COMPUTATIONAL FLUID DYNAMICS FOR NATURAL VENTILATION IN A MULTI-SPAN GREENHOUSE

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1. INTRODUCTION

Greenhouse ventilation is a key method of controlling of greenhouse parameters such as air temperature, air humidity, and CO2 concentration which strongly influence the growth and development of the crops that are grown. Natural ventilation is air exchange between inside and outside which occurs through controlled openings due to natural pressure variations inside and outside the greenhouse. Natural ventilation systems generally require less electrical energy, less equipment maintenance, and are much quieter than mechanical ventilation systems. In spite of the large amount of commercial use of natural ventilation, little information and data were available on full scale multispan greenhouse natural ventilation designs.

A successful numerical model was assumed to be an ideal tool to help understanding the complex phenomena of natural air flows and help designers choose optimum designs. There was an increasing interest in applying computational fluid dynamics (CFD) numerical techniques to analyze air distribution in agricultural structures as well as air quality and thermal conditions (Short, 1996). CFD tools, however, were not yet commonly used by designers because they require special skills, experience and extensive computational processing time.

Prior to CFD models, there were many different techniques used to measure leakage and ventilation rates in greenhouses such as energy balance model (Sase et al., 1984; Fernandez, 1992), tracer-gas techniques (Bot, 1983; De Jong, 1990; Boulard, 1995), and wind-buoyancy effect model (Bruce, 1975; Timmons, 1981; Zhang, 1989). They found that the natural ventilation was influenced by wind speed, wind direction, window opening size and location, and temperature difference between inside and outside greenhouse. Boulard (1995) and Kittas (1996) concluded that the buoyancy effect could be neglected if the wind velocities were greater than 2.0m/s and 1.5m/s, respectively.

Okushima (1989) established the computational code to predict the distributions of environmental factors inside and outside naturally ventilated greenhouses. While the experimental results showed little correlation with the computational model, his study demonstrated the possibility of using a CFD model to predict environmental distributions for naturally ventilated greenhouses. Short et al. (1996a) stated that the roof vent opening should be leeward when even possible, and then the natural ventilation could be achieved by a vacuum effect at the top of roof vent opening. Kacira (1996) and Woodruff (1997) studied various naturally ventilated greenhouse types by using a computational fluid dynamics numerical model. They found that the maximum air exchange rate could be obtained when both side and roof vents were used. Mistriotis et al. (1997) also studied ventilation process in greenhouses with the use of CFD. He investigated the validation of the CFD model by comparing the numerical results with the experimental results of Sase (1984) and a good agreement between the numerical data and the experimental measurements was found.

ASAE Standard (1984) indicated that a ventilation rate of ¾ ~1 air change per minute was recommended for most greenhouses. Temperature rise from air inlet to exhaust was inversely proportional to volumetric airflow. Woodruff (1997) investigated the weather data from 1991 to 1995 collected at Wooster, Ohio weather station (40° 47' N latitude, 81° 55' W longitude, elevation 1020 ft). He found that the average wind speed was around 2.5 m/s and the minimum for a given year were usually above 1 m/s, when the air temperature was 26.7°C or greater.

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The main objective of the study was to investigate the effects of wind speed and direction, vent opening size, and internal shading screen on the natural ventilation in a double layered polyethylene four and half span greenhouse by using the Computational Fluid Dynamics (CFD) code FLUENT 4.3.

2. MATERIALS AND METHODS

Greenhouse environmental data were needed to develop the FLUENT CFD model. The experimental greenhouse used in this study was a four and half span, double polyethylene commercial greenhouse at Quailcrest farm located near Wooster, Ohio (Fig 1). Data were collected on strategic days during a period of three months, from June 1 to August 30, 1997. The roof cover and east side wall of the greenhouse were double layer polyethylene and single layer glass, respectively. The roof vent was operated by hinged.

Fifteen sensors and one datalogger were installed inside the greenhouse to measure dry and wetbulb temperatures, leaf temperatures, and solar radiation. Inside and outside ground surface temperatures and cover temperatures were also measured by the Infrared Gun (The had-held Raynger II Data System) for each ten minutes. A weather station tower (3.25m height) was installed outside the greenhouse to measure the local weather such as dry and wet bulb temperatures, wind speed, wind direction, and solar radiation.

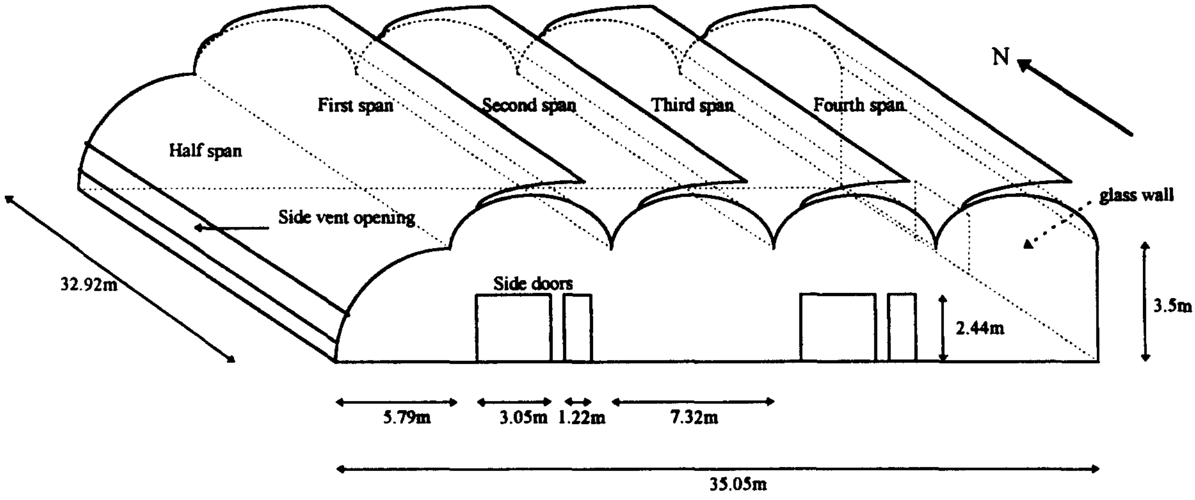

Fig 1. The picture of the four and half span commercial greenhouse in Quailcrest farm located near Wooster, Ohio.

Basic program structure of Fluent CFD numerical model

FLUENT was a general purpose computer program for modeling fluid flow, heat transfer, and chemical reaction. FLUENT software enabled users to apply computer simulation methods to analyze and solve their practical design problems. FLUENT modeled the wide range of phenomena by solving the conservation equations for mass, momentum, energy, and chemical species using a control volume based on finite difference method. The governing equations are discretized on a curvilinear grid to enable computations in complex/irregular geometries.

FLUENT was a two part program consisting of a preprocessor, either preBFC or GeoMesh, and a main module, FLUENT. Either preBFC or GeoMesh (or any other structured grid generator) could be used to define the geometry and a structured grid for the model. Then the grid information was transferred from the preprocessor to FLUENT via a grid file. Following this transfer, FLUENT was used to define physical models, fluid/material properties, and boundary conditions that describe your problem. This information was added to the grid information and stored in a case file that was a record of all your inputs for problem definition. The user also performed all calculations and post-processing in FLUENT, storing the results of the calculation in a data file.

Experimental procedures

2-dimensional four and half span greenhouse was developed in the CFD model. The total grid size was 271×84 for the computational domain, and the grid model used a Body-Fitted Coordinate (BFC) grid method. The standard k-ε model had been the workhorse of engineering turbulence models for more than two decades, and, until recently, no alternative turbulence model offered any major reason to switch (FLUENT manual, 1995). So, the k-ε turbulence model was chosen as the CFD turbulence model in this study. The inlet air flow was incompressible, vertically uniform air speeded, steady state air flow. This study was conducted without any plants in the greenhouse.

The constant input values for the FLUENT model for 2-dimension were presented in Table 1.

Table 1 The constant input values for the 2-dimensional FLUENT model. The weather data were collected during the west wind and cloudless sky (July 16, 1997).

Factor	value	unit	Factor	value	unit
floor area in greenhouse	35.05	m^2	inside floor temperature	313	°K
polyethylene area (roof)	42.24	m^2	outside ground temperature	309	°K
glass area (east side wall)	3.35	m^2	Stefan-Boltzmann constant	5.67E-08	W/m^2 K
roof vent open (vertical)	0.76	m	gravitational acceleration	9.81	m/s^2
side vent open (vertical)	0.91	m	cover emissivity	0.13	***
inlet air temperature	303	°K	glass emissivity	0.90	***
wind speed	2.5	m/s	outside ground emissivity	0.95	***
wind direc. (left to right)	west	***	inside ground emissivity	0.90	***
roof temperature	308	°K	turbulence intensity of inlet	5	%
glass temperature	309	°K	turbulence length of G.H.	3.5	m

In the CFD model, the inlet air velocities (0.1m/s to 6.0m/s) were simulated to investigate the effect of wind speed on natural ventilation. The wind direction effect was also investigated as comparing the winds coming from west and east. Eight different cases were made for each wind direction. The combination effects of roof and side vent opening sizes on natural ventilation were investigated when the wind of 2.5 m/s came from west and east. Four cases were only roof vents open, only side vent open, all vents open, and all vents closed. The effects of the internal shading screen which had zero porosity were also investigated when the screen was rolled to east and west with the west wind of 2.5m/s. Each case had different shading area for each span such as 0%, 25%, 50%, 75%, 80%, 85%, 90%, 95%, and 100%. The percentage of the shading area for each span was the ratio of the shading screen area to the ground area for each span.

3. RESULTS AND DISCUSSIONS

When the wind came from west, the air moved in through the side vent and the first roof vent openings and moved out through all the roof vents. As shown in Fig 2, the side vent and the fourth roof vent were the most active openings as inlet and outlet, respectively. The average percentages of mass flow inlet at side vent and first roof vents were 90.12% and 9.85%, respectively. The average percentages of mass flow outlet at the first, second, third, and fourth roof vents were 3.49%, 12.92%, 29.53%, and 54.06%, respectively. Fig 2 showed the inlet airflow moving more downward upon entering the greenhouse and then traveling more along the floor than with the benches. It resulted in the first roof vent operating as both an inlet and outlet.

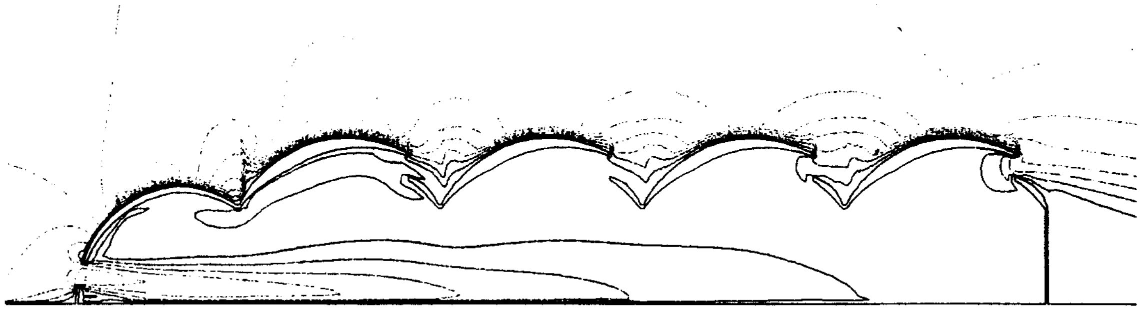

Fig 2 The contour of air velocity in the CFD computational domain when the wind of 2.0m/s came from west. The darker line indicates the bigger air velocity.

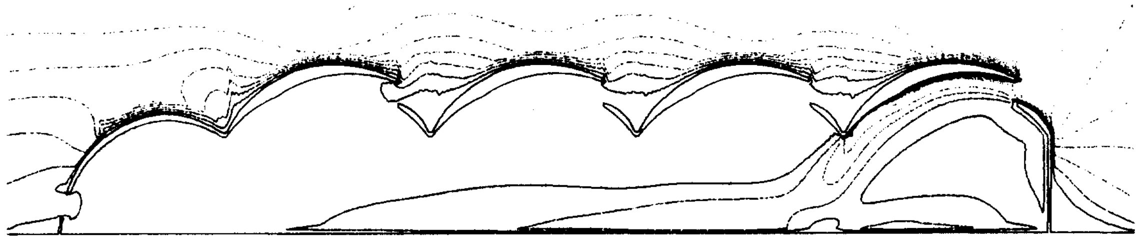

Fig 3. The contour of air velocity in the CFD computational domain when the wind of 2.0m/s came from east. The darker line indicates the bigger air velocity.

When the wind came from east, the air moved in through the second, third, and fourth roof vent openings and moved out through the side vent and the first and second roof vent openings. The fourth roof vent acted as a main inlet as shown in Fig 3. The average percentages of mass flow inlet at second, third, and fourth roof vents were 1.16%, 3.52%, and 95.32%, respectively. The average percentage of mass flow outlet at the side vent and the first, second, and third roof vents were 49.72%, 41.08%, 7.37%, and 1.83%, respectively. The second roof vent acted as only outlet as the wind speed increased. As considering that a ventilation rate of ¾ ~1 air change per minute was recommended for most greenhouses (ASAE Standard, 1984), the optimum air exchanges (volume/min) were obtained when the wind speeds of west and east winds were over 2.3m/s and 3.3m/s, respectively. When the wind (0.1-6.0m/s) came from west and east, the ranges of the air exchange rate were 0.0354-2.1114 vol./min and 0.0209-1.2828 vol./min, respectively.

The results show that the vent opening sizes strongly influenced the natural ventilation in the greenhouse. When the wind came from west, the effect of vent opening on the natural ventilation was the biggest when the side and roof vents were fully opened together. The side vent opening size influenced more significantly on the air exchange rates than the roof vent opening size. When the side vent was totally closed, the air exchange rates were very low, and the air exchange rates were rarely influenced by the roof vent opening size. When the wind came from east, the side vent opening size did not influenced the air change rate in the greenhouse, however, the effect of the roof vent opening size on the natural ventilation was so significant.

With west wind and the system of rolled to east, the air exchange rates were not significantly influenced by the internal shading screen when the percentage of the shaded area was below 90%, and they got even the better air exchange rates than no shaded case. The air exchange rate was the biggest when the shading area for each span was 50%. However, the air exchange rate was strongly influenced by the shaded area as the percentages of the shaded area were over 95%. It indicated that the presence of the shading screen influenced the natural ventilation rate if the width of the unshaded area was smaller than the width of the roof vent openings. If the width of the unshaded area was bigger than the width of the roof vent, the air exchange rate was rarely affected by the shading screen. The system of rolled to east made better air exchange rate than the system of rolled to west. When the shading areas were 25%, 50%, 75%, 80%, 85%, 90%, and 95%, the percentages of the better air exchange rates were 18.22%, 15.40%, 18.45%, 17.35%, 16.19%, 12.34%, and 8.02% respectively. When the shading screen was rolled to east, the airflow followed the smooth roof line, and moved toward the leeward roof vent openings. It was assumed that the shading screen rolled to west interrupted the smooth upward airflow to the roof vent more than the shading screen rolled to east.

4. CONCLUSIONS

When the wind came from west, the main inlet and outlet were the side vent and the fourth roof vent, respectively. The fourth roof vent acted as a main inlet when the wind came from east. The air exchange rates in the greenhouse increased as the wind speed increased. The optimum air exchanges were obtained when the west and east winds were over 2.3m/s and 3.3m/s, respectively.

The vent opening size strongly influenced the natural ventilation in the greenhouse. When the wind came from west, the vent opening effect on the natural ventilation was the biggest when the windward side and leeward roof vents were fully opened together.

The side vent opening size affected more significantly on the air exchange rate than the roof vent opening size when the wind came from west. When the wind came from east, the side vent opening size did not influenced the air change rate in the greenhouse, however, the effect of the roof vent opening size on the natural ventilation was so significant.

If the width of unshaded area for each span was bigger than the width of the roof vent opening, the air exchange rate was rarely affected by the internal shading screen. The system which the shading screen was rolled to east made better air exchange than the system rolled to west.

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