University, 599, Gwanakno, Gwanakgu, 151-921 Seoul, Republic of Korea*

[b] *Department of Agricultural Engineering, Nueva Vizcaya State University, 3700 Bayombong, Nueva Vizcaya, Philippines*

[c] *Saemangeum Project Office, Korea Rural Community & Agriculture Corporation, 605-1 Shinpoong-Dong Gimje, Shi Jeon-buk, Republic of Korea*

[d] *Department of Agricultural Engineering, Faculty of Agriculture, Cairo University, 12613 Giza, Egypt*

[e] *College of Horticulture and Gardening, School of Tropical Agriculture and Life Sciences, Hainan University, Hainan province, China*

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In this study, computational fluid dynamics (CFD) was utilised to investigate the flow characteristics around tree windbreaks. The efficiency of windbreaks depends on many factors which can be investigated in field experiments, though this is limited due to several reasons such as unstable weather conditions, few measuring points, etc. Fortunately, the investigation is possible via computer simulations. The simulation technique allows the trees to be modelled as a porous media where the aerodynamic properties of the trees are utilised in the model. The trees employed are Black pine trees (*Pinus thunbergii*) with a drag coefficient value of 0.55. The simulation provides analysis of the effect of gaps between trees, rows of trees, and tree arrangements in reducing wind velocity.

The simulations revealed that 0.5 m gap between trees was more effective in reducing wind velocity than 0.75 and 1.0 m. The percentage reduction in velocity at the middle of the tree section for 0.5, 0.75 and 1.0 m gap distance was found to be 71, 65 and 56%, respectively. Two-rows of alternating trees were also found to be more effective than one-row and two-rows of trees. The reduction at the middle of the tree region for one-row and two-rows of trees and two-rows arranged alternately was 71, 88 and 91%, respectively. Results revealed that the percentage reduction in wind velocity measured at distance 15*H*, where *H* is the tree height, for one-row, two-rows of trees and two-rows arranged alternately was approximately 20, 30 and 50%, respectively.

1. Introduction

South Korea is mostly surrounded by bodies of water with approximately 2413 km of coast line along three seas. To the west is the Yellow Sea, to the south is the East Sea, and to the east is Ulleung-do and Liancourt Rocks (Dokdo) in the East Sea. The country has geographical land mass of approximately 100,032 km^2 with limited land resources. This prompted the country to implement several land reclamation projects especially near the coastlines. By 2006, 38% or 1550 km^2 of coastal wetlands had been reclaimed, including 400 km^2 in the Saemangeum area (Korea Statistical Information Service, 2006).

The wind velocities in the coastal areas and in the reclaimed lands are usually higher because of the sea wind. In

* *Corresponding author*. Tel.: +82 2 880 4586; fax: +82 2 873 2087.
E-mail address: iblee@snu.ac.kr (I.-B. Lee).
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Nomenclature

$C_{1\varepsilon}$	constant (1.42)
$C_{2\varepsilon}$	constant (1.68)
$C_{3\varepsilon}$	$\tanh(\nu_1/\nu_2)$, ν_1 and ν_2 are components of the flow velocities parallel and perpendicular, respectively to the gravitational vector
C_α	empirical constant specified in the turbulence model (approximately 0.09)
C_D	drag coefficient
G_k	generation of turbulent kinetic energy due to the mean velocity gradients (kg m^{-1} s^{-2})
I	turbulence intensity (dimensionless)
k	turbulent kinetic energy (m^2 s^{-2})
l	turbulence length scale (m)
m	thickness or diameter of tree canopy (m)
p	pressure (Pa)
$\overline{P}$	mean pressure (Pa)
R	additional term
S_i	source term.
t	time (s)
V_{avg}	average wind velocity (m s^{-1})
v	velocity (m s^{-1})
$\overline{v_i}$	respective mean velocity components (m s^{-1})
$\overline{v_i^1 v_j^1}$	Reynolds stresses (m^2 s^{-2})
x_i	component of length (m)

Greek symbols

ε	turbulent dissipation rate (m^2 s^{-3})
α_k	inverse effective Prandtl number for k
α_ε	inverse effective Prandtl number for ε
μ	the fluid viscosity (N s m^{-2})
α	permeability constant
ρ	fluid density (kg m^{-3})
μ_{eff}	effective viscosity (N s m^{-2})

these areas, the recorded average wind velocity at 5 m height can reach up to 7.0 m s^{-1} especially during the dry months of the year from February to May (Hwang et al., 2006). This has caused generation and diffusion of dusts to nearby areas, such as agricultural and animal farms. In addition, the dusts from the reclaimed lands contain significant quantities of sodium chloride (NaCl) which is very detrimental to plants, animals and humans (Bitog et al., 2011). These problems can be reduced by minimising the wind velocity especially in the dust source areas, where it is the main catalyst of dust generation and diffusion. Constructing artificial barriers or planting natural windbreaks such as trees to control the wind velocity are the best options. However, for long term protection, tree windbreaks are strongly recommended (Zhou, Brandle, Mize, & Takle, 2004).

Natural windbreaks, especially trees, direct winds over or around protected areas such as agricultural farms, and livestock farms. They are very effective in reducing wind speed in the protected area. Windbreaks operate by creating pressure at the windward side of the trees as wind blows against them, with the direction of large air flows shifted in direction over the top or around the ends of the windbreaks (Bitog et al., 2011). Especially in coastal areas and in reclaimed lands, windbreaks can control the wind velocity to a level usually lower than the threshold velocity required for the generation and diffusion of dust. The amount of wind speed reduction depends on several factors such as the tree height, density, width, shape, arrangement, porosity, etc. (Bitog et al., 2011).

However, several studies have already shown that, among the factors, tree porosity has the most influence on windbreak efficiency (Bitog et al., 2009; Cornelis & Gabriels, 2005; Heisler & Dewalle, 1988). Determining the actual tree porosity is complex, considering the irregular size and shape of the trees as well as the varied distribution of the gaps. However, this can be well represented by the drag coefficient (C_D). As mentioned by Jacobs (1985), the resistance to wind flow or the drag coefficient of the windbreak can provide information on its effectiveness and efficiency in reducing high velocity winds. Therefore, knowing the dimensionless drag coefficient value of the tree windbreak is very important index to evaluate the wind protection effect of the tree (Bitog et al., 2011). In principle, the flow characteristics around windbreaks are being disrupted because of a net loss of momentum as the tree exerts a drag force on the incoming winds (Raine & Stevenson, 1977).

Performing computer simulation has been in the forefront for studying the effectiveness and efficiency of natural and artificial windbreaks including the relevant flow mechanisms around barriers. This is evidenced by the numerous published papers. A number of small-scale windbreaks studies were also conducted in wind tunnels (Dong et al., 2008; Dong, Qian, Luo, & Wang, 2006; Gromke & Ruck, 2008; Guan, Zhang, & Zhu, 2003) since the results could be applied to full scale model or actual field conditions with reliable scale-up procedures. The use of correct aerodynamic and engineering equations to resolve the scaling up technique, especially the dimensional difference of the models, must also be carefully managed. The continuing development of both wind tunnel and numerical simulation techniques has paved the way for more accurate and reliable laboratory investigations and computer simulation studies (Li, Wang, & Bell, 2007). The analysis of the flow characteristics of these simulation studies was based on the objectives for the windbreaks, with the main emphasis on the effect to the leeward. However, most of the simulations were still limited to 2-dimensional models because of insufficient computer memory to process the computations. The simulation study presented by Raine and Stevenson (1977) measured and analysed the wind velocity and energy spectra to leeward of a modelled fence. Similar studies by Castro and Garo (1998) and Judd, Raupach, and Finnigan (1996) were conducted on a porous barrier where the mean velocity and turbulence stress downstream of the barrier were investigated. A numerical model has been developed by Wilson (1985, 1987) and Wilson and Yee (2003) to accurately simulate the wind flow characteristics around a single fence and multi-array windbreaks. These simulation studies proved their reliability by showing similar results when compared to wind tunnel or field experimental results.

Computer simulation, particularly computational fluid dynamics (CFD), has now become very popular for studying