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Research Paper

# Wind-driven natural ventilation of greenhouses with vegetation

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A large eddy simulation (LES) model was used to examine the wind-driven cross ventilation of gable-roof greenhouses containing vegetation. The obstruction of air flow by vegetation was described by a porous drag model in the numerical model, and the simulation results were validated using wind tunnel experiments. The numerical model was then utilised to inspect the influences of vegetation and greenhouse length (in the wind direction) on the ventilation rate. The results revealed that the diminishing effects of the vegetation, insect screen and internal friction on the ventilation rate can all be quantified by a physical-based resistance model. The driving force (the difference between windward and leeward pressures) of long, multi-span greenhouses was found to be less than that of a short, single-span greenhouse leading to a lower ventilation rate. The resistance factor of the vegetation and the insect screen depends on their porosity, while the resistance factor of the internal friction increased as the greenhouse length increased. In addition, the internal friction of multi-span greenhouses should be considered when the length of the greenhouse was greater than six times the greenhouse height.



## 1. Introduction

Natural ventilation is an effective way to maintain an agreeable micro-climate in greenhouses, as well as a means to reduce the energy consumption required for mechanical ventilation (Kumar, Tiwari, & Jha, 2009; Von Zabeltitz, 2011). Natural ventilation can be separated into wind-driven and buoyancy-driven ventilation (Boulard, Haxaire, Lamrani, Roy, & Jaffrin, 1999; Santamouris & Allard, 1998). However, both types of ventilation are dependent on the external wind speed, direction, temperature, and the configuration of the greenhouse and the size of the openings (Burnett and Boulard, 2010; Etheridge, 2011). Greenhouse designers need to evaluate the cooling effects of natural ventilation before using mechanical ventilation.

In recent years, computational fluid dynamics (CFD) models have successfully simulated the micro-climate of greenhouses. Reichrath and Davies (2002) and Norton, Sun, Grant, Fallon, and Dodd (2007) provided comprehensive reviews of past studies on the application of CFD models to simulate the micro-climates in greenhouses. A good numerical model could simulate all the flow parameters (wind speed,

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-section area of the opening |
| $A_V$ | void area (porous area) of the vegetation |
| $A_T$ | total cross-sectional area of the vegetation |
| $A^*$ | effective opening area |
| $C_d$ | discharge coefficient of the opening |
| $C_D$ | drag coefficient |
| $C_F$ | momentum loss coefficient |
| $C_p = (P - P_o)/0.5\rho U^2$ | pressure coefficient |
| $C_s$ | Smagorinsky parameter |
| $d$ | average size of the leaves |
| $g$ | gravitational acceleration |
| $H$ | height of the greenhouse roof |
| $H_e$ | height of the greenhouse eave |
| $h_v$ | height of the vegetation |
| $I_u = \sigma_u/U(z)$ | turbulence intensity |
| $L$ | length of the greenhouse |
| $LAI$ | leaf area index of the canopy |
| $n$ | porosity of the vegetation |
| $Q$ | ventilation rate |
| $Q^*$ | dimensionless ventilation rate |
| $Re = U_H H/\nu$ | Reynolds number |
| $S_{ij}$ | rate of strain |
| $U_H$ | wind speed at the height of greenhouse roof |
| $u^*$ | shear velocity |
| $W$ | width of the greenhouse |
| $W_v$ | width of the vegetation |
| $z$ | height from the ground |
| $\alpha$ | permeability coefficient |
| $\beta$ | inertia factor |
| $\delta$ | boundary layer thickness |
| $\Delta C_p = C_{pw} - C_{pL}$ | difference between windward and leeward pressure coefficient |
| $\lambda$ | thickness of the vegetation |
| $\kappa$ | von Karman constant |
| $\theta$ | wind direction |
| $\rho$ | air density |
| $\sigma_u$ | standard deviation of stream wise velocity |
| $\tau = tU_H/H$ | dimensionless time |
| $\nu$ | kinematic viscosity of the air |
| $\mu$ | dynamic viscosity of the air |
| $\mu_{eff}$ | effective viscosity |
| $\mu_{SGS}$ | viscosity of sub-grid scale turbulence |
| $\zeta$ | resistance factor |

*Subscripts*

| | |
|---|---|
| i | internal |
| L | leeward |
| v | vegetation |
| w | windward |

temperature, and humidity) of different greenhouse configurations under various climatic conditions.

Mistriotis, Arcidiacono, Picuno, Bot, and Scarascia-Mugnozza (1997) used the k-ε turbulence model to investigate the natural ventilation of a two-span greenhouse under no wind and low wind speed conditions. They also analysed the effects of different ventilators and showed that CFD can be a powerful tool for improving the ventilation efficiency of greenhouses. Campen (2005) applied numerical simulation to investigate the micro-climate of four different greenhouse designs and showed that a greenhouse without a top opening has the highest ventilation rate, and the lowest maximum temperature when there is external wind. In the case of no wind, the climate in the greenhouse without a top opening was shown to be slightly worse than that of other designs, and insect screens can reduce ventilation rate by more than 50%. Teitel, Ziskind, Liran, Dubovsky, and Letan (2008) studied the wind-driven natural ventilation and temperature distribution of multi-span greenhouse using a CFD model, wind-tunnel tests, and measurements in a full-scale greenhouse. They showed that the flow patterns inside the greenhouse and at the roof openings were considerably affected by the external wind direction. The ventilation rate and the crop temperature distribution were dependent on the wind direction.

Majdoubi, Boulard, Fatnassi, and Bouirden (2009) used field observation and the standard k–ε model to inspect the airflow pattern in a 1-ha Canary type greenhouse. They found that the insect screen significantly reduced indoor wind speed and increased the temperature and humidity inside the greenhouse. Their simulation results also showed that the wind speed above the canopy is greater than that within the canopy.

Bournet and Boulard (2010) employed turbulent models (standard k–ε model and realisable k–ε model) to simulate the climatic environment in greenhouses, and found that the ventilation rate of a naturally ventilated greenhouse was directly proportional to the size of the side wall opening and to the wind velocity when the wind force prevailed. They also confirmed that the insect screens and dense rows of crops perpendicular to the airflow can substantially hinder the wind-driven ventilation of greenhouses.

In view of the above studies on greenhouse ventilation, there is a need for a simple and accurate model to estimate the ventilation rate and the cooling effect of natural ventilation, especially when there are internal vegetation and insect screen on the greenhouse openings. This study used wind tunnel experiments and a large eddy simulation (LES) model to investigate the wind-driven ventilation through greenhouses containing vegetation. The LES model was used because the numerical model is an in-house computer code, and it did not have the option of different turbulence models. Moreover, the accuracy of LES model is better than that of standard k-ε models (Tominaga et al., 2008). The simulation results were validated by the wind tunnel experiments, and then utilised to develop a physical-based resistance model for wind-driven natural ventilation of greenhouses.

## 2. Materials and methods

### 2.1. Physical model

Wind-driven natural ventilation through buildings can be assessed by physical-based ventilation models (Etheridge,