Newest Computational Technology for Greenhouse Production Systems - Computational Fluid Dynamics (CFD) Numerical Techniques

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INTRODUCTION

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 wind velocity and direction. The optimization of these systems for acceptable climate control requires a thorough knowledge of the airflow rates and patterns as related to weather conditions and greenhouse structural details.

A successful numerical model was assumed to be an ideal tool to help understanding the complex phenomena of natural airflows and help designers choose optimum designs. There especially was interest in computational fluid dynamics (CFD) numerical techniques to analyze air distributions in agricultural structures as well as air quality and thermal conditions [4].

The objective of this study was to evaluate the consequences of various modifications to natural ventilation systems by using a CFD code Fluent Version 4.5 [1]. This research 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 distributions inside and outside multi-span greenhouses.

Lee [4] simulated the natural ventilation of a two-dimensional four and one-half span greenhouse in a CFD numerical model and compared it to a control volume energy balance model. The CFD model was found to be the most reliable. Lee [5] numerically analyzed temperature distributions 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 distributions 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.

MATERIALS AND METHODS

1. CFD numerical model

The CFD technique numerically solved the Reynolds-averaged form of the Navier-Stokes equations [1,3] within each cell in the domain. The governing equations were discretized on a curvilinear grid to enable computations in complex and irregular geometries. The standard k-ε turbulence model was used in this study because its results were observed to be most typical to known ventilation flows [1,2,3]. The Boussinesq model [1,3] was activated for the buoyancy effect in the computational domain.

Fluent V4.5 was a two-part package consisting of a preprocessor, Geomesh, and a main module, Fluent/UNS [1]. Geomesh was used to create geometry and generate structural grids, and the triangular grids were created to efficiently model 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 computations were performed assuming steady-state conditions.

2. Experimental procedures

A simulated four span, double polyethylene greenhouse and hinged open roof single layer covered greenhouse were designed with a side vent and roof vents. The four span greenhouse was slightly modified from a four and one-half span, double polyethylene greenhouse at Quailcrest farm located near Wooster, Ohio [4]. Both greenhouses had 7.3m and 3.4m, respectively for width of each span and gutter height. The hinged open roof greenhouse was assumed to have similar gutter configuration as 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 span from west to east. Weather data were collected on hot summer (35 °C) days with 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.

In this study, the two-dimensional CFD models were developed to investigate the effects of side vent location, side vent opening size, roof vent opening type, number of span, wind speed, and wind direction on 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 representations of the airflow distributions in the greenhouse were created via vectors with the CFD model.

RESULTS AND DISCUSSIONS

The CFD computed results showed that the west side vent of the double polyethylene covered four span greenhouse was a very active vent opening as either an inlet or outlet depending on both wind speed and direction when the vertical opening size of the side vent was 0.9m. It indicated that the side vent was predicted to become a more active vent opening as the side vent location was lower. The lowest side vent location (0.5 m above floor) was predicted to give the highest natural ventilation rate for both wind directions and the west wind resulted in an average 11 % higher natural ventilation rate than the east wind. An east wind of 0.5 m/s, however, showed 17 % higher natural ventilation rate than a west wind of 0.5 m/s while a west wind of 2.5 m/s showed 20 % higher natural ventilation rate than an east wind of 2.5 m/s shown in Table 1. With low east wind speed, the conjunction of buoyancy and wind effects presented 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 a west wind with a same speed.

When the bottom of the side vent was at 2.5 m above floor, approximately 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 very low velocity predictions near the plant level in the third and fourth spans in spite of a favorable overall natural ventilation rate.

Table 1 also shows the effects of vertical west side vent opening size, wind speed, and wind direction on natural ventilation rate in a double polyethylene covered four span greenhouse when the bottom of the side vent opening was at 0.5 m above floor. It shows that the averaged natural ventilation rates with the vertical side vent opening sizes of 0.9 m, 1.8 m, and 2.7 m in height, were 0.42 A.C./min, 0.71 A.C./min, and 0.95 A.C./min, respectively for a west wind and 0.36 A.C./min, 0.64 A.C./min, and 0.78 A.C./min, respectively for east wind. The CFD computed results indicated that the west side vent opening size could greatly affect the natural ventilation rate of the greenhouse, especially for west wind and high east wind speed.

Table 1 The CFD computed natural ventilation rates (Volumetric air change per minute, A.C./min) in a double polyethylene covered four span greenhouse according to west side vent location, side vent size, wind direction, and wind speed.

	Wind speed (m/s)	west side vent location from floor (m)		
		0.5	1.5	2.5
West/east winds	0.5	0.21/0.23	0.19/0.23	0.18/0.22
	1.0	0.32/0.28	0.27/0.23	0.27/0.24
	2.5	0.72/0.57	0.65/0.53	0.58/0.53
	Wind speed (m/s)	west side vent opening size (m)		
		0.9	1.8	2.7
West/east winds	0.5	0.21/0.23	0.34/0.26	0.43/0.30
	1.0	0.32/0.28	0.53/0.31	0.70/0.33
	2.5	0.72/0.57	1.27/0.67	1.71/0.89

Table 2 The CFD computed percentages of volumetric airflows at vent openings according to 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 floor.

Vent open size (m)	West wind (m/s)	Percentages of inlet/outlet airflow at vent opening (%)				
		side	roof1	roof2	roof3	roof4
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)	Percentages of inlet/outlet airflow at vent opening (%)				
		side	roof1	roof2	roof3	roof4
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

For west winds, the side vent was the only inlet of airflow with the vertical side vent opening sizes of 1.8 m and 2.7 m in height shown in Table 2 while the side vent and the first roof vent openings were inlets with the vertical side vent opening size of 0.9 m in height. For east winds of 0.5 m/s 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.

The natural ventilation rate of double polyethylene covered greenhouses was predicted to be 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. It was also predicted that the flow rates of the roof vents as outlets increased from windward to leeward walls with the windward side vent open. Without the windward side vent open, however, the air was predicted to mainly move into the greenhouse through the middle roof vents and moved out through both end side roof vents.

For hinged open roof multi-span greenhouses with a west wind of 2.5 m/s, significantly higher natural ventilation rates were predicted compared to the double polyethylene greenhouses for all spans, especially when no side vent or a small side vent was used. It indicated the influence of roof vent opening size and shape and the possibility of air going over the windward wall and given reverse flow in the greenhouse at plant level.

There was not any consistent relationship between natural ventilation rate in the hinged open roof greenhouse and the number of span and side vent opening with the vertical windward side vent opening sizes of 0.0 m 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. With the 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 bigger side vent opening was predicted to give best natural ventilation rates.

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