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Development and Validation of a Mathematical Model for Ventilation Rate in Crop Protection Structures

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ABSTRACT

Natural ventilation is defined as the number of air exchanges per hour per unit floor area necessary to reduce high indoor air temperature and humidity. In addition, it maintains the concentration of carbon dioxide. Natural ventilation is preferred in mechanical system as the ventilation opening is built into the greenhouse, with lower construction cost and no energy and maintenance inputs are required. A mathematical model to quantify natural ventilation rates was developed and verified in large-scale greenhouse structures. For this purpose, four Naturally Ventilated Tropical Greenhouse Structures were designed and constructed at the Malaysian Agricultural Research and Development Institute (MARDI). These were single, double, triple, and quadruple span structures with floor areas of 500 m^2, 1000 m^2, 1500 m^2 and 2000 m^2, respectively. This paper presents the validation of a mathematical model which was developed to quantify natural ventilation rates which are very crucial to reduce high in-house temperature built up in the tropics. Regression equations of natural ventilation against wind speed were found to be $\Phi_w = 0.0632V$, $\Phi_w = 0.0395V$, $\Phi_w = 0.0316V$ and $\Phi_w = 0.0276V$ for the single, double, triple and quadruple spans, respectively. Meanwhile, coefficients of determination showed strong relationships between ventilation rate and wind speed, with $R^2 = 0.9999$ for all structures. Larger floor area was found to have higher in-house temperature than smaller ones. Ventilation rate inside the single-span structure was found to be higher compared to the multi-span structures, which increased linearly with the increasing wind speed at the eaves of structure.

Keywords: Natural ventilation, wind effect, multi-span, greenhouse structure

NOMENCLATURE

A_g	the floor area of the greenhouse	(m^2)
A_n	area of the nth opening	(m^2)
ΣA_{TO}	total areas of vent openings	(m^2)
C	ventilation coefficient	(m^2/m^2)
C_{pe}	external pressure coefficient	(dimensionless)
C_{pi}	internal pressure coefficient	(dimensionless)
C_d	discharge coefficient	(dimensionless)

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j	number of opening (1, 2,…)	
n	total number of openings	
V	outside wind speed at eaves level	(m/s)
V_n	air velocity moving through the nth opening	(m/s)
Φ_w	ventilation rate by wind effect	(m^3/m^2s)

INTRODUCTION

A greenhouse is defined as a construction used to protect plants from undesirable climatic variation and it provides an in-house environment conducive to plant production (Bin Gadhi and Haidrah, 1999). This technique is necessary to replace the high risk of open field production against damaging elements such as high rainfall, extreme solar radiation, weed competition, as well as damages caused by diseases and insects. The main function of the greenhouse is to increase the yield and quality of vegetable, fruit, flower and herb productions. Moreover, the production can be made continuous throughout the year. In Malaysia, crop production in the greenhouses plays an important role to supply sufficient food to substitute the high import bill of processed and unprocessed horticultural products. Currently, the import bill for food is more than RM 13 billion annually (Rezuwan, 2002).

The design of the greenhouses in the tropics is significantly different from that in regions with cooler climates. In particular, the greenhouses in the tropics require heat dissipation as opposed to heat conservation in temperate regions. This is usually followed by ventilation to remove the excess heat which builds up during hot sunny days. The ventilation rate is the number of air exchanges between inside and outside the greenhouse through the openings per unit time and floor area. Ventilation systems, in general, are operated as either natural ventilation or forced ventilation (Baptista *et al.,* 1999). Natural ventilation is usually induced by the stack (buoyancy) or wind effects or a combination of both, while forced ventilation is driven by electrical fans or other mechanical means. Natural ventilation is preferred because it uses less energy, requires lower maintenance and is quieter in operation than the forced ventilation method (Rezuwan, 1999).

Air exchange occurs when there is a pressure difference across the ventilator opening. Pressure differences induced by the wind force are acted at the eave level (wind effect) or temperature difference between the inside and outside of the greenhouse (stack or chimney effect). In general, both wind and stack effects occur together. Ventilation is necessary to provide air exchange and good climatic control in the greenhouse. It limits the temperature rise on hot days, controls excessive humidity caused by transpiration and prevents excessive depletion of the concentration of carbon dioxide. Therefore, an understanding of air exchange rate is necessary because it directly affects both the development and production of crops (Rezuwan, 1999; Rezuwan, 2005). When the average maximum outside temperature is less than 27°C, ventilation can prevent excessive internal temperatures during the day. However, if the average maximum outside temperature exceeds 28°C, artificial cooling may then be necessary. It is important to note that the maximum greenhouse temperature should not exceed 30-35°C for prolonged periods (Bailey, 2004).

Generally, open field farming gives low production, poor quality, and crops are totally destroyed at times. For example, losses by insects and diseases have been reported to range from 50-100% when infestation levels are high (Hawa *et al*., 1992). Moreover, heavy rainfalls throughout the year cause damages to crops, difficult working conditions, make them susceptibility to diseases and fertilizer loss by surface runoff. Furthermore, extreme solar radiation can be detrimental to crops. In addition, hot and humid weather does not seem to be conducive for the growth and production of sub-tropical and temperate crops. As these conditions are more pronounced in enclosed greenhouses, the requirement for good ventilation is increased. To address these problems, naturally ventilated tropical crop protection structures have been developed by the Malaysian Agricultural Research and Development Institute (MARDI). The structures were introduced to replace the imported naturally ventilated polytunnel or glasshouse, which are less suitable for use in the tropics. The imported structures were designed to conserve heat in cold temperate weather, while the requirement in the tropics is for a heat dissipation type of greenhouse (Rezuwan, 1999; Rezuwan, 2005; Rezuwan *et al.,* 2001). This naturally ventilated greenhouse relies primarily on the air blowing into a windward side opening and out the open roof vents. Work on ventilation rate have been carried out by several researchers (e.g. Bailey *et al*., 2003; Montero *et al*., 1997; Munoz *et al*., 1999; Sase and Christianson, 1990; Teitel and Tanny, 1999; Von Zabeltitz, 1999) and only a few of these studies have considered ventilation rate and microclimate of the greenhouses under humid tropics. Models estimating the ventilation rate in some specific greenhouse structures have been studied by Baptista *et al*. (2001) and Munoz *et al*. (1999), but the structures used only had small ventilation openings. For the humid tropics, naturally ventilated greenhouses normally have larger ventilation openings. This paper presents the development and validation of a mathematical model to quantify natural ventilation rates by the wind effect, which is very crucial to reduce high in-house temperature built up in the tropics.

MATERIALS AND METHODS

Greenhouses Structure

Naturally ventilated tropical greenhouse structures were designed and constructed at the Malaysian Agricultural Research and Development Institute (MARDI). The single-span structure was made 50 m long x 10 m wide x 4.0 m high with straight side walls and tunnel roof shape with a jack-roof. Moreover, the double, triple, and quadruple spans were also constructed in the prefabricated and modular form. *Plates 1* and *2* are typical types of the single and quadruple span structures, respectively. All the structures were made of galvanized steel frame, transparent polyethylene film roofing, and polyethylene insect-screen side cladding with 32 mesh netting. The dimensions of the greenhouse structures are listed in Table 1.

Plate 1: Single-span greenhouse structure

Plate 2: Quadruple-span greenhouse structure

TABLE 1
Dimensions of naturally ventilated tropical greenhouse structures

Structure	Length (m)	Width (m)	Height (m)	Floor area (m^2)	Volume (m^3)
Single span	50	10	4.0	500	2300
Double span	50	20	4.0	1000	4600
Triple span	50	30	4.0	1500	6900
Quadruple span	50	40	4.0	2000	9200

Data Collection

The micro climate parameters were measured continuously for more than six months using an Integrated Data Acquisition and Monitoring System. In addition, thermometers were used to support and check the measurements. The system consists of computer software, circuit integration, data logger, electronic actuators, and sensors. The sensors were used for the temperature, wind speed, and wind pressure. Each location had three sensors. The locations of the sensors are shown in *Fig. 1*. All the sensors were calibrated before the measurement in order to minimize error or unreliable data by verifying using hand-held thermometers for the temperature, and standing fan for wind speed. A total of 30 readings were recorded for each structure.

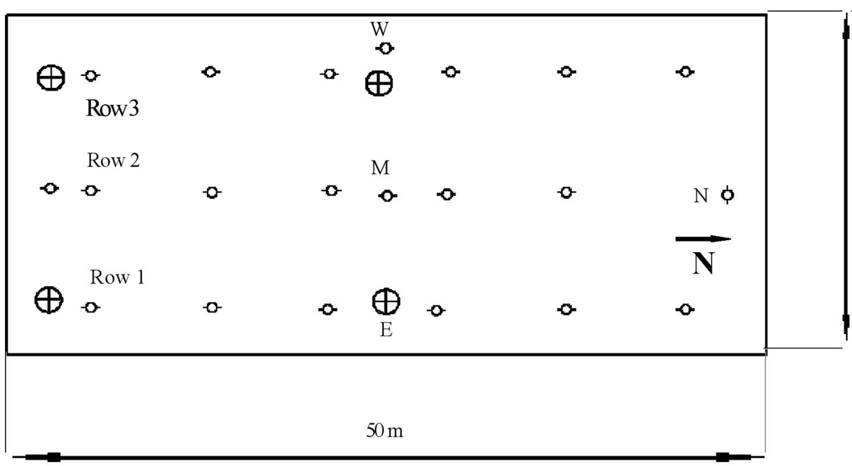

Fig. 1: Layout of the system in the experimental greenhouse (⊕ Misting Fan, ⭘ -location of sensors, N – North, S – South, W – West, E – East, M - Middle)

MODEL DEVELOPMENT

Ventilation by Wind Effect

The theory on the prediction of ventilation rate was first developed by Bruce (1982), and it was experimentally verified by Foster and Down (1987) using the half-scale models. Wind around a building creates a pressure field at the openings and hence produces air flow through them. These pressures may be positive when the air flows into the building or negative (suction) when the air flows out. As the wind speeds measured were higher than 1m/s and reaching as high as 4.26m/s at 12.00 noon, the buoyancy effect (i.e. the temperature difference between inside and outside the greenhouse generating the density difference of air) is considered small and the ventilation rate can therefore be considered as only a function of the wind. Bruce (1975) described the ventilation due to wind as:

$$\Phi_w = \sum_{j=1}^{n} A_j \frac{\left| C_{pei} - C_{pi} \right|}{C_{pej} - C_{pi}} \tag{1}$$

Where, C_{pe} is external pressure coefficient, C_{pi} is internal pressure coefficient, and j is opening (1,2,…). The ventilation rate can be calculated using the formula adopted by Rezuwan *et al.* (2001), as follows:

$$\Phi_w = \frac{1}{2A_g} \sum_{i=1}^{n} A_n V_n \tag{2}$$

Where, Φ_w is the ventilation rate by wind effect (m^3/m^2s), A_n is the area of the nth opening, V_n is the air velocity moving through the nth opening and A_g is the floor area.

$$V_n = C_d \frac{\left| C_{pej} - C_{pi} \right|^{\frac{3}{2}}}{C_{pej} - C_{pi}} \tag{3}$$

For the greenhouse structures in this study, the ventilation rate can be calculated using the following equation:

$$\Phi_w = \frac{1}{2A_g} \sum \left(A_1 V_1 + \dots + A_n V_n \right) \tag{4}$$

which can be reduced to:

$$\Phi_w = \frac{1}{2A_g} C_d \frac{\left| C_{pe} - C_{pi} \right|^{\frac{3}{2}}}{C_{pe} - C_{pi}} \sum \left(A_1 + \dots + A_n \right) . V \tag{5}$$

Finally, the ventilation rate due to wind can be calculated using the following formula:

$$\Phi_w = C_d \frac{\sum_{i=1}^{n} A_{TO}}{2A_g} V \frac{\left| C_{pe} - C_{pi} \right|^{\frac{3}{2}}}{C_{pe} - C_{pi}} \tag{6}$$

Where, C_d is the discharge coefficient, V is the speed of the outside wind and ΣA_{TO} are the total areas of the vent openings.

RESULTS AND DISCUSSION

Temperature

The highest average values of the inside temperature were 41.00ºC, 41.25ºC, 41.50ºC, and 41.75ºC at 14:00 pm, with the standard errors of 0.49ºC, 0.39ºC, 0.43ºC, and 0.34ºC for single, double, triple and quadruple-span, respectively, while the highest value of the outside temperature was 34.20ºC, with a standard error of 0.49ºC as shown in *Fig. 2*. The differences between the inside and outside temperatures were between 6.80ºC, 7.05ºC, 7.30ºC, and 7.55ºC for the single, double, triple and quadruple spans, respectively. These results showed that the temperature increased from early morning until afternoon, and then declined towards late evening. The increasing and declining trends are in line with the solar radiation intensity and the outside air temperature throughout the day. The average in-house temperature was found to be higher than that of the outside of the structures. This is because any enclosed structure restricts air movement and the cooling effect is more dependent on natural ventilation rate. Meanwhile, small floor area has lower in-house temperature compared to larger floor area due to fast air movement and air exchanges (Hemming *et al.,* 2006).

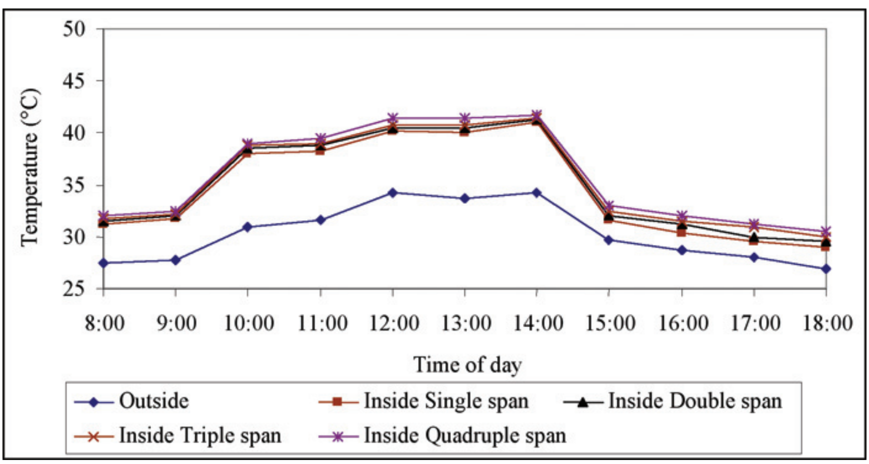

Fig. 2: Effects of single, double, triple and quadruple floor areas on in-house average air temperature

Wind Speed

Wind speed is influenced by many factors such as surrounding vegetative growth, ground formation and local climate. *Fig. 3* shows the comparison between single, double, triple, and quadruple-span structures in terms of wind speed. The highest average wind speed was recorded at 14:00 pm, i.e. 1.39 m/s for the outside and 0.4 m/s for the inside single span structure of 500 m^2 floor area. At 12:00 noon, this was 4.257 m/s for the outside, 0 m/s, 0 m/s, 0.15 m/s, and 0.25 m/s respectively for the inside single, double, triple, and quadruple-structure. There was a significant difference in terms of wind speeds between the outside and inside of the structure. This was due to the effects of wind speed and direction and pressure outside the greenhouse. Moreover, the main contributing factor could be the effect of pressure drop when the wind flowed across the insect screen wall. Smaller screen size tends to reduce the wind speed and hence reduces its pressure. For this study, only 32 mesh netting was used.

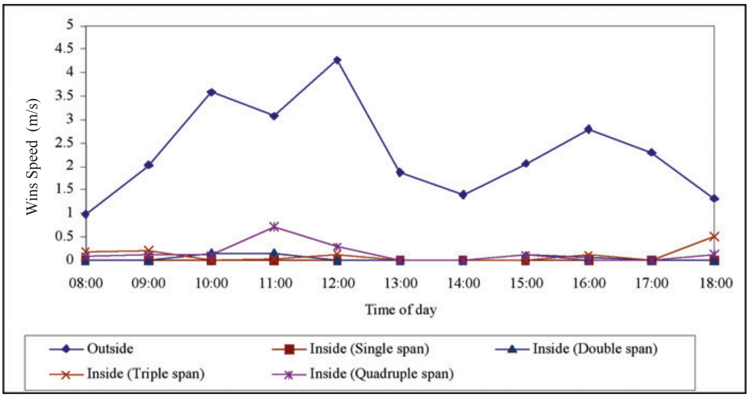

Fig. 3: Comparison between single, double, triple and quadruple-span structures in terms of wind speed

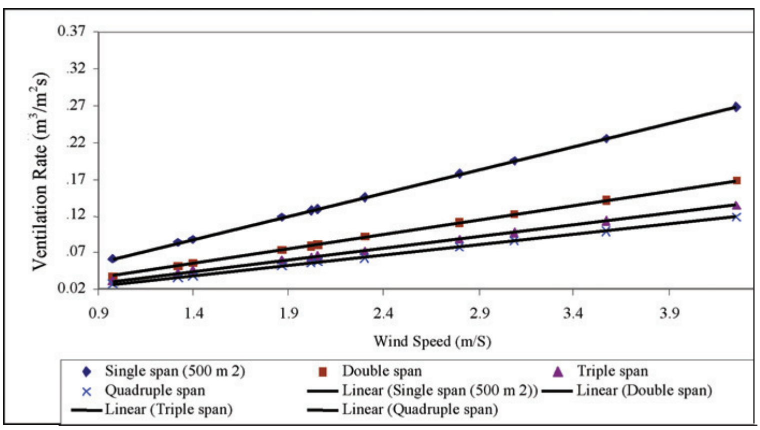

Fig. 4: Effect of wind speed on ventilation rate for various floor areas

Ventilation Rate

Ventilation rates by the wind effects were calculated using equation (6) for the single and multi-span structures. The discharge coefficient, the outside pressure coefficient, and the inside pressure coefficient were based on the recommended values of 0.411, 0.46, and 0.05, respectively (Rezuwan, 1999). *Fig. 4* shows the relationships between ventilation rate and wind speed in the single, double, triple, and quadruple-span structures. The results indicated that the ventilation rate increased with increasing wind speed at the eaves height of the structure. In addition, the ventilation rate in the single span structure was found to be greater than in the other structures, since the small floor area allowed the wind to flow in and out much faster than the larger area. The regression equations of the single, double, triple and quadruple-span structures are summarized in Table 2. These results are in a good agreement with the previous studies by Rezuwan (1999), De Jong (1990) and Bot (1983). Moreover, the adjusted coefficients of determinations (R^2) showed a strong relationship between the ventilation rate and wind speed. All the coefficients of determination are 0.9999. Based on the data presented in Table 2, a general regression equation can therefore be formulated as:

$$\Phi_w = CV \tag{7}$$

where Φ_W is the ventilation rate by wind effect (m^3/m^2s), V is the outside wind speed at eaves level (m/s) and C is the ventilation coefficient, which is a function of screen size, coefficient of discharge, wind direction, floor area and opening area, as shown in equation (6), where C can be written as:

$$C = C_d \frac{\sum_{i=1}^{n} A_{TO}}{2A_g} \cdot \frac{\left| C_{pe} - C_{pi} \right|^{\frac{3}{2}}}{C_{pe} - C_{pi}} \tag{8}$$

TABLE 2
Regression equations showing effects of wind speed on the ventilation rate for various floor areas

Structure	Regression equation	Adjusted R^2	No. of observation
Single-span ($500m^2$)	$\Phi_w = 0.0632$ V	0.9999	30
Double-span ($1000m^2$)	$\Phi_w = 0.0395$ V	0.9999	30
Triple-span ($1500m^2$)	$\Phi_w = 0.0316$ V	0.9999	30
Quadruple-span ($2000m^2$)	$\Phi_w = 0.0276$ V	0.9999	30

CONCLUSIONS

The developed mathematical model of ventilation rate, which takes into consideration the effects of wind, has helped in the design and quantification of the ventilation rates for the single, double, triple, and quadruple-span versions of the naturally ventilated greenhouses for the tropics. Understanding of wind effect is very important because of the high in-house air temperatures during the no wind condition. This gives heat stress which is detrimental to the growth of crops or plants. When there is wind, the stress is reduced as ventilation is dominated by the wind, together with the pressures of the differences in temperature. The ventilation rate caused by the wind effect increases linearly as the wind speed becomes greater. In addition, the ventilation rate in the single-span became higher than in the multi-span structure. This was due to the small floor area which allows the wind to flow in and out much faster than the larger area.

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