Developing a Natural Ventilation Model for Open-Roof Greenhouses

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Abstract

A computer simulation model for natural ventilation in open-roof greenhouses was developed to predict the ventilation performance. The model predicts ventilation rate and the temperature differences between inside and outside, based on the weather and structural conditions including internal net radiation, wind velocity, and height and area of the roof openings. The ventilation rate was calculated from thermal buoyancy and wind forces. A sensible heat balance was incorporated to calculate the ventilation rate and the temperature difference simultaneously. A four-span open-roof greenhouse with roof sections hinging at the gutters and opening at the ridge, constructed on the Rutgers University campus, was used for data collection. Measurements of climate conditions in the direct vicinity of the greenhouse were conducted. Using the observed outdoor and greenhouse conditions, the model parameters were calibrated statistically. The accuracy of the model and the modifications to the model are discussed by comparing the predicted and observed greenhouse temperatures. It is shown that the internal temperature rise depends on the roof configuration as well as solar radiation and wind velocity. The resulting simulation model can be used to implement new environment control strategies for open-roof greenhouses.

Introduction

During the last five years, open-roof greenhouse designs have become very popular in the US. Most greenhouse manufacturers in North America sell at least one type of an open-roof greenhouse design. Growers have reported two main advantages of open-roof greenhouses compared with traditional fan ventilated greenhouses: (1) during warm(er) conditions, the greenhouse temperature closely tracks outside temperatures with little or no energy requirements (to operate the fans), and (2) spring plants can be easily hardened off by opening the roof. Despite their popularity, little research data is available to support the grower enthusiasm for open-roof greenhouses. In an attempt to study open-roof greenhouse design and operation, a small greenhouse (Van Wingerden Greenhouse Company, Horse Shoe, NC, USA, the MX-II style) was constructed on one of the research farms at Cook College, Rutgers University in New Brunswick, NJ, USA.

Because the design of open-roof greenhouses differs significantly from traditional mechanical or natural ventilated greenhouses, it became clear that a study of the ventilation in open-roof greenhouses was warranted. In particular, it is necessary to verify that open-roof greenhouses provide sufficient and uniform air exchange rates between the inside and outside greenhouse environment. In this paper, we have attempted to model the natural ventilation patterns in a small open-roof greenhouse.

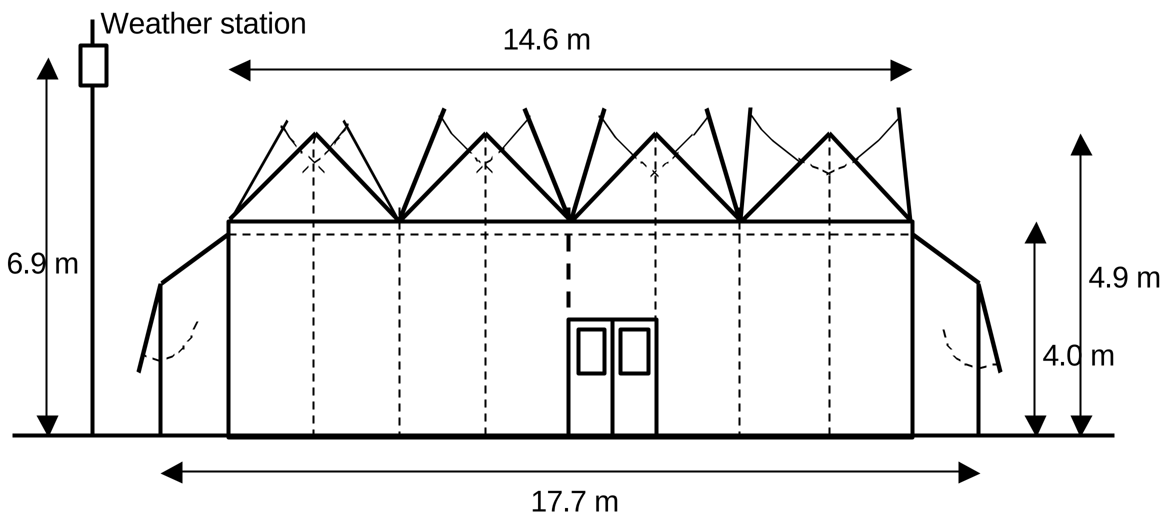

Figure 1. Side view of the greenhouse south wall (not to scale).

Materials and methods

Observation

The dimensions of the open-roof greenhouse used for this study are shown in Figures 1 and 2. The direction of the greenhouse gutters was slightly rotated from the north-south direction (15°) as a result of the location of adjacent roads and buildings. Although the greenhouse was outfitted with additional ventilation openings in the sidewalls (the east and west walls), these sidewall ventilation openings were kept closed during the measurement intervals from which the data was used for the validation of the ventilation model.

The greenhouse environment was controlled with a commercial control system (Argus Control Systems, Ltd., White Rock, BC, Canada). The temperature set point for ventilation was 21 °C (70 °F) and the roof position was operated based on the measured temperature at a height of 1.2 m (4 ft). In some cases, the roof position was kept manually at a constant opening. When the roof sections were fully opened, the ratio of the roof opening area to the greenhouse floor area was 0.66. No crops were grown in the greenhouse during the period of data collection, except for a short period of several days when approximately 30% of the floor area was filled with potted plants. All measurements were recorded as 15-minute averages.

Outside the greenhouse, a weather station was installed containing sensors to measure outdoor conditions. The 7.9 m (26 ft) mast was equipped with instrumentation to measure the following parameters at a height of 6.9 m (22.5 ft): temperature, relative humidity, wind speed and direction, and rain detection. In addition, a quantum sensor (LI-COR, Inc., Lincoln, NE, USA) was installed to measure photosynthetically active radiation (PAR, with wavelengths between 400 and 700 nm), as well as a precision pyranometer (The Eppley Laboratory, Inc., Newport, RI, USA) to measure total solar radiation (short wave, with wavelengths between 280 and 2,800 nm).

Inside the greenhouse, temperature was measured at three different heights: 1.2, 2.4, and 3.6 m (4, 8, and 12 ft) above the floor. A LI-COR quantum sensor and pyranometer, an Eppley precision pyranometer, and a Micromet net radiometer (Campbell Scientific, Inc., Logan, UT, USA) measuring wavelengths between 250 and 60,000 nm were mounted at 1.2 m (4 ft) above the floor, and positioned underneath one of the roof ridges, to measure radiation conditions inside the greenhouse (Figure 3). Prior to the measurements, all radiation sensors were calibrated using the "Instrument Package" provided by the NCR-101 Committee on Controlled Environment Technology and Use.

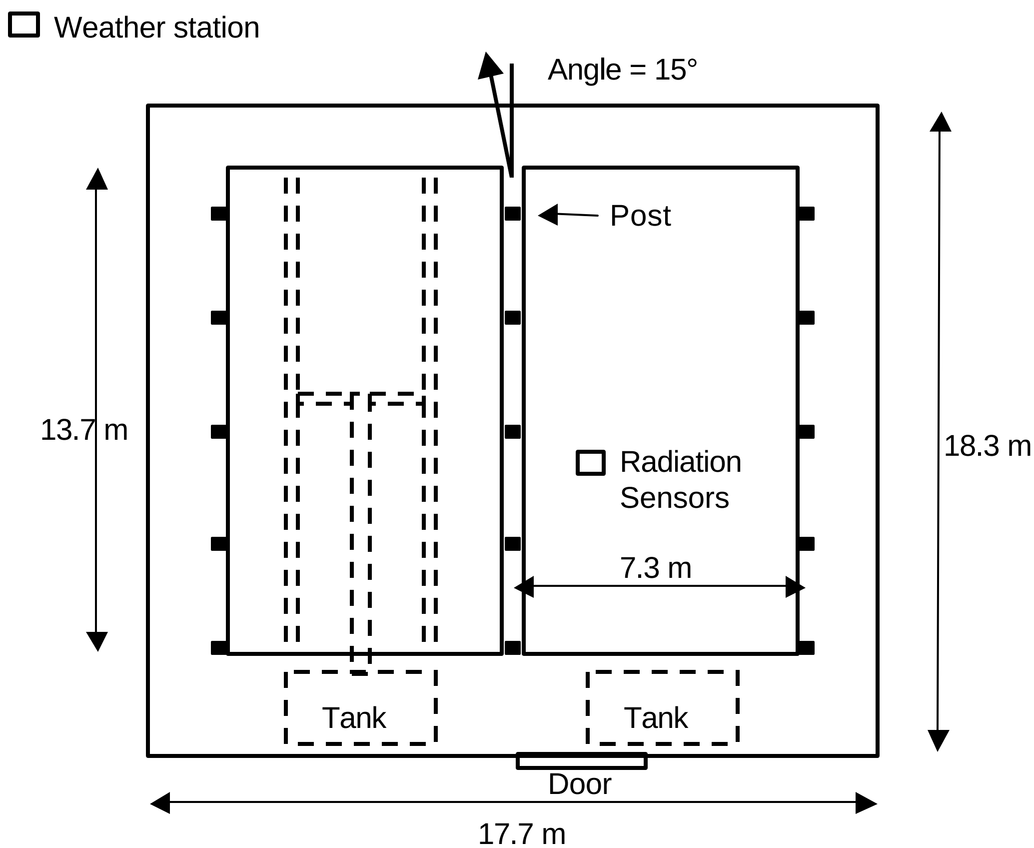

Figure 2. Greenhouse layout (not to scale).

Figure 3. View of the placement of the radiation sensors inside the greenhouse.

Model description

The model proposed by Boulard et al. (1996) to estimate the natural ventilation rate in greenhouses with only roof openings was used. The model is based on the two driving forces for natural ventilation: thermal buoyancy and wind forces. The model can be written in the following form:

$$G = A_o \left(a_1 \, H/2 \, \Delta T + a_2 \, V^2 \right)^{1/2} \quad (1)$$

where G is the ventilation rate per unit greenhouse floor area ($m^3/m^2/s$), A_o is the ratio of roof opening area to the greenhouse floor area, H is the height of the opening above the floor (m), ΔT is the air temperature difference between inside and outside (°C), V is the wind velocity (m/s) at a height of 6.9 m, a_1 is the buoyancy constant ($m^2/s^2/°C$), and a_2 is the wind effect coefficient (dimensionless). The parameters, a_1 and a_2 include the discharge coefficient of the roof opening(s).

A typical model for the sensible heat balance was incorporated to calculate the ventilation rate and the temperature difference between inside and outside simultaneously. It is based on a steady state condition and shown as follows:

$$G = \left(\alpha \, R_n / \Delta T - U \, \beta \right) / \left(C_p \, \rho \right) \quad (2)$$

where G is the ventilation rate per unit greenhouse floor area ($m^3/m^2/s$), α is the ratio of sensible heat gain to the inside net radiation, R_n is the inside net radiation (W/m^2), U is the overall heat transfer coefficient ($W/m^2/°C$), β is the ratio of the greenhouse surface area to the greenhouse floor area, C_p is the specific heat of air (1006 J/kg/°C), and ρ is the specific mass of air (kg/m^3).

Approximately 500 data points collected during the period of March through May, 2000, were used to determine the parameters a_1 and a_2 using least squared residuals between the observed and predicted temperature differences. Prior to the analysis, other necessary parameters were determined or normalized. The sensible heat gain can be related to the evapotranspiration in a greenhouse and varies according to the greenhouse environment in general. During the observation, no crops were grown in the greenhouse and the soil surface condition was mostly dry. The value of α was determined using Equation (2) when the roof segments were closed. This value gradually decreased from 0.78 to 0.67 during the time period of the measurements. This is likely due to the fact that weeds started growing inside the greenhouse and due to the time a batch of potted plants covered approximately 30% of the greenhouse area during the month of May. The observed inside net radiation fluctuated markedly on clear days because of the shadows caused by the construction materials and the light reflection from opened roof surfaces. Such data of net radiation were normalized using the statistical relation between the outside solar radiation and the inside net radiation, and then used as model input data. The U value was assumed to be 4 $W/m^2/°C$ for the experimental greenhouse covered with two layers of air-inflated polyethylene film. The term β for the experimental greenhouse was 2.18.

Results and Discussion

Using approximately 500 measurements, the parameters, a_1 and a_2 for the height of 1.2 m (4 ft) were determined to be 0.0067 and 0.023, respectively. They are slightly larger than the parameters (0.004 and 0.017, respectively) Kittas et al. (1997) determined for a twin-span greenhouse with continuous roof ventilators using the tracer gas method. On the other hand, the determined parameters for the measurement height of 2.4 m (8 ft) were 0.0026 and 0.0077, respectively. They were smaller than those for the height of 1.2 m (4 ft). This reflects the warmer temperature at the measurement height of 2.4 m (8 ft) compared to a height of 1.2 m (4 ft) because of the vertical temperature gradient in the greenhouse. The observed temperature at 1.2 m (4 ft) was always lower than that at 2.4 m (8 ft) during the daytime.

Figure 4 shows an example of the diurnal changes in predicted and observed temperature differences between inside and outside. Note that the control system operated the position of the roof segments based on the deviation from the measured temperature at a height of 1.2 m (4 ft) from the temperature set point (21 °C or 70 °F), and to a lesser extent based on the outside temperature and solar radiation. Figure 4 shows that the predicted temperature differences agreed closely with the observed temperature differences at a small opening, while those were overestimated when the roof segments were more widely opened. The temperature difference decreased with an increase in the outside temperature, which peaked in the late afternoon on clear days. When the roof segments were widely opened, the inside temperature, particularly at a height of 1.2 m (4 ft) occasionally dropped below the outside temperature. This negative temperature difference might be due to cooling caused by evaporation and/or long-wave radiation from the greenhouse floor. Furthermore, an outside temperature gradient might exist. Note that the outside temperature was measured at a height of 6.9 m (22.5 ft). The outside temperature generally decreases with an increase in height above the ground during the daytime. It was assumed that the temperature difference at 2 m (6.6 ft) height above the ground is up to 0.3 °C (0.5 °F) larger than that at 6.9 m (22.5 ft) height. However, the model described here does not take this into account and is not capable of predicting negative temperature differences.

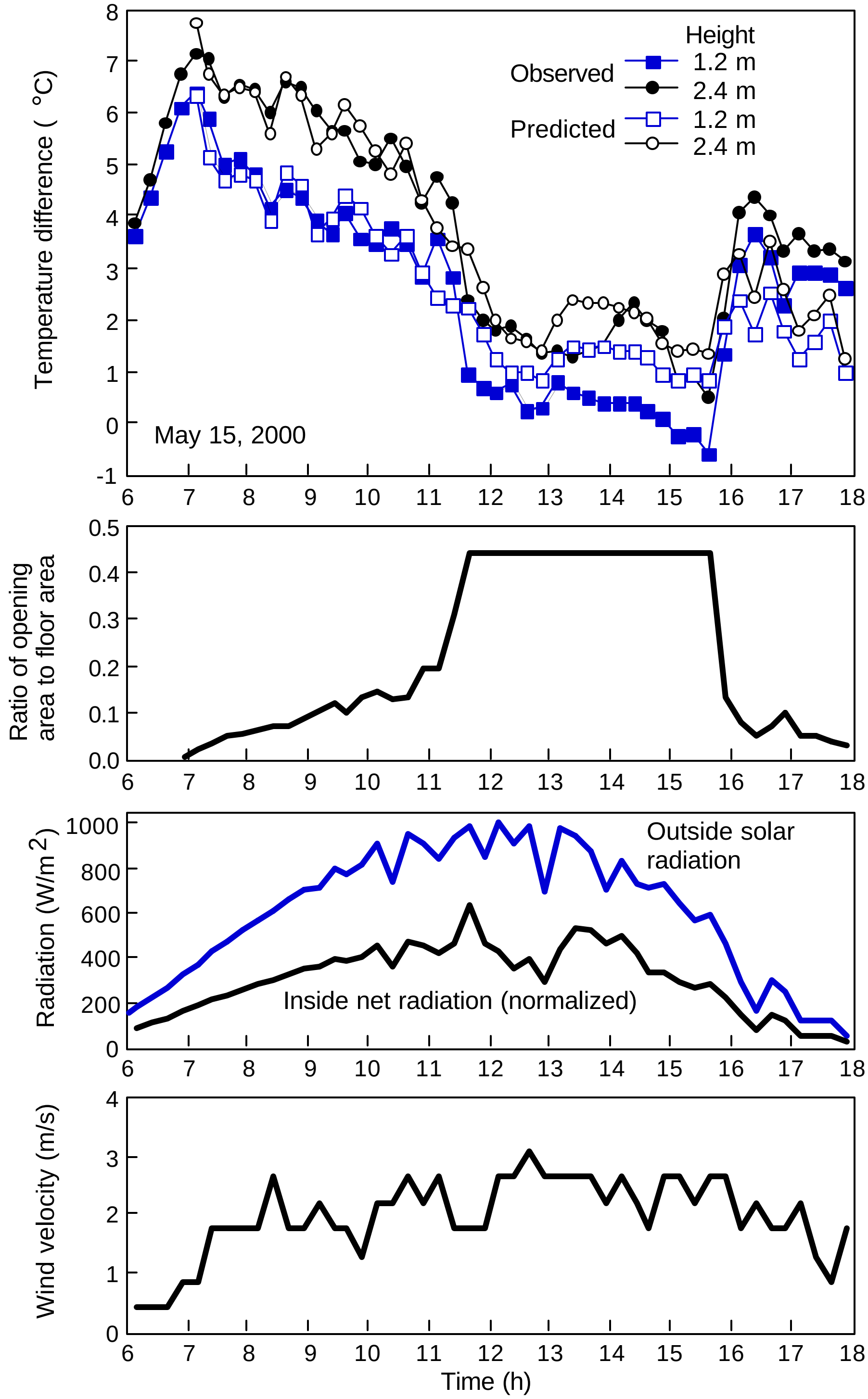

Figure 4. Comparison of the diurnal changes in predicted and observed temperature differences between inside and outside. The changes in the input parameters used for the model predictions are also illustrated.

A comparison of the observed and predicted temperature differences for four ratios of opening area to the floor area is shown in Figure 5. The standard errors of the temperature differences for the heights of 1.2 and 2.4 m (4 and 8 ft) were 0.82 and 0.89 °C (1.5 and 1.6 °F), respectively. The predicted temperature difference was found to be highly sensitive to the changes in the roof opening and the inside net radiation. This feature seems reasonable since they have linear relations with the ventilation rate as shown in the Equations (1) and (2).

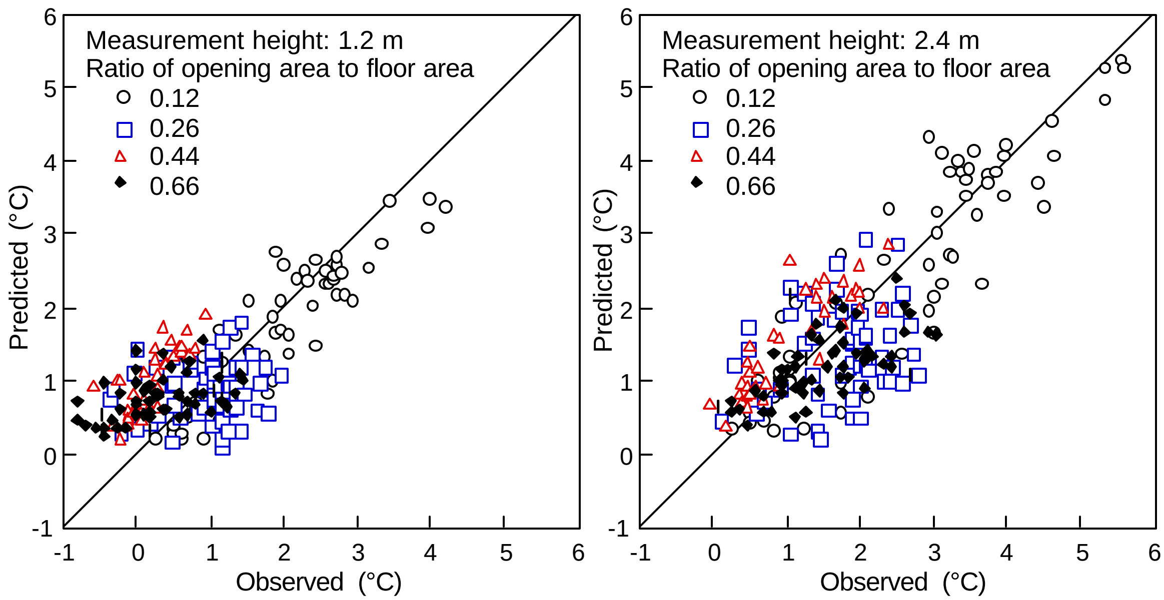

Figure 5. Comparison of observed and predicted temperature differences for four ratios of opening area to the floor area: 0.12, 0.26, 0.44 and 0.66.

In order to demonstrate the general ventilation characteristics under typical conditions, Figure 6 shows the predicted effects of the opening area and the inside net radiation on the temperature difference and the ventilation rate. The parameters for the height of 1.2 m (4 ft) were used to predict the environment at crop level. The term α was assumed to be 0.5 representing a greenhouse with moderate vegetation. The wind velocity of 1 m/s (197 fpm) was chosen as an expected minimum under normal conditions. The temperature difference decreased rapidly with an increase in the opening area when the ratio of the roof opening area to the floor area was smaller than 0.3 to 0.4. At larger opening areas, the slope of the temperature difference curve decreased and the temperature difference was less affected by the opening area. Under these conditions, the temperature difference was almost proportional to the inside net radiation. The ventilation rate showed a linear increase with an increase in the opening area.

The predicted effect of the outside wind velocity on the ventilation rate at a constant opening is illustrated in Figure 7. It was shown that the ventilation rate was less dependent on the wind velocity when the wind velocity was approximately 1 m/s (197 fpm) or less, which indicates that the thermal buoyancy effect is predominant for such a low wind velocity. At a higher wind velocity, the ventilation rate increased almost linearly with an increase in wind velocity, and the differences in ventilation rate due to different levels of net radiation decreased.

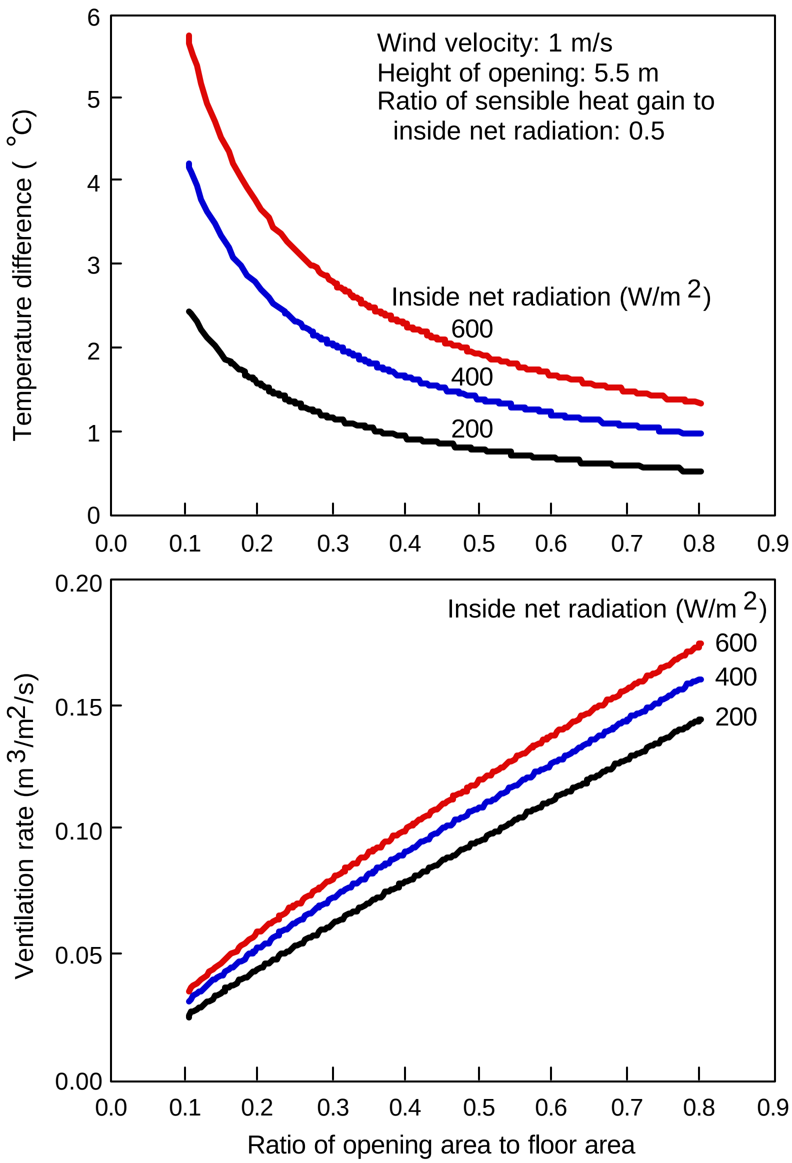

Figure 6. Predicted effects of the opening area and the inside net radiation on the temperature difference and the ventilation rate.

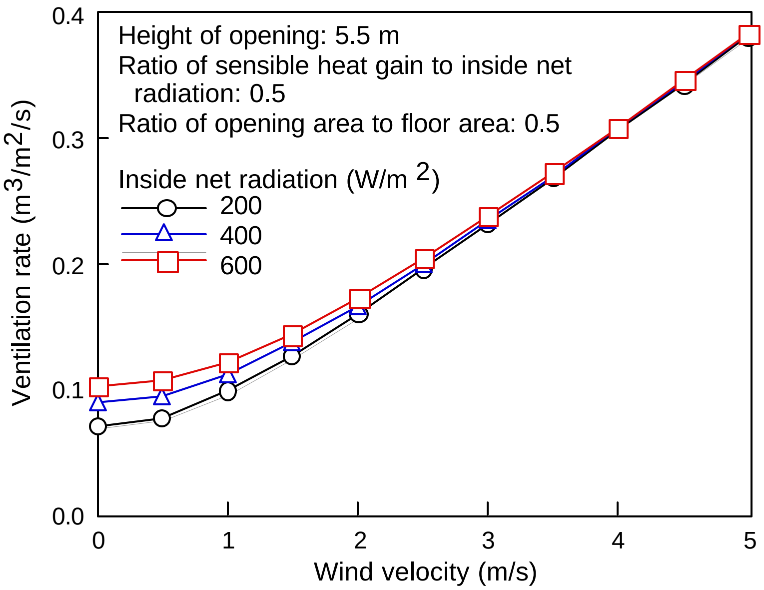

Figure 7. Predicted effect of the outside wind velocity on the ventilation rate using a constant ratio of opening area to floor area (0.5).

Conclusions

A simulation model for open-roof greenhouses was developed to predict the temperature difference between inside and outside and the natural ventilation rate simultaneously. The model parameters were calibrated statistically using the observed conditions of an open-roof greenhouse. The standard errors of the temperature differences for two measurement heights were within 0.9 °C (1.6 °F). There was a trend for the predicted temperature difference to be slightly overestimated when the roof segments were more widely opened. In addition, the observed inside temperature occasionally dropped below the outside temperature. The model is not capable of predicting such negative temperature differences. Although further modification is required, the model can provide a useful means to implement new environmental control strategies for open-roof greenhouses.

Acknowledgements

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