Influence of Insect Screens with Different Mesh Sizes on Ventilation Rate and Microclimate of Greenhouses in the Humid Tropics

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ABSTRACT

An investigation on the effect of the use of nets with different mesh-sizes on the internal microclimate and ventilation rate in greenhouses located on the humid tropics was carried out. Three greenhouses (each measuring 10 m wide × 20 m long) were constructed and covered with a plastic film on the roof, and different insect proof nets on the sidewalls, respectively. Net sizes of 40-mesh, 52-mesh and 78-mesh were used. Water vapour, transpired from 300 tomatoes cultivated in each greenhouse, was used to determine the ventilation rate. In addition, an energy balance method which offers a simple, rapid and accurate way to predict ventilation rate was developed based on common climatic data and used in this study. A good agreement ($R^2 = 0.85$) was obtained between two methods. Statistically, the use of insect screens with different mesh-sizes had a significant effect on ventilation rate and internal microclimate. The reduction of ventilation rate about 50% and 35% for the 78-mesh and 52-mesh greenhouses, respectively was obtained compared to the 40-mesh greenhouse. Consequently, the internal air temperature was also increased by 1 to 3 °C. Although, a small temperature difference was observed, the absolute humidity among treatments was significantly different. The use of a higher mesh-size resulted in more humidity. Ventilation rate and temperature rise in the greenhouses were strongly correlated to the net porosity. Since their correlations were good in agreement, the simple equation derived from the experiment will be very useful in predicting air exchange rate and temperature rise when a new type of net is applied.

Keywords: Mesh size, insect net, ventilation rate, microclimate, greenhouse, humid tropics

1. INTRODUCTION

Air exchange rate is one of the most important parameters of ventilation systems to control the microclimate inside a greenhouse. In order to provide a better environment of climatic condition for plant growth, a ventilation system has to supply sufficient and uniform ventilation rate between inside and outside greenhouse environment. Furthermore, better ventilation rate helps to reduce the greenhouse air temperature and humidity as well as to improve the evapotranspiration process for crops.

The use of insect-proof nets placed on the ventilation openings of a greenhouse is widely used now and it is become popular in some regions, due to its ability to prevent crop damage caused by insect pests and viruses. Moreover, insect-screens have several advantages among them reducing the number of insects entering a greenhouse, reducing the need for pesticides and offering simple structural design thereby lowering construction cost.

Even though nets are affective in protection from insect pests, putting the screening net on ventilation openings, in practice, may cause a restriction to the air flow, so a larger screened area is needed to permit the same air flow as originally existed. For instance; to provide sufficient ventilation, the ratio of total ventilator opening to the greenhouse floor in Hanover, Germany conditions area should be greater than 15-25% (von Zabeltitz, 1999). Many authors (Bailey et al., 2003; Montero et al., 1997; Munoz et al., 1999) reported that there is a reduction of air flow resistance (as shown as discharge coefficient parameter) when the insect net was applied on greenhouse. The reduction of the air flow rate in a greenhouse due to the effect of insect nets may lead to an increase the air temperature and relative humidity. Although Bethke (1990) recommended some screen sizes for excluding several insects from a greenhouse, their effect on microclimate inside greenhouses located in the humid tropic is not well-understood.

In line with the respective subject, a study on the pressure drop across insect-proof nets was made by Teitel and Shklyar (1998). They concentrated on the resistance of screens to flow not parallel to the screen, since their objective was calculating ventilation rates for greenhouses whose vertical or inclined openings are covered with insect-proof screens. Other authors (Montero et al., 1997; Sase & Christianson, 1990) considered the effect of screens installed in greenhouses, either horizontally above the crop or in the greenhouse openings, on the ventilation rate. Only a few of the above studies considered an enclosure that is conducted under humid tropics.

In addition, estimation of ventilation rate has been studied by some authors (Boulard & Draoui, 1995; Roy et al., 2002; Baptista et al., 1999) using a common technique of tracer gas with different media such as: methane (CH_4), nitrous oxide (N_2O) or carbon dioxide (CO_2). Moreover, a number of models, derived from energy, mass and momentum balance equation have been developed to calculate ventilation rate in some specific greenhouse structures which mostly have small ventilation opening (Baptista et al. 2001; Munoz et al., 1999). For the humid tropics, naturally ventilated greenhouses usually have very large ventilation openings; hence it is important to develop an appropriate method which offers quick, simple and accurate means for estimating the ventilation rate.

The objective of the recent work was to study the effect of the mesh size of nets, placed in front of vent opening, on the ventilation rates and internal microclimate of greenhouses located in the humid tropics. Furthermore, a comparison between two methods used to estimate ventilation rates *i.e.*: water balance methods (using water vapour as a tracer gas) and an energy balance method estimated from the common climatic data (local weather station), was evaluated.

2. MATERIALS AND METHODS

2.1 Experimental Set up and Measurements

The experiment was conducted at the greenhouse complex in the Asian Institute of Technology, Thailand (13.06^{o} N latitude and 100.62^{o} E longitude at an altitude of 2.7 m above sea level) from June to October 2004 (rainy season of the year). Three similar greenhouses covered with different net materials namely: (1) 40×38-mesh (40-mesh, Econet M, anti leaf miners and larger); (2) 52×22-mesh (52-mesh, anti whiteflies and larger); and (3) 78×52-mesh (78-mesh, Econet T, anti thrips and larger) were used. Geometric characteristics and properties of the nets are presented in Table 1.

Table 1. Properties of insect-proof nets used for the experiment

Nets	Hole size		Thread	Light	Porosity	Discharge
	Length, mm	Width, mm	diameters, mm	transmission, %	(ε)	coefficient (C_d)
40-mesh	0.44	0.39	0.25	87	0.41	0.31
52-mesh	0.80	0.25	0.31	70	0.38	0.28
78-mesh	0.29	0.18	0.19	86	0.30	0.21

Each greenhouse measured 10m wide × 20m long and had an East-West orientation was used. An ultraviolet (UV)-stabilized polyethylene film was used to cover every greenhouse roof, gables and lower part of the side walls (up to a height of 0.8 above the ground). The sidewalls and the ventilation openings on the roof were covered with the insect proof nets mentioned above (one mesh size per greenhouse). In addition, each greenhouse was equipped with two exhaust fans with a total capacity of 1,100 $m^3\ min^{-1}$, 2.2 kW power at the front side (Figure 1). The fans were only used in case of emergency or when the air temperature was extremely high, but during the experiment all fans were turned off, so that all of the greenhouses were working under natural ventilation. Black plastic mulch was spread on the floor of each greenhouse.

For the microclimate inside the greenhouse, air temperature and relative humidity were measured by two aspirated psychrometer using K type (NiCr-Ni) thermocouple sensors (0.5 mm diameter). Two psychrometers were positioned at a height of 0.5 m above the crops (with a 10 m distance between them) Incoming solar radiation was measured by solarimeter CM 11/14 type (Kipp and Zonen, Delft, The Netherlands) with an accuracy of between 4 and 6 $\mu V\ W^{-1}\ m^{-2}$ and a daily error of 2% of measurement. The solarimeter was placed at the centre of greenhouse at a height of 2.5 m above the floor. Leaf temperature was measured by means of thin and sheathed K-type thermocouple sensors (Temperatur Messtechnik Hanau (TMH) GmbH, Germany) of 0.1 mm diameter attached under the leaf. Soil (substrate) temperature was measured using a thermocouple sensor similar to the one used for measuring air temperature.

In order to record outside climatic conditions, several sensors were installed in a meteorological station located 25 m away from the greenhouses. Air temperature and global radiation were measured using the same sensors described above. Wind speed and direction were measured using a cup anemometer and wind direction transmitter (Thies Klima GmbH, Germany), respectively. All sensors outside the greenhouse were placed at a height of 6.9 m above the ground level. All sensors, both in the greenhouse and at the meteorological station, were connected to a data logging system developed at the Institute of Horticultural and Biosystems Engineering, University of Hannover, Germany. The climatic data were measured at an interval of 15 s, and then average values were stored every minute on the disk for further evaluations. All sensors were calibrated prior to use.

The crop transpiration rate was directly measured by incoming water flow and outgoing water flux sensors. Two water flow meters FTB603 model (Omega Engineering, USA) with flow range at 0.5 to 15 ℓ min^{-1} and relatively high accuracy of $\underline{+}$ 1% of reading were installed at irrigation pipe and outlet drainage pipe. The sensors were also connected to the data logging system and the data were recorded every minute. The crop transpiration rate was simply calculated by averaging the difference reading of two flow meters along certain period of time (from 8:00 to 17:00 h).

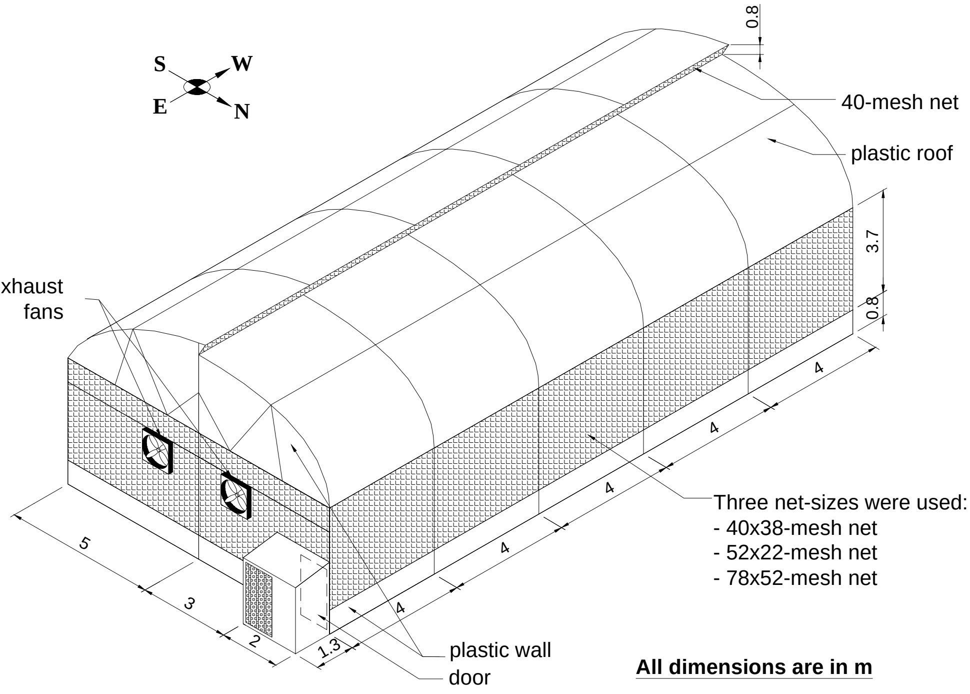


Figure 1. Isometric view of the greenhouse structure used for the experiment.

Tomato (*Lycopersicon esculentum*, cv. King Kong 2) seedlings were transplanted, three weeks after sowing, into large pots (one plant per pot) filled with soil substrate (28% of organic matter) with a pH of 5.3. The soil texture was 30% of sand, 39% of silt and 31% of clay. In each greenhouse, total of 300 tomato plants were planted within six rows with spacing of 1.5 m between the rows (50 pots for each row). Initially, the crops covered about 20% of floor surface area but this fraction gradually increased up to 80%. An assumption was made that water vapour transpired from each plant was uniform for all points in the greenhouse. The plant heights were measured and recorded every week.

The crops were cultivated and maintained at a similar practice for each treatment. In order to accommodate non-stressed condition of tomato crops, irrigation water (about 20 – 30% over actual water requirement) was given based on light integral from global solar radiation. On average, the number of irrigation frequencies was 8 times per day. Two fertilizers, 5 kg of Hakaphos (N-P-K) and 7.5 kg of Calcinit (Ca), were diluted into 100 litres of water and directly mixed with the irrigation water through two fertilizing injectors, DI 150/16 model (Dosatron International, France), at a rate of 3.5% and 1.5%, respectively.

2.2 Determination of Ventilation Rate

In the recent study, ventilation rates were determined using two approaches or methods, namely water vapour mass balance and an energy balance methods.

2.2.1 Water Mass Balance Method

Water vapour mass balance method uses a tracer gas technique to measure ventilation rate. This method is commonly used by some authors (Boulard and Draoui, 1995; Muňoz et al., 1999; Baptista et al., 1999) to directly measure the ventilation rate. This uses tracer gases in the greenhouse, and is based on a mass balance of the gas, which can be a natural or artificial constituent of the air. Water vapour is one of gas media that relatively fulfils the requirement in terms of uniformity along whole greenhouse volume, since all crops in the greenhouse evaporate water vapour during the transpiration processes.

Measuring water transpiration directly either using water fluxes balance or Lysimeter from the greenhouse is the most practical method used. In line with the technique adopted by Boulard and Draoui (1995), greenhouse crop transpiration rate can also be estimated from the measurement of the transpiration of a crop by means of an electronic balance supporting four plants disposed in a row (by sampling method). Furthermore, they compared the results of measured ventilation rates using this method with the other two methods of tracer gas of nitrous oxide (N_2O) and carbon oxide (CO_2), respectively. Good agreement was found between these different technique approaches.

Measurement ventilation rate using water vapour as tracer gas allows estimating the irrigation water being transformed into the water vapour inside greenhouse during evaporation and transpiration processes which mainly occur in the daytime. This water vapour has to be dissipated out by replacing it with drier air from outside the greenhouse. The amount of water to be evaporated should be equivalent to the difference between water vapour density inside and outside the greenhouse during a day. The movement of water vapour due to its difference will generate daily ventilation rate. Assuming uniform humidity conditions in the whole greenhouse volume, a steady state condition and considering that evaporation loss from the crop substrate and the soil are negligible, the following equation can be used to calculate ventilation rate:

$$G(t) = \frac{\rho_w [W_{fi}(t) - W_{fo}(t)]}{A_f [X_i(t) - X_o(t)]} \qquad (1)$$

where $G(t)$ is the measured ventilation rate per unit greenhouse surface floor area over period of time (t) in $m^3\ m^{-2}\ s^{-1}$, ρ_w is water density ($\cong 1.0$ kg ℓ^{-1}), $[W_{fi}(t) - W_{fo}(t)]$ is crops transpiration rate which is measured using water flux incoming to and outgoing from the greenhouse during t time in $\ell\ s^{-1}$, A_f is greenhouse surface floor area in m^2, and $[X_i(t) - X_o(t)]$ is absolute humidity difference between inside and outside the greenhouse over period of time (t) in kg m^{-3}. The calculation of ventilation rates was conducted by averaging of measurements during daytime over certain period of time from 8:00 to 17:00h (9 hours).

2.2.2 Energy Balance Method

The energy balance method in determining ventilation rates uses either static or dynamic models (Roy et al., 2002). Static models are less accurate due to their simplicity and involve only a few parameters. Dynamic models, on the other hand, are better in terms of accuracy, but involve more parameters. A number of dynamic models have been developed (Roy et al., 2002; Wang and Boulard, 2000; Teitel and Tanny, 1999). Most of these models used the transient behavior of greenhouse interior climate to simulate the ventilation rate. The greenhouse energy balance is the sum of the heat gains and losses during a certain period of time. This method assumes a steady state and uses the principle of energy conservation; heat gains are equal to heat losses. Heat gains and losses affect the greenhouse energy content, which is determined by the change in temperature. Heat exchange between the inside and outside of a greenhouse is complex mechanism, involving all the process of radiation, conduction, convection and latent heat.

In general, equations of the energy balance of a natural ventilated greenhouse given by some authors (Bailey, 1988; von Zabeltitz, 1988) have the form as follows:

$$Q_{sun} - (Q_c + Q_l) - Q_v - Q_{gr} - Q_p = 0 \tag{2}$$

where Q_{sun} is the solar radiation absorbed within the greenhouse in W; Q_c is the heat transferred through the cladding in W (due to the use of screen net, the heat loss can be ignored); Q_l is the heat loss by air leakage in W (only for greenhouse with heating system); Q_v is the heat removed by ventilation in W; Q_{gr} is the heat flow into the soil in W; Q_p is the energy used in photosynthesis in W (it is about 2 – 3% of the total solar radiation, it also can be ignored). Hence, the Eq. (2) above can be simplified into:

$$Q_{sun} = Q_v + Q_{gr} \tag{3}$$

The solar radiation absorbed inside the greenhouse, Q_{sun} depends on the external global solar radiation and the transmissivity of plastic roof and upper sidewall. The percentage of solar intercept of heat to the plants used for evapotranspiration also influences the net solar heat and it was assumed that 80% of solar heat was used. Therefore, inside net solar radiation is obtained from the following equation:

$$Q_{sun} = n_{so} R_n A_f \tag{4}$$

where R_n is the average incoming net solar radiation inside greenhouse during day time in W m^{-2}; A_f is floor area of greenhouse in m^2; n_{so} is the percentage of solar heat used for convection, evaporation and transpiration processes of plants in decimal.

The energy removed by ventilation consists of sensible (Q_{si}) and latent heat (Q_{lt}) and it can be expressed as follow:

$$Q_v = Q_{si} + Q_{lt} = GA_f \left(c_p \rho_a (T_i - T_o) + (X_i - X_o) L_v \right) \tag{5}$$

where G is ventilation rate per greenhouse floor area due to ventilation system in m^3 m^{-2} s^{-1}; A_f is greenhouse surface floor area in m^2; c_p is the specific heat of air in J kg^{-1} K^{-1}; ρ_a is the specific mass of air ($\cong$ 1.3 kg m^{-3}); $(T_i - T_o)$ is the air temperature difference between inside and outside greenhouse in K; $(X_i - X_o)$ is the absolute humidity difference between inside and outside greenhouse in kg m^{-3}; L_v is the latent heat of vaporization in J kg^{-1}.

Heat flows to the soil (Q_{gr}) was mostly caused by radiation or convection from interior temperature to the soil substrate as a media growth for tomato plants. Since the soil surrounding the pots was covered by the plastic sheet and soil surface at the pots were also covered by tomato leafs when they were full-grown up, the heat fluxes to the soil could be neglected from Eq. (3).

By substituting Eqs. (4), (5) into Eq. (3) above and rearranging, the energy balance equation can be written in a simplified form as follows:

$$n_{so} R_n A_f = G A_f \left(c_p \rho_a (T_i - T_o) + (X_i - X_o) L_v \right) \tag{6}$$

Hence, the ventilation rate could be predicted based on the environmental climatic data, as follows:

$$G = \frac{n_{so} R_n}{[c_p \rho_a (T_i - T_o) + L_v (X_i - X_o)]} \tag{7}$$

where G is the predicted ventilation rates of a greenhouse based on energy balance approach using the common microclimate greenhouse in m^3 m^{-2} s^{-1}.

2.3 Data analysis

The statistic software package of SAS version 8.2 (SAS Institute, 2003) was used for evaluation of the data.

3. RESULTS

3.1 Ventilation Rate along the Crop Season

The measurement of ventilation rates was conducted in greenhouses covered with insect-net of different mesh-sizes. The values of ventilation rates averaged over 9 hours during daytime (from 8.00 to 17.00 h) were calculated from measured crops transpiration rate and absolute humidity difference between in and outside the greenhouse. The measured values were compared with those predicted using an energy balance method based on the external microclimate (including net solar radiation). Figure 2 shows average ventilation rates on daily basis from the initial stage (young tomato plants) up to harvesting. In general, the ventilation rates were fluctuated day by day using the two methods according to the microclimatic condition during the respective day. When the crops were young (leaf area index, LAI less than 1.5), the ventilation rates were fluctuated more, while upon crop maturity (LAI ranging 1.5 to 3.0), the different values of ventilation rates were clear among the treatments. Unstable weather conditions experienced during the experiment (which was running in the rainy season) was believed to be the main reason for the fluctuation of daily ventilation rate. In addition, the less amount of vapour transpired by the young plants in greenhouses caused the error of measurement of vapour concentration and non uniform condition.

Based on the lower limit of ideal ventilation rate of 0.062 $m^3\ m^{-2}\ s^{-1}$ as recommended by ASAE (1989), only the 40-mesh greenhouse can provide better ventilation rate compared to the others of both 52- and 78-mesh greenhouses. In the mature plants condition, their values were always lower than the limit of ideal ventilation rate.

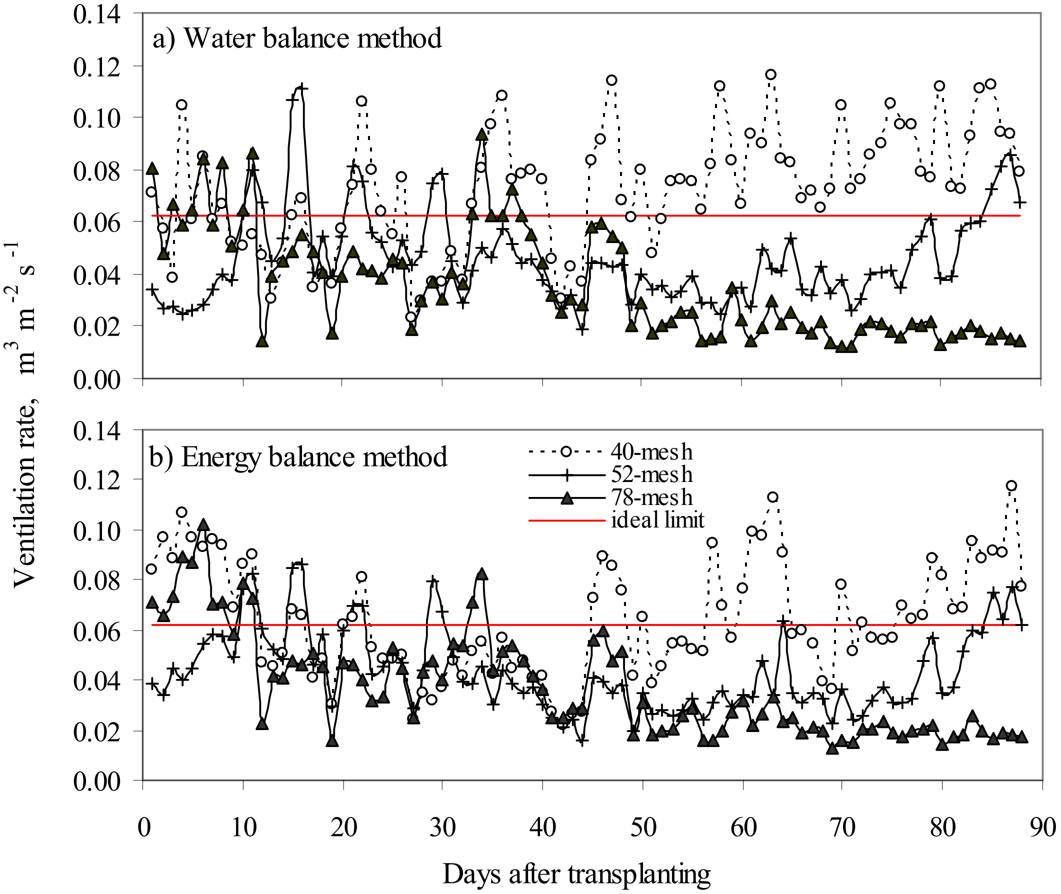


Figure 2. Ventilation rates in the greenhouses covered by three different mesh-sizes of nets measured using two different methods along the crop season.

Statistically, the ventilation rate was significantly different for each treatment for both water vapour and energy balance methods using GLM t-test at *P* = 0.05. The finer the insect screen placed on the ventilation openings; the lower ventilation rate obtained. During the experiment, the greenhouse covered by 78-mesh net showed the lowest ventilation rates ranging between 0.015 to 0.085 $m^3\ m^{-2}\ s^{-1}$ compared to the others, whereas the greenhouse with 52-mesh has from 0.030 to 0.085 $m^3\ m^{-2}\ s^{-1}$ while at the 40-mesh greenhouse the values were between 0.055 to 0.111 $m^3\ m^{-2}\ s^{-1}$ (Fig. 2). On average, the ventilation rate in the 78-mesh greenhouse was significantly different to the 52-mesh and 40-mesh greenhouses (Table

2). Compared to the 40-mesh greenhouse, the use of the finer insect-proof net i.e. 78-mesh, indeed reduced the ventilation rate by 50%, while with 52-mesh net significantly reduced it up to 35%. This reduction might be caused by the porosity of net (as the 78-mesh was less porous) and the resistance of the finer net was higher compared to 40-mesh so that the accumulation of the water vapour content due to crop evapotranspiration processes could not be easily removed out. The reason is also supported by the absolute humidity difference among the treatments whereas the 78-mesh greenhouse was relatively higher than those of 52-mesh and 40-mesh (Table 2).

3.2 Comparison between Two Methods to Estimate Ventilation Rate

Since an energy balance method offers a simple, rapid and relatively accurate way to predict ventilation rates in the greenhouse, it is very important to verify the method with the ones obtained from a tracer gas method (water mass balance method) as a standard method to measure ventilation rates. Moreover, the energy balance method has another advantage over the tracer gas method that a shorter period of time is needed to estimate ventilation rates. To validate the results obtained from this method, a comparison of ventilation rates between two methods at three different greenhouses is plotted in Figure 3. The results show that the relationship between two methods was good in agreement for each treatment, especially in the 78-mesh greenhouse. For the greenhouse covered with net of 78-mesh, their relationships was better at R^2 =0.85 than that at 52-mesh and 40-mesh greenhouses which gave the coefficient of correlation of 0.71 and 0.33, respectively. This means that the energy balance method could well predict the ventilation rate at the greenhouse with smaller ventilation opening. This result is similar to the work done by Shilo et al. (2004) who conducted the experiment under four-span greenhouse with insect-proof screens over its openings.

Figure 3 also illustrates that the good relationship between two methods was obtained when the values of ventilation rates were relatively low at lower than 0.060 m^3 m^{-2} s^{-1}. Above this rate, the values were much dispersed. Moreover, a bit overestimation of values was observed using this method when ventilation rates were recorded at lower than the rate mentioned above, while above 0.060 m^3 m^{-2} s^{-1}, the ventilation rates were under. Among the treatments, the relationships between two methods was better at the greenhouse with finer mesh-size (78-mesh) compared to 52-mesh and 40-mesh. The possible reason for this was that external wind speed was becoming a major factor influencing to the ventilation rate in the greenhouses covered by the smaller mesh-size especially in 40-mesh house. This is because the wind speed recorded during the experiment ranged from 2 to 7 m s^{-1}. Kittas et al. (1997) mentioned that wind speed more than 2 m s^{-1} has a bigger effect on ventilation rate than the temperature difference or ‘buoyancy effect’.

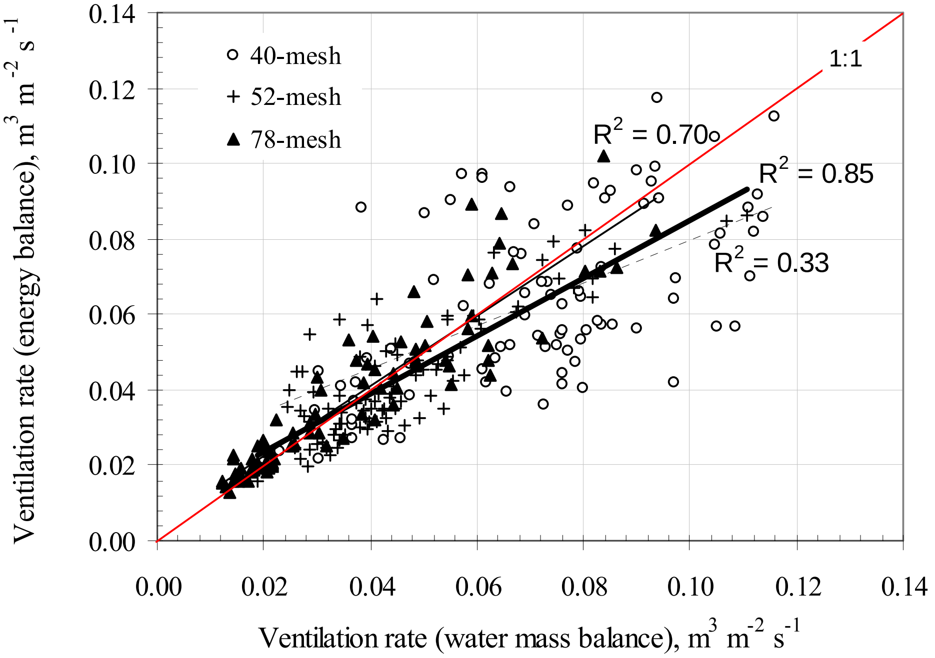


Figure 3. The relationship between two methods to measure ventilation rate in the greenhouses covered by three different net types, ——, ideal line of 1:1; R^2 = coefficient of determination.

In order to further evaluate relationship between two methods along the crop season, a comparison between two in the 78-mesh greenhouse is presented in Figure 4. As the accuracy of estimated ventilation rate was much better in greenhouse with mature plants, it is possible to indicate the best time to measure using a parameter of plant height. From the experiment, the plant height had a similar trend to leaf area index during the experiment. It can be seen that the plant height ranging from 0.2 to 1.6 m represented young plants, while mature plants was indicated by the plants height of 1.7 to 3.2 m. In addition, measuring the plant height is much easier to perform than leaf area index due to the use of non-destructive sample. Figure 4 depicts a good example how plants stage influences the relationships between two methods.

When the plants were young, for instance, both measured and predicted ventilation rates were more fluctuated than for the mature plants. In that condition, the water vapour transpired from all of plants was also less and not equally distributed to the greenhouse space resulting possibly to an error in measuring absolute humidity. On the contrary, when the greenhouse was full with plants, less greenhouse space was occupied by relatively high amount of water vapour, thus reducing the error in measuring absolute humidity in the greenhouse.

Since the ventilation rates predicted from the energy balance method were very sensitive to the change of climatic parameters, it suggested that the estimation of ventilation rate should be predicted based on microclimatic data taken from a stable weather and no rain condition in order to avoid the measurement errors. In this regard, the estimation of ventilation rate using the method conducted under different seasons *i.e.* cool season and hot season of the year should be explored whereas the energy balance method might also be influenced by the different seasons of the year.

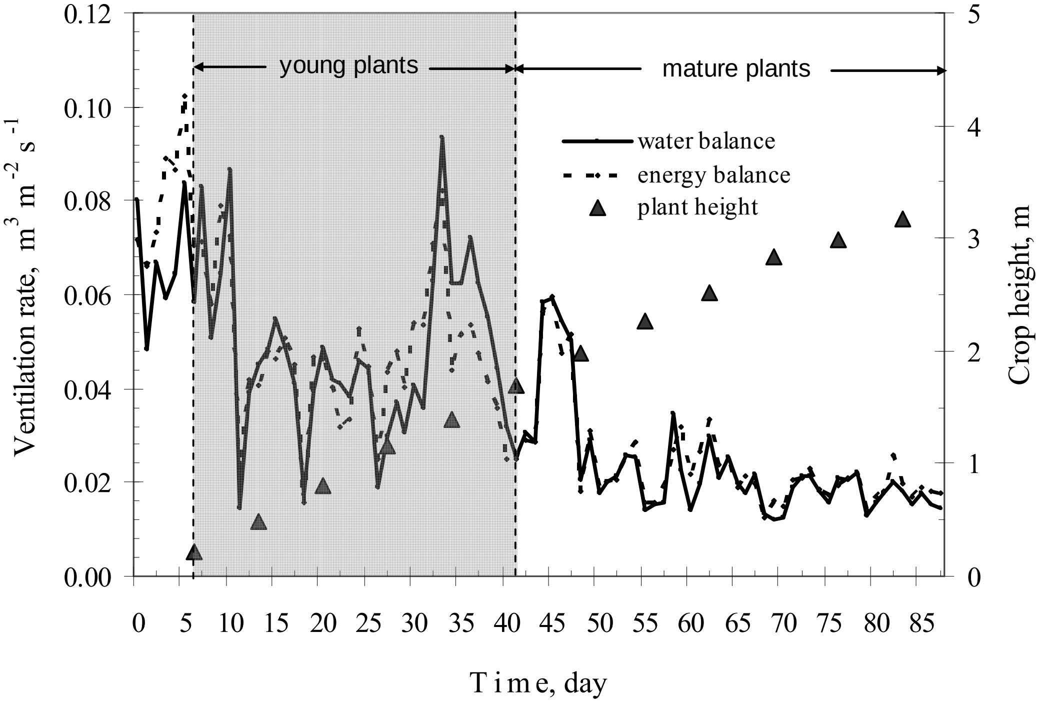


Figure 4. A comparison of ventilation rates measured by two different methods in a humid tropical greenhouse covered with 78-mesh net during the cultivation period.

3.3 Effect of Mesh Size of Nets on Ventilation Rates and Microclimate

Table 2 shows the effect of different mesh-sizes of nets placed on the ventilation openings on the ventilation rates and microclimate condition in the greenhouse. The means of those were compared using analysis of variance (ANOVA) (GLM procedure; SAS Institute, 2003). The results revealed that there was a significantly effect of different net-sizes on the ventilation rate despite the very big ventilation opening (ratio of vent opening to the surface floor area is 1.02) was applied. The greenhouse with finest mesh-size (78-mesh, anti thrips net) showed the lowest means of ventilation rate compared to the two greenhouses with 40 and 52-mesh, respectively. Therefore, the use of insect-proof net with finer hole-size would significantly reduce the ventilation rate.

Concerning to the microclimate condition, the means of some important parameters are also compared (Table 2). The air temperature in the greenhouse covered with 78-mesh was only increased by 1 °C (or 3% increment) compared to the 40-mesh greenhouse, but there was no difference between the 52- and 40-mesh greenhouses. The means of relative humidity for each treatment was not significantly different ($P = 0.8211$, $N = 88$) as the experiments were carried out in rainy season, except for the 78-mesh greenhouse. The relative humidity was significantly different (P < 0.003, N = 88) and it was higher in the 78-mesh greenhouse compared to the 52- and 40-mesh greenhouses.

Table 2. Mean (± standard error, SE) ventilation rate, air temperature, relative humidity and absolute humidity difference in the greenhouses at three different mesh-sizes of net.

Nets (mesh)	Ventilation Rate ($m^3\ m^{-2}\ s^{-1}$)	Air Temperature (°C)	Relative Humidity (%)	Absolute Humidity Difference (g/m^3)
40-mesh	$0.0719^a \pm 0.0025$	$30.8^b \pm 0.1$	$69.7^a \pm 0.3$	$1.05^c \pm 0.08$
52-mesh	$0.0461^b \pm 0.0019$	$31.1^b \pm 0.1$	$70.3^a \pm 0.3$	$1.63^c \pm 0.09$
78-mesh	$0.0361^c \pm 0.0022$	$31.9^a \pm 0.1$	$74.1^a \pm 0.3$	$2.21^a \pm 0.12$

[a] Within column, means followed by the same letters are not significantly different at P = 0.05, General Linear Model, t – Test (LSD)

Even though there was no significant difference of air temperatures inside the greenhouses covered by 52- and 40-meshes (Table 2), the diurnal air temperature for typical day taken from October 10, 2004 (Figure 5) showed that internal air temperature was a significant different for each greenhouse mostly during day time from 8:00 to 17:00 h. It is clear that in the 78-mesh greenhouse internal air temperature was dramatically higher than that in the 52- and 40-mesh greenhouses, while the increase of air temperature in the 52-mesh was quite less if not similar to the one in the 40-mesh greenhouse. However, during night time their air temperatures (for all greenhouses) were quite similar.

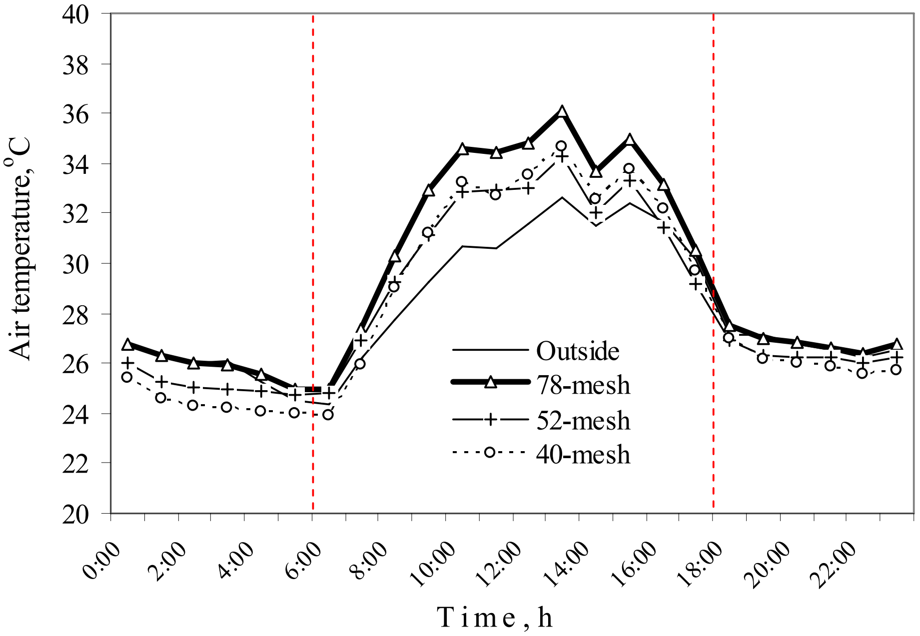


Figure 5. Diurnal air temperature in each greenhouse and ambient for the typical day.

Moreover, the values of temperature differences between inside and outside greenhouse for each treatment were always positives during experiment as shown in Figure 6. This means that air temperature in the greenhouses was always higher than outside. On average, air temperature in both 40- and 52-mesh greenhouses were 1 to 1.5 °C higher than ambient temperature. Similarly, air temperature inside the 78-mesh greenhouse was 2 to 3 °C higher than ambient temperature. The increase of temperature inside the greenhouse was mainly caused by the use of insect-proof screen over the ventilation opening. As the ventilation rate in the 78-mesh greenhouse was low, the temperature rise was significantly higher compared to the ambient temperature. This may affect to the growth of tomato crops cultivated in the greenhouse, especially in the 78-mesh greenhouse.

Statistically, there was a significant effect of the use of higher mesh-size on absolute humidity at confident level of 95% as shown in Table 2. Under natural ventilation, the greenhouse covered with 78-mesh, the absolute humidity difference between inside and outside the greenhouse was almost 50% and this increased the air temperature by 1 to 2 °C compared to the 40-mesh greenhouse (Figure 6) even though their relative humidity seem very close to each other (Table 2). On the contrary, the water vapour density in the greenhouse covered with 40-mesh was very close to the ambient condition (about 1 to 2 g/m^3), while for the greenhouse with 78-mesh their differences were up to 5 g/m^3. This may lead to increased incidences of fungal diseases and subsequent yield reduction. The accumulated water vapour could not be transported out from the greenhouse due to lower ventilation rate.

Figure 6 shows the daily average air temperature and absolute humidity difference that occurred during daytime over the experimental period. When the plants were young, the temperature differences were relatively high, while absolute humidity differences were less. In this case, the sensible heat was more dominant than the latent heat involved in the ventilation rate measurements. On the contrary, the latent heat induced by the microclimate was more dominant when the crops were mature. In this condition, the temperature difference was relatively low, while absolute humidity difference was relatively higher. Along the crop season, the trend of temperature difference did not show any changes since the beginning at 1 – 2 °C (except at the 78-mesh increasing up to 4 °C at mature stage) while humidity difference gradually increased as the crops approached maturity. The combined increment of both temperature and humidity in the 78-mesh greenhouse was the cause of significant reduction of the ventilation rate from 0.04 to 0.02 $m^3\ m^{-2}\ s^{-1}$ (Figure 2).

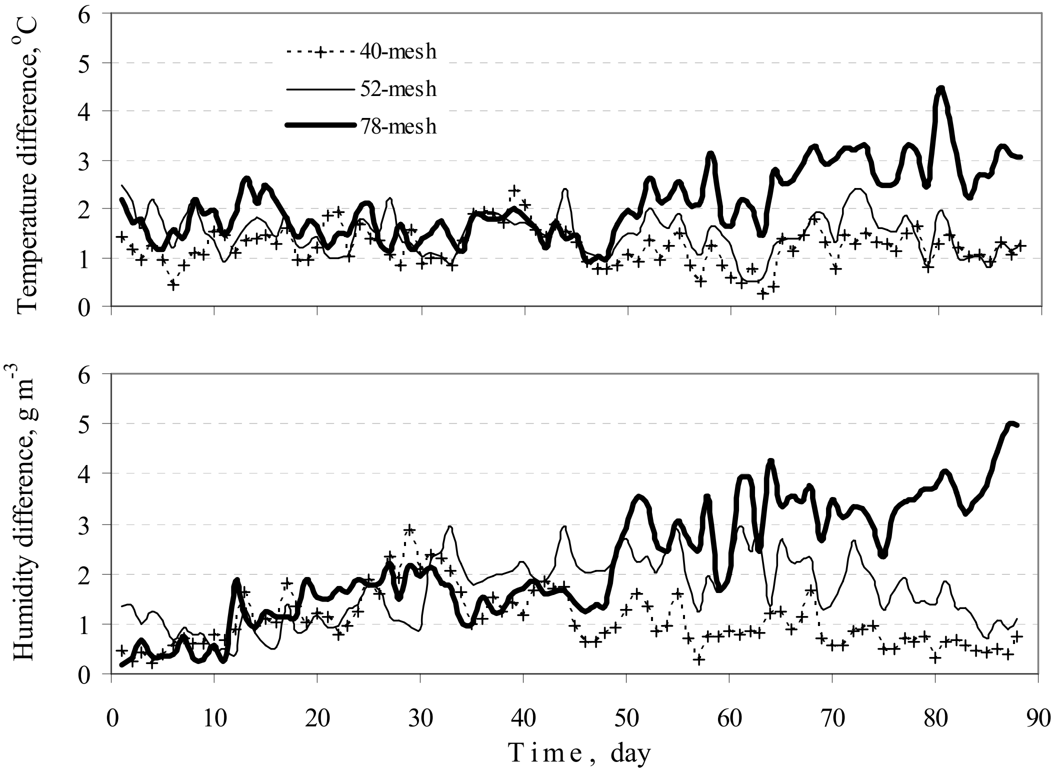
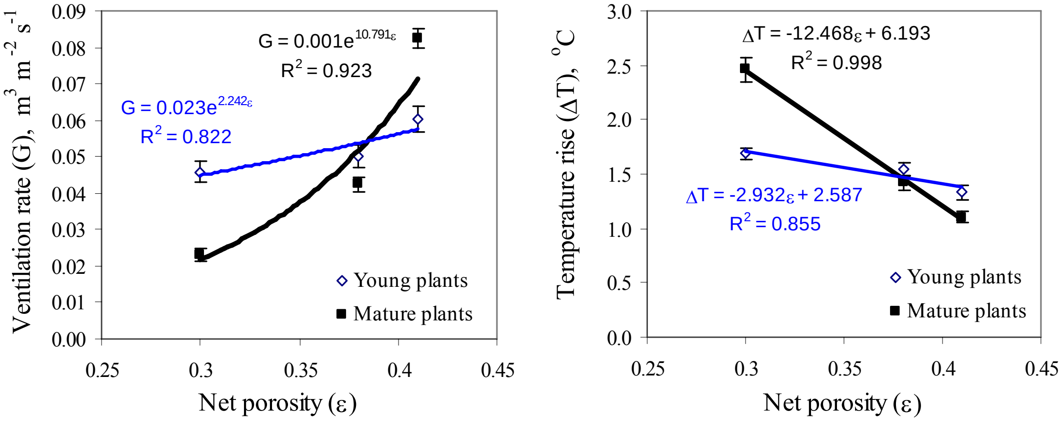


Figure 6. Daily variations of temperature and humidity differences measured over daytime (8:00 to 17:00 h) in the greenhouses covered by different mesh-sizes of nets.

3.4 Mesh Size of Nets Related to Ventilation Rate and Temperature Rise

Since insect screens are available in different types, they are normally described by mesh sizes which give the number of threads per inch length for each direction. In scientific manner, screen porosity is used as important parameter to describe the screen types (Table 1). The effect of screen porosity on the ventilation rate is presented in Figure 7(a). It is clear that ventilation rate was reduced when a net with a lower porosity was applied. Ventilation rate seems an exponential function against the porosity and their correlations were good in agreement (R^2 = 0.923 and R^2 = 0.822 for mature and young plants conditions, respectively).

Figure 7(b) shows the relationships between screen porosity and temperature rise in the greenhouse. Again, the temperature rise in such greenhouse was more if lower porosity of net (78-mesh) was used to cover vent opening. The temperature rise was a linear function of screen porosity. In general, a good agreement between two was also obtained. From the experiment, correlation between two parameters was better if the measurement was done in the greenhouse with mature plants (LAI of 1.5 to 3.0). Since its coefficient correlation, R^2 was 0.998, it can be said that a better agreement was achieved. Therefore, it is important that the simple equation deduced from this study might be very useful to predict the temperature rise if such new nets would be applied to the greenhouse.



(a) (b)

Figure 7. The relationships between (a) net porosity and ventilation rate and (b) net porosity and temperature rise in tropical greenhouses; R^2, coefficient of determination.

4. DISCUSSION

It is interesting recites from the study that the use of higher mesh size of nets was significantly reduced the ventilation rate as well as increased internal microclimate mostly during daytime. These results are in line with the results of Fatnassi et al. (2003); Bailey et al. (2003) who investigated the use of insect-proof screens put on the ventilation openings on air flow pattern, discharge resistance and the change of micro climate in the greenhouse. Air flow and discharge coefficient were well related to the porosity and mesh size of the nets. The reduction of ventilation performance due to the use of other types of nets (anti-Thrips and anti-Aphids) firstly requires the estimation of the discharge coefficient of these nets (Fatnassi et al., 2002). It is clear that the fine meshes of screening net applied to the ventilation openings became an obstacle to air flow or air exchange to renew interior micro climate hence resulting in an increase of air temperature and humidity. Furthermore, this may affect plant growth and yield.

The use of insect-proof net, however, might be unable to significantly reduce the ventilation rate when the ventilation opening is kept as large as possible. Therefore, the ratio of ventilation area to the floor area becomes the important point (or critical factor). As such for tropical region, this value should be more than 0.15, the value required for Germany condition (von Zabeltitz, 1999). In the current study, the ratio of vent opening to surface floor area was 1.05. This helps to maintain the internal temperature close to ambient temperature and to improve ventilation system. The previous study conducted in warmer area had recommended that the ventilation ratio should vary according to the local condition-for instance; in Malaysia at 40% (Kammaruddin, 2000), in New Zealand and Mediterranean at 30% (Hanan, 1998), in USA at 15 – 25% (ASAE, 1989) and warmer region of Mediterranean at 30 – 33% (Montero et al., 1997). So, keeping very large vent opening is the key point to enhance ventilation system. This is also supported by the result of Muňoz et al. (1999) who investigated that the larger ventilation opening (the roll-up roof vent) could provide a ventilation rate about three times greater than the smaller opening of the continuous roof vent covered with insect-proof net (40-mesh). Tanny et al. (2003) also emphasized that the ventilation rates at the screen house with Bio-Net 50-mesh were higher than the normal greenhouses with the same size.

From the experiment, it is not the case that the large vent ratio of greenhouse at 1.05 would assure a better ventilation rate at an ideal level. As per recommended by ASAE (1989) that the ideal ventilation rate for better ventilation system is about 0.75 – 1 times per minute or equivalent 0.062 – 0.083 $m^3\ m^{-2}\ s^{-1}$. It was only in the 40-mesh greenhouse (average ventilation rate of 0.072 $m^3\ m^{-2}\ s^{-1}$) that met the recommended value, while for both 52-mesh and 78-mesh greenhouses the average ventilation rates were less than the ideal value. In this respect, an appropriate size of horizontal axial fans which can provide a positive pressure in the greenhouse may be necessary. This would help to increase air flow inside the greenhouse since very low wind speed was recorded in the greenhouse. When the air flows were improved, ventilation rates were also increased. During our experiment, airflow was a key issue and might have been influenced by dust and/or rain as both might have blocked some of holes of the insect-proof net resulting in a reduction in the ventilation opening. In this condition, the water may form a thin layer over sidewall during some period of time, thereby significantly reducing the airflow through the net.

In line with the finding of Boulard and Draoui (1995) and Roy et. al. (2002), ventilation rate estimated using an energy balance method has a good agreement to the ones measured from the tracer gas. A better correlation between two methods was obtained when the measurements were conducted in the greenhouse covered by less porous net (lower vent opening) and under mature plants condition. More accurate results may be achieved if a the measurements are conducted under stable condition (e.g. clear sunny day). Hence, the energy balance method is a good alternative for predicting ventilation rate as it is simple, quick and accurate method.

Despite the fact that only a limited number of screen types was used for this study,(only three), the equations deduced can be used to predict ventilation rate and temperature rise. Screen porosity was used as the main parameter to predict these parameters. As lower porosity of nets was used, ventilation rates were exponentially reduced as well as linearly increasing the temperature in the greenhouse. This finding is in accordance with the result from Fatnassi et.al (2003) who investigated the linearity of air exchange rate against discharge coefficient (C_d) of insect-proof net. Since a good correlation was mostly obtained from the experiment, the simple equation achieved from the study would be useful to the grower.

5. CONCLUSIONS

The use of different net-sizes placed on the greenhouse ventilation openings showed a significant effect on the ventilation rates and internal microclimate. During experiment, the reduction of ventilation rate by about 50% and 35% for the 78-mesh and 52-mesh greenhouses, respectively were obtained compared to the 40-mesh greenhouse. Consequently, the internal air temperature was increased by 1 to 3 °C. Even though, a small difference of temperature was observed, the absolute humidity among treatments was significantly different. Higher mesh-size of net used resulted in more humidity. The use of finest hole-size of insect-proof net significantly increased internal air temperature and absolute humidity during daytime, which might promote the incidence of fungal diseases.

An energy balance method, which offers a simple, quick and accurate means to predict the ventilation rate has been developed and used in the recent study. The method could simply calculate the ventilation rate based on the common microclimatic data available (including solar radiation). This method was also valid to predict the ventilation rates in the greenhouses located in the humid tropics since a good agreement between two methods (a tracer gas and an energy balance methods) was obtained especially at plant maturity in the 78-mesh greenhouse ($R^2 = 0.85$).

Ventilation rate and temperature rise in such greenhouse covered by the net were strongly correlated to its net porosity. Since their correlations were good in agreement ($R^2 = 0.998$), the simple equation derived from the experiment might be useful to the grower to predict expected temperature rise when a new net (to exclude a certain insect) is applied to the greenhouse.

6. ACKNOWLEDGEMENTS

Financial support from the German Research Foundation (DFG), University of Hanover, and Ministry for Economic Cooperation and Development (BMZ), Germany, is gratefully acknowledged.

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