The effect of vent openings on the microclimate inside multi-span greenhouses during summer and winter seasons

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In research literature, little attention has been applied to the effect of vent openings on greenhouse climates during cooling and dehumidification processes with natural ventilation, which would provide guidelines for greenhouse management. To address this problem, a 3D CFD model was successfully designed based on 11-span plastic greenhouses. The model was validated with the measured air temperature and relative humidity, and then used to investigate the effects of vent configuration and opening size on the greenhouse climate. The simulations show that the vent configuration affects greenhouse microclimate patterns and the spatial and temporal variations of the internal climate. Meanwhile, the vent opening size affects greenhouse dehumidification time, air temperature and relative humidity during the dehumidification process. Finally, the assessments of ventilation performance highlight that the roof plus side opening is most suitable for summer cooling, while the roof opening is most suitable for winter dehumidification.

Keywords: vent configuration; greenhouse microclimate; ventilation performance; natural ventilation; CFD model

1. Introduction

Greenhouse cultivation can enable vegetable production and thus remove the constraints of season and climate, which is becoming an important factor in traditional vegetable production in fields in China. China is a huge country, covering a wide range of latitude and longitude. The extreme differences of climate and geographical environment give rise to the existence of many different types of representative greenhouses in different regions. For example, solar greenhouses are common in northern China (Tong, Christopher, & Li, 2009), but this type of greenhouse is hardly ever used in eastern China, where the tunnel greenhouse is popular.

Greenhouse climate management depends on its natural ventilation system. Through promoting the exchange between indoor and outdoor air, natural ventilation can dissipate surplus heat and vapor in summer, while it can exclude excessive vapor and provide a suitable thermal climate in winter (Baptista, Bailey, Randall, & Meneses, 1999). However, the ventilation mechanism is complex and poorly understood, since it depends on many factors.

In eastern China, the usage of multi-span plastic greenhouses has rapidly expanded in the past decade, traditional, simple structures covering a large cultivated area. There are economic advantages to building this type of greenhouse, so these greenhouses play an important role in horticultural production. However, for the management of large greenhouses, it is very difficult to maintain uniform, suitable environmental factors such as internal airflow, air temperature and humidity (Hong et al., 2008). Moreover, greenhouse management faces the major challenge of controlling excess temperature in summer and high humidity in winter.

In recent years, the computational fluid dynamics (CFD) technique has become an important tool which is widely used in many fields, such as waterfront planning (Zhang, You, & Zhao, 2014), aeronautical engineering (Yu, Xu, & Gan, 2014), and fuel-cell design (Bao et al., 2014). In the greenhouse engineering community, many researchers have employed CFD to study the effects of greenhouse design (Bartzanas, Boulard, & Kittas, 2004; Bournet, Ould Khaoua, & Boulard, 2007, Bournet, Ould Khaoua, Boulard, Migeon, & Chassaériaux, 2007; Hong et al., 2008; Kacira, Sase, & Okushima, 2004; Kacira, Short, & Stowell, 1998; Kittas and Bartzanas, 2007; Lee, Short, Sase, Okushima, & Qiu, 2000; Ould Khaoua, Bournet, Migeon, Boulard, & Chassaériaux, 2006), specific equipment (Baeza et al., 2009; Fatnassi, Boulard, & Bourden, 2003; Fatnassi, Boulard, Poncet, & Chave, 2006; Montero et al., 2013; Tamimi, Kacira, Choi, & An, 2013) and external weather conditions (Hong et al., 2008; Lee & Short, 2000; Nebbali, Roy, & Boulard, 2012; Ould

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Khaoua et al., 2006; Teitel, Ziskind, Liran, Dubovsky, & Letan, 2008; Tong et al., 2009) on greenhouse climates. Their results provide valuable guidance for ventilation system management; however, they are limited to specific greenhouse structures and local climate conditions.

So far, most numerical studies of natural ventilation have focused on greenhouse climate and ventilation performance during the summer (Baeza et al., 2009; Bartzanas et al., 2004; Bournet, Ould Khaoua, & Boulard, 2007; Bournet, Ould Khaoua, Boulard, et al., 2007; Fatnassi et al., 2003, 2006; Hong et al., 2008; Kacira et al., 1998, 2004; Kichah, Bournet, Migeon, & Boulard, 2012; Lee et al., 2000; Lee & Short, 2000; Nebbali et al., 2012; Ould Khaoua et al., 2006; Teitel et al., 2008). Few have examined the effect of vent opening on greenhouse climates during the different seasons of summer and winter when natural ventilation is respectively used for cooling and dehumidification. Therefore, a CFD model is designed for the type of multi-span plastic greenhouses employed in eastern China to investigate the internal climate mechanism associated with the ventilation processes. CFD-assisted exploration can help horticulturists to improve the efficiency of ventilation system management according to the seasonal climate variations.

In this paper, a 3D CFD model was designed to investigate greenhouse climates during the cooling and dehumidification processes with natural ventilation. First, the effect of vent configuration on the greenhouse microclimate patterns was investigated. Then, the spatial and temporal variations of the greenhouse climate were revealed. In addition, the effect of the vent opening size on the greenhouse dehumidification time, air temperature and relative humidity was studied. Finally, the ventilation process was assessed using different vent configurations in different seasons.

2. Materials and methods

2.1. Greenhouse and plant material

The studied multi-span plastic greenhouse is north-south (N-S) oriented and located in the Sunqiao Modern Agriculture Development Zone, Shanghai (31°18′ N, 121°63′ E). The greenhouse is divided into two independent compartments by a central partition: the experimental section (Compartment I) composed of five spans and the adjacent section (Compartment II) composed of six spans. Each span has two roof vents (roll-up type, 1 m × 30 m each) except for the first and last spans. This type of vent is also installed in the sidewalls. A sketch of the greenhouses is given in Figure 1.

In the greenhouse, lettuces (Lactuca Satira L, ‘Yang Shan’) are laid out with an N-S orientation in 22 rows with a row spacing of 0.4 m and an in-row spacing of 0.2 m. They are grown in bare soil and cultivated by using drip irrigation during the greenhouse crop management.

2.2. Experimental design

Two measurements were conducted in Compartment I during summer and winter days, when the wind was almost perpendicular to the greenhouse orientation. The first measurement (EXP1) was performed on 11:00–12:20, 11 July 2011. The roof vents were fully open for the entire of the experimental period. The second measurement (EXP2) was performed on 11:20–12:20, 16 January 2012. The greenhouse was initially kept closed. The internal air temperature and relative humidity were 20.6°C and 93%. After 20 minutes, the roof vents were fully opened.

The external climate parameters were monitored by a meteorological station (WE800, Global Water Instrumentation Inc, USA) which was set at a height of 2.0 m and positioned far away from the greenhouse. The air conditions inside the greenhouse were measured with five temperature and humidity sensors (PH100TMPA/PH100HUMA, XPH Inc, China) placed uniformly at a height of 1.6 m along the greenhouse width in the intermediate cross-section of the greenhouse. The ground temperature was recorded with an infrared radiation thermometer (CA380, Cason Inc, Hong Kong). The crop and cover temperatures were measured by means of Pt100 probes that were fixed on the lower surface of the leaves and on the inner surface of the covers. The inside radiation was monitored by a net radiometer (Q-7.1, Campbell Scientific Inc, USA) located at a height of 0.5 m (just above the crop canopy). The leaf area index was recorded by a crop canopy analyzer (LAI-2200, LI-COR Inc, USA). All experiments were performed under almost steady-state weather conditions. Outside and inside climate parameters

Figure 1. Sketches of multi-span plastic greenhouses.
were recorded at a sample rate of 10 Hz and then averaged every 5 minutes with two data acquisition cards (PCI9112 and PCI9118, ADLINK Technology Inc, Taiwan).

3. CFD Model design

3.1. Governing equations

In this study, a 3D CFD model was designed with reference to the 11-span plastic greenhouses cultivated with a mature lettuce. The model is based on the resolution of the governing equations (Patankar, 1980) with the finite volume method. These equations can be expressed as

\[ \frac{\partial(U\phi)}{\partial x} + \frac{\partial(V\phi)}{\partial y} + \frac{\partial(W\phi)}{\partial z} = \Gamma \nabla^2 \phi + S_\phi, \quad (1) \]

where \( \phi \) represents the concentration of the transported quantity in a dimensional form (the momentum, the scalars mass and energy conservation equations), \( x, y \) and \( z \) are the Cartesian space coordinates, \( \Gamma \) is the diffusion coefficient, \( U, V \) and \( W \) are the components of velocity vector, \( S_\phi \) is the source term, and \( \nabla^2 \) is the Laplace operator.

As pointed out by Roy, Boulard, Kittas, and Wang (2002), the fluid flow becomes turbulent once the Reynolds number exceeds \( 5 \times 10^4 \). In our studies, the Reynolds number was estimated to range between \( 2.4 \times 10^2 \) and \( 4.2 \times 10^2 \) with different vent openings and inlet velocities. Therefore, it can be concluded that the airflows in the naturally ventilated multi-span greenhouse were turbulent for all the cases studied. In the greenhouse engineering community, the standard \( k-\epsilon \) model is widely used for describing the phenomenon of turbulence. For the simulated cases (with a Reynolds number value of \( 1.9 \times 10^6 \sim 4.7 \times 10^6 \)) of Boulard and Wang (2002), Bartzanas et al. (2004) and Bourret, Ould Khaoua, and Boulard (2007), it has been proved that the model can provide not only the easiest convergence but also acceptable accuracy. Therefore, the standard \( k-\epsilon \) model was adopted to describe the turbulence (for the complete set of equations for the \( k-\epsilon \) model, see Launder & Spalding, 1974). The Boussinesq model was activated to treat the density as the constant value in all solved equations except for the buoyancy term. The standard wall function was used for the near-wall treatment (Launder & Spalding, 1974). The species model was activated to calculate the transport equation.

The discrete ordinate model (DOM) was adopted to account for the radiative transfer between the greenhouse and the atmospheric environment. The no-gray model was activated by dividing the radiative spectrum into the solar radiation band [0.4–2.4 μm] and the long wave band [2.4–180 μm]. The crop radiation parameters were only valid for the solar radiation band. However, as for other materials, the radiation parameters were considered as the constants independent of the wavelength band. The beam direction and irradiation were computed by a solar calculator according to a given position, date and time. The flow iteration was set to 10 per radiation iteration. The DOM solution required material optical parameters, as summarized in Table 1.

3.2. Computational domain and mesh

The pre-processing software Gambit 2.3.16 was utilized to generate a large computational domain (90 m × 132 m × 30 m) composed of a greenhouse and its surroundings. A coupled approach was used to model the internal and external greenhouse airflows, since the decoupled approach may introduce significant errors in the case of large ventilation openings (Ramponi & Blocken, 2012). Therefore, the greenhouse ventilation openings were considered to be open in the simulation and both the external and internal airflows were solved simultaneously by using the governing equations within the same computational domain.

The indoor domain was meshed with an unstructured 0.4 m grid, whereas the outdoor domain was meshed with an unstructured grid with a size varying from 1.0 m to 2.0 m. Meanwhile, the crop canopy was meshed with a structured, 0.05 m grid. The grid density in the vicinities of cover, ground and ventilator was increased. A check for grid dependency was made with three different mesh numbers (4,289,292 cells, 5,215,444 cells, and 7,125,810 cells) to ensure that the grid resolution would not have a noticeable influence on the numerical solution. The details of the mesh created in different regions with three different mesh numbers are presented in Table 2. Table 3 exhibits a substantial increase in the ventilation rate between the first and second grids, indicating that the grid resolution does have an influence on the solution. A small increase in the ventilation rate between the second and third grids indicates that the grid resolution has almost no influence on the solution. Finally, the grid with 5,215,444 cells was created in the domain. The choice resulted from a good compromise between a refined grid which required excessive computation time and a coarser one which reduced the accuracy.

| Properties                      | Sidewall/partition | Roof | Crop | Soil |
|---------------------------------|-------------------|------|------|------|
| Density (kg m⁻³)                | 920               | 920  | 1,001| 2,000|
| Specific heat (J kg⁻¹°C⁻¹)      | 2,600             | 2,600| 3,300| 1,550|
| Thermal conductivity (W m⁻¹°C⁻¹)| 0.33              | 0.33 | 0.4  | 1.58 |
| Absorptivity                    | 0.92              | 0.06 | 0.95 | 0.9  |
| Scattering coefficient          | 0                 | 0    | 0    | -15  |
| Refractive index                | 1.53              | 1.53 | 1.51 | 3    |
| Emissivity                      | 0.70              | 0.70 | 0.95 | 0.92 |

Table 1. Thermal and optical properties of the materials involved in the simulation.
Table 2. Statistics of the mesh created in the domain with three different mesh strategies.

| Domain             | Mesh type       | Mesh size (m) |
|--------------------|-----------------|---------------|
|                    | Mesh strategy 1 | Mesh strategy 2 | Mesh strategy 3 |
| Greenhouse         | TGrid, Tet/     | 0.4           | 0.4           | 0.4          |
|                    | Hybrid          |               |               |              |
| Crop canopy        | Map, Hex        | 0.05          | 0.05          | 0.05         |
| Surroundings A     | Cooper, Hex     | 1.5           | 1.5           | 0.5          |
|                    | Wedge           |               |               |              |
| Surroundings B     | Cooper,         | 2.0           | 1.0           | 1.0          |
|                    | Wedge           |               |               |              |
| Surroundings C     | Map, Hex        | 2.0           | 2.0           | 2.0          |

Table 3. Calculated ventilation rates for the numerical model with three different mesh strategies.

| Mesh strategy | Cell number | Ventilation rate (m³ m⁻² s⁻¹) |
|---------------|-------------|-------------------------------|
| Mesh strategy 1 | 4,289,292  | 0.112                         |
| Mesh strategy 2 | 5,215,444  | 0.125                         |
| Mesh strategy 3 | 7,125,810  | 0.127                         |

of the numerical calculations. The maximum value of the EquiAngle skew along with the detail of the mesh in the ventilator region and near the wall is about 0.4, which falls within the acceptable range. The generated boundary-layer mesh for the ground consists of five layers. The growth factor of the boundary-layer mesh was set to 1.2. The value of the $y^+$ criterion is controlled within the region of the validity of the logarithmic distribution (i.e., $20 < y^+ < 200$). Likewise, for the other cases, the $y^+$ criterion can be also satisfied. The computational domain and mesh are shown in Figure 2.

3.3. Boundary condition

The velocity-inlet boundary condition was imposed for the domain inlet with a logarithmic velocity profile (Richards & Hoxey, 1993). The profile was linked to the CFD main module using the user-defined function (UDF). The surface roughness length was set to 0.015 m, given for the local terrain according to the responding standard (Wieringa, 1992).

The pressure-outlet boundary condition was selected for the domain outlet. The symmetry boundary condition was applied at the top of the domain. The wall boundary condition was used along the solid regions (ground, walls and roofs). The fixed temperature condition was imposed at the limits of the domain and all wall boundaries. The ground was treated as the opaque and diffuse wall. The temperature of the ground of each span was taken as the constant. The roof and sidewall were considered as the semi-transparent walls with finite thicknesses. The diffuse fraction of the irradiation was set to 20% for the roof. The sidewall was treated as the opaque and adiabatic material. The boundary condition settings of the wall stem from the material properties, as summarized in Table 1. The input values in the boundary conditions are derived from experimental data, as shown in Table 4.

In the simulation, the lettuce crop was treated as a porous medium to incorporate its resistance on the ambient airflow. The drag force generated by the airflow through the porous medium can be described by the...
Darcy-Forchheimer equation,

\[ S_\phi = - \left( \frac{\mu}{K_p} U + \rho \frac{C_F}{\sqrt{K_p}} U^2 \right), \]  

(2)

where \( \rho \) is the air density (kg m\(^{-3}\)), \( U \) is the air velocity (m s\(^{-1}\)), \( K_p \) is the permeability (m\(^2\)), \( \mu \) is the dynamic viscosity (kg m\(^{-1}\) s\(^{-1}\)), and \( C_F \) is the non-linear momentum loss coefficient.

For simplification, it is assumed that the pressure force constitutes the major portion of the total drag of the crop canopy (Wilson & Shaw, 1977). The sink of the momentum per the crop volume can be expressed as

\[ S_\phi = -\rho I_{LAD} C_d U^2, \]  

(3)

where \( \rho \) is the air density (kg m\(^{-3}\)), \( I_{LAD} \) is the leaf area density (m\(^2\) m\(^{-3}\)), \( U \) is the air velocity (m s\(^{-1}\)), and \( C_d \) is the drag coefficient of the crop canopy.

For the crop canopy and the range of the air speed, the term in \( U \) of Eq. 2 is much smaller than the quadratic term, and thus can be ignored. Consequently, combining Eq. 2 and Eq. 3, one can deduce the permeability and the non-linear momentum loss coefficient of the porous medium:

\[ \frac{C_F}{\sqrt{K_p}} = I_{LAD} C_d. \]  

(4)

In the study, \( I_{LAD} \) was defined as \( I_{LAI}/H \) (the leaf area index, \( I_{LAI} \): 4.5 m\(^2\) m\(^{-2}\) and 3.8 m\(^2\) m\(^{-2}\); the crop height, \( H \): 0.20 m and 0.18 m). The drag coefficient \( C_d \) was determined to be 0.32. Boulard and Wang (2002) successfully used this value (0.32) for the drag coefficient for a mature lettuce in their simulation.

The crop-air interactions of thermal and water vapor were implemented with a UDF programmed in C++ (for details, see Boulard & Wang, 2002).

### 3.4. Numerical procedure

The CFD software package ANSYS FLUENT 12.0 was used to perform two sets of simulations. The first set is the steady simulation employed for summer ventilation to reveal the greenhouse climate mechanism during the cooling process with natural ventilation. The second set is the unsteady simulation employed for winter ventilation to investigate the time-dependent greenhouse climate parameters during the dehumidification process with natural ventilation.

The semi-implicit method for the pressured-linked equation (SIMPLE) and the pressure-implicit splitting of operators (PISO) algorithms were applied to solve the flow field for the steady and unsteady flows, respectively. The body-force weighted scheme was used for the pressure discretization. The second-order upwind discretization scheme was selected for the momentum and turbulence equations. The first-order implicit scheme was employed for the time discretization. The unsteady simulation was continuously executed until the initial humidity (i.e., 93%) in the crop canopy dropped to a value below 75%, which indicates the end of the greenhouse dehumidification. Considering the computational efficiency and the temporal accuracy, the time step size was set to 0.05 s based on the preliminary grid-dependence test. The maximum iterations was set to 20 per time step. The convergence criterion was set to \( 10^{-6} \) for all variables. The under-relaxation factors used for the CFD simulation are shown in Table 5. These factors are appropriately reduced when the scaled residuals become unstable.

| Table 4. Boundary conditions used in the CFD simulations. |
|-----------------|-----------------|
| Parameters      | Values          |
| Air speed (m s\(^{-1}\)) | 1.3 | 2.0 |
| Air temperature (°C) | 35.0 | 10.5 |
| Air relative humidity (%) | 60 | 47 |
| Air density (kg m\(^{-3}\)) | 1.15 | 1.25 |
| Air specific heat (J kg\(^{-1}\) °C\(^{-1}\)) | 1,006.7 | 1,005.8 |
| Air thermal expansion coefficient (°C\(^{-1}\)) | 0.00325 | 0.00353 |
| Air thermal conductivity (W m\(^{-1}\) °C\(^{-1}\)) | 0.0267 | 0.0249 |
| Air dynamics viscosity (kg m\(^{-1}\) s\(^{-1}\)) | \( 1.89 \times 10^{-5} \) | \( 1.77 \times 10^{-5} \) |
| Air gravitational acceleration (m s\(^{-2}\)) | 9.81 | 9.81 |
| Solar radiation (W m\(^{-2}\)) | 688 | 340 |
| Net radiation (W m\(^{-2}\)) | 490 | 228 |
| Leaf surface temperature (°C) | 37.2 | 14.0 |
| Outside ground temperature (°C) | 42.0 | 12.6 |
| Inside ground temperature (°C) | 41.0 | 21.5 |

Note: Case 1: 11:00–12:20, 11 July 2011; Case 2: 11:20–12:20, 16 January 2012.

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| Under-relaxation Factors | Values |
|-------------------------|-------|
| Pressure                | 0.3   |
| Density                 | 1     |
| Body Forces             | 1     |
| Momentum                | 0.7   |
| Turbulent Kinetic Energy| 0.8   |
| Turbulent Dissipation Rate| 0.8  |
| Turbulent Viscosity     | 1     |
| H\(_2\)O                | 1     |
| O\(_2\)                 | 1     |
| Energy                  | 1     |
| Discrete Ordinate       | 1     |

| Table 5. Under-relaxation factors used in the CFD simulation. | Values |
|-------------------------------------------------------------|-------|
| Pressure                                                   | 0.3   |
| Density                                                    | 1     |
| Body Forces                                                | 1     |
| Momentum                                                  | 0.7   |
| Turbulent Kinetic Energy                                   | 0.8   |
| Turbulent Dissipation Rate                                 | 0.8   |
| Turbulent Viscosity                                        | 1     |
| H\(_2\)O                                                   | 1     |
| O\(_2\)                                                   | 1     |
| Energy                                                    | 1     |
| Discrete Ordinate                                          | 1     |
4. Results and discussion

4.1. Validation of the CFD model

The experimental and simulated temperature profile (Figure 3) at a height of 1.6 m during the cooling process shows good agreement, with a difference of less than 1 °C. The reasons for the difference are: a) any heat loss through the covers was ignored in the simulation; b) the crop parameters (such as the crop drag coefficient) were roughly estimated in the model. The results of the field measurements indicate that the model is able to provide an acceptable prediction of inside air temperature during the cooling process.

The experimental and simulated relative humidity profile (Figure 4) at a height of 1.6 m after the four-minute dehumidification process with natural ventilation gradually decreases with the increase of the distance from the side opening, with a difference of less than 6%. The explanations for this difference are: a) the leakage of air vapor from the internal to external environments is unavoidable in practice, whereas this leakage was ignored in the simulation; b) the heterogeneity of the internal humidity is inevitable in practice, whereas a perfect homogenization was assumed in the simulation; and c) the fluctuations of the outside climate are inevitable in practice, whereas the steady-state climate condition was assumed in the simulation. Nevertheless, the close agreement between the experimental and simulated humidity indicates that the model can be suitable for exploring the dynamic response of the indoor humidity to the external climate during the dehumidification process.

4.2. Effect of the vent configuration on the greenhouse microclimate patterns and the turbulent kinetic energy distribution

Figures 5–7 show that, during the cooling process, the external colder airflow enters into the greenhouse and excludes the hotter internal air. The greater the airflow velocity (Figure 5), the lower the air temperature (Figure 6). During the dehumidification process, drier airflow from outside penetrates into the greenhouse and replaces the wetter internal air. The humidity pattern (Figure 7) at the dehumidification end is the consequence of the airflow pattern (Figure 5) in the greenhouse.

With the side opening, a recirculation loop occurs in the first span with a good mixing and a relatively higher velocity. However, stiller air conditions prevail in the other span. The temperature pattern (Figure 6(a)) shows that the air temperature in most of the regions of the first three spans is over 1 °C lower than in the other span. The humidity pattern (Figure 7(a)) shows that the relative humidity in the vicinity of the crop canopy is lowered to reach the level of 40–50% at the dehumidification end. However, a significant amount of wet air is still confined adjacent to the roofs of the leeward area.

With the roof opening, most of the airflow enters the greenhouse through the windward roof vents, travels along the interior and finally towards the last two roof vents. The temperature pattern (Figure 6(b)) shows that the air temperature in the first span where the airflow is stagnant is approximately 2–3 °C warmer than in the other span. The air temperature reaches 35.0 °C in the vicinity of the roofs. The humidity pattern (Figure 7(b)) shows that the relative humidity is approximately 48% in the center. As a result of low velocities in the first and last spans, the relative humidity ranges between 60% and 75%.

With the roof plus side opening, the external airflow penetrates into the windward side vent and is then shunted. A part of the inlet airflow combined with inside hot air produces a circulation in the first span. The remaining airflow travels through the center and moves towards the last two roof vents and the leeward side vent. Compared to the other configurations, this one induces larger reductions in the indoor temperature and humidity level. The temperature pattern (Figure 6(c)) shows that the air temperature varies from 35.8 °C to 37.2 °C in the lower part of the side openings, while, in the upper part of the side openings, with the air speed being greater, the air temperature ranges between 34.4 °C and 35.8 °C. The humidity pattern (Figure 7(c)) shows that the relative humidity in most regions is lowered...
Figure 5. Airflow pattern inside the greenhouse with three different vent configurations: (a) side opening; (b) roof opening; and (c) roof plus side opening.

Figure 6. Temperature pattern inside the greenhouse during the cooling process with natural ventilation in summer: (a) side opening; (b) roof opening; and (c) roof plus side opening.

Figure 7. Humidity pattern inside the greenhouse at the end of the dehumidification with natural ventilation in winter: (a) side opening; (b) roof opening; and (c) roof plus side opening.

to a value below 55% except in the vicinity of the ground of the last span, where the humidity ranges between 63% and 73%.

Figure 8 shows the different turbulent kinetic energy (referred to as turbulence level) distributions in the greenhouse with three different vent configurations. It is clear that, in the greenhouse, the higher the airflow velocity, the higher the level of turbulence. A high level of turbulence may occur in the first span or in the vicinities of the first two windward roof ventilators and the last roof ventilator. Meanwhile, an increase in turbulence level tends to induce more homogenous temperature and humidity distributions in the greenhouse.

4.3. Effect of the vent configuration on the spatial and temporal variations of the greenhouse climate

The horizontal profiles of the differences between inside and outside air temperature and humidity at a height of 1.0 m during the cooling and dehumidification processes are shown (Figures 9 and 10). With the side opening, internal air temperature and humidity elevations are increased
Figure 8. Turbulent kinetic energy distribution inside the greenhouse with three different vent configurations: (a) side opening; (b) roof opening; and (c) roof plus side opening.

Figure 9. The difference between inside and outside air temperature at a height of 1.0 m during the cooling process in summer.

Figure 10. The difference between inside and outside air humidity at a height of 1.0 m after the one-minute dehumidification process in winter.

It is well known that the prerequisite of condensation formation is that the indoor air temperature is lower than the air dew-point temperature. The horizontal profiles of the difference between the air temperature and the air dew-point temperature at a height of 1.0 m in the middle of the greenhouse after the one-minute dehumidification process (Figure 11) show that the air in the leeward area is prone to condensation. Moreover, compared to other configurations, the side opening more easily induces condensation formation.

The time courses of the indoor mean temperature and relative humidity during the dehumidification process with natural ventilation (Figure 12) show that, in the first two minutes, the side opening induces a slower decrease in the indoor air temperature and relative humidity than the roof opening and the roof plus side opening. The latter two configurations result in similar variation trends in the air temperature and relative humidity. With roof, side and roof plus side opening, the greenhouse dehumidification
time is 2.5 minutes, 3.7 minutes and 1.3 minutes, respectively. Correspondingly, the mean values at the dehumidification end are 12.4 °C, 11.6 °C and 13.2 °C for the air temperature, and 50%, 54% and 48% for the relative humidity.

4.4. Effect of the vent opening size on the greenhouse dehumidification time and inside climate

The relationship between the greenhouse dehumidification time and vent opening size is illustrated (Figure 13). The data can be fitted to a function \( y = a + b \exp(-c \cdot x) \) where \( y \) is the dehumidification time and \( x \) is the vent opening size. Under the roof opening sizes of 0.2 m, 0.4 m, 0.6 m, 0.8 m and 1.0 m, the dehumidification time is 6.5 minutes, 4.0 minutes, 2.8 minutes, 2.6 minutes and 2.5 minutes, respectively. By using this equation, the dehumidification time can be estimated across the whole range.

It is clear that as the vent opening is increased from 0.2 m to 1.0 m, the dehumidification time decreases exponentially from 6.5 minutes to 2.5 minutes. As shown in Figure 14, at the dehumidification end, the mean values of inside temperature and humidity drop from 13.9 °C to 12.4 °C and from 66% to the value around 50%, respectively. The corresponding standard deviations vary in the range of 0.85–1.3°C and 7.4–9.0%.

4.5. Optimization of vent opening during the cooling and dehumidification process with natural ventilation

From the growers’ viewpoint, the primary aim of a ventilation management system is to fix the optimal vent configuration according to the prevailing weather conditions. Therefore, in this study, the summer ventilation process was assessed based on cooling efficiency and homogeneity performance, while the winter ventilation process was assessed based on heat loss, dehumidification efficiency and homogeneity performance. The natural ventilation performance corresponding to different vent configurations is summarized in Tables 6 and 7.

During the summer ventilation process, the side opening has the poorest cooling capacity. Moreover, it offers
the worst cooling efficiency \( Y_c = 8.3 \text{ °C m}^{-2} \). Therefore, this configuration is not recommended. Roof opening offers a better cooling performance than side opening, but slightly increases the indoor climate heterogeneity. This finding differs from the previous results (Bartzanas et al., 2004; Bourret, Ould Khaoua, & Boulard, 2007; Ishii et al., 2008; Kittas, Katsoulas, Bartzanas, Mermier, & Boulard, 2008). In those studies, roof opening offers the best homogeneity performance. The reason for this difference is that the non-symmetric design of the roof vents of the studied greenhouse results in a relatively worse homogeneity. Roof plus side opening provides the best ventilation efficiency of approximately 6.4 times more than that of side opening alone and approximately 1.2 times more than that of roof opening alone. Moreover, it offers a good homogeneity performance \( \eta_T = 1.58, \eta_{RH} = 21.7 \). Therefore, from the considerations of cooling efficiency and homogeneity performance, the roof plus side opening configuration tends to be recommended.

Presently, a small number of research studies have been conducted concerning the ventilation performance during the winter period. In this study, the greenhouse climate has characteristics with a more obvious heterogeneity at the dehumidification end. Roof plus side opening provides the best dehumidification performance, whereas this configuration results in significantly higher heat loss than the other configurations. The side opening is more appropriate for reducing the heat loss and offers the best dehumidification efficiency \( Y_d = 9.7\% \text{ m}^{-2} \text{ s}^{-1} \), but it provides the worst homogeneity of the air temperature and humidity in the crop canopy \( \eta_T = 3.56, \eta_{RH} = 110 \). Therefore, from the considerations of dehumidification efficiency, heat loss and homogeneity performance, the roof opening configuration makes a good compromise and tends to be suggested. Moreover, from a practical point of view, this configuration can prevent very cold external air from flowing into the crop canopy directly.

5. Conclusion

In this paper, the comparative effect of vent opening on the greenhouse microclimate under different ventilation processes was investigated. The results reveal that vent configuration strongly affects not only greenhouse microclimate patterns but also the spatial distribution and dynamics behavior of the internal temperature and relative humidity. Moreover, during the dehumidification process, increasing the vent opening size induces an exponential decrease in the greenhouse dehumidification time and further affects the inside climate. The assessment of ventilation performance demonstrates that the roof plus side opening is the most suitable for greenhouse cooling in summer, while the roof opening is the most suitable for greenhouse dehumidification in winter. These results can help the horticulturists not only to understand the ventilation mechanism but also to have better control of the ventilation system in different conditions.
seasons. One limitation of this study is that some physical mechanisms (e.g., condensation) were not taken into consideration in the CFD model. Meanwhile, another limitation is that the grid density across the sidewall vents should be further increased. Therefore, the suggested improvement is to enhance the accuracy of the CFD model. In the future, the main direction of this work will be to investigate the effects of external climate conditions (e.g., the wind regime) and internal elements (e.g., insect screens) on the greenhouse microclimate.

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Nomenclature
\[A\] ventilation area (m\(^2\))
\[C_d\] drag coefficient
\[C_F\] non-linear momentum loss coefficient
\[C_p\] volumetric specific heat of air (J m\(^{-3}\) °C\(^{-1}\))
\[G\] air exchange through the window (m\(^{-3}\) s\(^{-1}\) m\(^{-2}\))
\[H\] crop height (m)
\[I_{LAI}\] leaf area index (m\(^2\) m\(^{-2}\))
\[I_{LAD}\] leaf area density (m\(^2\) m\(^{-2}\))
\[K_p\] permeability of the porous medium (m\(^2\))
\[Q_{sen}, Q_{lat}\] sensible and latent heat flux (W m\(^{-2}\))
\[RH_{in}\] initial indoor humidity before the dehumidification begins (%)
\[RH_{out}\] outside air humidity (%)
\[RH_{in}\] mean indoor relative humidity at the dehumidification end (%)
\[S_{\phi}\] source term
\[T_i, T_o\] inside and outside air temperature (°C)
\[T_m\] mean indoor temperature after the cooling process (°C)
\[t\] ventilation time (s)
\[U, V, W\] components of velocity vector
\[u_h\] air velocity at the reference height (m s\(^{-1}\))
\[x_i, x_o\] concentration of vapor in the air inside and outside the greenhouse (kg m\(^{-3}\))
\[x, y, z\] Cartesian space coordinates
\[Y_c\] cooling efficiency (°C m\(^{-2}\))
\[Y_d\] dehumidification efficiency (% m\(^{-2}\) s\(^{-1}\))

Greek letters
\[\Gamma\] diffusion coefficient (m\(^2\) s\(^{-1}\))
\[\Delta RH\] difference of the maximum and minimum value of the relative humidity in the crop canopy (%)
\[\Delta T\] difference of the maximum and minimum value of the air temperature in the crop canopy (°C)
\[\eta_{RH}\] humidity homogeneity in the crop canopy
\[\eta_T\] temperature homogeneity in the crop canopy
\[\lambda\] latent heat of evaporation (J kg\(^{-1}\))
\[\mu\] dynamic viscosity (kg m\(^{-1}\) s\(^{-1}\))
\[\rho\] air density (kg m\(^{-3}\))
\[\phi\] concentration of the transported quantity
\[\nabla^2\] Laplace operator

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