BIOSYSTEMS ENGINEERING XXX (2017) 1–22

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Evaluation of wind pressure acting on multi-span greenhouses using CFD technique, Part 1: Development of the CFD model

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ARTICLE INFO

Article history:
Received 25 November 2016
Received in revised form
19 September 2017
Accepted 25 September 2017
Published online xxx

Keywords:
Computational fluid dynamics
Greenhouse
Model evaluation
Wind pressure coefficient
Wind tunnel test

The CFD-computed and wind tunnel (WT)-measured wind pressure coefficients (C_p) were compared for development of CFD model. First, the y^+ values were considered to identify the optimum conditions of the first cell height from the adjacent wall. The CFD-computed C_p values closely corresponded to the measured C_p values when the first cell height was 1.5×10^{-4} m. The computational domain test and the grid independence test were also conducted to determine the optimum domain size and mesh size. As a result of the computational domain test, the length of the upstream portion was fixed at 3*H* (*H* = ridge height), and the length of the downstream, side and upper portions were determined to be 15*H*, 5*H* and 5*H*, respectively. The mesh size was designed to be 1.0×10^{-2} m based on the grid independence test. Using the given design criteria, an appropriate turbulence model was selected, and the Shear stress transport (SST) k–ω model was eventually chosen as the turbulence model. Finally, the computed and measured C_p values were compared using statistical indices, demonstrating that the CFD-designed model could accurately compute the C_p values.

1. Introduction

The greenhouse cultivation area in South Korea has greatly increased with the introduction of the greenhouse modernisation policy put forth by the Korean government in the 1990s. The greenhouse cultivation area reached a total of 51,787 ha in 2014 in accordance with the enlargement and corporatisation policy for greenhouses (Ministry of Agriculture, Food and Rural Affairs of Korea, 2015). The total agricultural economic production in the country was 43 billion US dollars in 2014, and the horticultural industry accounted for approximately 28% of the total agricultural economic production (Ministry of Agriculture, Food and Rural Affairs of Korea, 2015).

In South Korea, greenhouses have been constructed based on various domestic greenhouse standards such as the “Design guide for greenhouse structures” (Rural Research

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https://doi.org/10.1016/j.biosystemseng.2017.09.008
1537-5110/

Nomenclature

C_p	pressure coefficient or wind pressure coefficient
C_μ	model fitting parameter (0.09)
CFD	computational fluid dynamics
C01–C15	definition of monitoring row for scaled greenhouse model
D	roof slope (°)
d	index of agreement
ESDU	engineering sciences data unit
EV	even-span
H	ridge height (m)
k	turbulent kinetic energy ($m^2\ s^{-2}$)
MSE	mean square error
p_p	static pressure at an arbitrary point (Pa)
p_∞	static pressure at a point located far from the structure (Pa)
PC	peach
PE	potential error
q_H	design velocity pressure (Pa)
R	roof curvature radius (mm)
R^2	coefficient of determination
RANS	Reynolds averaged Navier–Stokes
RMSE	root mean square error
RNG	re-normalisation group
RSR	root mean square error-observations standard deviation ratio
S	distance from windward side of greenhouse cross-section (m)
Smax	total length of greenhouse cross-section (m)
SIMPLE	semi-implicit method for pressure-linked equations
SST	shear stress transport
u	average wind velocity ($m\ s^{-1}$)
u^*	wall friction velocity ($m\ s^{-1}$)
u_∞	velocity at a random point ($m\ s^{-1}$)
UDF	user-defined functions
W	width (m)
WT	wind tunnel
y	distance from the wall (m)
y^+	dimensionless distance from the wall
y_0	aerodynamic roughness length (m)
α	coefficient of roughness
Δp	static pressure difference (Pa)
ε	turbulent energy dissipation ($m^2\ s^{-3}$)
κ	Von Karman constant (approximately 0.41)
ρ	air density ($kg\ m^{-3}$)
ω	specific dissipation rate (s^{-1})

Institute of Korea, 1995), "Standards and explanations of greenhouse structural design" (Ministry of Agriculture, Food and Rural Affairs of Korea, 1995), and the "Korean building code-structural" (Ministry of Land, Infrastructure and Transport of Korea, 2009). However, domestic greenhouse standards are not well defined in terms of design criteria for structural stability, especially for wind load, and the current versions were introduced more than 20 years ago. In other countries, greenhouse standards (e.g., NEN-EN 13031-1-2002, 2002) originated over 10 years ago, and wind pressure was measured using outdated experimental equipment. For these reasons, many conventional greenhouses collapse every year due to a variety of natural disasters. For example, Typhoon Muifa in 2011 was reported to damage an area of approximately 42.1 ha with a loss of 4.1 million US dollars (Ministry of Public Safety and Security of Korea, 2012).

The Korean government recently announced a construction plan for new greenhouse complexes in 12 reclaimed coastal lands, including the Saemangeum reclaimed coastal land region (Ministry of Agriculture, Food and Rural Affairs of Korea, 2007). The wind characteristics of the reclaimed coastal land are quite different from those inland because of the prevalence of strong wind conditions near the seashore. The wind pressure on greenhouses built on reclaimed coastal land is higher than that in other sites due to the high coastal wind velocity and atmospheric turbulence scale (Korea Meteorological Administration, 2014). For these reasons revision of greenhouse design standards, especially for reclaimed coastal lands, is required to secure the structural safety of greenhouses in response to the strong wind environment.

Structural safety evaluation of greenhouses for wind loads has traditionally been performed using field experiments and wind tunnel tests. Field experiments are a reliable method that uses a full-scale greenhouse model. However, it is difficult to conduct aerodynamic studies in field experiments because of unstable and unpredictable weather conditions. In addition, field experiments encounter limitations in terms of simultaneous measurement of the wind pressure on full-scale greenhouse surfaces. Wind tunnel tests have been widely used as an accurate alternative for conducting aerodynamic research and obtaining sufficient quantitative data (Lee et al., 2003). However, wind tunnel tests also have experimental limitations: 1) limited number of channels for simultaneous measurement, 2) limited greenhouse model size due to the blockage ratio, 3) cost of manufacturing of a greenhouse model under various experimental conditions, and 4) time- and labour-consumption problems. Because of these limitations, obtaining reliable results from a wind tunnel test for large-sized multi-span greenhouses is difficult. Recently, many researchers have used numerical models to overcome these limitations. Numerical approaches such as computational fluid dynamics (CFD) have been effectively applied and broadly used to obtain reliable quantitative and qualitative data (Norton, Sun, Grant, Fallon, & Dodd, 2007).

Various CFD studies have been conducted to measure the wind pressure at agricultural facilities. Mathews and Meyer (1987, 1988) predicted the wind loads on a semicircular greenhouse using a two-dimensional numerical model, and Mathews, Crosby, Visser, and Meyer (1988) evaluated the wind pressure distribution on various types of greenhouses, such as semicircular and even-span type greenhouses. Hoxey, Robertson, Basara, and Younis (1993) analysed the geometric parameters that affect wind loads on low-rise pitched roof buildings using a two-dimensional CFD simulation. Hoxey et al. (1993) also presented flow patterns and pressure distributions according to the geometric parameters of pitched roof buildings. Mistriotis, De Jong, Wagemans, and Bot (1997) and