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Evaluation of Structural Characteristics of Naturally Ventilated Multi-Span Greenhouses Using Computer Simulation

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Abstract
Natural ventilation system modifications were evaluated using a computational fluid dynamics (CFD) numerical model (code: Fluent Version 4.5). Wind speed and direction, side vent opening size and location, roof vent opening type, and number of spans were examined in terms of ventilation rates and airflow distribution. For the side vent located at 2.5 m above the floor with a west wind of 2.5 m/s, 59% of the incoming air through the side vent was predicted to move out through the first roof vent opening without reaching distant areas in the greenhouse, resulting in high inside air temperatures. The air mainly moved in through the side vent and fourth roof vent openings for an east wind of 0.5 m/s while the third and fourth roof openings were the only predicted inlets of airflow for an east wind of 2.5 m/s. The hinged open roof multi-span greenhouses were predicted to have significantly higher natural ventilation rates than the double polyethylene-covered multi-span greenhouses for all the spans in the absence of side vent.

Discipline: Agricultural facilities
Additional key words: computational fluid dynamics

Introduction

While mechanical ventilation systems are still widely used throughout the industry presently, high energy costs associated with market-driven production methods have forced growers to consider alternative means of ventilating their greenhouses in order to remain competitive. While natural ventilation systems can be very difficult to design properly, increased emphasis is being placed on such systems for greenhouses as they generally require less electrical energy, less equipment operation and maintenance, and are much quieter than fan ventilation systems.

A common goal of ventilation system designs for greenhouses during hot summer weather is to keep the inside air temperature as close as possible to the outside air temperature. For natural ventilation, this objective is generally achieved by using high air exchange rates, evaporative cooling systems such as fogging, evaporative cooling from plants, and some forms of shading systems. Natural ventilation is achieved by air exchanges through multiple openings due to natural pressure variations inside and outside the greenhouse. Wind is the primary driving force making natural ventilation systems very difficult to design properly because of variations in the wind velocity and direction. The optimization of these systems for suitable climate control requires a thorough knowledge of the airflow rates and patterns in relation to weather conditions and greenhouse structural characteristics[6].

A successful numerical model was assumed to be an ideal tool to analyze the complex phenomena of natural airflow and help designers choose optimum designs. There was a particular interest in computational fluid dynamics (CFD) numerical techniques to analyze the air distribution in agricultural structures as well as air quality and thermal conditions[6].

The objective of this study was to evaluate the consequences of various modifications of natural ventilation

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systems by using a computational fluid dynamics (CFD) numerical model (code: Fluent Version 4.5)[2]. The studies focused on the effects of wind speed and direction, side vent opening size and location, roof vent opening type, and number of spans on ventilation rates and airflow distribution inside and outside multi-span greenhouses.

Woodruff[10], Kacira et al.[4] and Lee[6] studied various naturally and mechanically ventilated greenhouse types by using a CFD numerical model. They mainly investigated the effects of weather conditions, greenhouse structural specifications, internal and external shading screens, number of greenhouse spans, and presence of plants and benches on the air exchange rates in greenhouses.

Lee[6] simulated the natural ventilation of a 2-dimensional four and one-half-span greenhouse in a CFD numerical model and compared it to a control volume energy balance model. Assuming the results of the control volume energy balance model as the standard, the results of the steady state CFD model during a sunny day showed errors (negative values) as high as 15% in the morning and comparable errors (positive values) in the afternoon. Such errors were assumed to be due to heat storage in the floor, benches, and greenhouse structure and the CFD model was found to be the most reliable.

Lee[7] numerically analyzed the temperature distribution in a naturally ventilated multi-span greenhouse with plants by a CFD simulation program using the standard k-ε turbulence model. The computed CFD results of air temperature distribution showed a maximum error of ± 3.2% for west and east winds compared to air temperatures measured in the greenhouse for the same boundary conditions. The measured air temperature distribution showed that the air came into the greenhouse through the leeward side vent opening for low wind speed.

Materials and methods

1) CFD numerical model

The CFD technique numerically solved the Reynolds-averaged form of the Navier-Stokes equations[2,5] within each cell in the domain. The equations were discretized on a curvilinear grid to enable computations in complex and irregular geometries. The Reynolds-averaged process considered the instantaneous fluid velocity to be the sum of a mean and a fluctuating component of turbulence[1,3]. Since the high-frequency and small-scale fluctuations of turbulent flow could not be directly quantified, turbulence numerical modeling related some or all of the turbulent velocity fluctuations to the mean flow quantities and their gradients.

The standard k-ε turbulence model was used in this study because the results were found to be most typical to known ventilation flows[2,4,5,10]. The k-ε turbulence model was an eddy-viscosity model in which the Reynolds stresses were assumed to be proportional to the mean velocity gradients, with the constant of proportionality being the turbulent eddy viscosity. The turbulent viscosity was obtained by assuming that it was proportional to the product of a turbulent velocity scale and length scale. In the k-ε model, these velocity and length scales were obtained from 2 parameters ; the turbulent kinetic energy (k) and the dissipation rate of k (ε).

Close to solid walls, there were boundary layer regions where the local Reynolds number was so small that viscous effects predominated over turbulent effects[2]. To account for this effect and for the large gradients of variables near the wall, the wall function method of Launder and Spalding[5] was used in the CFD model. Wall functions, when used in conjunction with the standard k-ε equations, were intended to reproduce the logarithmic velocity profile of a turbulent boundary layer near the wall.

Fluent V4.5 was a two-part package consisting of a preprocessor, Geomesh, and a main module, Fluent/UNS[2]. Geomesh was used to create geometry and generate structural grids, and the triangular grids were developed to efficiently model the complex geometries of greenhouse structures. Fluent/UNS was used to specify physical models, boundary conditions, and fluid properties in the computational domain. The inlet air flow was assumed to be incompressible, vertically uniform in speed, and all the computations were performed assuming steady-state conditions.

The Boussinesq model[2,5] was used for simulating the buoyancy effect in the computational domain. Thermal boundary conditions were defined at all the fluid inlets and at all the wall/fluid interfaces in the CFD computational domain. At the fluid inlet, the air temperature, air velocity, air velocity direction, atmospheric pressure, gravitational acceleration, turbulence intensity, and characteristic length were specified. The thermal conditions of density, specific heat, viscosity, and thermal conductivity were also specified for the fluid inlets. For the walls, several thermal boundary conditions were specified such as surface temperature, emissivity of the wall, and conductive heat transfer coefficient.

2) Experimental procedures

A simulated four-span, double polyethylene greenhouse (a) and a hinged open roof single-layered glass greenhouse (b) were designed with a side vent and roof vents (Fig. 1). The four-span greenhouse was slightly

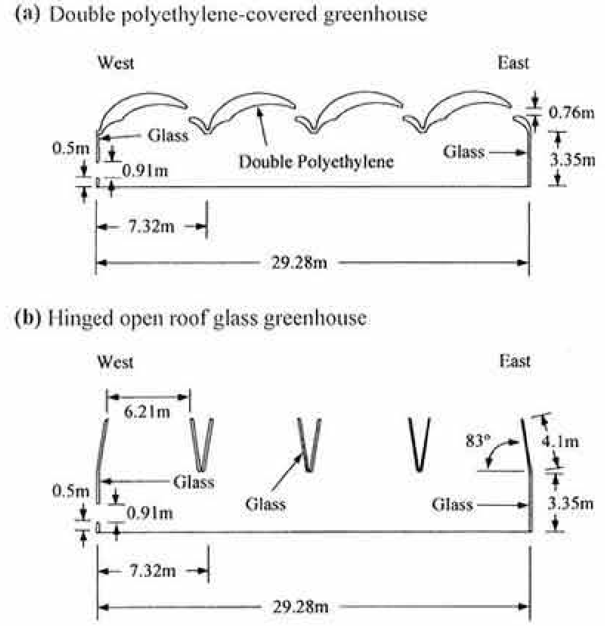


Fig. 1. Sketches of the four-span double polyethylene-covered greenhouse (a) and hinged open roof greenhouse (b) when the vertical west side vent opening size was 0.9 m in height

modified from a four and one-half-span, double polyethylene greenhouse at Quailcrest farm located near Wooster, Ohio[6]. The glass greenhouse was assumed to have a similar gutter configuration to that of the double polyethylene greenhouse. It was assumed to be a peaked-roof house with hinged roof panels that opened and closed via rack-and-pinion drives. For convenience, the spans between gutters were called the first, second, third, and fourth spans from west to east.

Weather data were collected on hot summer (35°C) days for westerly and easterly winds from June 1 to August 30, 1997 near Wooster, Ohio (40°47'N, 81°55'W, elevation 310 m), and generalized for the CFD model inputs shown in Table 1. The input data sets were based on 4 averaged values for 4 min when the weather conditions such as wind speed, wind direction, and solar radiation were stable[6]. Air density, viscosity, specific heat, thermal conductivity, and emissivity of various materials were calculated from the table of thermophysical properties[8,9]. In the 2-dimensional CFD models, no end wall effects were assumed because the input data used in this study were collected when the wind direction was generally perpendicular to the vent openings.

In this study, the 2-dimensional CFD models were developed to investigate the effects of side vent location, side vent opening size, roof vent opening type, number of spans, wind speed, and wind direction on the natural ventilation of multi-span greenhouses without plants and benches. The CFD-computed results of volumetric air change rate per minute (A.C./min), vent opening efficiency, and airflow distribution were compared according to greenhouse structural specifications and weather boundary conditions. The visual representation of the airflow distribution in the greenhouse was obtained via vectors with the CFD model.

Side vent placement was very important to prevent plant damage and yet avoid short-circuiting of airflow out through an adjacent roof vent. The effect of the west side vent location on the natural ventilation of a four-span double polyethylene-covered greenhouse was investigated for west and east winds of 0.5, 1.0, and 2.5 m/s when the vertical roof and side vent opening sizes were 0.76 and 0.9 m in height, respectively. The distance between the bottom of the west side vent opening and floor varied from 0.5 to 2.5 m.

The 2-dimensional CFD models were developed to investigate the effect of the vertical opening size of the west side vent on the natural ventilation of the greenhouse with west and east winds. All the vertical roof vent openings were 0.76 m wide and the distance between the bottom of the west side vent and floor was

Table 1. Constant main input values for the 2-dimensional CFD model

Factor	Value
Wind direction	West (left to right)
	East (right to left)
Roof cover temperature	40°C
Side wall temperature	40°C
Inside ground temperature	43°C
Outside ground temperature	40°C
Sky temperature	32°C
Temperature of inlet (outside) air	32°C
Density of inlet air	1.1448 kg/m^3
Viscosity of inlet air	1.97E-05 kg/m·s
Thermal conductivity of inlet air	0.0267 W/m·°C
Specific heat of inlet air	1007.2 J/kg·°C
Thermal expansion coefficient	0.0033 L/°C
Thermal conductivity of double polyethylene	4.0 W/m·°C
Thermal conductivity of single glass	6.3 W/m·°C
Turbulence intensity	5%
Turbulence length of greenhouse	3.5 m
Gravitational acceleration of inlet air	9.81 m/s^2
Atmospheric pressure	101,324 Pa
Sky emissivity	0.90
Cover emissivity	0.93
Glass emissivity	0.90
Outside ground emissivity	0.95
Inside ground emissivity	0.90

0.5 m. The vertical opening size of the west side vent varied from 0.9 to 2.7 m.

The effects of the roof vent opening type and number of greenhouse spans on natural ventilation rates of multi-span greenhouses were investigated. The predicted natural ventilation rates of the double polyethylene greenhouse (Fig. 1(a)) and hinged open roof greenhouse (Fig. 1(b)) were compared to each other. The average wind speed of 2.5 m/s was assumed based on a statistical analysis of the weather data conducted in Ohio from 1991 to 1995[10]. The distance between the bottom of the west side vent and floor was 0.5 m for all cases. The vertical roof vent opening sizes of the double polyethylene greenhouse were 0.76 m in height while the horizontal roof vent opening sizes of the glass greenhouse were 6.2 m.

Results and discussion

1) Effect of side vent location on natural ventilation

Fig. 2 shows the predicted effects of side vent location, wind speed, and wind direction on the natural ventilation rates in a double polyethylene-covered four-span greenhouse when the vertical side vent and roof vent opening sizes were 0.9 and 0.76 m, respectively. The CFD-computed results showed that the west side vent location exerted the most pronounced effect on the total ventilation rate for a west wind where the rates were reduced by approximately 20, 16, and 14% for winds of 2.5, 1.0, and 0.5 m/s, respectively when the west side vent was moved from the lowest to highest position. The results indicated that the lowest side vent location (0.5 m above floor) gave the highest natural ventilation rate for both wind directions and the west wind led to an average of 11% higher natural ventilation rate than the east wind. An east wind of 0.5 m/s, however, showed a 17% higher natural ventilation rate than a west wind of 0.5 m/s while a west wind of 2.5 m/s showed a 20% higher natural ventilation rate than an east wind of 2.5 m/s. With low east wind speed, the combination of buoyancy and wind effects exerted a positive pressure on the fourth roof vent and the west side vent openings. This resulted in both vent openings being inlets and a greater natural ventilation rate than in the case of a west wind with the same speed.

The CFD-computed results in Table 2 showed that the side vent was a very active vent opening as either an inlet or outlet depending on both wind speed and direction. The air mainly moved in through the side vent and fourth roof vent openings for an east wind of 0.5 and 1.0 m/s while the third and fourth roof openings were the only predicted inlets of airflow for an east wind of 2.5 m/s.

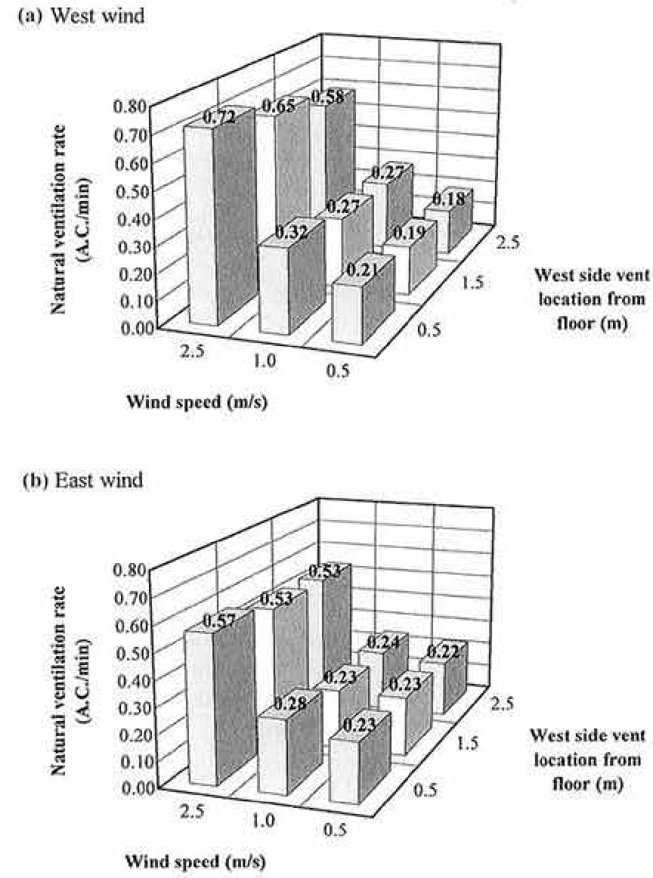


Fig. 2. CFD-computed natural ventilation rates (A.C./min) in a double polyethylene-covered four-span greenhouse based on west side vent location, wind direction, and wind speed when the vertical side vent and roof vent opening sizes were 0.9 and 0.76 m, respectively

When the bottom of the side vent was located at 0.5, 1.5, and 2.5 m above the floor, the percentages of airflow through the side vent as an inlet were 70, 44, and 37%, respectively for an east wind of 0.5 m/s while 57, 44, and 42%, respectively as an outlet for an east wind of 2.5 m/s. It indicated that the side vent was likely to become a more active vent opening as the side vent location was lower.

For a west wind, as shown in Table 2, the incoming air was predicted to enter the side vent and the first roof vent openings and to move out at all the other roof vents when the bottom of the side vent was located at 0.5 and 1.5 m above the floor. The incoming air, however, was predicted to enter the side vent and the fourth roof vents for a low west wind speed when the bottom of the side vent was located at 2.5 m above the floor. For the same vent configuration and a west wind of 2.5 m/s, approxi-

Table 2. CFD-computed percentages of volumetric inlet and outlet airflow at vent openings based on west side vent location (W.S.V.L.), wind speed, and wind direction when the vertical west side vent and roof vent opening sizes were 0.9 and 0.76 m, respectively

W.S.V.L.[b)] (m)	West wind (m/s)	Percentage of inlet/outlet airflow at vent opening[a)] (%)				
		Side	Roof 1	Roof 2	Roof 3	Roof 4
0.5	0.5	94/0	6/2	0/20	0/39	0/39
	1.0	98/0	2/7	0/24	0/32	0/37
	2.5	94/0	6/1	0/20	0/33	0/46
1.5	0.5	88/0	12/0	0/23	0/40	0/37
	1.0	95/0	5/4	0/26	0/32	0/38
	2.5	90/0	10/0	0/24	0/31	0/45
2.5	0.5	92/0	0/19	0/22	0/45	8/14
	1.0	98/0	0/39	0/11	0/33	2/17
	2.5	92/0	0/54	8/0	0/11	0/35
Vent location (m)	East wind (m/s)	Percentage of inlet/outlet airflow at vent opening[a)] (%)				
		Side	Roof 1	Roof 2	Roof 3	Roof 4
0.5	0.5	70/0	0/15	0/39	0/46	30/0
	1.0	29/0	0/28	0/52	0/20	71/0
	2.5	0/57	0/20	0/12	5/11	95/0
1.5	0.5	44/0	0/26	0/57	0/17	56/0
	1.0	11/0	0/55	0/36	0/9	89/0
	2.5	0/44	0/27	0/16	5/13	95/0
2.5	0.5	37/0	0/52	0/44	3/4	60/0
	1.0	22/0	0/65	0/23	0/12	78/0
	2.5	0/42	0/28	0/17	5/13	95/0

a): The roof (vent) number is counted from the west span to the east span.
b): W.S.V.L. indicates the distance between the bottom of the west side vent opening and floor.

mately 59% of the incoming air through the side vent was predicted to "short-circuit" out through the first roof vent opening. This also resulted in a very low velocity prediction near the plant level in the third and fourth spans in spite of a favorable overall natural ventilation rate as shown in Fig. 2.

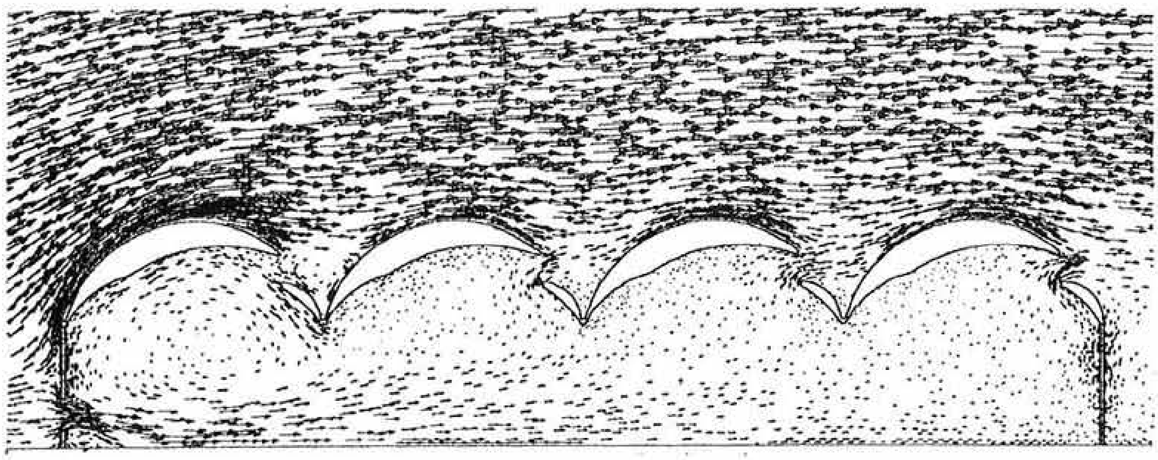
Fig. 3 shows the CFD-computed vectors of airflow in a double polyethylene multi-span greenhouse for a west wind of 2.5 m/s when the bottom of the west side vent opening was located at 0.5 m (a) and 2.5 m (b) above the floor. Fig. 3(a) shows that the predicted inlet air moved along the floor from west to east in the greenhouse when the side vent was located at 0.5 m above the floor. A large portion of the inlet air through the side vent located at 2.5 m above the floor, however, was predicted to move out through the first roof vent opening and the air flow was very low at the second, third, and fourth vents of the greenhouse.

2) Effect of side vent opening size on natural ventilation

Fig. 4 shows the effects of the vertical west side vent opening size, wind speed, and wind direction on the natural ventilation rate in a double polyethylene-covered four-span greenhouse when the bottom of the side vent opening was located at 0.5 m above the floor. Fig. 4 shows that the averaged natural ventilation rates with the vertical side vent opening sizes of 0.9, 1.8, and 2.7 m in height, were 0.42, 0.71, and 0.95 A.C./min, respectively for a west wind and 0.36, 0.64, and 0.78 A.C./min, respectively for an east wind. The CFD-computed results indicated that the west side vent opening size could markedly affect the natural ventilation rate of the greenhouse, especially for the west wind and high east wind speed.

Table 3 shows the CFD-computed percentages of volumetric airflow at each vent opening based on the vertical west side vent opening size, wind speed, and wind direction. For west winds, the side vent was the only inlet of airflow with vertical side vent opening sizes of 1.8 and 2.7 m in height while the side vent and the first roof vent openings were inlets with a vertical side vent opening size of 0.9 m in height. For east winds of

(a) Side vent located at 0.5 m above the floor



(b) Side vent located at 2.5 m above the floor

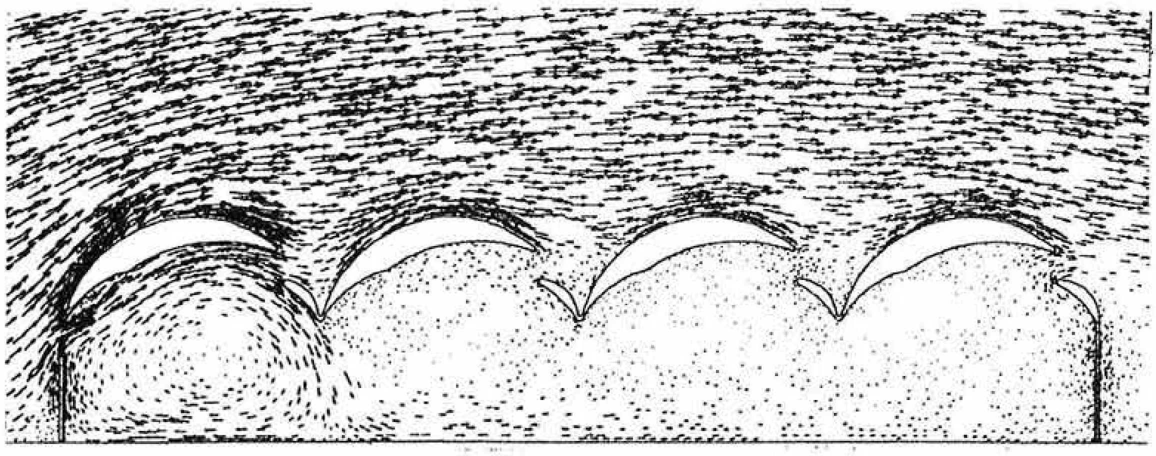
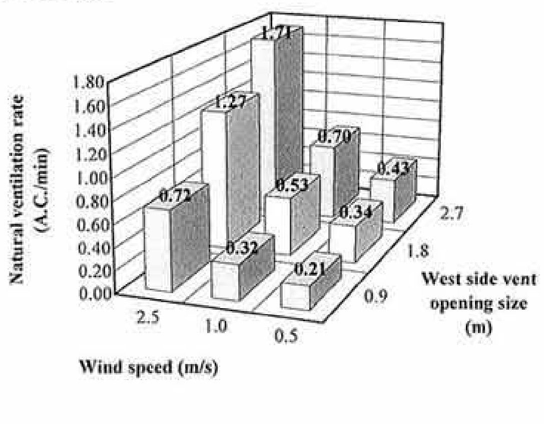


Fig. 3. CFD-computed vectors of airflow in a double polyethylene multi-span greenhouse for a west wind of 2.5 m/s when the bottom of the west side vent opening was located at 0.5 and 2.5 m above the floor

The vertical side vent opening size was 0.9 m in height. The minimum and maximum computed air velocities in the computational domain were (a) 0.004 and 4.48 m/s, respectively and (b) 0.002 and 4.49 m/s, respectively.

(a) West wind



(b) East wind

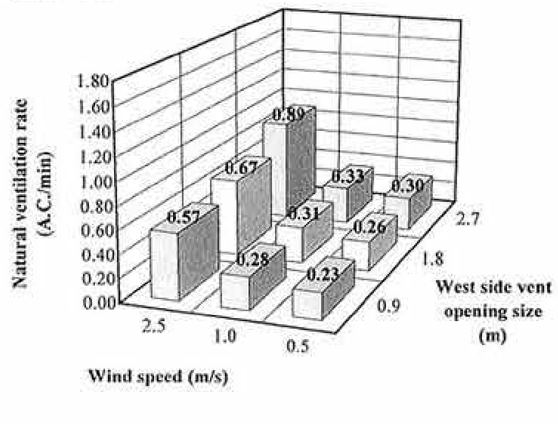


Fig. 4. CFD-computed natural ventilation rate (A.C./min) in a double polyethylene-covered four-span greenhouse based on west side vent opening size, wind direction, and wind speed when the bottom of the side vent was located at 0.5 m above the floor

0.5 and 1.0 m/s, the side vent became a more active inlet of airflow as the vertical side vent opening size increased while the side vent was predicted to be a significant outlet for an east wind of 2.5 m/s.

3) Effect of number of spans and roof vent opening type on natural ventilation

The predicted effects of the number of spans and vertical west side vent opening size on the natural ventilation rate in double polyethylene multi-span greenhouses for a west wind of 2.5 m/s are shown in Fig. 5(a). The CFD-computed results indicated that the natural ventilation rate decreased as the number of greenhouse spans increased while the natural ventilation rate was directly proportional to the vertical west side vent opening size for all cases. Even an 8-span greenhouse (60 m wide) was predicted to have a high natural ventilation rate when a large side vent opening was used. The CFD-computed results also showed that the natural ventilation was very low without the windward side vent opening. As shown in Table 4(a), the air generally was predicted to come into the greenhouse through the windward side vent and the first roof vent with a 0.9 m side vent opening while the side vent was predicted to be the only inlet of airflow with a windward side vent opening of 2.7 m in height. It was also predicted that the flow rates of the roof vents as outlets increased from windward to leeward walls when the windward side vent was open. When the windward side vent was closed, however, the air was predicted to mainly move into the greenhouse through the middle roof vents and move out through both end side roof vents.

The predicted effects of the number of spans and vertical west side vent opening size on natural ventilation rate for a hinged open roof multi-span greenhouse with a west wind of 2.5 m/s are shown in Fig. 5(b). Significantly higher natural ventilation rates were predicted compared to the double polyethylene greenhouses for all the spans, especially when no side vent or a small side vent was used. It indicated the influence of the roof vent opening size and shape and the possibility of air moving over the windward wall and the creation of reverse flow in the greenhouse at plant level.

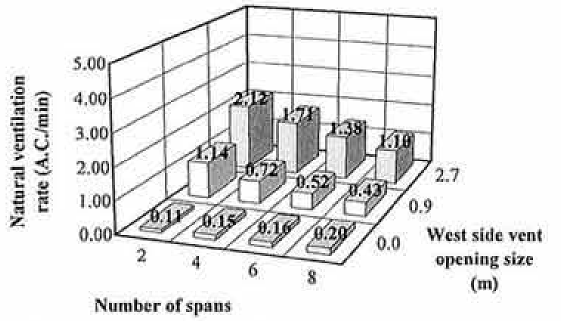
No consistent relationship was revealed between the natural ventilation rate in the hinged open roof greenhouse and the number of spans and side vent opening

Table 3. CFD-computed percentages of volumetric airflow at vent openings based on vertical west side vent opening size, wind speed, and wind direction when the bottom of the side vent was located at 0.5 m above the floor

Vent open size (m)	West wind (m/s)	Percentage of inlet/outlet airflow at vent opening[a] (%) Side	Roof 1	Roof 2	Roof 3	Roo 4
0.9	0.5	94/0	6/2	0/20	0/39	0/39
	1.0	98/0	2/7	0/24	0/32	0/37
	2.5	94/0	6/1	0/20	0/33	0/46
1.8	0.5	100/0	0/10	0/25	0/32	0/33
	1.0	100/0	0/12	0/27	0/30	0/31
	2.5	100/0	0/7	0/26	0/29	0/38
2.7	0.5	100/0	0/16	0/25	0/29	0/30
	1.0	100/0	0/19	0/26	0/27	0/28
	2.5	100/0	0/18	0/23	0/26	0/33
Vent open size (m)	**East wind (m/s)**	**Percentage of inlet/outlet airflow at vent opening[a] (%) Side**	**Roof 1**	**Roof 2**	**Roof 3**	**Roof 4**
0.9	0.5	70/0	0/15	0/39	0/46	30/0
	1.0	29/0	0/28	0/52	0/20	71/0
	2.5	0/57	0/20	0/12	5/11	95/0
1.8	0.5	83/0	0/15	0/34	0/51	17/0
	1.0	37/0	0/29	0/45	0/26	63/0
	2.5	0/85	4/2	17/0	0/13	79/0
2.7	0.5	92/0	0/16	0/31	0/45	8/8
	1.0	41/0	0/28	0/43	0/29	59/0
	2.5	0/92	16/0	17/0	4/8	63/0

a): The roof (vent) number is counted from the west span to the east span.

(a) Double polyethylene greenhouse



(b) Hinged open roof greenhouse

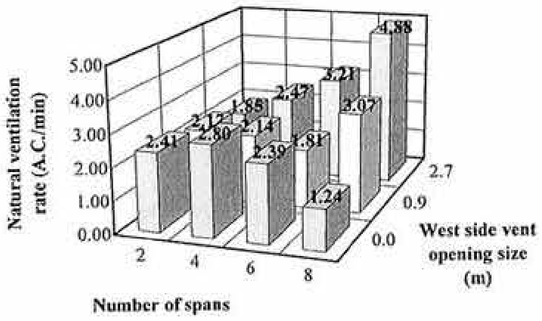


Fig. 5. Effects of number of spans and vertical windward side vent opening size on natural ventilation rate in a double polyethylene greenhouse (a) and a hinged open roof greenhouse (b) for a west wind of 2.5 m/s

Table 4. CFD-computed percentages of volumetric airflow at vent openings based on roof vent opening type, number of spans, and vertical windward side vent size for a west wind of 2.5 m/s when the bottom of the side vent was located at 0.5 m above the floor

(a) Double polyethylene multi-span greenhouse

Side vent	No. of	Percentages of inlet/outlet airflow at vent opening[a] (%)								
(m)	spans	Side	Roof 1	Roof 2	Roof 3	Roof 4	Roof 5	Roof 6	Roof 7	Roof 8
	2	0/0	100/0	0/100						
0.0	4	0/0	0/36	33/0	67/0	0/64				
	6	0/0	0/15	25/0	34/0	41/0	0/56	0/29		
	8	0/0	0/21	0/18	0/20	0/9	26/0	34/0	40/0	0/32
	2	100/0	0/25	0/75						
0.9	4	94/0	6/1	0/20	0/33	0/46				
	6	89/0	9/0	2/2	0/13	0/18	0/28	0/39		
	8	89/0	11/0	0/6	0/11	0/9	0/8	0/12	0/19	0/35
	2	100/0	0/43	0/57						
2.7	4	100/0	0/18	0/23	0/26	0/33				
	6	100/0	0/5	0/15	0/16	0/16	0/22	0/26		
	8	97/0	3/0	0/8	0/9	0/11	0/14	0/16	0/18	0/24

a): The roof (vent) number is counted from the west span to the east span.

(b) Hinged open roof multi-span greenhouse

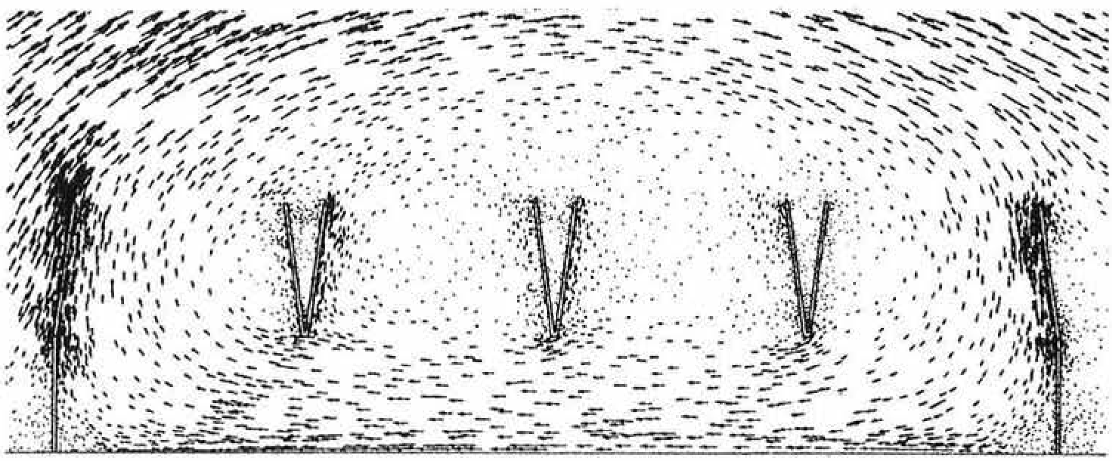
Side vent	No. of	Percentages of inlet/outlet airflow at vent opening[a] (%)								
(m)	spans	Side	Roof 1	Roof 2	Roof 3	Roof 4	Roof 5	Roof 6	Roof 7	Roof 8
	2	0/0	43/53	57/47						
0.0	4	0/0	0/69	12/20	15/11	73/0				
	6	0/0	0/53	8/11	16/8	32/0	44/0	0/28		
	8	0/0	0/57	8/12	7/6	8/7	21/0	31/0	25/3	0/15
	2	36/0	51/17	13/83						
0.9	4	36/0	41/19	19/28	0/47	4/6				
	6	23/0	17/14	9/16	2/21	2/38	7/11	40/0		
	8	14/0	10/13	5/10	0/32	3/30	5/11	12/4	27/0	24/0
	2	66/0	29/13	5/87						
2.7	4	50/0	23/9	12/16	13/14	2/61				
	6	63/0	19/10	5/15	5/7	4/18	0/5	4/45		
	8	58/0	20/9	4/12	3/9	0/6	9/8	0/20	3/2	3/34

a): The roof (vent) number is counted from the west span to the east span.

with vertical windward side vent opening sizes of 0.0 and 0.9 m. This was because the air flow was predicted to pass up and over the west, windward wall and come down in reverse flow as shown in Fig. 6. With a side vent opening size of 2.7 m, the natural ventilation rate was predicted to increase proportionally to the number of spans. When the open roof multi-span greenhouse had more than 6 spans, the larger side vent opening was predicted to provide the optimum natural ventilation rates. As shown in Table 4(b), the CFD-computed results indicated that the roof vents acted as inlet or outlet of airflow according to the number of spans and windward side vent opening size while the windward side vents always acted as an inlet to airflow.

Fig. 6 shows the CFD-computed vectors of airflow in a hinged open roof greenhouse for a west wind of 2.5 m/s when the vertical windward side vent opening sizes were 0.0 m (a) and 2.5 m (b) in height. The fourth and first roof vents were the main inlet and outlet openings, respectively without the side vent open while the side vent and the fourth roof vent were the main inlet and outlet openings, respectively while the side vent was open. The CFD results predicted that the same ventilation patterns would develop as in the double polyethylene greenhouse when the windward side vent was fully open. When the windward side vent was closed, however, the air went up and over the windward side wall and entered the greenhouse at the fourth roof vent opening, creating a reverse flow across the greenhouse.

(a) Side vent opening size of 0.0 m



(b) Side vent opening size of 2.7 m

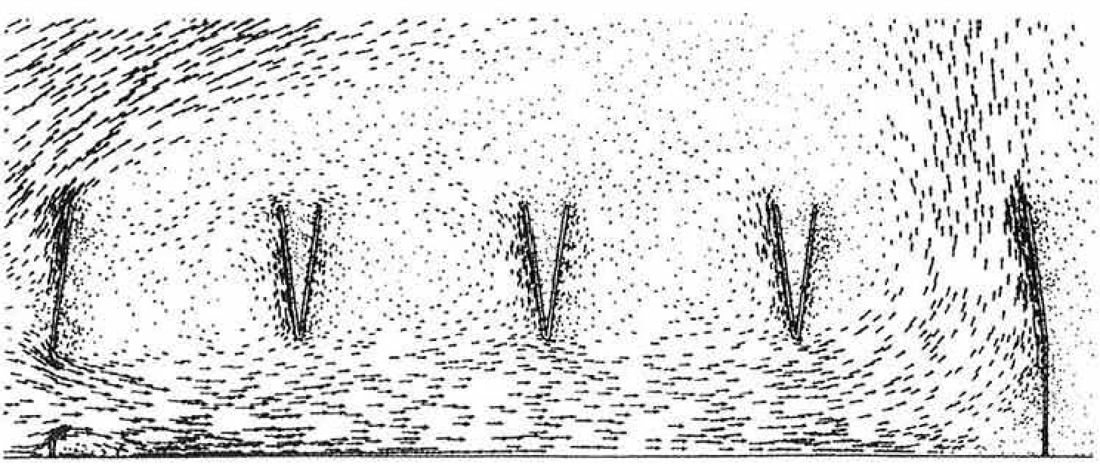


Fig. 6. CFD-computed vectors of airflow in a hinged open roof glass greenhouse for a west wind of 2.5 m/s when the vertical windward side vent opening size was 0.0 (a) and 2.7 m (b) in height and the bottom of the side vent was located at 0.5 m above the floor

The minimum and maximum computed air velocities in the computational domains were (a) 0.002 and 4.27 m/s, respectively and (b) 0.003 and 3.72 m/s, respectively.

Conclusions

The CFD-computed results predicted that the west side vent location did not strongly affect natural ventilation rates in a four-span double polyethylene-covered greenhouse for both wind directions as much as the wind speed.

It was predicted that the lowest side vent location at 0.5 m above the floor resulted in a higher natural ventilation rate in the double polyethylene multi-span greenhouse for both wind directions than the higher vent location. The west wind cases were predicted to show an average of 11% higher natural ventilation rate than the east wind.

An east wind of 0.5 m/s showed an average of 17% higher natural ventilation rate than a west wind of 0.5 m/s with a west side vent opening while a west wind of 2.5 m/s showed an average of 20% higher natural ventilation rate than an east wind of the same velocity.

The CFD-computed results indicated that the west side vent was a very active vent opening as inlet and outlet of airflow, respectively for low and high east wind speeds. The air mainly moved in through the side vent and fourth roof vent openings for an east wind of 0.5 m/s while the third and fourth roof openings were the inlets of airflow for an east wind of 2.5 m/s. It was also predicted that the side vent would become a more active vent opening as the side vent location was lower.

For the bottom of the 0.9 m side vent located at 2.5 m above the floor for a west wind of 2.5 m/s, approximately 59% of incoming air through the side vent was predicted to move directly out through the first roof vent opening without reaching the other areas of the greenhouse.

The CFD-computed results indicated that the west side vent opening sizes markedly affected the natural ventilation rate in the greenhouse, especially for the west wind. For west winds, the side vent was the only inlet of airflow with the vertical side vent opening sizes of 1.8 and 2.7 m in height while the side vent and the first roof vent openings were inlets with a vertical side vent opening size of 0.9 m in height.

The natural ventilation rate in the double polyethylene greenhouse was predicted to decrease as the number of greenhouse spans increased while the natural ventilation was very low without the windward side vent opening. It was also predicted that the windward side vent opening size was very important for good natural ventilation of the multi-span greenhouse.

The hinged open roof vent greenhouses generated significantly higher natural ventilation rates than the double polyethylene greenhouses for 2, 4, 6, and 8 spans. It indicated the importance of the roof vent opening size and shape and the possibility of achieving reverse airflow at plant level when no side vent was used with the hinged open roof greenhouse.

For the hinged open roof vent greenhouse, the highest natural ventilation rate for the widest span tested (8 spans) was obtained with a side vent opening size of 2.7 m. When the multi-span greenhouse had more than 6 spans, larger side vent openings were predicted to generate better natural ventilation.

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