Air Movement and Climate Uniformity in Ventilated Greenhouses

S. Sase
Department of Agricultural Environment Engineering
National Institute for Rural Engineering
Tsukuba, Ibaraki 305-8609, Japan

Keywords: airflow pattern, CFD, natural ventilation, vent configuration, wind effect

Abstract

Air movement caused by ventilation in greenhouses is an important factor that affects the uniformity of greenhouse environment and consequently the uniformity of plant growth and quality. Natural ventilation systems have been widely adopted. The studies of the air movement in naturally-ventilated greenhouses have been performed by means of field experiments, laboratory tests such as wind tunnel tests using scale models, and numerical simulations using computational fluid dynamics (CFD) approach. The primary characteristics of the air movement caused by wind and stack effects in a single-span greenhouse are described. Recent studies on the air movement and the uniformity of environment under natural ventilation are reviewed and discussed with respect to the multi-span greenhouses, the effect of plants, the vent configuration, and the effect of wind direction.

INTRODUCTION

Greenhouse production has been expanding in the regions under mild climate. Year-round production in greenhouses is one of the primary concerns to increase the greenhouse efficiency and the plant productivity. The technologies to cool greenhouse air on hot sunny days have been becoming more important. Particularly, natural ventilation systems, which are significantly less energy intensive than fan ventilation systems, have been widely adopted. Under mild climate, a large amount of ventilation is required to prevent an excessive rise in internal air temperature and it is often difficult to realize such amount of ventilation less economically with fan ventilation. Ventilation is important through the year to supply CO_2 from the external air and control humidity. Ventilation also affects the plant growth through the induced airflow, which promotes gas and energy exchange between the plants and the surrounding air.

The greenhouse design and control technologies have made significant progress. The eaves (gutter) heights of greenhouses have been increased to ensure the uniformity and stability of environment. The wider vent openings are expected to improve the natural ventilation performance. One of the innovations in the greenhouse structures is the open-roof design, which has been introduced as a solution in the middle of the 1990s (Roberts, 2001). In order to cool the internal temperature below the external temperature, evaporative cooling is only a method that is the most practical and inexpensive in operating cost. Although the pad-and-fan cooling has been widely utilized for fan ventilated greenhouses, the fog cooling in combination with natural ventilation has been introduced. Another method to prevent an excessive rise in greenhouse temperature is shading to decrease incoming solar radiation. Evaporative cooling and/or shading systems function well in combination with proper ventilation.

Air movement caused by ventilation in greenhouses is an important factor that affects the uniformity of greenhouse environment and consequently the uniformity of plant growth and quality. The temperature distribution has a close relationship with internal airflow caused by ventilation. The studies of the air movement in greenhouses have been performed by means of field experiments, laboratory tests such as wind tunnel tests using scale models, and numerical simulations (Bailey, 2000; Boulard et al., 2002; Critten and Bailey, 2002). Advancements in velocity vector measurement techniques such as sonic anemometer systems for field experiments and particle imagery velocimetry

(PIV) systems for laboratory tests have allowed the airflow distribution to be quantitatively analyzed. In recent years, rapid progress in computational fluid dynamics (CFD) codes has taken and CFD techniques has been increasingly applied to study the airflows in greenhouses (Reichrath and Davies, 2002). In common CFD simulations, the computational domain is divided into cells and the discretized governing equations such as continuity equation and Navier-Stokes equation are solved across each cell. The advantages of CFD include the investigation of environmental parameters at many points of interest, the easy change in weather and structural conditions, the visualization of airflow, and the saving of time, labor and cost. The accuracy of CFD results has been improved by verification tests and improvement of related models. More recent concerns in the CFD studies have focused on the internal airflows in a greenhouse with plants and the interactions between the plant canopy and the ventilated air by incorporating the heat and mass balance models (Boulard and Wang, 2002).

In this paper, the primary characteristics of the air movement caused by wind and stack effects in a single-span greenhouse are described. Recent studies on the air movement and the uniformity of environment under natural ventilation are reviewed and discussed with respect to the multi-span greenhouses, the effect of plants, the vent configurations, and the effect of wind direction.

PRIMARY AIRFLOW CHARACTERISTICS FOR A SINGLE-SPAN GREENHOUSE

The phenomenon of natural ventilation is complex and its design is more difficult than fan ventilation. Natural ventilation is induced by the pressure differences across the vent openings. The pressure differences are caused by external wind force (wind effect) and buoyancy force (stack effect) based on the temperature rise (temperature difference between internal and external airs). The theory based on Bernouilli's equation indicates that the natural ventilation rate varies linearly with external wind velocity and area of vent openings. Previous works (for example, Baeza et al., 2005) have shown the features. When stack effect exists, the natural ventilation rate varies linearly with the square roots of height of openings and temperature rise.

The air movement in the naturally-ventilated greenhouses is affected by the shape, size and arrangement of vent openings as well as external wind velocity and direction. Fig. 1 shows the airflows caused by wind effect under isothermal condition in a single-span greenhouse equipped with continuous ridge and side vents when wind blows into a side wall (Sase et al., 1984). It was obtained by a wind tunnel test using a 1/10 scale model. It was indicated that the airflow patterns were influenced primarily by the shape of vent opening through which the external air entered. The incoming air through the windward side vent tended to move up immediately by the influence of inclined vent flap and mainly followed the inner surfaces of the roof. In the space to be occupied with a crop, the reverse flow due to secondary circulation resulted in the significant decrease in air velocity. With the roll-up vents in side walls, on the other hand, the incoming air moved directly toward the leeward side vent causing the air velocity in the crop space to increase. The investigations of various arrangements of vents showed that the airflow pattern depended primarily on the shape of the windward side vent and similar airflow patterns were observed whenever the windward side vent and some of other vents were open.

Figure 2 shows a transition of airflow patterns affected by the combination of wind and stack effects for a same greenhouse with all hinged vents open (Sase et al., 1984). The stack effect was simulated using a heated floor and Archimedes number was taken into account to ensure the similarity of the model test. Under calm conditions as shown in top drawing of Fig. 2, the cool incoming air through both side ventilators followed horizontally on the floor, and as it was heated during this movement it went up at the center of the greenhouse. This airflow determined the temperature distribution characterized by the horizontal increase of temperature from both side walls to the center of the greenhouse and caused a high temperature in the center vertical space.

For the case of combined action of wind and stack effects, the airflow pattern considerably changed with increasing wind velocity and the temperature distribution was closely related with the airflow pattern (Fig. 2). These were summarized as follows. At a wind velocity of 0.2 m s^{-1}, a small amount of increase of wind velocity caused the cool air incoming through the windward side vent to be directed upward but this air fell immediately by the effect of large density. Then the air went up again below the leeward roof and mixed together with the incoming air through the leeward side vent. Consequently, the high temperature region shifted to the leeward side. With increasing wind velocity, such as 1.0 m s^{-1}, the incoming air went deeper into the greenhouse and came out through the leeward side vent, and a portion was drawn off at the leeward edge of the ridge opening. Temperature was maximum at the windward floor due to secondary circulation. At wind velocity higher than 2.2 m s^{-1}, the airflow pattern was similar to that under isothermal conditions described previously, which gave no significant difference in the pattern of temperature distribution. It was concluded that the airflow pattern is transitional below a certain wind velocity and wind effect dominates at higher wind velocity. For the greenhouse with hinged vents, the transition of airflow pattern may occur in the range of wind velocity less than 1-2 m s^{-1}. With roll-up side vents, the lower limit of wind velocity above which wind effect acts dominantly seems to decrease due to the induced straight flow passing smoothly through the crop space.

AIRFLOW IN MULTI-SPAN GREENHOUSES WITH ONLY ROOF VENTS

One of typical multi-span greenhouse types is a Venlo greenhouse. Since only the multiple roof vents are positioned in a staggered arrangement on the ridge, the internal airflows are complicated. Fig. 3 shows an example of the internal airflow in a Venlo greenhouse with all roof vents open by means of wind tunnel testing (Okushima et al., 1998). A PIV system was used for the two-dimensional visualization of airflow patterns and the measurement of velocity vectors. Although the greenhouse model used for testing was only two-span, it was found that the external air entered through the vent opening facing the windward on the windward span and an air circulation with reverse flow above the floor was induced. The intensity of circulation was affected by the combination of open and closed roof vents. The windward vent opening on the windward span showed the most significant effect on the intensity of circulation. On the other hand, the circulation was much weaker when the windward vents were closed.

Lee et al. (2003) reported similar but more complicated airflow patterns in 2- to 10-span Venlo greenhouse by means of wind tunnel testing and PIV measurements. Fig. 4 shows the measured velocity vectors of a 6-span greenhouse with all roof vents open. The air circulation in the windward two spans was similar to that shown in Fig. 3, but another circulation was found from the third to sixth spans from the windward side, where the external air entered through the vents in the most leeward span and moved toward the windward spans. As a result, the airflow direction in the crop space was opposite to the external wind. Lee et al. (2003) also conducted a wind test of an open-roof greenhouse with hinged roofs at the gutter. It was shown that the external air entered into the leeward span and went out from the windward span, resulting in a strong reverse flow across the greenhouse. The internal air velocities as well as ventilation rate were found to be much greater than those for the 6-span Venlo greenhouse.

Wang and Deltour (1999) measured the air velocities in a 12-span Venlo greenhouse using a multi-point two-dimensional sonic anemometer system and found similar reverse airflows with the leeward vents open. Reichrath and Davies (2002) conducted a two-dimensional CFD analysis of a 60-span Venlo greenhouse with the leeward vents open. It was found that a reverse flow existed in the windward part of the greenhouse and at approximately 60% of the total greenhouse length from the windward side a low velocity zone or dead zone was located. It is interesting to note that the dead zone separated the reverse flow section from a section on the leeward side where the internal flow direction was same as the external wind. Similar effects of the increase in greenhouse width on airflow pattern were reported for a gothic greenhouse using CFD (Kacira et al., 2004a).

Okushima et al. (2000) investigated the temperature distribution in a model 6-span Venlo greenhouse in a wind tunnel with a wind direction perpendicular to the gutters and with electric heating mats on the floor to simulate solar heating. The model greenhouse contained a simulated tomato crop with the rows parallel to the gutters. The results indicated that the temperature distribution was related to the air circulation affected by wind velocity and crop canopy. It was found that the highest air temperatures occurred in the windward space of greenhouse when the wind velocity was 1 m s^{-1}, while the spatial average temperature decreased linearly with an increase in wind velocity above 1 m s^{-1}. The temperature distribution without crop was similar, but the air circulation above the crop canopy became weaker as the crop height was increased.

Growers occasionally point out the additional vent openings for multi-span greenhouses to improve poor ventilation with only roof vents. Kacira et al. (2004a) conducted CFD simulations to investigate the effect of side vents in relation to the span number of a gothic greenhouse with a continuous roof vent on the leeward side of each ridge. It was found that when both sides were fully open the internal airflow pattern changed significantly and the ventilation rate increased for the 6-span greenhouse. However, the ventilation rate decreased exponentially as the span number increased up to 24. This reduction is reasonably explained by the fact that the area of side vent openings is kept constant and the area per greenhouse floor decreases with an increase in the span number.

AIRFLOW AFFECTED BY PLANTS

When the tall plants such as tomato plants are grown in a greenhouse, the plant arrangement including plant density and canopy structure affects the internal airflow and the consequent ventilation performance. However, most of wind tunnel tests and CFD studies to investigate the internal airflow have been carried out for empty greenhouses.

Sase (1989) showed a considerable effect of the orientation of tomato plant rows on the internal airflow resulting from the side vents in a two-span glasshouse with continuous hinged side and ridge vents. At a wind direction perpendicular to the side walls, the internal air velocity was almost proportional to the wind velocity and the average of internal air velocity increased up to 36% of the external wind velocity when the plant rows were perpendicular to the side walls. When the plant rows were parallel to the side walls in a conventional way, the average was 13 to 18%. At a wind direction parallel to the side walls, the average was 13 to 21% and the internal air velocity was almost independent of row orientation. When only the ridge vents were open, the average was 12% and the internal air velocity was independent of row orientation and wind direction. Similar internal air velocities (10-15% of the external wind velocity) were found in a two-span greenhouse occupied by mature tomato plants and equipped with two continuous roof vents (Wang et al., 1999).

These effects of plant row orientation on the internal air velocity were later confirmed in the verification process of the CFD study including the plant canopy (Kacira et al., 2004b). Fig. 5 shows a comparison of the velocity vectors caused by wind effect without and with plants for the plant rows parallel to the side walls in a two-span greenhouse with continuous roll-up side and hinged ridge vents. The plant canopy was approximated as a porous medium, where the necessary drag coefficient of the tomato plant canopy was determined by means of wind tunnel tests. The plant density and the row arrangement were assumed to be same as those in Sase (1989). It was demonstrated that without the existence of plants most of the air entering the greenhouse from the windward side opening traveled along the greenhouse floor and left the greenhouse from the leeward side opening. However, the airflow pattern changed when plants existed in the greenhouse. The magnitudes of air velocities were reduced dramatically due to the drag effect of the plants, and the air tended to move upward, toward the roof opening in the leeward span of the greenhouse. It is likely that the horizontal airflow through the plant canopy resulting from the side vents is prevented in the leeward spans as the span number increases. Lee and Short (2000) showed similar effects of the presence of plants and benches on the airflow patterns in a 4.5-span curved-roof greenhouse, and reported 12% reduction in the average air exchange with plants.

EFFECT OF VENT CONFIGURATION

To ensure the sufficient ventilation and the uniformity of greenhouse environment, optimization of vent configuration is important. Studies on vent configuration have been conducted to improve the airflow and the consequent uniformity of greenhouse environment, particularly for the regions under mild climate.

Montero et al. (2001) investigated the effect of vent configuration of a single-span curved-roof greenhouse equipped with roll-up side and raised roof vents on the wind-induced ventilation. A 1/15 scale model of the greenhouse was installed in a flume tank filled with water and four different vent configurations were compared. With all vents open, an incoming jet-like flow crossed the greenhouse from the windward side vent to the leeward side vent and established a recirculating flow below the roof. With only the roof vent, the internal flow velocities were very low due to the passing air through the space of the raised roof vent. Nielsen (2002) offered a unique method to direct the passing airflow at the hinged ridge vents into the crop space. Using a 1-m high vertical screen mounted to the ridge, improvements were achieved in the air exchange in the plant zone of about 50% on average.

Kacira et al. (2004b) investigated the effect of different vent configurations on the wind-induced ventilation and the airflow patterns in a two-span greenhouse with tomato plants under transverse wind conditions using CFD approach. To exclude the ventilated air that did not reach the plant canopy, the ventilation rate for plant canopy zone was defined and compared with the greenhouse ventilation rate. Eight vent configurations were investigated by combining continuous roll-up vents for side walls and continuous hinged vents for side walls and ridges. The results showed that the maximum greenhouse ventilation rate was achieved when roll-up side vents and hinged ridge vents were fully open (Fig. 6). The minimum rate was predicted when only hinged side vents were open. Concerning the ventilation for plant canopy zone, fully-open roll-up side and leeward ridge vents with closed windward ridge vents improved the airflow and advanced the ventilation rate by 11% in the plant canopy zone compared with the vent configuration where the maximum greenhouse ventilation rate was obtained. When the windward ridge vent of the windward span was closed, the ridge opening acted as an air outlet and the incoming airflow rate through the windward side vent increased. This increase in airflow rate was likely to lead to an improvement of the horizontal airflow in the plant canopy zone.

Bartzanas et al. (2004) investigated numerically the effect of four vent configurations of a tunnel greenhouse with tomato crop for a wind direction perpendicular to the vent openings. The solar radiation and transpiration models based on the heat and water balances of the crop were incorporated into the original CFD code. The results demonstrated that the temperature distributions followed the airflow patterns and high air temperatures occurred near the greenhouse corners where air velocity was low. With only the roof vent open, the most uniform distribution of air temperatures was obtained due to a better air mixing caused by the circulating airflow, but the average air temperature was 2 °C higher than the outside air. With the roof vent and both the roll-up side vents open, the ventilation efficiency was the best due to the incoming air through the windward side vent, which moved directly toward the leeward side vent, but the uniformity of air temperature distribution was poor. These indicated that the higher ventilation efficiency to cool the greenhouses led to the lower homogeneity of air temperature field.

EFFECT OF WIND DIRECTION

Most of the works described in the previous sections are associated with the winds perpendicular to the gutters or the side walls. For this wind direction, the ventilation rate is increased when the windward side and/or roof vents are open. Bailey et al. (2004) conducted a wind tunnel test for a 5-span Venlo greenhouse and investigated the effect of windward and leeward vent openings on the ventilation rate. It was found that windward ventilation gave higher ventilation rates than leeward ventilation, and the combined windward and leeward ventilation gave higher ventilation rates than the sums of the windward and leeward ventilation rates.

However, there have been few studies on the effect of different wind directions on the internal airflow distribution. Sase et al. (1984) investigated the effect of wind direction on the air temperature distribution in a single-span greenhouse mentioned above. The three-dimensional temperature distributions showed that considerably higher temperatures occurred in the space adjacent to the windward gable-end with the wind direction approaching to a parallel direction to the ridge. This resulted from the air inflow through the leeward side vents and the air outflow through the ridge and side vents.

Haxaire et al. (2000) found similar airflow patterns experimentally and numerically in a two-span greenhouse with only continuous roof vents. With the wind direction parallel to the gutters, the external air entered through the leeward part of the roof vents, flew in counter current with respect to wind direction, and left through the first 2 m of the windward roof vents. It was demonstrated that the airflow patterns were caused by a longitudinal variation of wind pressure on the vent openings from the leeward side (strong negative pressure) to the windward side (weak negative pressure). Similar CFD study was conducted for a tunnel greenhouse with insect screens on the side vents by Bartzanas et al. (2002). The effect of different wind directions including a 45° angle was investigated. It was shown that wind direction considerably affected the airflow and temperature distributions. Roy and Boulard (2005) investigated the effect of wind direction for a tunnel greenhouse equipped with separated side vents using CFD in combination with the tomato crop model for the heat and humidity transfers between the crop and the internal air. With the wind direction parallel to the side walls, the air velocity was lower near the side walls and the air temperature and relative humidity were higher in the entire greenhouse space compared with the wind directions of perpendicular and 45° angle. The differences in those between the wind directions of perpendicular and 45° angle were smaller.

Campen and Bot (2003) investigated the effects of wind direction varying at 15° intervals and vent configuration on the natural ventilation for a 5-span Spanish parral greenhouse without a crop using CFD. It was demonstrated that the ventilation rate was significantly dependent of wind direction for both roll-up and flap vents, and the lower and higher peaks of ventilation rates also occurred with the wind directions which were different from the directions parallel and perpendicular to the gutters. With the roll-up vents, the ventilation rate was less dependent of wind direction and the average ventilation rate over wind direction was higher than the flap vents due to the difference in the vent opening area.

CONCLUSIONS

The internal air movement in a naturally-ventilated greenhouse is affected by many factors such as wind velocity, wind direction, temperature difference between internal and external air, greenhouse structure and vent configuration that includes size, shape and arrangement of vent openings. The understanding of the air movement has been advanced through the scale model and field experiments with the improved measurement techniques. Recent progresses in the CFD techniques have accelerated the more detailed analysis of the air movement in combination with verification tests.

Recent works have focused on the more specific topics related to the air movement. In the CFD studies, the solar radiation and transpiration models based on the heat and water balances of the crop have been incorporated to investigate the distributions of air temperature and humidity, and the interactions between the crop and the air, in addition to the airflow distribution. These approaches are more complicated and need more verification, but will provide a realistic simulation of the greenhouse environment. From the environmental concerns, some studies have been conducted to investigate the ventilation and the internal airflow in the greenhouses equipped with insect screens which restrict the airflow. The improvement of ventilation of the specific greenhouses is an another concern. Particularly under mild climate, appropriate design and control of ventilation are required to ensure the effective cooling and the uniformity of environment. There may be a conflict between the increase in ventilation and the improvement of uniformity. In a fog-cooled greenhouse in combination with natural ventilation, the cooled air by fogging above the plants is likely to go down. There is little information on the air movement affecting the cooling efficiency and the uniformity of environment.

Future attempts to optimize the vent configurations in relation to the greenhouse structures are needed for the proper ventilation design which provides the sufficient ventilation rate and the uniformity of environment. More sophisticated environmental control strategies based on the understanding of the air movement are also required for the efficient greenhouse production.

Literature Cited

Baeza, E.J., Perez-Parra, J. and Montero, J.I. 2005. Effect of ventilator size on natural ventilation in parral greenhouse by means of CFD simulations. Acta Hort. 691:465-488.

Bailey, B.J. 2000. Constraints, limitations and achievements in greenhouse natural ventilation. Acta Hort. 534:21-30.

Bailey, B.J., Robertson, A.P. and Lockwood, A.G. 2004. The influence of wind direction on greenhouse ventilation. Acta Hort. 633:197-204.

Bartzanas, T., Boulard, T. and Kittas, C. 2002. Numerical simulation of the airflow and temperature distribution in a tunnel greenhouse equipped with insect-proof screen in the openings. Compt. Electron. Agri. 34:207-221.

Bartzanas, T., Boulard, T. and Kittas, C. 2004. Effect of vent arrangement on windward ventilation of a tunnel greenhouse. Biosyst. Eng. 88:479-490.

Boulard, T., Kittas, C., Roy, J.C. and Wang, S. 2002. Convective and ventilation transfers in greenhouses, Part 2: determination of the distributed greenhouse climate. Biosyst. Eng. 83:129-148.

Boulard, T. and Wang, S. 2002. Experimental and numerical studies on the heterogeneity of crop transpiration in a plastic tunnel. Compt. Electron. Agri. 34: 173-190.

Campen, J.B. and Bot, G.P.A. 2003. Determination of greenhouse-specific aspects of ventilation using three-dimensional computational fluid dynamics. Biosyst. Eng. 84:69-77.

Critten, D.L. and Bailey, B.J. 2002. A review of greenhouse engineering developments during the 1990s. Agri. For. Meteorol. 112:1-22.

Haxaire, R., Boulard, T. and Mermier, M. 2000. Greenhouse natural ventilation by wind forces. Acta Hort. 534:31-40.

Kacira, M., Sase, S. and Okushima, L. 2004a. Effects of side vents and span numbers on wind-induced natural ventilation of a gothic multi-span greenhouse. Japan Agri. Res. Quart., 38(4):227-233.

Kacira, M., Sase, S. and Okushima, L. 2004b. Optimization of vent configuration by evaluating the greenhouse and plant canopy ventilation rates under wind induced ventilation. Trans. ASAE. 47:2059-2067.

Lee, I., Sase, S., Okushima, L., Ikeguchi, A., Choi, K. and Yun, J. 2003. A wind tunnel study of natural ventilation for multi-span greenhouse scale models using two-dimensional particle image velocimetry (PIV). Trans. ASAE, 46(3):763-772.

Lee, I.B. and Short, T.H. 2000. Two-dimensional numerical simulation of natural ventilation in a multi-span greenhouse. Trans. ASAE, 43:745-753.

Montero, J.I., Hunt, G.R., Kamaruddin, R., Anton, A. and Bailey, B.J. 2001. Effect of ventilator configuration on wind-driven ventilation in a crop protection structure for the tropics. J. Agri. Eng. 80:99-108.

Nielsen, O.F. 2002. Natural ventilation of a greenhouse with top screen. Biosys. Eng. 81:443-452.

Okushima, L., Sase, S., Maekawa, T. and Ikeguchi, A. 1998. Airflow patterns forced by wind effect in a Venlo type greenhouse. J. Soc. Agri. Struct., Japan, 29:159-167. (in Japanese with English summary)
Okushima, L., Sase, S., Maekawa, T., Ikeguchi, A. and Bailey, B.J. 2000. Temperature distribution in a naturally ventilated Venlo greenhouse with six spans and high eaves. A wind tunnel study. J. Soc. Agri. Struct., Japan, 30(4):343-352.
Reichrath, S. and Davies, T.W. 2002. Using CFD to model the internal climate of greenhouses: past, present and future. Agronomie. 22:3-19.
Roberts, W.J. 2001. Let the sunshine in. Resource. 8(7):7-8.
Roy, J.C. and Boulard, T. 2005. CFD prediction of the natural ventilation in a tunnel-type greenhouse: Influence of wind direction and sensibility to turbulence models. Acta Hort. 691:457-464.
Sase, S. 1989. The effects of plant arrangement on airflow characteristics in a naturally ventilated glasshouse. Acta Hort., 245:429-435.
Sase, S., Takakura, T. and Nara, M. 1984. Wind tunnel testing on air flow and temperature distribution of a naturally ventilated greenhouse. Acta Hort., 148:329-336.
Wang, S., Boulard, T. and Haxaire, R. 1999. Air speed profiles in a naturally ventilated greenhouse with a tomato crop. Agri. For. Meteorol. 96:181-188.
Wang, S. and Deltour, J. 1999. Lee-side ventilation-induced air movement in a large-scale multi-span greenhouse. J. Agri. Eng. Res. 74:103-110.

Figures

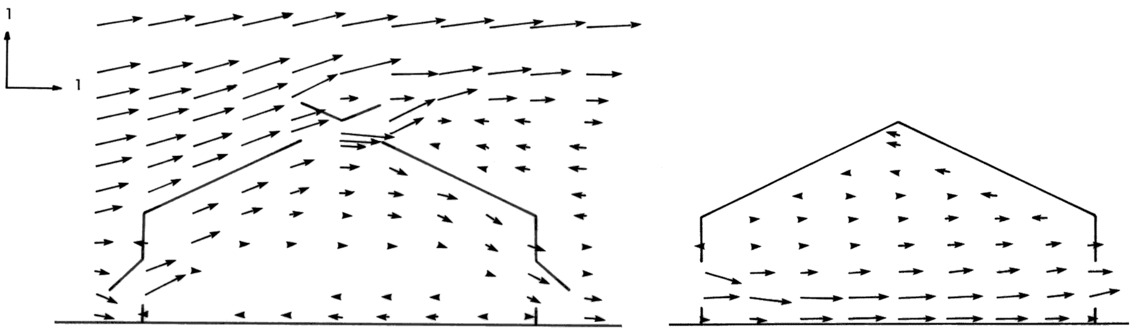

Fig. 1. Comparisons of velocity vectors under isothermal and transverse wind conditions between with hinged vents (left) and with roll-up side vents (right) (Sase et al., 1984). The reference height of the outside wind velocity is 10 m.

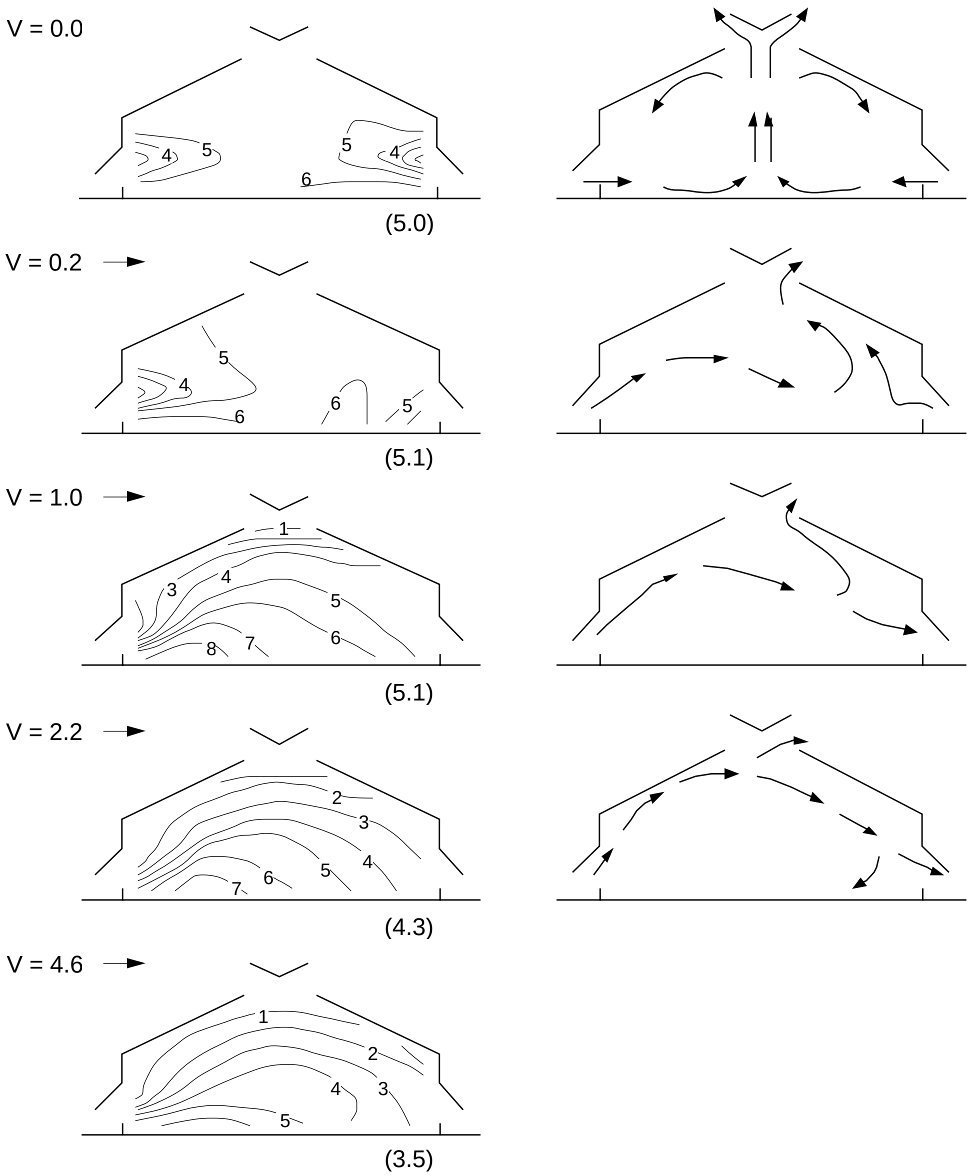

Fig. 2. Effects of wind velocity on the distribution of temperature rise and the airflow patterns under transverse wind conditions (Sase et al., 1984). The airflow patterns were drawn from the flow visualization with smoke. V denotes the reference wind velocity (m s^{-1}) at a height of 10 m. The values in parenthesis are the average temperature rise in the crop space defined as the space below the eaves height.

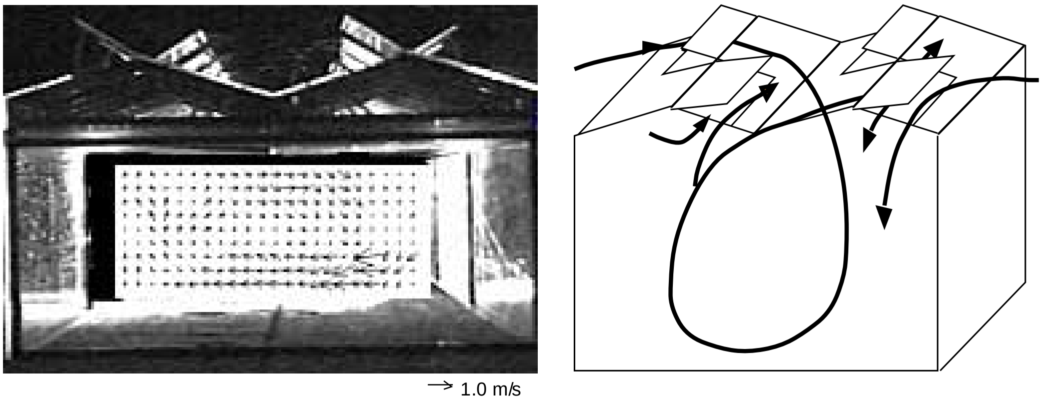

Fig. 3. Airflow caused by wind effect in a Venlo greenhouse (Okushima et al., 1998). Left: velocity vector image obtained with PIV. Right: airflow pattern drawn from observation.

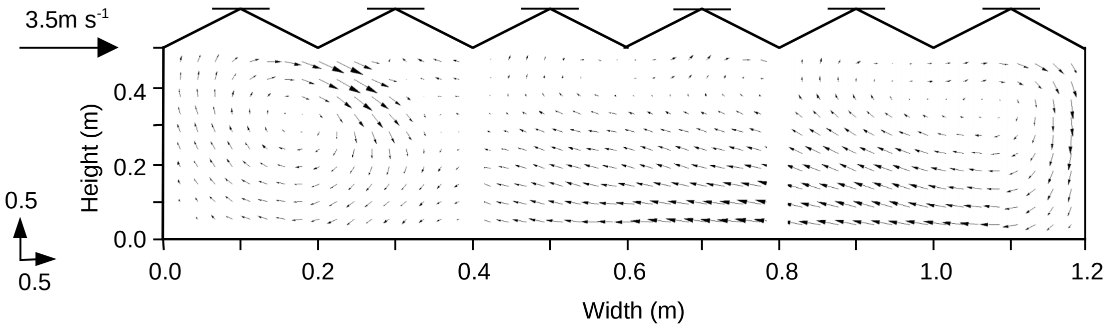

Fig. 4. PIV-computed velocity vectors in a 6-span Venlo greenhouse at an external wind velocity of 3.5 m s^{-1} at gutter height (Lee et al., 2003).

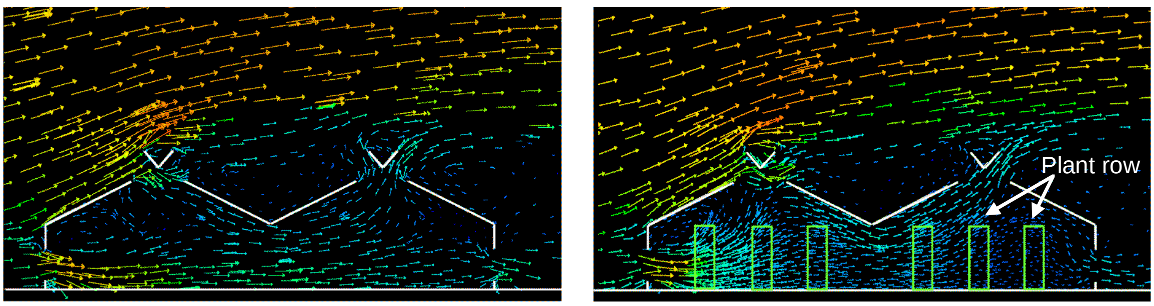

Fig. 5. Comparison of velocity vectors without (left) and with (right) plants for the plant rows parallel to the side walls in a two-span greenhouse with continuous roll-up side and hinged ridge vents (Kacira et al., 2004b).

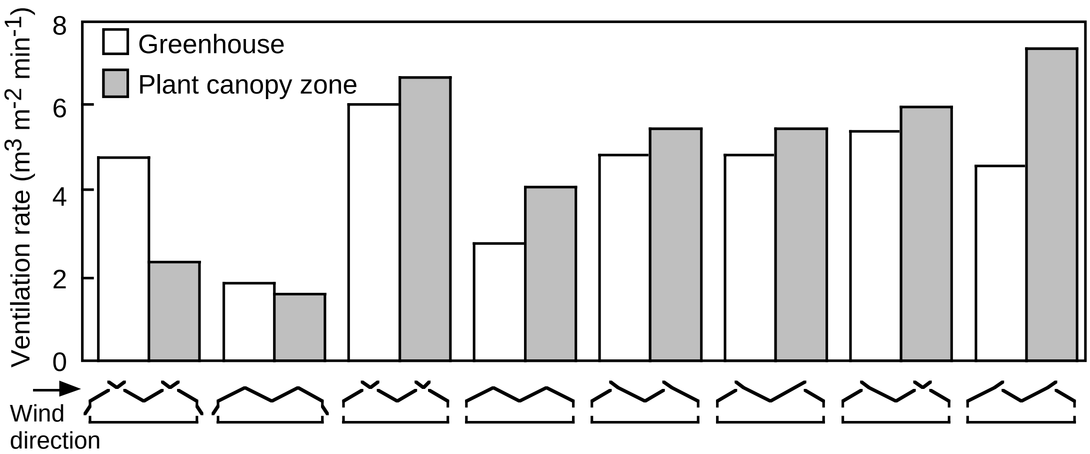

Fig. 6. Effect of vent configuration on ventilation rates for the greenhouse and the plant canopy zone in a two-span greenhouse (Kacira et al., 2004b).