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Research Paper

Investigating air leakage and wind pressure coefficients of single-span plastic greenhouses using computational fluid dynamics

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Air leakage from greenhouses not only influences heating load and the carbon dioxide supply, but also affects wind loads on the greenhouse structure. Quantitative evaluation of the greenhouse air leakage is essential to estimate variable costs and achieve reasonable designs for greenhouses with adequate strength. In this study, greenhouse leakage rate was estimated through a combination of CFD simulation of the external pressure coefficients of the greenhouse cladding and modelling of airflow through leakage paths on the greenhouse walls. The simulation results of the leakage rate were validated by the experimental results obtained from two greenhouses with the same structure but different orientation. The correlation coefficients between the simulated and measured values ranged from 0.82 to 0.99, and the RMSE of the simulated leakage rate ranged from 0.014 to 0.052. The simulation results indicated that a strong transverse wind created lower leakage rate and internal pressure coefficient. These findings and methodology will be helpful for designing light-weight greenhouses in windy regions.

1. Introduction

Air leakage is regarded as the unintentional exchange of inside and outside air. Air leakage can account for 20% of the heating load for heated greenhouses (Takakura & Okada, 1972) and approximately 50% of the carbon dioxide (CO_2) supply for CO_2-enriched greenhouses (Kuroyanagi, Yasuba, Higashide, Iwasaki, & Takaichi, 2014). In addition, air leakage is regarded as a factor that affects the pressure balance between the inside and the outside of the greenhouse (Reichrath & Davies, 2002), which causes bending moment and shear force on the structure. Therefore, it is essential to quantitatively evaluate greenhouse air leakage not only to estimate the variable costs of heated and CO_2-enriched greenhouses but also to achieve reasonable designs for greenhouses with adequate strength.

Available information on greenhouse air leakage is primarily based on field experimentation. A number of experiments to measure the leakage rate on full-scale greenhouses have been conducted using either the tracer gas technique or

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Nomenclature

a	the total area of leakage paths, m^2
a_c	the area of leakage paths in galvanised channels, m^2
C_d	pressure-jump coefficient
C_e	external pressure coefficient
C_i	internal pressure coefficient
C_μ	a model fitting parameter
d	distance between the bottom of the channel and the top of the wire cramp, m
d_w	diameter of a wire cramp, m
K	von Karman constant
k	turbulent kinetic energy, $m^2\ s^{-2}$
k_c	flow coefficient
l_w	lineal length of wire cramps, m
n	leakage rate, h^{-1}
P	pressure, Pa
P_{ref}	the reference pressure, Pa
Q	airflow rate through leakage paths, $m^3\ s^{-1}$
t_c	thickness of thin plate of a galvanised channel, m
U	windspeed, $m\ s^{-1}$
U_{ref}	the reference windspeed, $m\ s^{-1}$
u_*	friction velocity, $m\ s^{-1}$
V	greenhouse volume, m^3
z	vertical distance from ground, m
z_0	friction length, m
ρ	density of air, $kg\ m^{-3}$
ε	turbulent dissipation rate, $m^2\ s^{-3}$

energy balance equations (Nederhoff, van de Voorent, & Udink, 1985; Fernández & Bailey, 1992; Baptista, Bailey, Randall, & Meneses, 1999; Kuroyanagi et al., 2014). The experimental results indicate that greenhouse leakage rate correlates significantly with windspeed, whilst the leakage rate dependency on the air temperature difference between inside and outside is lower than that for windspeed. However, information concerning the leakage rate dependency on the pressure variations over the greenhouse cladding is limited.

There are few studies that associate the pressure exerted by the wind with the phenomena of greenhouse air leakage. Information on the wind exerting pressure variations over the greenhouse cladding is based on field experimentation (Hoxey & Richardson, 1984; Richardson, 1986), wind tunnel experiments (Kwon, Kim, Kim, Ha, & Lee, 2016; Moriyama, Sase, Uematsu, & Yamaguchi, 2010), and computational fluid dynamics (CFD) simulations (Mistriotis & Briassoulis, 2002; Mistriotis, de Jong, Wagemans, & Bot, 1997; Reichrath & Davies, 2002). In contrast to field experiments, the advantages of the latter two methods are the reproducibility and promptness of the results. The implementation of the wind tunnel test and CFD simulation requires an explicit definition of the boundary conditions of the greenhouse configuration in order to obtain the reliable results from the computations. However, the paths of air leakage, which are through unspecified apertures on the greenhouse cladding, are hardly depictable through wind tunnel modelling or the computational domain.

Field experimentation might be suitable for the investigation of the relationship between the air leakage and the pressure of from the wind. An experiment on a full-scale greenhouse also allows for accurate quantification without the application of scaling laws. However, the experimental results have limited applicability to other greenhouses, considering the diverse characteristics and situations of greenhouses between localities, regions, and countries. Furthermore, the measurement of wind pressure on the cladding is an invasive experiment which requires tapping numerous holes over the claddings. It would be impossible to eliminate the possibility of air leakage thorough the tapping points. It is therefore a reasonable compromise to conduct a CFD simulation of the external pressure distribution of the greenhouse cladding and then estimate both the leakage rate and the internal pressure coefficient with a model of the airflow through the leakage paths on the greenhouse cladding.

The objective of this study was therefore to evaluate the effect of transverse and longitudinal wind on air leakage and the external and internal pressure coefficients for greenhouses. Field experiments for the wind profile and leakage measurements were conducted on single-span plastic greenhouses, and the experimental results were used to validate the simulation results obtained from the CFD method and a greenhouse leakage model. The simulation results for the external and internal pressure coefficients for the greenhouses were validated using literature data. The method used to estimate the area of the leakage paths through the walls of light-weight plastic greenhouses is reported in an appendix to this paper.

2. Material and methods

2.1. *Field experiment*

2.1.1. *Experimental facilities*

Leakage measurements were conducted in two arch-roof greenhouses which were built according to the same overall specifications (floor area, 6.0 m × 14 m; eaves height, 2.0 m; ridge height, 3.5 m; greenhouse volume, 254 m^3). One greenhouse lay in the north-south direction (NS-greenhouse), and the other lay in the east-west direction (EW-greenhouse). They had roll-up side vents on the side walls and double sliding doors on the ends. The area of each side vent and door were 12.0 m × 1.24 m and 1.96 m × 1.83 m, respectively. The greenhouses were equipped with thermal curtains and a forced-air heater which ran when the air temperature in the greenhouses fell below 12 °C. Tomatoes were grown in a rockwool culture using a drip fertigation system. The greenhouses were covered with plastic film in the same manner on 30 April 2015 (NS-greenhouse) and on 28 August 2015 (EW-greenhouse). On 25 November, holes that formed on the roof of both greenhouses due to bird attacks were patched with waterproof seal tape; bird-preventing wires were also installed on the roof of the greenhouses.