BIOSYSTEMS ENGINEERING 171 (2018) 120–142

Available online at www.sciencedirect.com

ScienceDirect

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

Research Paper

Evaluation of wind-driven natural ventilation of single-span greenhouses built on reclaimed coastal land

Sang-yeon Lee [a], *In-bok Lee* [a,b,*], *Rack-woo Kim* [a]

[a] *Department of Rural Systems Engineering, Research Institute of Agriculture and Life Sciences, College of Agriculture and Life Sciences, Seoul National University, 1, Gwanakno, Gwanakgu, Seoul, 08826, Republic of Korea*

[b] *Research Institute of Green Eco Engineering, Institute of Green Bio Science and Technology, Seoul National University, 1477, Pyeongchang-daero, Daehwa-myeon, Pyeongchang-gun, Gangwon-do, 25354, Republic of Korea*

ARTICLE INFO

Article history:
Received 19 October 2017
Received in revised form
11 April 2018
Accepted 18 April 2018

Keywords:
Computational fluid dynamics
Natural ventilation rate
Particle image velocimetry
Reclaimed land
Single-span greenhouse

Recently, the government of South Korea announced the construction plan for a large-scale greenhouse complex on reclaimed coastal lands. Wind characteristics of the coastal regions are quite different from those of inland. Natural ventilation of greenhouses is strongly dependent on the exterior wind characteristics; therefore, the effects of topographical and meteorological characteristics of the coastal regions on ventilation rate should be carefully evaluated to ensure stable and uniform production of the crops. In this study, wind-driven natural ventilation rates of single-span greenhouses were evaluated using a computational fluid dynamics (CFD) technique examining greenhouse type and typical wind conditions found in reclaimed lands. The accuracy of the designed CFD model was validated by comparing the result of the CFD simulation with the results of particle image velocimetry (PIV) measurements that were conducted in a wind tunnel. Furthermore, grid independence test and turbulence model test were conducted for validation of the designed CFD model. From these validated CFD model, the overall ventilation rates were estimated using two methods, mass flow rate (MFR) and tracer gas decay (TGD) methods according to greenhouse type, wind speed, wind direction, and configuration of the ventilator. Furthermore, local ventilation rates of the greenhouse were estimated using the TGD method. The CFD computed ventilation rates of greenhouses were evaluated by comparing them with the ventilation rates required for controlling the temperature in greenhouses. Finally, charts, which can be used to predict the natural ventilation rate of the single-span greenhouse built on reclaimed land, were developed.

* *Corresponding author*. 1, Gwanakno, Gwanakgu, Seoul, 08826, Republic of Korea. Fax: +82 2 873 2087.
E-mail address: iblee@snu.ac.kr (I.-b. Lee).

https://doi.org/10.1016/j.biosystemseng.2018.04.015

Nomenclature

AER	Air exchange rate
A_c	Cover area of greenhouse (m^2)
A_f	Floor area of greenhouse (m^2)
A_{vent}	Area of the vent
CFD	Computational fluid dynamics
C_0	Concentrations of tracer gas at t_0 time (ppm)
C_t	Concentrations of tracer gas at t time (ppm)
C_v	Volumetric specific heat of air (kcal m^{-3} °C^{-1})
C_μ	Empirical constant
d	Index of agreement
ESDU	Engineering science data unit
f	Evapotranspiration coefficient
G	Mass flow at vent (kg s^{-1})
k	Von Karman constant (approximately 0.42)
k'	Overall heat transfer coefficient (kcal m^{-2} °C^{-1} min^{-1})
MAE	Mean absolute error
MFR	Mass flow rate
MSE	Mean square error
PE	Potential error
PIV	Particle image velocimetry
R^2	Coefficient of determination
RMSE	Root mean square error
RNG	Re-normalisation group
RSR	Root mean square error-observations standard deviation ratio
S	Solar radiation (W m^{-2})
SIMPLE	Semi-implicit method for pressure-linked equations
SST	Shear stress transport
$STDEV_{obs}$	Standard deviation of measured values
t_0	Initial time (s)
t	Ventilation time (s)
TGD	Tracer gas decay
ΔT	Difference of air temperature (°C)
u^*	Shear velocity (m s^{-1})
U(z)	Wind speed at z height (m s^{-1})
$U(z_R)$	Wind speed at the reference height (m s^{-1})
UDF	User-defined functions
V	Volume of greenhouse (m^3)
v_x	Wind speed of x-axis at vent (m s^{-1})
Y_i^{obs}	i-th measured value
$\overline{Y^{obs}}$	Average of measured values
Y_i^{si}	i-th simulation value
$\overline{Y^{si}}$	Average of simulation values
y^+	Dimensionless distance from the wall
z_0	Roughness length (m)
α	Coefficient of roughness
α'	Correction rate of the heated area
ε	Turbulent energy dissipation (m^2 s^{-3})
ρ_{air}	Air density (kg m^{-3})
τ	Solar transmissivity of the greenhouse cover
ω	Specific dissipation rate (s^{-1})

1. Introduction

Since the 1970s, greenhouse cultivation in South Korea has been developing owing to such advantages as environmental control, intensive cultivation, stable production and the possibility of producing high-quality agricultural products. Total greenhouse area in South Korea has increased from 700 ha in 1970 to 52,526 ha in 2015. The production of protected cultivation, 2,558,310 tonnes, accounted for approximately 30% of the total agricultural production in 2015 (Ministry of Agriculture, Food and Rural Affairs of Korea, 2016).

Environmental control of greenhouse is necessary to prevent problems that can be derived from the excessively high air temperatures found in summer. Many methods to properly control heat environment have been used, such as evaporative cooling systems with high-pressure fog cooling and fan and pad system, natural ventilation system, forced ventilation system, etc. Because of low initial and maintenance costs, natural ventilation has been recognised as an effective and economical method to control indoor air quality, the air temperature in summer, and excess humidity. Most single-span greenhouses in South Korea have operated using natural ventilation because of the cost of installation and operation of forced ventilation systems (Kwon et al., 2011).

The use of reclaimed land for agriculture has been steadily developing in South Korea since the 1910s. The government recently announced a development plan for establishing greenhouse complexes of 5185 ha on reclaimed lands to increase the price competitiveness of local vegetables in the market (Ministry of Food, Agricultural, Forestry and Fisheries of Korea, 2010). While natural ventilation is greatly influenced by external wind environments, the characteristics of the wind environment, such as wind speed, wind direction, turbulence intensity, and gust frequency in reclaimed lands are different from those found inland owing to the low topography and oceanic climate (Korea Meteorological Administration, 2014). Studies are required to analyse the ventilation of greenhouses built on reclaimed land by considering the wind profiles and other characteristics of the reclaimed land.

The studies on greenhouses built on reclaimed land to date have mainly focused on the structural safety of greenhouses. Yun, Choi, Lee, Lee, and Yoon (2013) analysed the design wind speed and snow cover depth according to the return period using the weather data of 72 weather stations located near reclaimed land in South Korea. Yu, Ku, Cho, Ryu, and Moon (2014) analysed the problems that can occur when a greenhouse is built on reclaimed land using wooden piles. Kim, Kim, Ryu, Kwon, and Lee (2014) evaluated the wind pressure coefficient of an Even-span type greenhouse considering the wind environment of reclaimed land according to roof slope. Choi, Yun, Yu, Lee, and Yoon (2015) measured the settlement of a foundation using wooden pile at a 1–2W greenhouse built on Gyehwa reclaimed land. Lee et al. (2015) tried to establish a technique for designing the foundation of a greenhouse built inside a greenhouse. Kwon, Kim, Kim, Ha, and Lee (2016) conducted wind tunnel test to evaluate the wind pressure