# Evaluation of net greenhouses for tomato production in the tropics

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| | | |
|---|---|---|
| $A_c$ | cover surface area | [$m^2$] |
| $A_f$ | floor area | [$m^2$] |
| $A_g$ | soil surface area | [$m^2$] |
| $A_o$ | effective vents opening area | [$m^2$] |
| $A_r$ | roof area | [$m^2$] |
| $A_s$ | side area | [$m^2$] |
| $a$ | constant of predicted air exchange rate | [ - ] |
| $C$ | gas concentration | [$kg_{(gas)}\ kg^{-1}{}_{(air)}$ ] |
| $C_{con}$ | condensation rate on ground or crop | [$kg_{(water)}\ m^{-2}\ s^{-1}$] |
| $C_d$ | discharge coefficient | [ - ] |
| $C_h$ | convective heat exchange coefficient | [$W\ m^{-2}\ K^{-1}$ ] |
| $C_i$ | inside gas concentration | [$kg_{(gas)}\ kg^{-1}{}_{(air)}$ ] |
| $C_o$ | outside gas concentration | [$kg_{(gas)}\ kg^{-1}{}_{(air)}$ ] |
| $c_p$ | specific heat transfer of air | [$J\ kg^{-1}\ K^{-1}$] |
| $C_w$ | wind speed coefficient | [ - ] |
| $dC_i$ | variation of gas concentration during a time interval | [$kg_{(gas)}\ kg^{-1}{}_{(air)}$ ] |
| $dt$ | time interval | [s] |
| $dX_i$ | water vapour difference | [$kg\ m^{-3}$] |
| $E_s$ | soil evaporation | [$kg_{(water)}\ m^{-2}\ s^{-1}$] |
| $E_T$ | crops evapotranspiration (latent heat) | [$W\ m^{-2}$] |
| $F$ | water supply into the greenhouse (misting) | [$kg_{(water)}\ m^{-2}\ s^{-1}$] |
| $F_g$ | soil thermal flux | [$W\ m^{-2}$] |
| $G$ | ventilation rate per unit greenhouse floor | [$m^{-3}\ m^{-2}\ s^{-1}$] |
| $g$ | acceleration of gravity | [9.81 $m\ s^{-2}$] |
| $H$ | height of vent opening above the floor | [m] |
| $H_c$ | energy loss to the greenhouse wall | [$W\ m^{-2}$] |
| $H_s$ | sensible energy gain | [$W\ m^{-2}$] |
| $H_v$ | energy loss due to ventilation | [$W\ m^{-2}$] |
| $K$ | global sensible heat loss coefficient | [$W\ m^{-2}\ K^{-1}$] |
| $K_v$ | coefficients of heat transfer by ventilation | [$W\ m^{-2}\ K^{-1}$] |

| | | |
|---|---|---|
| $L_v$ | latent heat of vaporization of water | [J kg$^{-1}$] |
| $M$ | gas injection rate | [kg$_{(gas)}$ kg$^{-1}$$_{(air)}$ s$^{-1}$] |
| $N$ | air exchange rate | [h$^{-1}$] |
| $n_s$ | percentage of solar heat used for evapotranspiration | [ - ] |
| $Q_c$ | heat losses due to the use of cladding material | [W] |
| $Q_g$ | heat losses by the soil substrate | [W] |
| $Q_l$ | heat losses by air leakage | [W] |
| $Q_p$ | heat losses by photosynthesis processes | [W] |
| $Q_s$ | solar radiation absorbed within greenhouse | [W] |
| $Q_{si}$ | sensible heat | [W] |
| $Q_v$ | heat removed by ventilation | [W] |
| $Q_{lt}$ | latent heat | [W] |
| $Re$ | Reynold number | [ - ] |
| $RH$ | relative humidity | [%] |
| $R_n$ | average net solar radiation | [W m$^{-2}$] |
| $t$ | time | [s] |
| $T_i$ | inside temperature | [K] |
| $T_o$ | outside temperature | [K] |
| $T_p$ | predicted internal air temperature | [K] |
| $T_r$ | crops transpiration rate | [kg$_{(water)}$ m$^{-2}$ s$^{-1}$] |
| $U$ | overall heat transfer coefficient | [W m$^{-2}$ K$^{-1}$] |
| $v_{10}$ | wind speed at height 10 m above ground level | [m s$^{-1}$] |
| $V_g$ | greenhouse volume | [m$^3$] |
| $V_r$ | ratio of vent opening to floor surface area | [ - ] |
| $v_w$ | wind velocity | [m s$^{-1}$] |
| $W_{fi}$ | incoming water flux to the greenhouse | [ℓ h$^{-1}$] |
| $W_{fo}$ | outgoing water flux from the greenhouse | [ℓ h$^{-1}$] |
| $W_v$ | loss water vapour from leakage and ventilation | [kg$_{(water)}$ m$^{-2}$ s$^{-1}$] |
| $X_i$ | absolute humidity inside greenhouse | [kg m$^{-3}$] |
| $X_o$ | absolute humidity outside greenhouse | [kg m$^{-3}$] |
| $X_p$ | predicted humidity inside greenhouse | [kg m$^{-3}$] |
| $\alpha$ | ratio of sensible to latent heat in | |

| | | |
|---|---|---|
| | greenhouse (Bowen ratio) | [ - ] |
| $\beta$ | ratio of total greenhouse surface area to floor area | [ - ] |
| $\varepsilon$ | screen porosity | [ - ] |
| $\Delta H_A$ | specific humidity ratio difference | [kg kg$^{-1}$] |
| $\Delta P_w$ | difference of pressure drop across ventilation opening | [Pa] |
| $\Delta T$ | temperature difference between inside and outside greenhouse | [K] |
| $\Delta T_c$ | temperature difference between inside greenhouse and plastic cover | [K] |
| $\rho_a$ | air density (air specific mass) | [kg m$^{-3}$] |
| $\rho_w$ | water density | [kg $\ell^{-1}$] |
| $\lambda$ | wavelength solar radiation | [nm] |

**Abbreviations**

| | |
|---|---|
| ANOVA | **An**alysis **o**f **Va**riance |
| ASAE | **A**merican **S**ociety of **A**gricultural **E**ngineering |
| BER | **B**lossom **E**nd **R**ot |
| Ca | **Ca**lcium |
| CFD | **C**omputational **F**luid **D**ynamics |
| DAT | **D**ay **a**fter **T**ransplanting |
| $ET_C$ | **C**rops **E**vapo**t**ranspiration |
| FV | **F**orce **V**entilated |
| GLM | **G**eneral **L**inear **M**odel |
| HAF | **H**orizontal **A**xial **F**ans |
| IPM | **I**ntegrated **P**est **M**anagement |
| ITG | **I**nstitut für **T**echnik in **G**artenbau |
| LAI | **L**eaf **A**rea **I**ndex |
| LSD | **L**east **S**quare **D**ifference |
| NA | **N**ot **A**vailable |

| | |
|---|---|
| NPK | Nitrogen (**N**) Phosphorus (**P**) and Potassium (**K**) |
| NV | **N**atural **V**entilated |
| NVTGS | **N**aturally **V**entilated **T**ropical **G**reenhouse **S**ystem |
| P | **P**robability (statistical analysis) |
| PE | **P**oly**e**thylene |
| ppm | **p**arts **p**er **m**illion |
| SD | **S**tandard **D**eviation |
| SE | **S**tandard **E**rror |
| UV | **U**ltra **V**iolet |

# Summary

The cultivation of vegetables in the humid tropics, which are mostly characterized by high temperature and humidity, abundant solar radiation throughout the year and occasionally high rainfall, is a vast challenge as well as a great opportunity. High humidity as a consequence of heavy rainfall and high temperatures are to be mentioned as the predominant constraints for vegetable production in the humid tropics. Furthermore infestations by pests and diseases lead to severe crop-damages, thus, the consumption of pesticides increases remarkably. In order to address these problems, an adapted greenhouse, having large ventilation opening area at 105% of total floor surface area and covered with insect-proof nets has been developed and tested.

The main goal of this recent study was to investigate the physical and technical basis of an integrated management system of an adapted greenhouse for sustainable vegetables production in the humid tropics. The investigation on the effect of insect-proof nets of different mesh-sizes, placed on the ventilation openings (sidewall and roof opening), on microclimate, air exchange rates as well as crop performance, biological plant protection, and fertigation system was simultaneously carried out in several greenhouses. Three kinds of insect-proof nets i.e. 40-mesh (anti-leafminers), 52-mesh (anti-whiteflies) and 78-mesh (anti-thrips) sizes had been selected to cover sidewalls vent openings. Each greenhouse had a size of 10 m × 20 m, with the top covered by UV-stabilized plastic film. The experiment was also conducted over three different seasons of the year. Tomatoes were chosen as the experimental crop due to its sensitivity against several diseases mostly affecting to tropical vegetables.

The results revealed that the use of different mesh-sizes of insect-proof nets as cladding materials over ventilation opening has a significant effect on microclimate, air exchange rate, crop performance, total production and fruit quality, pest infestation, and crop water requirement. The reduction of air exchange rate 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 also increased by 1 to 3 °C. Regarding air temperature only minor differences have been observed. However, differences in absolute humidity were much more pronounced and statistically significant. Humidity in 78-mesh greenhouse was consistently approx. two times higher than in 52- and 40-mesh greenhouses. 52-mesh houses showed the best results in crop performance, total production and fruit quality. Differences in microclimate between those mesh types were only marginal and statistically insignificant. Thus, and because of the ability to exclude smaller insects, 52-mesh was selected as a compromise size, appropriate for the adapted greenhouse in the humid tropics.

The season of the year has also significantly influenced the microclimate and air exchange rates in the greenhouse, crop production, insect abundances and irrigation water requirement. For the scheduling of the cropping period the fact, that maximum yields and highest fruit quality only could be achieved when fruit set is planned to be in cooler periods.

Two simulation models, based on an energy balance and water vapour balance respectively, were developed and used to predict greenhouse microclimate. A modified model, based on wind speed and temperature difference, was used to the recent study to simulate and predict air exchange rates. These models showed a good agreement between predicted and measured internal temperature and humidity. In addition, the simulation of air exchange rates showed only fair correlations when the measurement was carried out in early development-stages. More accurate predictions were achieved when these models were validated for greenhouse populated with mature crops (at LAI > 1).

Due to very large ventilation openings in the adapted greenhouse (mostly on all sidewalls), the external wind speed did not show strong effect on the air exchange rates. However, a fair correlation was found between air exchange rates and wind speed ($R^2$ = 0.5) whereas the air exchange rates were linearly a function of wind speed. Similarly, the relationship between air temperature difference and measured air exchange rates was found that a fair correlation was obtained at the finer net greenhouses. The effect of temperature difference on air exchange rates was better correlated if the daily average wind speed was less than 2 m $s^{-1}$.

To further reduce the material costs and to inhibit the potential immigration of smaller insect species to the greenhouse, a determination of minimum ventilation opening was performed. The results showed that the minimum ventilation opening area at 60% of total surface floor area is necessary to maintain a favourable microclimate and air exchange rate in the adapted greenhouse. The combination of sidewall- and roof-openings played an important role in providing better air exchange rates in naturally ventilated greenhouses under humid tropical conditions.

In order to avoid extreme internal temperatures that might occur during daytime the adapted greenhouses were additionally equipped with two exhaust fans (1,100 $m^3$ $min^{-1}$ capacity). The fans were installed at the front-sidewall. The effectiveness of exhaust fan operation was evaluated using some important parameters such as: microclimate, air exchange rates and irrigation water requirement. The results showed that only during daytime the operation of the exhaust fans resulted in a small reduction of air temperature (about 1 to 2 °C) as well as an increase of air exchange rate (at about 25 to75%). Even though the increase was significant, optimal air exchange rates (0.75 – 1 air changes $min^{-1}$, cp. ASAE, 1989) could not be achieved. Moreover, in terms of temperature reduction, during early plant growth stages the operation of exhaust fans was less effective, although its effect was significant. In addition, the operation of the exhaust fans during daytime increased the irrigation water requirement by about 15 to 25%.

**Keywords:** *Insect-proof nets; Adapted greenhouse; Microclimate; Air exchange rates; Tomato production; Tropics*

# Zusammenfassung


Gemüseanbau in den feuchten Tropen ist – vor allem - aufgrund der klimatischen Gegebenheiten eine enorme Herausforderung, bietet aber andereseits auch große Möglichkeiten. Vor allem Temperatur und Luftfeuchtigkeit übersteigen häufig die Optima vieler Gemüsearten. Durch die ganzjährig starke Sonneneinstrahlung, sowie – z.T. saisonal auftretende – heftige Regenfälle können Kulturen nachhaltig geschädigt, im Extremfall ganze Pflanzungen vernichtet werden. Hinzu kommt ein starker Befallsdruck durch Schadinsekten und Pathogene, der z.T. durch die Witterungsbedingungen zusätzlich begünstigt wird, was zu einem rapide ansteigendem Pestizideinsatz geführt hat. Geschützer Anbau, namentlich Gewächshäuser mit Insektenschutznetzen, stellt eine Möglichkeit zum Schutz vor Starkregen, exzessiver Einstrahlung und dem Eindringen von Schadinsekten dar, führt allerdings zu vermindertem Luftaustausch sowie erhöter Temperatur und Luftfeuchte. Um die nachteiligen Folgen abzumildern wurden Gewächshäuser mit sehr großen Belüftungsöffnungen von 105% der Gewächshausgrundfläche entwickelt und getestet.

Vorrangiges Ziel der vorliegenden Arbeit war es, technische Grundlagen für die Entwicklung eines integrierten Anbausystems, in Gewächshäusern deren Konstruktion an die Bedürfnisse einer nachhaltigen Gemüseproduktion in den feuchten Tropen angepaßt ist, zu ermitteln. Auf dem Gelände des Asian Institute of Technology, Klong Luang, Thailand (14° 04’ N, 100° 37’ E, 2,27 m ü N.N.) wurden dazu Seitenwände und Dachöffnungen von drei ansonsten baugleichen Gewächshäusern (B.: 10m, L: 20m, Dach aus UV-stabilisierter Plastikfolie) mit Insektenschutznetzen verschiedener Maschenweite (40, 52 bzw. 78 Faeden Inch, zum Schutz vor Minierfliege, weißer Fliege bzw. Thrips) ausgestattet. In drei verschiedenen Jahreszeiten wurden die Auswirkungen dieser Netzumhüllungen (im Folgenden als 40-, 52- bzw. 78mesh bezeichnet) auf Mikroklima, Luftaustausch, sowie Ertragsleistung, Pflanzenschutz und Bewässerungssystem untersucht. Nicht zuletzt aufgrund ihrer Anfälligkeit gegenüber in den Tropen häufig vorkommender Schaderreger wurde Tomate (*Lycopersicon esculentum, var King Kong 2 & var. FMTT260*) als Versuchskultur gewählt.

Es konnte gezeigt werden, dass die Maschenweite der zur Bedeckung der Belüftungsoffnungen eingesetzten Netze einen signifikanten Einfluß auf Mikroklima, Luftaustauschraten, Wasserbedarf, Schädlingsbefall sowie Fruchtertrag und -qualität ausübt. Gegenüber dem 40mesh Netz war die Luftaustauschrate bei 52mes“ um rund 35%, bei 78mesh sogar um 50% reduziert, die Lufttemperatur in den Gewächshäusern infolgedessen um 1°C (52mesh) bzw. 3°C (78mesh) erhöht. Obgleich die festgestellten Temperaturerhöhungen nur gering ausfielen, war ein signifikanter Anstieg der absoluten Luftfeuchtigkeit durch die Verwendung engmaschigeren Netzes zu beobachten. Gegenüber dem 40mesh-Netz war die abs. Luftfeuchtigkeit unter 78mesh nahezu verdoppelt. Aufgrund der relativ geringfügigen Beeinträchtigung von Mikroklima und Lufaustausch, der besseren Ergebnisse hinsichtlich Fruchtertrag und -qualität sowie der Eignung die Kultur auch vor kleineren Schadinsekten zu schützen, kann

das 52mesh als geeigneter Kompromiss für die Anwendung in, an tropische Bedingungen angepaßten Gewächshäusern, angeshen werden.

Auch die Jahreszeit hatte einen signifikanten Einfluß auf Mikroklima, Luftaustausch, Ertragsleistung, Schadinsektenabundanzen sowie dem Wasserbedarf der Kultuen in den Gewächshäusern. Bei der Planung der Kulturzeiten sollte in Erwägung gezogen werden dass maximaler Fruchtertrag und bestmögliche Qualität nur dann zu erzielen sind, wenn der Fruchtansatz in der weniger heißen Jahreszeit stattfindet.

Zur Vorhersage von Luftaustauschraten und Mikroklima in den Gewächshäusern wurden 2 Simulationsmodelle, die auf Grundlage der Energie- bzw. Wasserhaushaltsbilanzmethode entwickelt wurden, eingesetzt. Zur Simulation und Vorhersage von Luftaustauschraten wurde desweiteren ein modifiziertes Modell verwandt welches Windgeschwindigkeit und Temperaturunterschiede als Eingangsparameter nutzt. Hinsichtlich Temperatur und Luftfeuchte zeigten mittels dieser Modelle simulierte und gemessene Werte gute Übereinstimmung. Die Simulation der Luftaustauschraten war, vor allem bei jungen Beständen, weniger genau. Erst bei zunehmendem Alter der Bestände (ab LAI > 1) verbesserten sich die Übereinstimmungen zwischen gemessenen und simulierten Luftaustauschraten.

Aufgrund der sehr großen Belüftungsflächen der angepaßten Gewächshäuser übte die Außenwindgeschwindigkei nur geringen Einfluß auf die Luftaustauschraten aus. Die Korrelation zwischen Windgeschwindigkeit und Luftaustauschraten war nur mäßig ausgeprägt ($R^2$ = 0,5), der Zusammenhang jedoch liniear. Der Zusammenhang zwischen Lufttemperaturunterschieden und gemessenen Luftaustauschraten war ähnlich schwach ausgeprägt. Seine Stärke nahm jedoch mit abnehmender Netzmaschenweite sowie abnehmnder Außenwindgeschwindigkeit zu. Vor allem bei Außenwindgeschwindigkeiten unter 2 m $s^{-1}$ wurden gute Korrelationen festgestellt.

Um Materialkosten zu senken und mögliche Immigration von kleinen Schadinsekten zu unterbinden wurde weiterhin untersucht welche Fläche mindestens zur Belüftung des Gewächshauses geöffnet bleiben sollte. Es zeigte sich, dass mindestens eine Fläche entsprechend 60% der Gewächshausgrundfläche zur Belüftung notwendig ist um akzeptable mikroklimatische Bedingungen und Luftaustauschraten sicherzustellen. Die Kombination von Öffnungen in den Seitenwänden und am Dach ist gut geeignet um die Luftaustauschraten natürlich belüfteter Gewächshäuser in den Tropen zu verbessern.

Mit dem Ziel extreme Innentemperaturen in den Gewächshäusern zu vermeiden, die gelegentlich im Tagesverlauf auftreten können, wurden an den Stirnseiten der Gewächshäuser zwei Absaugventillatoren mit einer Kapazität von je 1100 $m^3$ $min^{-1}$ installiert.Mit Hilfe einiger Schlüsselparameter wie Mikroklima, Luftaustauschraten und Wasserverbrauch der Kulturen wurde die Effektivität des Ventillatoreinsatzes überprüft. Ein Betrieb der Ventillatoren verringerte die Innnenlufttemparatur um 1-2°C und führte zu signifikanten Steigerungen der Luftaustauschraten um 25 bis 75%. Obwohl der Luftaustausch durch die

Ventilatoren beachtlich gefördertert wurde, konnten optimale Luftaustauschraten (0,75 – 1 facher Luftaustausch min$^{-1}$, vgl. ASAE 1989) nicht erreicht werden. Hinsichtlich der Innentemperaturen war die Effektivität des Ventilatoreneinsatzes während der frühen Stadien der Pflanzenentwicklung am geringsten, die Verringerung der Temperatur gegenüber dem ausschließlich natürlich belüfteten Gewächshaus jedoch signifikant. Der Wasserbedarf der Tomatenkulturen wurde durch den Betrieb der Absaugventilatoren um rund 15-25% erhöht.

**Schlagworte**: Insektenschutznetze, Gewächshaus, Mikroklima, Luftaustausch

# 1. Introduction

The development of worldwide greenhouse to produce horticultural products with relatively safe and heath products for human life has increased due to the increase demand for fruits/vegetables (as increasing world population), and rising standard of living. Recently, the development of greenhouse is also expanding from highland (cooler) and temperate areas to lowland and warmer regions such as in sub-tropic or tropical region in order to fulfil the above demand. Moreover, the greenhouse concept for crops production is now migrating from the conventional technology either using glass or plastics film as cladding material to adapted greenhouses using insect-proof screen as covering material. This is stressed on the interest of biological security measures incorporated in greenhouses to reduce infestations of insect pests and diseases.

Meanwhile, growing vegetables in greenhouse in the humid tropic region, like Thailand, has many challenges because it has some specific conditions such as: high temperature, high humidity, and abundant solar radiation. Thus it is possible to cultivate crops along the year due to the availability of solar radiation. However, both higher temperature and humidity have become a serious problem for crop cultivation under tropical greenhouses. Plants stress and significant yield reduction can be caused by this temperature rise. Therefore, some efforts to reduce high temperature and humidity should be made in order to provide optimum conditions for growing plants in the greenhouse.

The concept of adapted greenhouse for tropical region has been proposed and recently tested. The greenhouse was designed to be a relatively simple structure, easy in operation, cheaper and low cost in maintenance. The material for building up the greenhouse should be locally available with relatively longer period of life use (mostly about 3 – 5 years). A naturally ventilated greenhouse is mostly common practice to meet these requirements. In addition, the ventilation opening area should be maintained to be as large as possible in order to achieve an internal air temperature close to the ambient temperature (von Zabeltitz, 1999), and it has become a cooling tool for crops inside the greenhouse in terms of microclimate management. In order to avoid the possibility of poor conditions in case of an extreme temperature in the greenhouse, the appropriate exhaust fans had been installed.

In the frame of integrated pest management (IPM) involved in the adapted greenhouse, some selected insect proof nets were used in greenhouse to exclude some insect pests. It is reported that insect pest is one of major problems in greenhouses located in humid tropics region. Therefore, the use of insect-proof nets for cladding material in the greenhouse has become very important because it can prevent crop damage by insects and other diseases. The practice to exclude insect disease by using the net as cladding material over the ultra-violet (UV) plastic film in the greenhouse is also known as protected cultivation. Moreover, insect screening reduces the number of insects entering a greenhouse and reduces the need for pesticides.

Even though nets are effective in protection from insect, putting the screening net can cause a restriction to the air flow, so a larger screened area is needed to permit the same air flow as originally existed. Many authors (Bailey et al., 2003; Montero et al., 1997; Munoz et al., 1999) investigated that there is a reduction as shown as discharge coefficient parameter or air flow resistance when the insect net was applied on greenhouse. Reduction of air flow rate in greenhouse due to the effect of insect screens can lead to increase air temperature and humidity.

A number of studies have already proven and recommended the use of appropriate mesh size of insect-proof nets for different insect pest exclusion (Bethke, 1990, Bell and Baker, 2000), but the knowledge about the effect of nets for crops plant protection on the climate inside the greenhouse is very low. The selection of a certain kind of nets to be used in the greenhouse was mainly based on the size of insects to be excluded, the stage of insects (young or adult insects) and their behaviours while they were flying or migrating into the greenhouse. Basic research on greenhouses with nets has to be done while examining the effects on vegetable crops, plant protection and irrigation has not to be carried out yet, because the influence of nets on inside climate is not well known so far.

Based on the problems mentioned above, some efforts on controlling microclimate under naturally ventilated greenhouse will be focused on applying the different widths of net meshes and installing the emergency ventilation by exhaust fans. With regards to the treatment, measuring air exchange rate and other climatic parameters (using both direct measurements and a model) has to be adapted. Therefore, the optimization of mesh-size of nets to be used in the adapted greenhouse for the humid tropics would then be possible.

Further work on determining the minimum ventilation opening area covered by insect-proof net has also been conducted. In order to provide sufficient ventilation, the ratio of total ventilator opening to the greenhouse floor area should be greater than 15-25% in Hanover, Germany (von Zabeltitz, 1999), more than 20% in warmer area of Australia (Connelan, 2002) and more than 10% in USA (Albright, 2002). None of above studies was conducted in the humid tropic region and the design construction of adapted greenhouse is also not similar. Furthermore, opening the ventilation area as large as possible are not effective and efficient ways if the cost of selected insect proof-net and the possibility of insect passing through the net are taken into account compared to the plastic-film as cladding material.

# 2. Literature Review

## 2.1 Greenhouse design approach for tropical region

The cultivation of vegetables conducted under greenhouse in the tropical region is characterized by some specific conditions such as: high temperature and humidity, the abundant of global radiation and heavy rainfall. These factors could be both as advantages on one side and as limiting factor for crops production on the other. Temperature and global radiation, for instance, are very suitable for the vegetable cultivation throughout the year, but heavy rainfalls and high humidity could damage the crops causing the infestation by diseases.

Greenhouse production at high, even over 35 °C, dry bulb temperatures are common for many tropical regions especially in lowland area and crops are potentially at risk. Crops stress usually occurs during the peak period of daytime. This can cause a significant effect on crop yield and the development of fruit setting (Pék and Helyes, 2004). Therefore, the reduction of air temperature inside the greenhouse or the regulation of air temperature to be similar to the ambient temperature was assumed as a key issue in crop production at these regions. There are numerous options available to minimize or eliminate these risks due to high temperature. The environmental modification techniques can be broadly categorized as: greenhouse design (shape, dimensions and roof configuration), reducing solar load through shading and venting, forced air circulation and evaporative cooling (Connellan, 2002).

The selection of the most appropriate technique for reducing internal air temperature in tropical greenhouse is a challenge in order to seek the profitable businesses in crop production. Natural ventilation system incorporated with an appropriate design of greenhouse is one of possible efforts to overcome the problem. This is economically viable in terms of low initial investment and low cost in operation and maintenance. A well designed; naturally ventilated greenhouse will provide acceptable air temperature conditions and better microclimate. Natural ventilation guidelines including minimum ventilation opening area of 20% of greenhouse floor area have been outlined by Connellan (2000).

Another study conducted by Albright (2002) mentioned that in bright sunshine, air temperature inside the greenhouse is a function of vent area as percentage of floor area. Indoor air temperature does not begin to approach outdoor air temperature until vent area (both roof and side wall) is more than 10% of floor area. A greenhouse which is not able to maintain the inside temperature within 5 to 6 °C of outside air temperature is considered to be performing poorly in terms of ventilation.

The adoption of roof ventilated greenhouse or the combination of both roof and side wall opening ventilation is widely used and more appropriate for humid tropic greenhouses. This allows better air exchange rate between inside and outside the greenhouse condition as a result that the microclimate inside the greenhouse is expected to be close to the ambient temperature. The best way to achieve this goal is to keep the ratio of ventilation opening to floor area to be as large as possible (von Zabeltitz, 1999). For tropical region, the side wall opening could be opened as much as possible, but the roof vent opening should be limited due to the presence of rain during the rainy season.

The greenhouse height is also another consideration in developing an adapted greenhouse for the humid tropical environment. From the conventional greenhouse which typically has height in the range of 1.5 to 2.0 m in the mid to late 90’s, the current wall height often in the range of 2.5 to 4.5 m (Connellan, 2002). These developments have improved the growing environment for greenhouse crops. Reductions in maximum greenhouse air temperatures have been the main benefit. The height of the greenhouse affects the ventilation efficiency by natural ventilation, if ventilation openings are positioned at the ridge and on the side wall. The higher the ridge and the greater the distances between ventilators at the ridge and side wall, the higher are pressure differences. The ventilation efficiency is proportional to the pressure differences (Bot, 1983). On the other hand, high greenhouses with large volumes provide better climatic condition.

In order to improve the ventilation efficiency above, the following measures should be taken into account (von Zabeltitz, 1999): (1) volume/floor ratio as large as possible, if local wind speed is not too high; (2) single-span and multi-span constructions with open side walls, gables and ridge ventilators which should remain open; (3) nets on ventilators, if protection from insects is necessary.

Since the insect disease is one of the main problems in growing vegetables in humid tropics greenhouse, the implementation of Integrated Pest Management (IPM) strategies as mentioned above has been strongly encouraged in recent times. The use of insect-proof net put in front of ventilation opening is now being implemented and widely used in tropical regions because it has some advantages such as: to prevent or exclude selected insect diseases and to reduce the use of pesticide. However, the impact on the greenhouse environment, in particular temperature rise and reduction in air exchange rate, is to be concerned. The nets placed on front of ventilation inlets reduce the amount of air passing through the inlet, and may prevent the ventilation system. Nets create resistance which reduces airflow and the smaller the hole-size, the greater the resistance. Thus it is important to use the proper size and mesh screen.

## 2.2 Type of insect-proof net for greenhouse

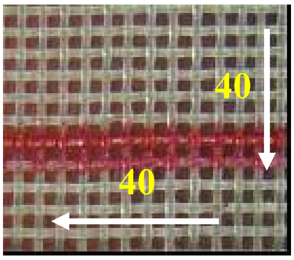
Screening on ventilation inlets and greenhouse entrances will prevent most vegetable insect pests from flying into the house. Selection of the proper net for a greenhouse depends on the size of the insect to be excluded. Bethke (1990) has found that the following common insect pests of greenhouses can be excluded using screen with the hole sizes (or smaller) shown in Table 2.1.

**Table 2.1: Screen hole sizes required to exclude several insect pests**

| Insect pests | Screen hole size | | |
|---|---|---|---|
| | Microns | Inches | Mesh |
| (Serpentine) Leafminers | 640 | 0.025 | 40 |
| (Sweet potato) Whiteflies | 462 | 0.018 | 52 |
| (Melon) Aphids | 340 | 0.013 | 78 |
| (Greenhouse) Whitefly | 288 | 0.0113 | 81 |
| (Silver leaf) Whitefly | 239 | 0.0094 | 123 |
| (Western flower) Thrips | 192 | < 0.0075 | 132 |

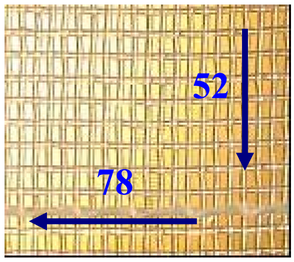
Source: Bethke, 1990

The classification of nets shown in Table 2.1 is categorized according to the holes size or mesh sizes, which give the number of threads per inch in each direction. A 40 mesh screen, for instance, has forty threads per inch length in each direction. This is a square type screen net. Within this mesh size category, there are two types of screen, i.e.: (1) square type mesh screen, whereas the number of threads per inch in each direction is equal and (2) rectangular type mesh screen, whereas the number of threads per inch is not equal in each direction. So, the mesh size of screen is generally described as the number of threads for both directions. A 78 × 52 mesh screen, for example, has seventy-eight threads per inch in one direction and fifty-two threads per inch in another direction. The illustration of two types of mesh size screen is shown in Fig 2.1.




(40×40 mesh)

(a) square screen type,




(78×52 mesh)

(b) rectangular screen type

**Figure 2.1: Two types of mesh-size screen used for the greenhouse**

In terms of the protection from insect-pest, the square screen is relatively better and more secure from the possibility of a certain insect pest getting into the greenhouse through the net at any possible position of insect flying compared to the rectangular one. This may exclude insects but also create an unfavourable growing environment due to air temperature rise and lack of air flow. The rectangular type, on the other hand, has more open area than square screen type and result in better ventilation and reduction of air flow resistance. According to Bell and Baker (2000), airflow resistance, indicative of mesh hole-size, did not necessarily correspond with degree of pest exclusion. Not all materials characterized as highly resistant to airflow provide significant exclusion. The possible reason was that both types of rectangular and square screen types were used in the experiment.

Klose and Tantau (2004) tested several types of insect screens in order to classify the screens into groups according to the mesh size and to evaluate their air permeability and light transmission. The group was categorized as the area of screen hole-size from 0.10 to 1 $mm^2$. The screens with smallest mesh size had the highest-pressure drop and less air permeability, but the open area of screen-hole (porosity) should be include into the consideration due to the difference in the thickness of the threads. Screens with a larger open area had better air permeability. The highest light transmission was obtained from the screens with the biggest mesh size, but the screen with the smallest mesh size did not have the lowest transmission. Other parameters such as the structure of the threads (wool threads) and dust (dirty) threads may influence to the light transmission.

According to the material used to make screens, there are four types of insect screen in USA (NGMA, 1996), i.e.: (1) stainless steel and brass screens, which is most expensive, (2) polyethylene screens: it is commonly used and available into two forms of monofilament and film, (3) polyethylene/acrylic screen: it is made of many fibres (multifilament) which causes resistance to smooth yarns sliding together and therefore maintains the integrity of the holes, (4) nylon screen: this is good for shorter-term, low cost and light duty exclusion. Meanwhile, based on its construction, screen is categorized into three types as follow: (1) weave - the most common screen construction done today, provides a trade off between exclusionary hole-sizes and air flow; (2) knit - each thread is tied around the next, forming a durable network of knots that resist tearing and raveling. The extra loops and knots may also cause greater air restriction; (3) film - polyethylene film can be punched full of micro holes creating an insect barrier.

Apart from the conventional insect screens, some special types of insect screens had been developed. They have been used for special purposes or applications, too. Bionet is one of the new inventions of screens that it is ultraviolet (UV)-absorbing. The study in comparison between two types of screens (UV-absorbing nets and regular nets) against insect infestation and disease incidence on tomatoes grown has been reported by Antignus et al. (1998). The study compared the insect infestation and disease incidence in tomatoes grown under a tunnel covered with a conventional screen on one hand and a bionet on the other hand.

The results showed that plastic screens with UV absorbency in the UV-A and UV-B range serve as optical barriers to protect tomatoes from certain insect pests. Reduced tomato disease incidences were also reported.

The other screens for special purpose are shading screen, open-woven screen and thermal screen. Shading screens is used for reducing the greenhouse heat load during the summer. In hothouses provided with roof openings, the open-woven screen allows the heated air rising from the plants to reach the roof and come outside (Cohen and Fuchs, 1999). In a greenhouse equipped with a sprinkler system or wet beds in order to increase humidity, the heated air passes through the screen, allowing humid and cool air running beneath it to reach the plants. Even in the case of eventual malfunctions in the humidity boosting system, no condensation will be observed on the screen.

The open-woven screen is the most adequate for cold climate conditions in winter and harsh heat during summers. This screen is used mainly for the heat load reduction inside greenhouses. An open-woven screen is a net woven with the inclusion of brilliant reflective fibres. The light they receive from the outside hits those fibres, passes through them and is diffused around the plants. The diffuse light thus received contributes to the photosynthetic process, and gives less heat than the direct sunlight radiation. For instance: a 60% open-woven net allows the passage of 40% of direct light and another 15% of diffuse light, as compared to the 60% black shading net, which only allows the passage of 40% of direct light .

In addition, a thermal screen is used for summer energy savings within the greenhouse (Cohen and Fuchs, 1999). The principal contribution of the open-woven screen to heat conservation inside the greenhouse is linked to its reflectivity. The open screen retains the infrared radiation and returns it to the plants, thus conserving the heat they require. The efficiency of the screen is higher if employed with a heating system using water instead of an air heating one. The higher the density of the fabric (depending on its shading level), the higher the efficiency of the screen will be in keeping the heat inside. Below an open-woven screen there is no condensation, and therefore the farmer is safe from the dangers of entry or diffusion of fungal diseases on the plants' leaves. For this reason it is not necessary to open the screens at any given periods in order to free the humidity surplus. The open-woven screens can be left in place the whole night without the risk of excessive humidity.

## 2.3 Previous works on insect-proof net used for greenhouse

Since insect proof-screens are becoming popular and widely used for protected cultivation in greenhouses, much research works on this subject have been conducted either in temperate/cooler region (Miguel et al., 1997; Montero et al., 1997; Teitel and Shlykar, 1998) or in tropical/ warmer environment (Mears and Both, 2002; Kamaruddin et al., 2002). Most of these studies had been conducted on the effect of opening ventilation which is covered by insect proof-net on the airflow resistance (Monterro et al., 1996), air exchange rates or ventilation rate (Boulard and Draoui, 1995) and microclimate as temperature rise.

A study on airflow resistance of greenhouses ventilators with and without insect screens had been conducted in temperate region (Bailey et al., 2003). They focused on the measurement of discharge coefficient of ventilation openings with and without flaps. The discharge coefficient of a ventilation opening with an insect screen was predicted by combining the separate flow resistances of the openings and of the screen. The experimental pressure loss coefficients for insect screens were found to be dependent on Reynolds number (based on fibre thickness) and screen porosity. These studies have shown that the values of discharge coefficients range from 0.05 to 0.7. In addition, they also developed a model to predict discharge coefficient of a screened opening vent based on the aspect ratio and flap angle of the openings, the fibre width of screen material, the porosity of the screen, and the design air speed. Kamaruddin et al. (2000) computed for various screens, a coefficient of discharge, which decreases with decreasing mesh size.

Meanwhile, Teitel and Shklyar (1998) studied the pressure drop across insect-proof nets. 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., 1996; Teitel, 2001) considered the effect of screens installed in greenhouses, either horizontally above the crop or in the greenhouse openings, on the ventilation rate.

According to Sase and Christianson (1990) insect screens with very small discharge coefficients ($Cd < 0.2$) could cause a temperature rise of up to 10 °C when the net radiation is 500 W/m² and wind velocity is 1 m $s^{-1}$. The exact magnitude of the temperature rise depends on the angle of the vent opening (area of the ventilation opening) i.e. the discharge coefficient depends on the angle of the vent opening. However, it should be noted that in a greenhouse with crops, the temperature increase would be less due to the latent heat of evapotranspiration. They also showed that with a discharge coefficient of 0.05 a screened house will have about one-third the air movement of a non-screened house where there is no wind.

Simulation models for predicting airflow rates across screened inlets have been presented by several researchers in naturally ventilated greenhouses covered with anti-insect screens (Sase and Christianson 1990; Montero et al. 1997; Boulard and Baille 1995). Munoz et al. (1999) developed a model of the air exchange rate in greenhouses with insect-proof screens over the vents. They used a simplified model incorporating the global wind effect coefficient and screen discharge coefficient to predict the greenhouse ventilation rate. They noted that vents located on lateral spans have a higher discharge coefficient than those located on central spans. Thus, better ventilation can be achieved with vents near the ridge of the roof instead of near the gutter of the tunnel–type greenhouse. A model for determining the air change rates in screened naturally ventilated greenhouses equipped with roof and side openings was given by Fatnassi et al. (2001a) who also gave equations for determining the increase in temperature attributable to the anti-insect screen effect. Montero et al. (2001) investigated the direct and diffuse light transmission of insect-proof screens for cladding greenhouses.

Computational fluid dynamics (CFD) approaches have also been used to study the spatial heterogeneity of climate inside the greenhouses (temperature, air speed and humidity) and to suggest design improvements for combining good ventilation performance and efficient protection against insect vectors for viruses (Teitel and Shlykar, 1998; Fatnassi et al. 2001b). Simulation of climatic conditions in full-scale greenhouse fitted with insect-proof screens was also carried out by Fatnassi et al. (2003), in which the fundamental calculation of climatic conditions was based on computational fluid dynamics. The approach uses the mass, momentum and energy conservation equations. In tropical region, Campen et al. (2004) used CFD software to develop a greenhouse system by simulating the airflow and temperature distribution during design stage to optimize greenhouse size, shape and the ventilation openings.

In tropical region, several investigations on the use of insect-proof screen for covering ventilation opening have been made. Mears and Both (2002) reported that a positive pressure ventilation system in mechanically forced ventilated greenhouse with screening can offer several advantages over standard exhaust system. Maintaining internal greenhouse pressure at high enough pressure that air velocities out through open doors, or other openings in the structure, exceed the flying speed of the insects of concern should be more effective in excluding insects than an exhaust system which tends to draw insects in through openings. With proper design, insect exclusion can be achieved with only one application of screening at the air inlet and small openings in the greenhouse glazing should not provide easy entry for insects. This concept seems interesting and particularly attractive for use in warm area where modest airflow rates can be used to maintain positive internal greenhouse pressure throughout the day.

A naturally ventilated tropical greenhouse system (NVTGS) was developed by Kamaruddin et al. (2002) for vegetable production in the lowland of Malaysia. The structure has a simple frame, transparent roof and insect screen sides. The result of study was that proper design and choice of covering material could control problems of extreme solar radiation, high rainfall, insect, disease, weeds, high temperature and humidity and reduce labour requirement. Specifically, the natural ventilation rate in the NVTGS was influenced very much by the combined effect of temperature difference and wind speed and it can easily be predicted using a model which is developed by these factors. The model was valid compared to the measured ventilation rates resulting from tracer gas method if the opening area was more than 20%. It is also reported that the development of NVTGS in tropical area was technically feasible and economically viable.

A study on the effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouse has been performed by Soni et al. (2005). Several small screen houses covered by four different screen porosities of 53, 34, 33, and 19% were used for the experiment. The size of each screen house was 3 m × 6 m × 3.2 m (W: L: H) with the ratio of vent opening to surface floor area of 3.0. The results revealed that a decrease in porosity increased the vertical temperature gradient from 5 to 10%. In addition, plant evapotranspiration with matured crops was less in the lower porous greenhouse than that in the more porous greenhouse.

## 2.4 Type and design of greenhouse ventilation openings

Since the ventilation rate plays an important role in managing and controlling the microclimate, transpiration processes and carbon dioxide exchange inside the greenhouse, design and type of ventilators to be used to such a greenhouse should be appropriate. Several factors such as: local microclimate condition, type of greenhouse, structure and design of greenhouse have mainly involved in designing ventilators to be built up in such a greenhouse.

One of the most important parameters of ventilation openings to recognize how a greenhouse is different from one to another is ratio of ventilation openings to floor surface area of the greenhouse. Generally, the bigger ratio of ventilation opening at a greenhouse, the better microclimate and air exchange rate will be achieved inside the greenhouse. In the other word, one empirical way of increasing the ventilation rate is to allow large openings ratio. To increase the ratio of ventilation openings, the arrangements of openings at the roof and side wall have been made.

The arrangement of ventilation openings of greenhouse is varied according to region, microclimate condition and local technology (Hanan, 1998). For example, the common design of ventilators from northern Europe (Netherlands, Germany, and UK) especially on the roof is arranged individually, alternating with each other on opposite side of the ridge. According to Bot (1983), almost all Dutch houses are built as large multi-span, gutter connected structures that preclude the use of side ventilation, especially where the sides are permanently sealed by double wall and only the leeward vents are opened. Based on this structure, the air flow in the greenhouse is linearly proportional to the wind speed. It is reported that the ventilation area should be about 16% of total floor area.

In middle latitudes, ventilator design frequently changes to continuous arrangements on the full length of the structure. Although it is highly expensive to apply the entire roof to be assigned as ventilation openings, continuous ventilators were common in southern Europe, the US and Japan (Hanan, 1998). It is incorporated with the sidewall to be arranged as additional ventilation openings, so that this structure gives maximum ventilation rate to the greenhouse. Side ventilation, in the case of single- or double-span structures, has the capability of quadrupling ventilation rates when combined with top ventilators (Both, 1983). In United State of America, ASAE (1989) has recommended to the grower that ventilation area of greenhouse should be about 15 to 25% of total floor area. The effects of total ventilator opening as a percent of floor area for roof vents only and for both sidewall and roof vents has been reported by White (1975). However, he did not find a mathematical model that could be used to predict a temperature rise under New Zealand conditions. He suggested that only small benefits could be expected from fitting greenhouses with openings much larger than 30% of the floor area.

In line with the type and design of greenhouse structures and ventilator openings described above, an integrated study on the effect of wind speed, wind angle and vent openings angle (type of design vents) on air exchange rate and temperature rise for a 7.2 $\times$ 7.2 m, single-span greenhouse had been carried out by Kozai et al. (1980). They reported that air exchange in single-span houses did not appear to vary remarkably, but with a continued wind velocity increase, air changes increased linearly except where the wind angle was parallel to the greenhouse length. About 60 air changes per hour were generally considered necessary to avoid heating above the outside air temperature or extreme temperature rise inside the greenhouse. Based on this study, it can be inferred that to achieve an adequate air exchange rates of 60 $h^{-1}$, side ventilation is necessary or fan ventilation.

Meanwhile in mild climates, the ultimate structure for warm climates has been designed as the structures with ventilation at the ridge and gutter as well as open sides. The high roof pitch is indicative of heavy rainfall. The objectives, of course, are to limit day temperatures and protect the crops from rain. Structures should be a minimum of 2 m at the eaves in order to allow maximum side ventilation. Newer structures can be 4.5 to the gutter. Low structure (i.e., 2 m to the ridge), with limited ventilation will be subjected to excessive temperatures unless the roofs are removed during the summer. This is common procedure in the Mediterranean where crops were grown through the winter (Hanan, 1998). It is reported that total ventilation area should, probably, never be less than 30% of total floor area.

As it is mentioned above that in order to get adequate even better air exchange rates in the greenhouse, the ventilation openings should be considered as large as possible. This approach has been followed in tropical countries, where radiation and open-air temperature are often extreme. Kamaruddin (2000) studied a simple crop protection structure which consisted of a single span, tunnel greenhouse with two-side openings and roof opening. Single-span tunnel greenhouses are also quite common in Mediterranean areas. In tropical countries, as well as in Mediterranean areas, ventilators are normally covered with insect-proof net to stop insects from entering the greenhouse. The single-span design can be improved if the relationship between the area of the openings, their location, the type of screening and the effect on ventilation is known. He further reported that the arrangement of ventilation opening by more than 40% of the surface floor area was quite enough to get good ventilation rate and avoid extreme temperature rise in the greenhouse. It is noted that the ventilation openings was also covered by insect-proof nets with medium mesh size.

A study on the arrangement of ventilator configuration in a 6 m wide single-span, tunnel-type greenhouse has been conducted by Montero et al. (2001). Four vent arrangements were considered: 16 and 33% of sidewall openings, 8% sidewall opening plus 10% roof opening and 16% sidewall opening plus 10% roof openings. For each configuration, expressions of the temperature rise as a function of the sensible heat given to the greenhouse air were presented. Also, the air exchange rate of all configurations studied with three types of net over the openings was given. The results showed the importance of combining roof and sidewall ventilation, especially when insect screen net of reduced permeability covers the openings. Specifically, better conditions were achieved when the size of the side wall openings was 33% of the floor area. An increase in temperature of 10 °C was expected to take place in an empty greenhouse, while a fully occupied greenhouse would be 4 °C warmer than the outside. So, if only side wall ventilation is available it seems that the minimum opening size for adequate ventilation under no wind conditions is around 30% of the floor area. Furthermore, quantitative information on reduction of ventilation due to the installation of insect-proof nets over the openings was that sidewall ventilation was not adequate even when the opening surface was 33% of the floor surface. Ventilator arrangements with a minimum 10% roof opening plus 10% sidewall openings seem to be adequate for good ventilation and protection against insect attack.

## 2.5 Air exchange rate

### 2.5.1 Measurement of air exchange rate

Air exchange rate is one of the most important parameters of ventilation systems in greenhouses. In order to provide better climatic conditions for growing plants, a ventilation system has to supply sufficient and uniform air exchange rate between inside and outside greenhouse environment. Furthermore, better air exchange rate helps to reduce air temperature inside the greenhouse and better evapotranspiration process for crops. Improved ventilation in the greenhouse is the most effective way to increase air exchange rate, so that microclimate in greenhouses will be optimum for plant growth.

Theoretically, the measurement of air exchange rate in a greenhouse involves some parameters and it is a very complex mechanism including heat transfer processes of conduction, convection or/ and radiation occurring in a greenhouse. Therefore, there is no single method (universal tool/method) to measure the air exchange rate because it is not only influenced by the microclimate and the presence of crops condition, but it is also affected by the structure and design of the greenhouse. It is very hard to measure air exchange rate directly due to the above reasons, so some approach or methods have been proposed in order to estimate air exchange rates in a greenhouse.

Various techniques have been used to predict and estimate air exchange rates in greenhouses, the most common being the energy balance and tracer gas. Baptista et al. (2001) reported that the energy balance was used to develop models permitting prediction of inside conditions of a greenhouse knowing the external climatic and construction characteristics. Tracer gas techniques are based on a mass balance of natural or artificial constituents of the air to measure air exchange rates directly in a greenhouse. The tracer gas method assumed that a perfect zone exists, which is characterised by Sherman (1990) as an isolated zone, homogeneous properties, where mixing of the gas with the greenhouse air is perfect.

The measurement of air exchange rate using a tracer gas in naturally ventilated greenhouse is common. There are two methods of measuring ventilation and leakage rate with a tracer gas, the continuous injection or static method and the pulse injection of dynamic method. In both methods, selection of the tracer gas is important. It should have the following characteristics: be easy to measure at low concentrations, inert, non toxic, non flammable, not a natural component of air and with a molecular weight close to the average weight of the air component (Sherman, 1990).

Estimation of air exchange rate has been studied by some authors (Roy et al., 2002; Muňoz et al., 1999, and 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 ($CO_2$), air water vapour ($H_2O$). The two gases most frequently used are $CO_2$ and $N_2O$. The $N_2O$ gas is better because it meets all the above requirements and its concentration is not influenced by the photosynthesis and respiration of the plants if the measurement is conducted in the cropped greenhouse. The use of $CO_2$ as tracer gas, on the other hand, can be used in greenhouses without a crop, but it is necessary to measure the concentration of $CO_2$ of external air and the rate of release from the soil. In addition, Boulard & Draoui (1995) used water vapour ($H_2O$) transpired from crops as one of gas media to estimate air exchange rates. They measured transpiration rate of four plants disposed in a row (by sampling method) by means of an electronic balance. It is believed that using water vapour relatively fulfils the requirement in terms of uniformity along whole greenhouse volume, because all crops in the greenhouse will evaporate water vapour from crop transpiration processes. 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 approaches.

As previously mentioned, the tracer gas technique is based on a mass balance or the principle of mass conservation. In this case, the following relation should be used (Bailey et al., 1993):

$$V_g \frac{dC_i}{dt} + G(C_i - C_o) = M \quad (2.1)$$

where $V_g$ is the volume of the greenhouse, $C_i$ is internal gas concentration, $C_o$ is external gas concentration, $dC_i$ is variation of gas concentration during a time interval $dt$, $M$ is the gas injection rate and $G$ is the ventilation rate.

The static method has been used by Bailey et al., (1993) and Boulard and Droui (1995) using the gas injected at constant rate into a greenhouse until an equilibrium concentration was reached. The gas supply and sampling system must be distributed around the greenhouse in order to obtain good dispersion of the gas and uniform sampling of the air. However, this method needs the high consumption of tracer gas. The dynamic method, on the other hand, uses less tracer gas to estimate ventilation rate and it has been used by Baptista et al. (2001), Fernadez and Bailey (1992) and Munoz et al. (1999). The tracer gas is injected and uniformly distributed in the greenhouse until a certain pre-determined concentration is reached and then stopped. The decay in the concentration of the gas is then measured. When the concentration has decreased to 10-20% of the initial value, another pulse of gas is injected, and the other decay is measured. The ventilation rate G can be calculated from the equation as follow:

$$G = \frac{V_g}{A_f} \frac{ln[C(t)/C(t_o)]}{(t - t_o)} \quad (2.2)$$

where $G$ is the ventilation rate per unit greenhouse floor area in $m^3\ m^{-2}\ s^{-1}$, $V_g$ is the volume of the greenhouse in $m^3$, Af is surface floor area in $m^2$, $C(t)$ is the internal concentration of the gas at t time in $kg_{(gas)}\ kg^{-1}_{(air)}$, $C(t_o)$ is the initial concentration of the tracer gas in $kg_{(gas)}\ kg^{-1}_{(air)}$ and t is the time in s.

In a mechanically ventilated greenhouse, the measurement of air exchange rates is very important to select the size of fans to be used in greenhouse. One important parameter should be taken into account i.e. the greenhouse volume. For instance, if the greenhouse has total volume of 1,000 $m^3$ and the ventilation rates are expressed as a minimum ventilation rate of 60 air exchanges per hour or it is equal to one air exchange per minute, so that the size of fans should be 1,000 $m^3\ min^{-1}$ (Buffington et al., 1993). However, it is not always the case that the capacity of fans can be easily deduced from the ventilation rate parameter alone. Design and structure of greenhouse, area and type of ventilation opening and the static pressure working across the fans are some important parameters that influence the selection of the fans capacity.

### 2.5.2 Estimating air exchange rate based on wind speed and chimney effect

Several studies have been conducted to measure ventilation rate in a greenhouse at different environment and greenhouse structures. Boulard and Baille (1995) have proposed a model to estimate the natural ventilation rate in greenhouse with only roof openings. The model is based on the two driving forces for natural ventilation i.e. temperature difference or "thermal buoyancy" and wind forces. The model can be written in the following form:

$$G = \frac{A_r}{A_f} C_d \left( 2g \frac{\Delta T}{T_o} \frac{H}{4} + C_w (v_w)^2 \right)^{0.5} \tag{2.3}$$

where $G$ is the ventilation rate per unit greenhouse floor area in $m^3\ m^{-2}\ s^{-1}$, $C_d$ is the discharge coefficient, $A_f$ is the greenhouse floor area in $m^2$, $A_r$ is roof opening area in $m^2$, $g$ is acceleration of gravity in $m\ s^{-2}$, $\Delta T$ is the air temperature difference between in and outside in K, $T_o$ is the outside temperature in K, $H$ is the height of the opening above the floor in m, $v_w$ is the wind velocity in $m\ s^{-1}$ at a height of 6.9 m, and $C_w$ is the wind pressure coefficient.

For a greenhouse equipped with a roof (opening area $A_r$) and side openings (opening area $A_s$), Kittas et al. (1997) derived the following equation:

$$G = \frac{C_d}{A_f}\left[\left(\frac{A_r A_s}{\sqrt{A_r^2 + A_s^2}}\right)^2 \left(2g\frac{\Delta T}{T_o}H\right) + \left(\frac{A_r + A_s}{2}\right)^2 C_w (v_w)^2\right]^{0.5} \tag{2.4}$$

Generally, temperature-driven ventilation is only significant at low velocities, that it is at wind speed below 1 m $s^{-1}$ for greenhouses equipped only with roof fans (Baptista et al., 1999) or below approximately 2 m $s^{-1}$ according to Roy et al. (2002), Boulard (1993) and Papadakis et al. (1996). For a greenhouse with roof and side vents, Kittas et al. (1997) believed that temperature-driven ventilation is only significant if $[v_w /(\Delta T)^{0.5}] < 1$. In addition, under Dutch condition, buoyancy effects due to temperature differences between inside and outside the greenhouse are relatively minor (Bot, 1983). Ventilation effects due to wind will be dominant if $3v_w > (\Delta T)^{0.5}$. Temperature effect increases with the square root of $\Delta T$.

In case the wind speed alone had more dominantly influenced to the ventilation rates in such a greenhouse, Kittas et al. (1996) reported that a simple equation based on pressure drop across the vent opening could be considered.

$$G = \frac{A_o C_d}{2A_f}\sqrt{C_w}\, v_w \tag{2.5}$$

where $A_o$ is the effective opening area of vents in $m^2$. In addition, they noted that both the predicted ventilation rate using Eq. (2.5) above and measured ventilation rate using $N_2O$ tracer gas were well correlated with the wind speed. This experiment was performed on a plastic tunnel with continuous side openings where the opening area greatly influenced on air exchange rate. It is also reported that the vent openings area at the roof was more effective than sidewall vent openings.

A very simple equation has been developed to predict natural ventilation rate in a double span arch type greenhouse in Mediterranean area. The greenhouse had side ventilators to achieve adequate ventilating system. It was reported that wind speed and wind direction were the main factors influencing the ventilation system

(Vassiliou et al., 2000). By installing wind sensors at a height of 10 m above the ground level, air exchange rate could be expressed by the following:

$$N = 17.7\ v_{10} \tag{2.6}$$

where $N$ is the volumetric air exchange per hour in $h^{-1}$, $v_{10}$ is the wind speed at height 10 m above ground level with wind direction normal to the side openings of the greenhouse in m $s^{-1}$. When the wind direction was parallel along the side opening of the greenhouse, air exchange in the greenhouse was estimated about a half of the one whereas the wind direction was normal to the side openings (Eq. 2.6).

### 2.5.3 Simulation and Modelling to predict air exchange rate

Several models to predict ventilation rate either using energy balance or mass balance method have been developed by some researchers. They mostly concentrated on naturally ventilated greenhouse with small opening at the roof or both roof and side openings. The model had also been validated with the experimental data and the result was closed between them. Generally, the model was developed using common microclimate data obtained from meteorological station around the greenhouse site.

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 openings (Baptista et al. 2001; Muňoz et al., 1999). However, another study conducted by Kamaruddin et al. (2002) mentioned that the ventilation rate predicted from a model had a good agreement with measured one when it was carried out in the greenhouse with ventilation area more than 20% of total openings area. For the adapted greenhouse which has relatively large openings that it is to be adapted to the humid tropics environment, an appropriate model has to be developed.

In order to predict ventilation rate, the energy balance method uses either static or dynamic models (Roy et al., 2002). The static model was less accurate due to its simplicity and only a few parameters were involved in the model. The dynamic model, on the other hand, was better in term of accuracy. A number of dynamic models have been developed (Roy et al., 2002; Wang and Boulard, 2000; Teitel and Tanny, 1999). The model used the transient behaviour of greenhouse interior climate to measure 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.

Demrati et al. (2001) proposed a model to predict ventilation rate in a large-scale of 1 ha naturally ventilated greenhouse for banana cultivation. A global energy balance of the greenhouse was deduced in order to develop the model. The greenhouse had ventilation opening area between 2.7 to 6% of total soil surface area. By considering all parameters involved in the heat transfer processes occurring in the greenhouse such as: solar net radiation as the input heat flux, and heat fluxes through the soil, plastic cover and ventilation system as heat loss, the following equation is used to estimate ventilation rate.

$$G = \frac{A_g(R_n - F_g) - A_g[K\Delta T + (A_c/A_g)C_h \Delta T_c]}{\rho_a[c_a \Delta T + L_v \Delta H_A]} \tag{2.7}$$

where $A_g$ is soil surface area in $m^2$, $R_n$ is net radiation in W $m^{-2}$, $F_g$ is soil thermal flux, W $m^{-2}$, $A_c$ is cover surface area in $m^2$, $K$ is global sensible heat loss coefficient through the plastic cover in W $m^{-2}$, $C_h$ is convective heat exchange coefficient in W $m^{-2}$ $K^{-1}$, $\Delta T_c$ is the temperature difference inside air and plastic cover in K, $c_p$ is the specific heat of air in J $kg^{-1}$ $K^{-1}$, $\rho_a$ is mass of air in kg $m^{-3}$, $L_v$ is latent heat of water in J $kg^{-1}$, and $\Delta H_A$ is the specific humidity ratio difference in kg $kg^{-1}$.

A typical model for sensible heat balance incorporated with temperature difference between inside and outside simultaneously was developed by Sase et al. (2002) in order to calculate ventilation rate. It is based on a steady state condition and can be expressed as follows:

$$G = \frac{(\alpha R_n / \Delta T) - U\beta}{c_p \rho_a} \tag{2.8}$$

where $\alpha$ is the ratio of sensible heat gain to the latent heat, $R_n$ is the inside net radiation in W $m^{-2}$, U is the overall heat transfer coefficient in W $m^{-2}$ $K^{-1}$, and $\beta$ is the ratio of the greenhouse surface area to the greenhouse floor area. They used the model to predict the temperature difference between inside and outside and natural ventilation rate simultaneously. This model has been validated on greenhouse with open-roof ventilation and no crops were grown in the greenhouse. A good agreement was obtained, but the predicted temperature difference was to be slightly overestimated when the roof segments were more widely opened. This model is also not capable of predicting such negative temperature differences.

The ventilation rate can also be modelled using static pressure drop across the ventilation openings especially when insect proof screen was applied to the ventilators. This approach is valid if the ventilation rates were mostly influenced by wind speed passed through the vent openings. If the pressure drop (difference) between inside and outside the greenhouse could be detected, then ventilation rate can be predicted using this parameter. However, some researchers mentioned that predicting ventilation rate based on the pressure drop across the vent openings was less accurate compared to other methods. Montero et al. (2001) used CFD and pressure drops at some different vent configurations to predict airflow and ventilation rate in the tropical greenhouse while Munoz et al (1999) developed a theoretical model for prediction of ventilation rate. By using the wind pressure on the greenhouse $\Delta P_w$ which is linearly influenced by the global wind effect coefficient $C_w$ and least square of wind speed $v_w$, and also neglecting the thermal effect, the airflow through the opening may be expressed as follow:

$$G = \frac{A_o C_d}{A_f} \sqrt{\frac{\Delta P_w}{C_w}} \tag{2.9}$$

For unscreened openings, the permeability tends to infinity and the porosity equals unity and assuming incompressible and non-viscous flow, the following equation will be considered (Bailey et al., 2003, Baptista et al., 1999).

$$G = \frac{A_o C_d}{2A_f}\sqrt{\frac{2\Delta P_w}{\rho_a}} \tag{2.10}$$

where $\Delta P_w$ is the difference of pressure drop across the vent opening in Pa.

Based on several models of ventilation rates stated from the Eq. 2.1 to 2.10 above, air exchange rate then can be calculated if the ratio of total volume and the floor area of the greenhouse (as the mean height) is known. Hence:

$$N = G\frac{A_f}{V_g} \tag{2.11}$$

where $N$ is air exchange rate in $h^{-1}$ and $V_g$ is the total volume of greenhouse in $m^3$.

# 3. Objectives and Hypothesis

## 3.1 Objectives

The main objective of the study was to investigate the influence of insect-proof net of different mesh sizes, placed on greenhouse ventilation openings (both roof and side openings), on the internal climate as well as crop performance, biological plant protection, fertilization and irrigation of the greenhouse. This study was a part of an integrated management system for the sustainable production of vegetable in humid tropics region.

In detail, the specific objectives of the study were:

- To estimate air exchange rates due to natural ventilation using two different approaches of energy balance and water balance methods occurred in the greenhouse,
- To investigate the microclimate and air exchange rate inside the screened greenhouse at different seasons of the year,
- To evaluate the effect of different mesh size of insect-proof screening material on the micro climate, tomato growth, plant protection and irrigation management,
- To develop models that can be used to predict air exchange rate and internal microclimate (temperature and humidity) under given greenhouse structure based on the availability of common climatic parameters,
- To determine the minimum size of ventilation opening area of a naturally ventilated greenhouse by closing some particular ventilation opening of nets with an UV-stabilized plastic film in order to reduce the material cost and minimize some finer insect pest passed through the cladding material.
- To evaluate the effectiveness of exhaust fans installed at the front side of greenhouse operated during the daytime.

## 3.2 Hypothesis

The hypothesis of this study was that the adapted greenhouse incorporated with the use of appropriate UV-absorbing insect-proof screens (nets) to cover ventilation openings under investigation could be suitable for vegetable production in the humid tropics. The application of smaller holes-net (bigger mesh-sizes) would affect on microclimate, air exchange rate as well as crop performance, biological plant protection and fertigation system, therefore with the arrangement of ventilation openings, the optimization of ventilation system for tropical environment then would be possible.

# 4. Material and Methods

This chapter describes general description, various materials and methods mostly used in a series of main experiments on optimizing the ventilation system in the adapted greenhouse. The first sub-chapter will be a general description of the experiment and the common instruments used for the whole experiment. The next sub-chapter describes the methodology of several experiments in the frame work of the main experiment on the ventilation system. In detail, these are as follow: performance of the adapted greenhouse, simulation and modelling for predicting air exchange rate, the determination of minimum size of ventilation openings, and evaluation on the effectiveness of exhaust fans.

## 4.1 General

### 4.1.1 Experimental site and greenhouse description

All experiments were conducted at the greenhouse complex in the Asian Institute of Technology, Bangkok, Thailand (13.06° N latitude and 100.62° E longitude at altitude of 2.7 m above sea level) from June 2003 to June 2005. Thailand lies within the humid tropics and remains hot throughout the year. In general, average temperatures are about 30 °C, ranging from 37 °C in April to 17 °C in December. Winds are variable with convective type precipitation. There are three seasons: the cool season (November to February), the hot season (April to May), and the rainy season (June to October), though downpours rarely last more than a couple of hours.

Three types of greenhouses covered with different net materials were used for the experiment, as follows:

- 40×38-mesh (40-mesh, Econet M, anti leafminers and larger);
- 52×22-mesh (52-mesh, Bionet, anti whiteflies and larger);
- 78×52-mesh (78-mesh, Econet T, anti thrips and larger).

The selection of these mesh sizes was considered based on a compromise between high temperature along the year and the most serious pest disease to be excluded from the greenhouse (Bethke, 1990). Since the maximum climate in

Bangkok could be up to 45 $^{o}C$, the use of net at more than 78-mesh (Table 2.1) was presumed to be very risk for growing tomatoes inside the greenhouse. The technical specification of the tested insect-proof nets used for this study is presented in Table A-1 (Appendixes).

Each greenhouse had a size of 10m $\times$ 20m with East-West orientation. An UV-stabilized PE-film was used to cover every greenhouse roof, gables and lower side one meter along the wall. The surface area of the greenhouse was 516 $m^2$ giving surface area to floor area of 2.58. The greenhouse was fitted with insect-proof screen at different mesh-sizes mentioned above placed on sidewall along the greenhouse with the total size of 196 $m^2$ and at the roof opening with the size of 0.8 m $\times$ 20 m. Therefore, the ratio of total ventilation openings to surface floor area was 1.06.

The greenhouse was also equipped with two exhaust fans with a total capacity of 1,100 $m^3$ $min^{-1}$, 2.2 kW power to exhaust the hot air out from the greenhouse (see detail in Fig. 4.1). The fans were only used in case of emergency or when the air temperature was extremely high, but during the experiment all fans were switched off, so that all of the greenhouses were working under natural ventilation.

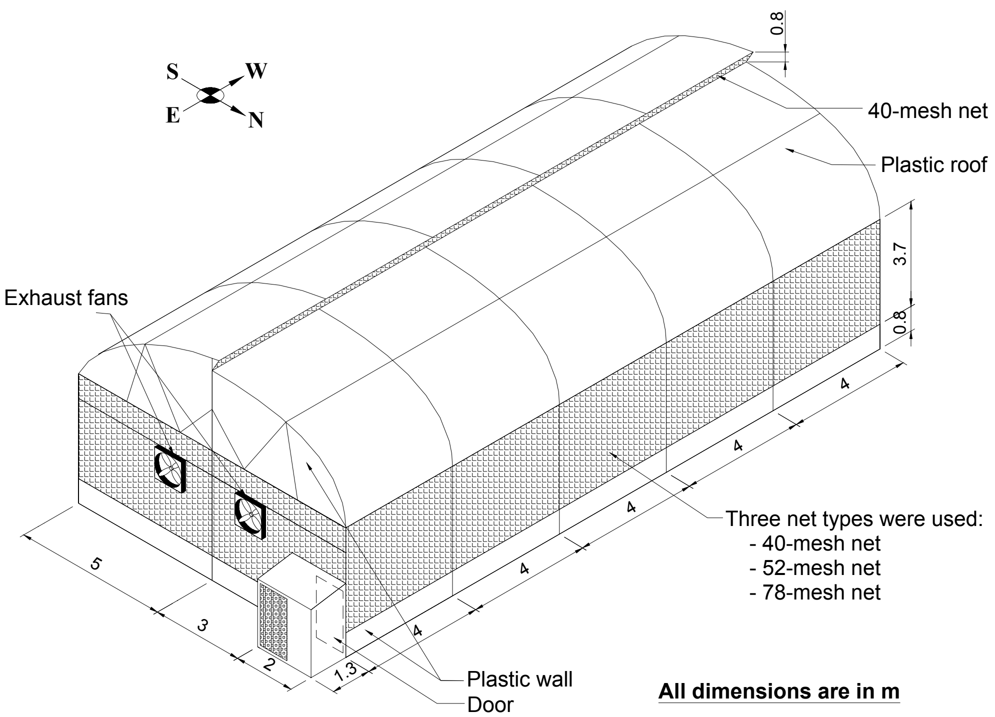



**Figure 4.1: Isometric view of net greenhouse with different mesh sizes as cladding material as well as roof opening**

### 4.1.2 Instrumentation for measuring climate

For measuring microclimate inside the greenhouse, air temperature and relative humidity were measured by aspirated psychrometers using K type (NiCr-Ni) thermocouple sensors (0.5 mm diameter) with precision of ± 0.3 K. Two psychrometers were positioned in the middle of the greenhouse at a distance of 10 m between them and maintained at a height of 0.5 m above the plants during the growth.

Incoming solar radiation in the greenhouse was measured by pyranometer CM 11/14 type (Kipp and Zonen, Delft, The Netherlands) with accuracy between 4 and 6 (± 0.5%) $\mu V$ / (W $m^{-2}$) and a daily total error of 0.2% of measurement. The spectral range for the pyranometer was 305 – 2800 nm. The pyranometer 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, delicate and sheathed thermocouple sensors K type (NiCr-Ni, Temperatur Messtechnik Hanau (TMH) GmbH, Germany) of 0.1 mm diameter attached under the leaf in order to avoid heated error caused by solar radiation. Two thermocouples were installed on two plants at different positions in the greenhouse. Meanwhile, soil (substrate) temperature was measured using a thermocouple sensor similar to the one used for air temperature K (NiCr-Ni) type but at the tips of the sensor it was covered by silica glass. Two thermocouples for measuring soil temperature were also installed on two pots at different position inside the greenhouse.

In order to record outside climatic condition, several sensors were installed in a meteorological station located 25 m away from the greenhouses. Air temperature, relative humidity and global solar radiation were measured using an aspirated psychrometer and a pyranometer, respectively, which had same technical specifications as described above. Both sensors were positioned at 1.5 m height above ground level. Wind speed and direction were measured using a cup anemometer and wind direction transmitter (Thies Klima GmbH, Germany), respectively. The wind sensors outside the greenhouse were placed at a height of 6.9 m above the ground level. All sensors, both in each greenhouse and at the meteorological station, were connected via RS-485 bus cable to a computer of data logging system developed by the Institute of Horticultural and Biosystems

Engineering (ITG), 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.

### 4.1.3 Crop cultivation and irrigation system

Tomato (*Lycopersicon esculentum,* cv. 'King Kong 2') plants were grown in pots placed at 1.60 m spacing and 0.30 m within a row. The number of tomato plants in the greenhouse was then about 300 plants. The crops were cultivated and maintained at a similar practice for every treatment. Tomato plants were grown in soil substrate using pots with one tomato plant per pot. The soil substrate consisted of 28% of organic matter with pH of 5.3. The soil texture was 30% of sand, 39% of silt and 31% of clay.

A drip irrigation system was installed in each greenhouse to supply water to the plants. Automatic control of the drip irrigation was achieved through the use of solenoid valves which were connected to the computer. The irrigation water was given about 20 – 30% over actual water requirement, based on light integral from global solar radiation, in order to accommodate non-stressed condition of tomato crops. The amount of irrigation water to be applied was varied according to the plant stages and it was gradually increased from time to time as the plants were increasingly grown. On average, the number of irrigation frequencies was about 7 – 8 times (cycle) per day with the irrigation time was ranging between 3 to 10 minutes per irrigation cycle. Two fertilizer stock solutions consisted of 2.5 kg of Hakaphos (N-P-K) diluted into the 100 litres of water and 1.8 kg of Calcinit (Ca) into 100 litres of water were directly mixed with irrigation water, in order to achieve proper concentration of fertilizer, through two fertilizing injectors, Dosatron DI 150/16 model at a rate of 1.5% for Hakaphos and 3.5% for Calcinit applications, respectively. Thus, the final concentration of N-P-K of 375 mg/L (ppm) and Ca of 630 mg/L (ppm) were given to the plants during cultivation period.

### 4.1.4 Measuring crop performance

In order to evaluate the adapted greenhouse at different treatments of mesh-size of insect-proof net, crops performance had been measured and analysed. Plant height, leaf area index (LAI) and crop yield were used to describe the crop performance. Plant height was measured by means of a meter tape 5 m with accuracy of ± 1 mm. The measurement was conducted every week starting one week after transplanting for each greenhouse at the same time. Three plants were randomly taken each greenhouse to get average value of weekly plant height.

A digital area meter model L1-3100 (LI-COR, inc. Nebraska, USA) instrument was used to measure crop leaf area for determining the leaf area index (LAI). The measurement was done using the destructive method from the crops sampling collected every two weeks starting 4 weeks after transplanting. This was done to reduce the number of samples. LAI was calculated from the sum of total leaf area of plants sample divided by the floor area occupied by the plants sample.

Crop yield of tomato plants was measured by harvesting all tomato fruits in each greenhouse treatment then weighted using a digital mass balance. The harvesting was done every week starting from 9 weeks after transplanting till the last harvesting (about 14 weeks after transplanting). The fruits were then sorted into marketable and non-marketable ones to further analyze the quality of tomato fruits. The marketable fruit is defined as harvested tomatoes with good looking, uniform (average weight more than 50 g) and no defected mark or over mature, while the non-marketable fruit is defined as harvested tomatoes with some defected properties such as: blossom end rot (BER), cat face, cracking, immature, small size, abnormal shape (twin, malformed fruit) and other imperfect conditions. The yield was calculated as the total harvested tomatoes divided by the area of greenhouse in t $ha^{-1}$.

### 4.1.5 Measuring crop transpiration rate

The crop transpiration rate was directly measured by incoming water flow and outgoing water flux sensors. Two water flow meters FTB603 model with flow range at 0.5 to 15 ℓ $min^{-1}$ and relatively high accuracy of $\pm$ 1% of reading were installed at irrigation pipe and outlet drainage pipe. These sensors were also connected to the data logging system and the data were recorded every minute. The crop transpiration rate was simply calculated by subtracting the amount of water flow rate reading at the irrigation pipe to the drainage canal along certain period of time from 8:00 to 17:00 h (9 hours).

Since the water flow meter had a problem with the reliability of sensors after used for two seasons of cultivation, the crop transpiration rate was then manually measured using the water balance method as the Lysimeter method (see Fig. 4.2). Three randomly selected potted plants inside the greenhouse were used in each of the three greenhouses (treatments). The irrigation water from emitters was collected in a small container and measured after every three-hour intervals. This was assumed as the amount of water to be added to the potted plant. In the same time, the drainage water from the pot was collected in a smaller container and the volume measured at every three-hour interval. The difference between the water added and drainage collected was taken as the evapotranspiration. The hourly average of total evapotranspiration measured from 8:00 to 17:00 h was taken as crop transpiration rate in kg $h^{-1}$ unit.

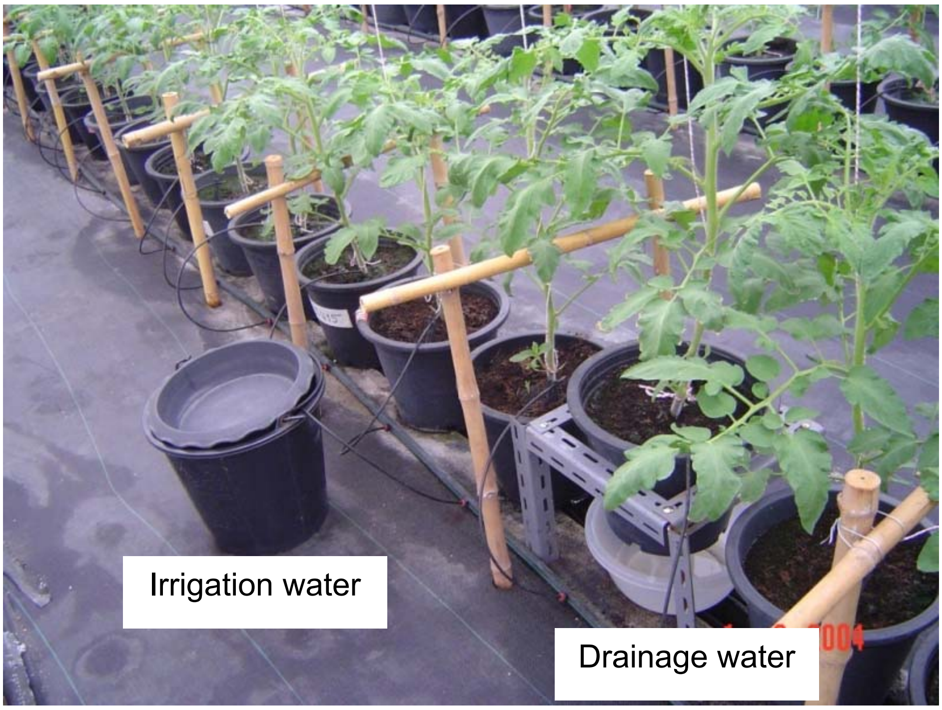



**Figure 4.2: Measurement of crop transpiration rate in greenhouse**

#### 4.1.6 Measuring insect pest infestation (abundances) in the greenhouse

Entomological observations were only concerned to two major insect pests i.e. whiteflies (*Bemisia tabaci sp.*) and thrips (*Thysanoptera: Thripidae sp.*). Then, their populations in each greenhouse treatment were measured. Since whiteflies mostly like to yellow colour while thrips are attractive to blue colour, the yellow and blue sticky traps were commonly used to capture these insect pests flying in the greenhouse. Four blue sticky traps and four yellow sticky traps, each trap had a size of 12 cm × 10 cm, were randomly placed in each greenhouse. All the traps were hanged at the height of similar to the plant height. Insects were counted every Friday and fresh traps were used to replace the older ones. The installation of all traps in each greenhouse is depicted in Fig 4.3.


**Figure 4.3: Placements of blue and yellow sticky traps in each greenhouse to monitor insect's infestation to the tomato crops**

## 4.2 Performance of the adapted greenhouse incorporated with screen ventilating system

As it is mentioned above that the concept of adapted greenhouse has been proposed and applied to the humid tropical condition at lowland area in order to fulfil the fresh vegetables demand. A number of greenhouses had been erected (Fig. 4.1) and tested for their performances throughout the year. In accordance with some limiting factor (high temperature, humidity and rainfall) and any advantages (abundant of solar radiation and needless heating system), it seems to be optimistic that the adapted greenhouse including fertigation systems with low maintenance can be an important component for the sustainable vegetable production. Those greenhouse systems have the following advantages such as (Tantau and Zabeltitz, 2001):

- higher yield and better qualities,
- less susceptibilities to diseases due to less wetting and damage by rain,
- minor risks for quality and yield,
- extending the harvest time,
- reduced water consumption,
- better use of fertiliser and pesticides.

Basically, the greenhouse has a simple structure with material locally available and it has relatively low in both capital and maintaining costs. Natural ventilated system incorporated with very large ventilation opening, which has the ratio of vent openings to floor area of 1.05 was chosen in order to provide better condition of microclimate inside the greenhouse. To accommodate the extreme temperature might be realised sometimes along the year, the greenhouse was equipped with two exhaust fans.

This experiment was carried to evaluate the adapted greenhouse at three different mesh-sizes of insect proof net and different seasons of the year. The integral factors such as: climatic, agronomical, entomological and technical aspects were evaluated.

### 4.2.1 Experimental set-up

Three greenhouses with different mesh-sizes of nets to cover ventilation openings were simultaneously tested. The preliminary experiment was done from June to October 2003. Due to the unacceptable reading of ambient climatic data, a similar experiment was repeated. Then, the experiment was conducted at three different seasons of the year, i.e.: from January to April 2004, July to October 2004 and December 2004 to March 2005. About 300 tomato plants were cultivated and maintained at a similar method of cultivation till harvesting time in each greenhouse. Transplanting was done 3 weeks after sowing. The tomato crops were planted within six rows with 1.60 m apart between row and 50 pots for each row, so that total of tomato plants in each greenhouse was 300 plants.

### 4.2.2 Data collection and analysis

During the experiment, the following parameters were recorded (the methods were described at the section of 4.1 above);

- Plant height : measured every week, 7 days after transplanting (DAT);
- LAI : measured every two weeks, from 28 DAT;
- Crops evapotranspiration: done manually every day from 7 DAT;
- The number of insect (sticky traps) : measured weekly from 7 DAT;
- Temperature and humidity : measured minutely from 1 DAT;
- Solar radiation : measured minutely from 1 DAT;
- Leaf and soil temperatures : measured minutely from 1 DAT;
- Outside climate (temperature, humidity, solar radiation, wind speed): measured minutely from 1 DAT.
- Air exchange rates: estimated using a tracer gas method which is described in the following section of 4.3.1. The measurements were conducted from 7 days after transplanting till harvesting time (about 3 months).

All data collected from each greenhouse at every season of experiments were calculated and analyzed using the statistical tool of general linear model, analysis of variance (ANOVA) (SAS Institute, 2003).

## 4.3 Simulation and modelling to predict air exchange rate and internal microclimate

This experiment was dealing with the estimation of air exchange rate in such a greenhouse using a model which was built up based on some parameters of both geometric greenhouse structure i.e. net porosity ($\varepsilon$) and ventilation ratio ($V_r$) and common climatic data i.e. solar radiation ($R_n$), temperature difference ($\Delta T$) and humidity difference ($\Delta X$) between inside and outside the greenhouse from an energy balance method. In addition, a comparison with the model modified from

Kittas et al. (1997)'s model was also performed. Meanwhile, the prediction of internal temperature and humidity of greenhouse was performed using models derived from the energy balance and water balance analysis. This experiment was carried out at the three greenhouses covered with different mesh-sizes of nets, while the examination of predicted air exchange rates of greenhouse at different seasons of the year was done only at the 52-mesh greenhouse.

### 4.3.1 Measuring air exchange rate

The measurement of air exchange rate can be determined using two methods i.e.: using a tracer gas method or known as water vapour balance method and using both water vapour and energy balance occurred in the greenhouse or known as energy balance method.

#### *4.3.1.1 Water vapour balance method*

It is mentioned from section **2.5.1** that the measurement of air exchange rate using a tracer gas method can give an accurate results and the use of water vapour as a tracer gas released from such crops in the greenhouse is a simple and quick method to estimate the air exchange rate. This method had been previously adopted by Boulard and Draoui (1995) in a two span plastic naturally ventilated greenhouse equipped with roof vents only. It was reported that in the tracer gas method using water vapour had a good agreement with other method using different gasses as media i.e. $N_2O$ and $CO_2$.

Basically, measurement of air exchange rate using water vapour as tracer gas allows the estimation of the irrigation water being transformed into the water vapour inside greenhouse during the evaporation and transpiration processes of such tomato crops which are mainly occurring in the daytime. Then, water vapour had to be dissipated out by replacing it with air of less water vapour from outside greenhouse. The amount of water to be evaporated should be equivalent to the difference between water vapour density inside and outside greenhouse during a day. The movement of water vapour due to its difference will generate daily air exchange rate.

Since water vapour was used as a tracer gas to estimate air exchange rate in the greenhouse, 300 tomato plants (*Lycopersicon esculentum*, cv. King Kong 2) were grown in each greenhouse to generate water vapour during the daytime. In this case, the water vapour inside ($X_i(t)$) and outside ($X_o(t)$) air the greenhouse were measured as absolute humidity (in kg $m^{-3}$) by means of psychrometers located at a height of 1.5 m. Greenhouse crops transpiration rate (in ℓ $h^{-1}$) of tomato crops was manually measured by means of the differences between irrigation flux $(Wf_i(t))$ and drainage water flux $(Wf_o)$ at three sampling plants, as it was described at the section of **4.1.5**. All the measurements were conducted every 3 hours interval from 8:00 to 17:00 h during daytime. The air exchange rates were calculated then based on daily basis starting from 7 days after transplanting till harvesting time.

The assumption had been made that water vapour transpired from each plant was uniform for all points in the greenhouse. In this case, the uniform humidity conditions in the whole greenhouse volume and considering that evaporation loss from the crop substrate and the soil (minimized by the presence of continuous plastic mulch on the soil surface) are negligible. If the condensation within the greenhouse is also neglected due to the use of insect proof net on the entire sidewall, the following equation based on mass-balance of the greenhouse air during period of time (t) holds:

$$V_g \frac{dX_i}{dt} = N(t)[X_i(t) - X_o] \pm \rho_w (Wf_i(t) - Wf_o) \tag{4.1}$$

Hence, air exchange rate can be simply calculated as follows:

$$N(t) = \frac{\rho_w (Wf_i(t) - Wf_o)}{V_g (X_i(t) - X_o)} \tag{4.2}$$

where $N(t)$ is measured air exchange rate over period of time (t) in $h^{-1}$, $\rho_w$ is water density (≅1.0 kg ℓ$^{-1}$), $(Wf_i(t) - Wf_o)$ is crops transpiration rate which is measured using water flux incoming to and outgoing from the greenhouse during t time in ℓ $h^{-1}$. $(X_i(t) - X_o)$ is absolute humidity difference over certain period of time (t) in kg $m^{-3}$.

#### *4.3.1.2 Energy balance method*

The concept of thermodynamics was used to estimate air exchange rate based on the energy balance method occurring in a greenhouse. Principally, air exchange rate was estimated using the balance of heat fluxes or heat transfer as well as water vapour balance in the greenhouse as a greenhouse system. The estimation was made from the common climatic parameters such as temperature, humidity and global solar radiation.

Moreover, a real-world greenhouse is characterized by time-varying dynamical properties resulting from non-stationary, non-linear and random disturbances that affect the greenhouse behaviour. It means that the greenhouse system changes by time to time. Therefore, this method can be such dynamic measurements using several main parameters involved in greenhouse heat transfer, so that the knowledge about heat transfer should be well understood and all the heat fluxes occurring in the greenhouse are taken into account, whereas the behaviour of the greenhouse dynamical system is too complex for a complete mathematical analysis. In order to simplify the greenhouse system and following mathematical equation, some assumptions and parameters which are less involved to the system can be neglected. In addition, a steady state condition along a small period of time of measurement [$(dN/dt) = 0$] was also taken into consideration.

Fig. 4.4 illustrates all the main heat fluxes occurring in the adapted greenhouse and the parameters measured during the experiment. The main input heat flux came from the solar radiation alone ($Q_s$) due to the absence of heater system in humid tropics condition. Then the heat losses were considered due to the use of cladding material ($Q_c$), ventilation system ($Q_v$), photosynthesis processes ($Q_p$) and soil (substrate) ($Q_g$).

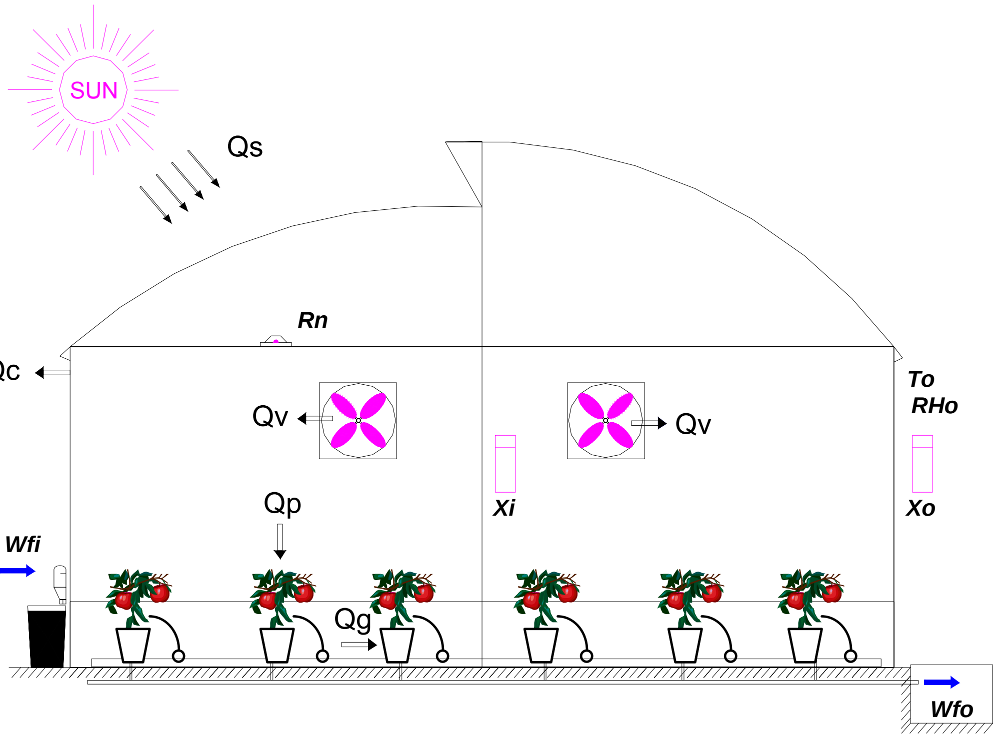



**Figure 4.4: Heat and mass fluxes occurring in such a greenhouse and measuring some climatic parameters to estimate air exchange rate**

Mathematically, the equation of the static energy balance of a naturally ventilated greenhouse given by some authors (Bailey, 1988; von Zabeltitz, 1988) has the general form as follows:

$$Q_s - (Q_c + Q_l) - Q_v - Q_g - Q_p = 0 \tag{4.3}$$

where $Q_s$ 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; $Q_g$ 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. (4.3) above can be simplified into:

$$Q_s = Q_v + Q_g \tag{4.4}$$

The solar radiation absorbed inside the greenhouse, $Q_s$ depends on the external global solar radiation and the transmissivity of plastic roof. 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 can be obtained from the following equation:

$$Q_s = n_s R_n A_f \tag{4.5}$$

where $R_n$ is the average incoming net solar radiation inside greenhouse during day time in W m$^{-2}$; $A_f$ is surface floor area of greenhouse (= 200 m$^2$), $n_s$ is the percentage of solar heat used for convection, evaporation and transpiration processes of plants in decimal ($\cong$ 0.8).

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

$$Q_v = Q_{si} + Q_{lt} = \frac{N}{3600} V_g \left( c_p \rho_a (T_i - T_o) + (X_i - X_o) L_v \right) \tag{4.6}$$

where $N$ is air exchange rate of a greenhouse due to ventilation system in h$^{-1}$; *3600* is the conversion value from hourly air exchange rate to secondly unit from specific and latent heat of air; $V_g$ is greenhouse volume (= 995 m$^3$), $c_p$ is the specific heat of air (= 1013 J kg$^{-1}$ K$^{-1}$); $\rho_a$ 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 (= 2.26×10$^6$ in J kg$^{-1}$).

The absolute humidity is the most important parameter of microclimate involved in determining air exchange rate. This is defined as the ratio of the mass of water vapour to the volume occupied by the mixture. Mathematically, it can be calculated based on mean air temperature and relative humidity measurements as follows (ASHRAE, 1993):

$$X_{i,o} = \frac{6.11(RH_{i,o})(10^{\left(\frac{7.5(T_{i,o}-273.15)}{T_{i,o}-35.45}\right)})}{461.5(T_{i,o})} \tag{4.7}$$

where $X_i$, *and* $X_o$ is the absolute humidity for respective inside and outside greenhouse in kg m$^{-3}$ ; $RH_{i,o}$ is inside or outside the relative humidity in %; and $T_{i,o}$ is inside or outside air temperature in K.

Heat flows to the soil was mostly caused by convective heat transfer 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 negligible from Eq. (4.4).

By rearranging Eqs. (4.5), (4.6), (4.7) into Eq. (4.4) above, the energy balance was taken place when the following equation is required and it can be simplified as:

$$n_s R_n A_f = \frac{N}{3600} V_g \left( c_p \rho_a (T_i - T_o) + (X_i - X_o) L_v \right) \tag{4.8}$$

So, the air exchange rate could be predicted based on the environmental climatic data and it can be written as follows:

$$N = \frac{3600 \times n_s R_n A_f}{V_g \left( c_p \rho_a (T_i - T_o) + L_v (X_i - X_o) \right)} \tag{4.9}$$

where $N$ is air exchange rate in the greenhouse in $h^{-1}$.

### 4.3.2 Development of a model to predict air exchange rate

Several models to predict air exchange rate had been developed either based on the combination of chimney effect and wind speed (Boulard and Baille, 1995; Kittas et al., 1997; Vassiliou et al., 2000) or a typical greenhouse sensible heat balance (Sase et al, 2002; Demrati et al., 2001) as well as pressure difference (Munoz et al., 2000; Baptista et al., 1999). Since these models were developed based on the specific greenhouse and condition, the development a model suitable for the adapted greenhouse located in tropical condition is necessary. The model was developed base on the validation of some models proposed by previous study in which the greenhouse structure was similar to one in this study. The verification of those models was compared to the data obtained from the experiment.

A model proposed by Kittas et al., 1997 has been further verified and modified to meet a better correlation between measured air exchange rate from experiment and a modified model. This model was chosen due to suitable for greenhouse with relatively large ventilation openings (roof and side openings) and it was able to accurately predict air exchange rate. Based on geometric parameter of greenhouse i.e.: net porosity and ventilation opening area and common microclimate of wind speed and air temperature difference between inside and outside, the air exchange rate can be predicted using the following equation:

$$N_p = a\,\frac{3600C_d}{V_g}\left[\left(\frac{A_r A_s}{\sqrt{A_r^2 + A_s^2}}\right)^2\left(2g\frac{\Delta T}{T_o}H\right)+\left(\frac{A_r + A_s}{2}\right)^2 C_w (v_w)^2\right]^{0.5} \qquad (4.10)$$

where $N_p$ is predicted air exchange rate in such a greenhouse in $h^{-1}$, $a$ is a constant determined from the experiment, no dim., $C_d$ is discharge coefficient, no dim., $V_g$ is greenhouse volume, $m^3$, $A_r$ and $A_s$ are ventilation opening area of roof and side wall, respectively in $m^2$, g is gravitational acceleration in m $s^{-2}$, $\Delta T$ is air temperature difference in K, $T_o$ is air temperature outside the greenhouse in K and $H$ is the height of opening above the floor, in m, $C_w$ is wind pressure coefficient, no dim., and $v_w$ is wind speed in m $s^{-1}$.

The value of discharge coefficient, $C_d$, was calculated using the simple parameter of screen (net) porosity, $\varepsilon$, because the screen porosity can be easily and rapidly measured under microscope. The approach from Forchheimer equation (Bailey et al., 2003) was used to estimate the value of $C_d$ as follows:

$$C_d = \frac{1}{\sqrt{F_s}} \qquad (4.11)$$

$$F_s = \left[\frac{18}{Re} + \frac{0.75}{log(Re + 1.25)} + 0.055log(Re)\right]\left[\frac{(1 - \varepsilon^2)}{\varepsilon^2}\right] \qquad (4.12)$$

where $F_s$ is pressure loss coefficient of screened opening, no dim., $Re$ is Reynolds number, no dim., and $\varepsilon$ is screen porosity, no dim.

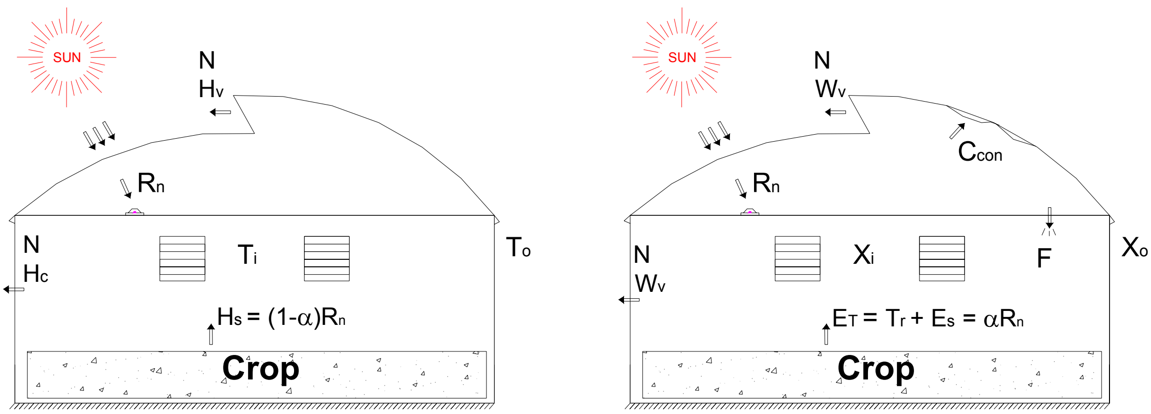
For computational procedure and input parameters of the model, meteorological data i.e., air temperature difference, ambient temperature and wind speed were collected and averaged during the daytime. Several inputs of design parameters of greenhouse presented in Table 4.1 were used for computation of greenhouse air exchange rates.

**Table 4.1: Design parameters used for computation of air exchange rate**

| Parameters | Values | Parameters | Values |
|---|---|---|---|
| $A_r$ | 18.2 $m^2$ | $c_w$ | 0.14 |
| $A_s$ | 186 $m^2$ | $\varepsilon_{40\text{-}mesh}$ | 0.42 |
| $H$ | 2.0 m | $\varepsilon_{52\text{-}mesh}$ | 0.38 |
| $V_g$ | 995 $m^3$ | $\varepsilon_{78\text{-}mesh}$ | 0.30 |
| $g$ | 9.81 $m\ s^{-2}$ | $Re$ | 13 |

### 4.3.3 Development of models to predict internal microclimate

The internal microclimate (air temperature and humidity) can be predicted using some models developed using energy and mass balance approach in a greenhouse. Simplified greenhouse models are available (Seginer and Kantz, 1986, Boulard and Baille, 1993) that allow to investigate the effect of numerous factors and processes involved in determination of the inside microclimate. These models use the energy and mass balance of the greenhouse which is assumed as solar collector. The main difference with the solar collector's equations is the presence of a transpiring surface from the crops inside the greenhouse which will give a special importance to the latent heat transfer processes.




**(a) Energy balance of a greenhouse**　　**(b) Water vapour balance of a greenhouse**

**Figure 4.5: Simplified heat and mass fluxes occurring in greenhouse assumed as a solar collector to predict internal microclimate**

As it is shown from Fig. 4.5(a) above that the solar energy gain of the greenhouse, $R_n$ from the heat transfer involved in an energy balance method is splitted into two components i.e.: a sensible energy component, $H_s$, that serves to heat the greenhouse air and a latent energy component, $E_T$, that represents the evapo-transpiration rate of the crop. The partition of net energy between sensible and latent heat gains is often expressed by a parameter called the Bowen ratio, $\alpha$ that depends upon the intensity of the evapotranspiration processes (Landsberg et al., 1979). In this case, the energy gain can be expressed as the following equation:

$$H_s = (1 - \alpha)\ R_n \tag{4.13}$$

where $H_s$ is the sensible energy gain in W m$^{-2}$, a is the Bowen ratio (from along the experiment was averaged at 0.7).

The sensible energy losses are mainly composed by:

(i) the losses by convection and radiation from the walls, $H_c$ that can be globally expressed as:

$$H_c = U\ (T_i - T_o) = U\ \Delta T \tag{4.14}$$

where $U$ is the overall heat loss coefficient in W m$^{-2}$ K$^{-1}$ in which for screened greenhouse is obtained as $2.97\ \Delta T^{0.33}$ ( Miquel et al., 1998, Roy et al., 2002).

(ii) the convective losses due to leakages and ventilation, Hv;

$$H_v = K_v\ \Delta T \tag{4.15}$$

where $K_v$ is the coefficient of heat transfer by ventilation in W m$^{-2}$ K$^{-1}$, that can be expressed as a function of air exchange rate, $N$ (h$^{-1}$):

$$K_v = \rho_a\ c_p\ (N/3600)\ (V_g/A_f) \tag{4.16}$$

Then, from the sensible energy balance:

$$(1 - \alpha)\ R_n = H_c + H_v \tag{4.17}$$

From Eq. 4.16, it can be deduced that the air temperature of the greenhouse, assuming steady state condition (dT/dt = 0), is expressed as follows:

$$T_p = T_o + \frac{(1-\alpha)R_n}{U + \rho_a c_p (N/3600)(V_g/A_f)} \tag{4.18}$$

where $T_p$ is predicted internal air temperature in K, $T_o$ is outside temperature in K and $N$ is air exchange rate in $h^{-1}$. Here, it is clear that internal air temperature is a function of several main parameters of ambient temperature, $T_{o,}$ net solar radiation, $R_n$ and air exchange rate, $N$.

In the same way than for sensible energy balance, the water vapour balance of the greenhouse (Fig. 4.5(b)) with the different terms relative to water production and water loss. The general form of water vapour balance of greenhouse air volume can be written as follows:

$$\frac{V_g}{A_f}\frac{dX}{dt} = T_r + E_s + F - W_v - C_{con} \qquad (4.19)$$

where $dX/dt$ is the rate of change of internal humidity in $kg_{(water)}$ $m^{-3}$ $s^{-1}$, $T_r$ is crops transpiration rate in $kg_{(water)}$ $m^{-2}$ $s^{-1}$, $E_s$ is soil evaporation in $kg_{(water)}$ $m^{-2}$ $s^{-1}$, $F$ is water supply into the greenhouse (misting, cooling pad) in $kg_{(water)}$ $m^{-2}$ $s^{-1}$ , $W_v$ is loss water vapour from leakage and ventilation in $kg_{(water)}$ $m^{-2}$ $s^{-1}$ , and $C_{con}$ is condensation rate on ground or crop in $kg_{(water)}$ $m^{-2}$ $s^{-1}$ .

During daytime, the greenhouse water balance depends mainly on the evapotranspiration, $E_T = T_r + E_s$, and on the loss from ventilation, $W_v$. Condensation seldom occurs during the day (however, the condensation term cannot be neglected during nighttimes). Soil evaporation is generally negligible if localized irrigation is practiced in soil substrate in pots. Then, in the majority of cases (no water supply from a mist system), the following equation is considered:

$$\frac{V_g}{A_f}\frac{dX}{dt} = T_r - W_v \qquad (4.20)$$

For steady state condition, a simple equation is obtained as:

$$T_r = W_v \qquad (4.21)$$

As $T_r$ is a function of solar radiation, $R_n$ and the Bowen ratio, $\alpha$, and $W_v$ is a function of air exchange rate, $N$ and the difference of humidity, $\Delta X$, Eq 4.20 above can be expressed as follows:

$$\frac{\alpha R_n}{L_v} = \left(\frac{N}{3600}\right)(V_g/A_f)(X_p - X_o)$$

$$X_p = X_o + \frac{\alpha R_n/L_v}{(N/3600)(V_g/A_f)} \qquad (4.22)$$

where $X_p$ is predicted humidity in the greenhouse in kg m$^{-3}$ and $X_o$ is ambient humidity in kg m$^{-3}$. So, the internal humidity is mainly a function of $X_o$, $R_n$, and $N$.

All these greenhouse models were designed using SIMULINK, a control package of MATLAB (version 6.5). SIMULINK is an interactive environment for modelling and simulating a wide variety of dynamic systems, including linear, non-linear, discrete-time, continuous-time, and hybrid systems. SIMULINK is built on top of MATLAB Technical Computing Environment. MATLAB and its tools are used for defining algorithms, analyzing data, and visualizing results. Together, SIMULINK and MATLAB provide an ideal integrated environment for developing models, performing dynamic system simulations and designing and testing new ideas. SIMULINK enables the quick and easy building of models of dynamic systems through block diagrams and equations. Hierarchical models are created by grouping into subsystems.

### 4.3.4 Models validation

A modified model which is originally developed by Kittas et al. (1997) to predict air exchange rates (Eqs. 4.10 and 4.11) was used in the recent study and it was validated using the measured values from the tracer gas method, as it has been described in the section of **4.3.1**. The comparison was made on daily basis from the average of daytime measurements starting from 8:00 to 17:00. The predicted and measured values of air exchange rate were calculated in terms of hourly basis and their values were different from a day to the other according to the local weather conditions during the study period.

For two greenhouse models, developed to predict internal air temperature (Eq. 4.18) and humidity (Eq. 4.22), the validation with the measured microclimates was conducted in coincide with the experiment for predicting air exchange rate. The comparison between predicted and measured microclimate was done in daily basis from the measurement during daytime along the experimental period of time. The correlations between the predicted and measured values of air exchange rates and internal microclimate were determined using a statistical analysis with PROC CORR tool (SAS Institute, 2003).

The comparison between the two (measured and predicted parameters) was made when the experiments were conducted in greenhouses covered with different mesh-sizes and in different seasons of the year. This is very important since both mesh-size and season might affect to these models. The effect of mesh-size on the validation of the model was carried out by performing in three similar greenhouses covered by 78-mesh, 52-mesh and 40-mesh nets as cladding material at the same time. Meanwhile, the effect of season of the year on the model was done at the 52-mesh greenhouse at three different seasons of the year, i.e.: from January to April 2004, July to October 2004 and December 2004 to March 2005.

## 4.4 Determination of a minimum size of ventilation openings

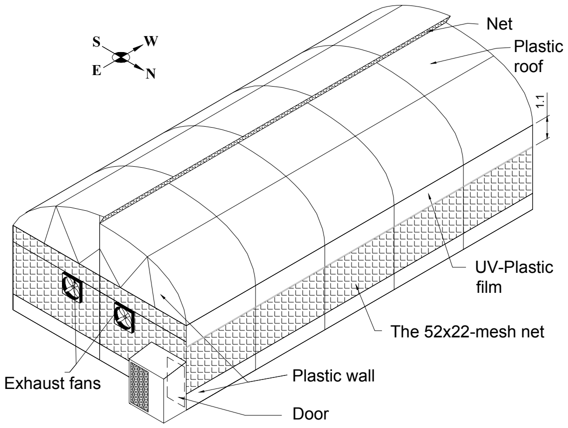
The experiment was conducted to evaluate the performance of ventilation system of the greenhouse designed for humid tropics condition having original ratio ventilation opening to floor area of 1.05. The main objective of the study was to minimize the use of insect-proof net to be replaced with UV-blocking plastic film as sidewall (cladding material) which is economically cheaper than the nets without changing the climatic requirement for crops cultivation and significantly reducing the air exchange rates inside the greenhouse. Another benefit from this effort is to reduce the possibility of insects entering the greenhouse possibly through the nets hence it minimizes disease infestation.

### 4.4.1 Experimental greenhouse

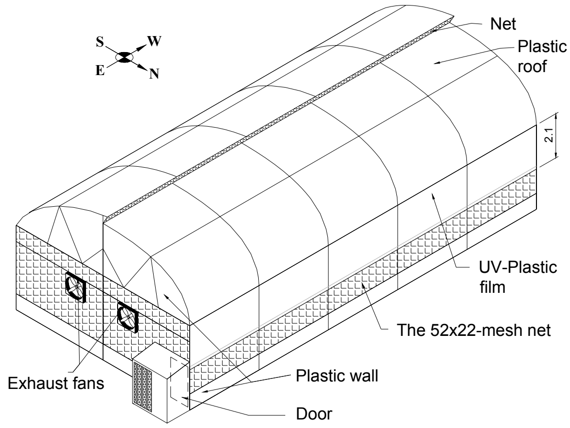
In general, the experiment was carried out under two different conditions, i.e.: the greenhouse with full tomato crops (leaf area index, LAI in between 2.5 to 3) and the greenhouse without any crops (empty). The first experiment was conducted from January 23 to March 20, 2005, while the later experiment was conducted from March 22 to May 11, 2005. The main goal for doing the experiment into two conditions was to differentiate the effect of the treatment on humidity in the greenhouse with full crops whereas in this case, the latent heat was more dominant than the sensible heat and the effect of temperature rise due to closing the particular vent opening area in an empty greenhouse whereas the latent heat was less important than the sensible heat.

All experiments were done at the greenhouse covered by 52-mesh net whereas the ventilation openings areas were varied from 20, 40, 60, 80 and 100% of the total ventilation opening area (from the original one) by covering a particular net at the sidewall with an UV-stabilized plastic film. The arrangement of experiment with the greenhouse covered with either the particular insect-proof net or the plastic-film is shown in Fig. 4.6. All in all, there were five treatments of ratio of vent opening to floor surface area ($V_r$) in this study, defined as:

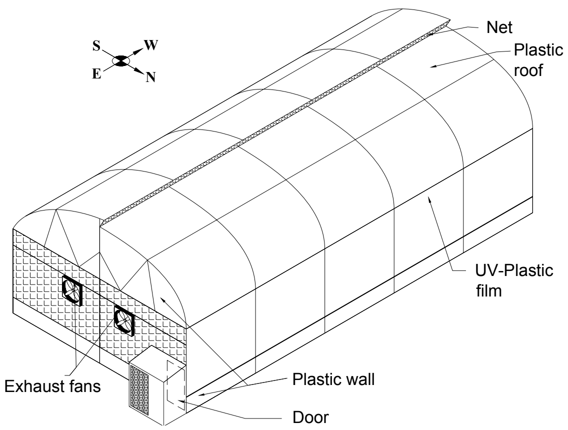
- $V_r$ = 1.05 or 100% of total vent opening area: it is defined as an original structure and no arrangement of ventilation openings was subjected;
- $V_r$ = 0.84 or 80% of total vent opening area: by closing along 1.1 m each at the sidewall with the roll-up type plastic film (Fig. 4.6 (a));
- $V_r$ = 0.63 or 60% of total vent opening area: by closing the nets both the sidewall along 2.1 m each from the top with the plastic film (Fig. 4.6 (b));
- $V_r$ = 0.42 or 40% of total vent opening area: by closing the surface of nets at the both sidewall with the plastic film (Fig. 4.6 (c));
- $V_r$ = 0.23 or 20% of total vent opening area: by closing all the surface of sidewall nets plus along 0.8 m at the front side and 2.4 m at the back side from the top (Fig. 4.6 (d)).



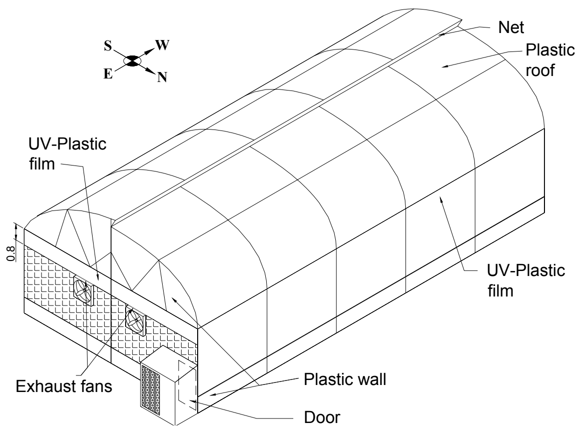

(a) 80% of total vent opening area




(b) 60% of total vent opening area




(c) 40% of total vent opening area




(d) 20% of total vent opening area

**Figure 4.6. Arrangements on closing particular vent opening of nets with an UV-stabilized plastic film to determine a minimum size of vent ratio**

Each treatment was done within ten (10) days period of time starting from ventilation opening of 100% to 20% of total vent opening area. Three times of daily measurement at the interval of three hours i.e.: 08:00 to 11:00 h, 11:00 to 14:00 h and 14:00 to 17:00 h was used as replication in each treatment. Since the experiment for each treatment can not be simultaneously conducted or it was performed in time sequence, the following assumptions have been taken into account:

- Plant condition was similar for one treatment to the other during experiment (with LAI maintained between 2.5 to 3.0)

- The diurnal climatic data for both inside the greenhouse and ambient condition were similar from day to day, and it was only the temperature or humidity differences were considered for data analysis
- Wind speed and direction during the experiment were assumed very close in variations (average daily wind speed ranging between 1.7 to 2.8 m $s^{-1}$).

### 4.4.2 Data measurement and analysis

Since the experiment was carried out in two conditions, tow main parameters were considered in the measurements: (1) measurements of air exchange rates and absolute humidity in fully mature crops grown inside the greenhouse; and (2) measurements of temperature rise and its gradient in an empty greenhouse.

#### 4.4.2.1 Air exchange rates and humidity measurements

Air exchange rates were measured using the decay rate methods, using water vapour ($H_2O$) as tracer gas, as it was precisely described at the section of **4.3.1**. The measurements were conducted three times a day and the average of three was become the measured value. This was also repeated during ten (10) days for each treatment of different vent configuration. For measuring absolute humidity, dry bulb temperature and relative humidity were measured using an aspirated psychrometer sensor and the absolute humidity difference between inside and outside the greenhouse was calculated using Eq. 4.7.

#### 4.4.2.2 Air temperature rise measurements

The objective of the experiment carried out in an empty greenhouse at different ventilation configurations was to explore the temperature rise and its gradient vertically inside the greenhouse due to closing vent openings area up to 20% of total vent opening. This was done because the temperature rise might not be detected in the greenhouse with fully grown tomato. Air temperature difference between inside and outside the greenhouse was measured using the aspirated psychrometer installed inside and outside the greenhouse. Moreover, the gradient of temperature difference was also vertically measured by installing three aspirated psychrometers in the middle of an empty greenhouse at the height of

0.5, 2.0 and 3.5 m from the floor surface, respectively. The measurement was conducted within ten (10) days for each treatment of ventilation configuration.

All data collected from both conditions stated above were averaged from ten days measurements as replication and standard error (SE) for each treatment was calculated. Analysis of Variance (ANOVA) was used to analyze data statistically (SAS Institute, 2003).

## 4.5 Evaluation on the effectiveness of exhaust fans used on the adapted greenhouse

The main concept of the adapted greenhouse here is how to maintain the climatic condition inside the greenhouse very close to the ambient condition under natural ventilation system. However, in case extreme conditions (the temperature over 35 °C) occurred, the exhaust fans were necessarily in order to dissipate the extreme heat out from the greenhouse. This experiment was aimed at evaluating the use of two exhaust fans installed on the sidewall of the greenhouse. The use of exhaust fans (operation) at the greenhouse was assigned to be the main treatment as force ventilated (FV) greenhouse while the absence of fans operation was assumed to be the control as natural ventilated (NV) greenhouse.

Theoretically, the use of fans can help to improve the ventilation system, to reduce the temperature rise and to remove the water vapour when crops were fully planted inside the greenhouse. This is the case if a small vent opening at the opposite of fans with fully closed sidewall structure was used in the greenhouse. When the most of sidewall becomes the ventilation opening, the management of exhaust fans operation will be very important because it is very costly in terms of electrical consumption.

In order to evaluate the effectiveness of exhaust fans operated in the adapted greenhouse, several experiments were conducted to compare some important parameters such as: air exchange rates, air temperature and humidity difference, and evapotranspiration between two greenhouses. These greenhouses were one greenhouse with exhaust fans fully operated as a treatment and another greenhouse without exhaust fans working as a control. All of the experiments were done coincide with the main experiment as it has already stated in the section of

**4.2.1** above. These experiments were also carried out at different conditions, as follows:

- with v.s. without plants inside the greenhouse,
- three different mesh-sizes of nets,
- different seasons of the year

The statistical analysis of t-test was used to test the main treatment of the exhaust fans usage again fully naturally ventilated greenhouse at different conditions. The PROC TTEST tool from the SAS software (SAS, 2003) was used to analyse the data of air exchange rate, temperature and humidity difference between inside and outside the greenhouse between the tested greenhouse and a control greenhouse at three different conditions. In order to avoid the error due to diurnal climatic difference, each experiment for a certain condition was conducted at the same period of time at respective condition. For instance, to test the effectiveness of fans working on the greenhouse under the absence and with crops conditions, four greenhouses were needed to run the experiment simultaneously.

# 5. Results

## 5.1 Performance of the adapted greenhouse

### 5.1.1 Microclimate and air exchange rate at different seasons of the year

In order to explore the effect of different seasons of the year on the microclimate and air exchange rate inside the greenhouse, the observation of the microclimate for several days on the respective season was conducted. The data were taken from April 11–15, 2003 representing the hot season; September 1–5, 2003 representing the rainy season and December 21–25, 2003 representing the cool season. The observation of microclimate was carried out from the same greenhouse covered by 78-mesh net. The diurnal air temperature and relative humidity parameters for common day over a period of 3 days are presented in Fig. 5.1 and 5.2.

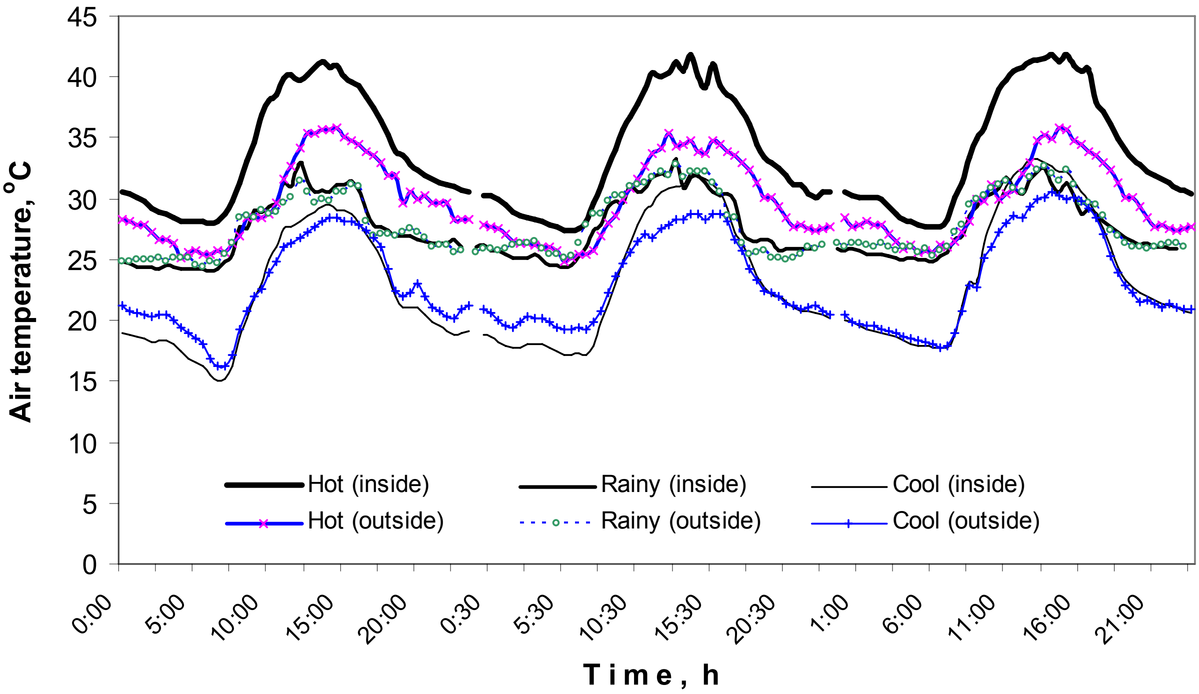



**Figure 5.1: Hourly air temperatures of inside and outside the 78-mesh greenhouse at different seasons of the year**

Figure 5.1 shows the diurnal air temperature for a couple of 3 days that both air temperature in and outside the greenhouse was significantly different among seasons of the year. The inside air temperature was ranging between 28 to 43 °C for the hot season, 25 to 33 °C for the rainy season and 15 to 30 °C for the cool season, respectively. Both cool and hot seasons have relatively big range of temperature difference between night and daytime compared to the rainy season. In addition, a large gap of temperature difference between inside and outside the greenhouse was also appeared in the hot season whereas the difference was about 3 – 5 °C during daytime. Meanwhile, the other seasons showed that air temperature difference between in and outside greenhouse was very less (about 1 – 2 °C).

In terms of relative humidity, the differences between inside and outside greenhouse were almost similar along the day for the hot and cool seasons while at the rainy season, their values were relatively large, especially during the daytime. Fig. 5.2 also shows very nice-looking results that during night time the average relative humidity for all seasons ranged between 80 to 95%, while during the day time relative humidity gradually went down to 40% in the hot and cool season. In the rainy season, the relative humidity was still very high at 60 to 95%. The high humidity mostly in nigh time tends to promote the incidence of fungal diseases to the tomato plants.

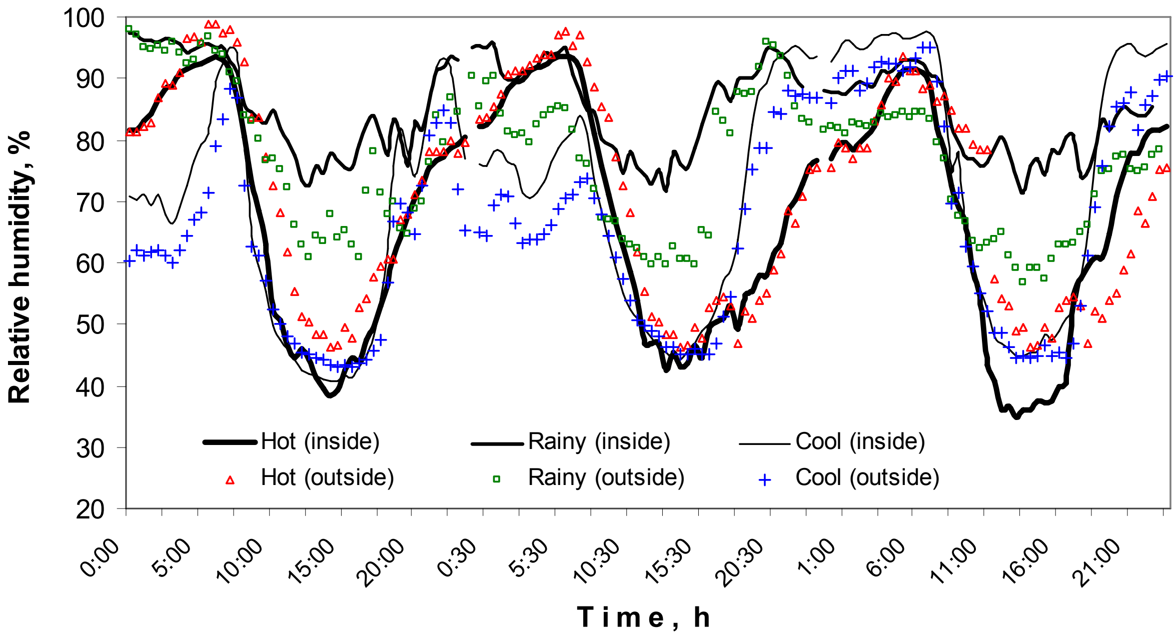



**Figure 5.2: Hourly relative humidity of inside and outside the 78-mesh greenhouse at different seasons of the year**

From the observation of global solar radiation measured from meteorological station as depicted in Fig. 5.3, it is clear that the daily solar radiation at hot season during daytime was constantly higher than both rainy season and cool season. The maximum solar radiation in hot season was more than 1000 W $m^{-2}$, hence it generated the maximum temperature in the 78-mesh greenhouse up to 43 °C during daytime. In contrast, in the cool season which mostly occurred from December to February the maximum outside solar radiation was mostly just reached up to in between 700 – 800 W $m^{-2}$ (Fig. 5.3), therefore the temperature in the greenhouse was more favourable for plant growth ranging between 15 to 30 °C (Fig 5.1). In addition, during rainy season the diurnal solar radiation varied time by time depending upon the sky condition i.e.: whether it was cloudy or clear, as shown in dash line in Fig 5.3. Their values were ranging in between those for the hot and for the cool season

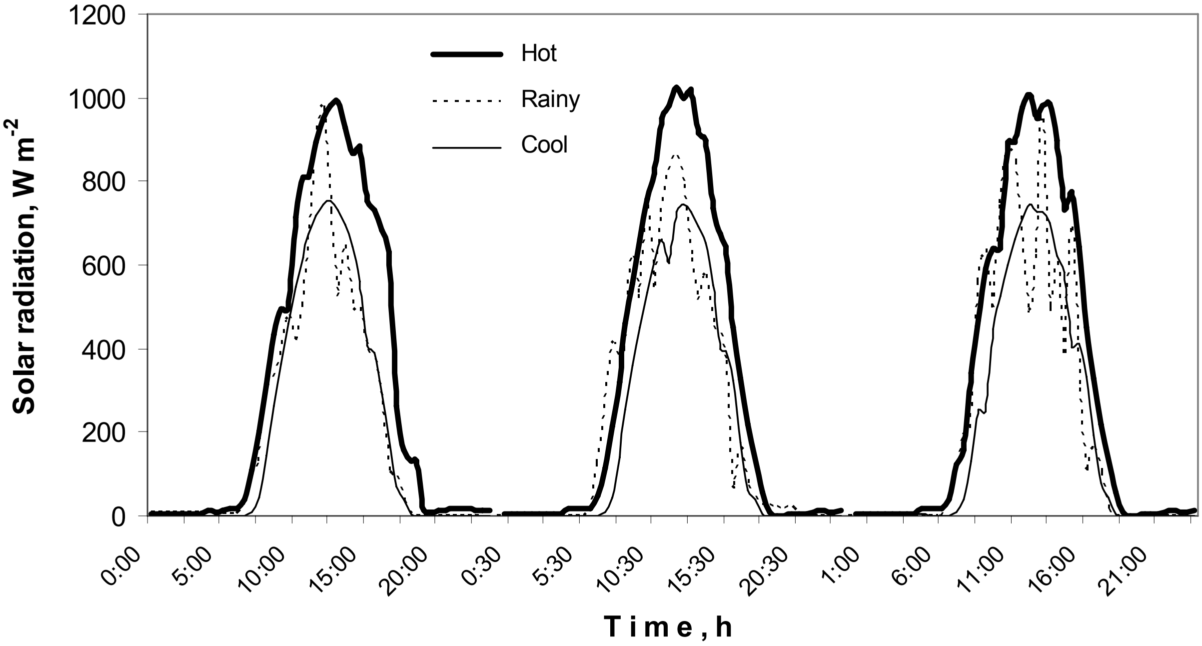



**Figure 5.3: Hourly solar radiation outside greenhouse at different seasons of the year**

More detail about the effect of seasons of the year on the micro climate inside the greenhouse along the cultivation time is presented in Fig 5.4. This shows the daily average air temperature and absolute humidity difference between inside and outside the greenhouse covered with the insect-proof net of 52-mesh size during experiment at the day time. When the plants were young, the temperature differences or temperature rises were relatively high and absolute humidity differences were less. In this case, the sensible process was more dominant compared to the latent process in heat fluxes in the greenhouse. On the contrary, the latent flux was more dominant induced to the micro climate when the crops were mature. In this condition, the temperature difference was less and absolute humidity difference was relatively higher.

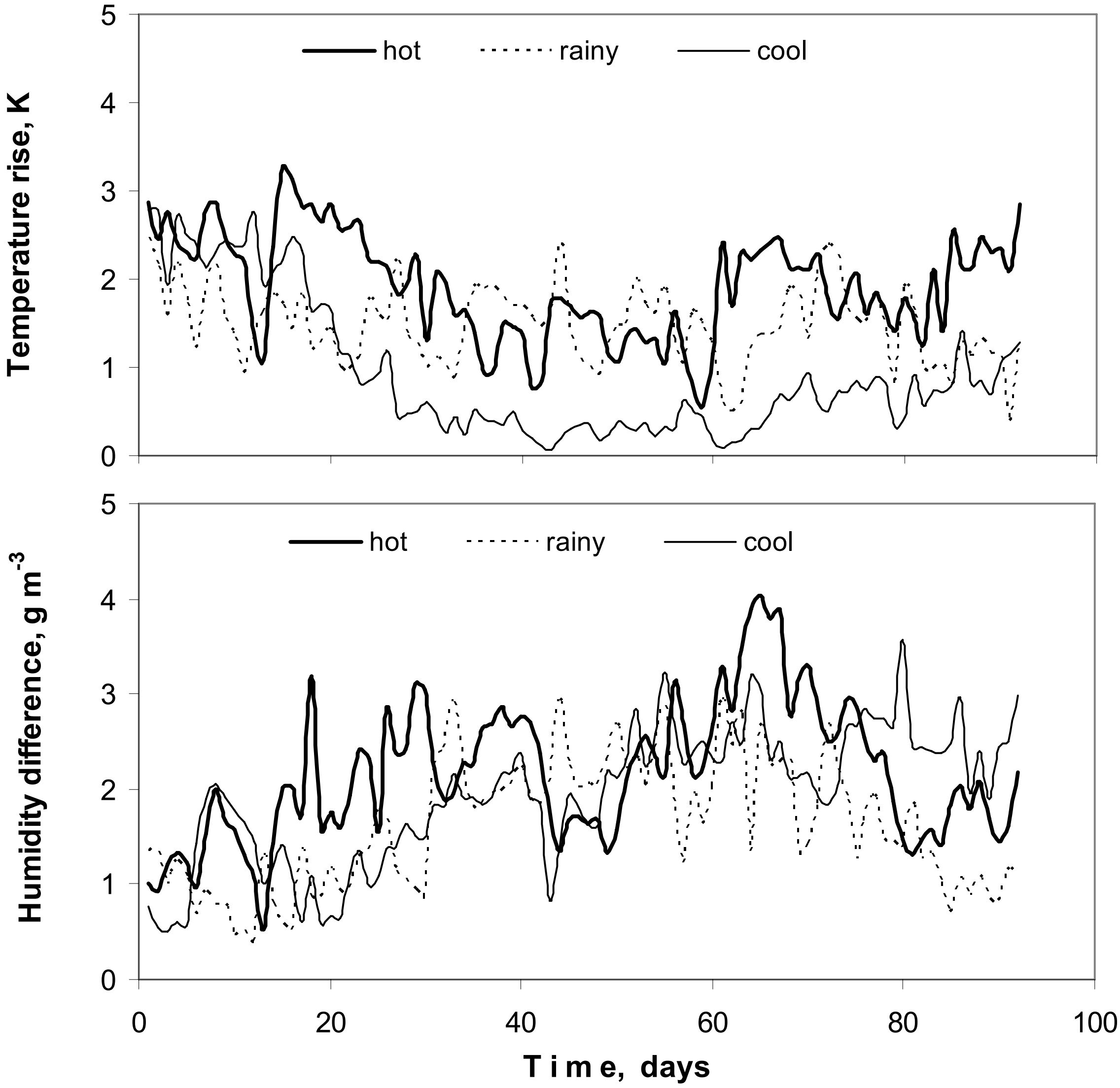



**Figure 5.4: Daily temperature and humidity difference between inside and outside the 52-mesh greenhouse during daytime (8:00–17:00h) at different seasons of the year**

In addition, the temperature rise due to the use of insect-proof net was much more in both hot and rainy seasons ranging from 1 to 3 K or on average of 2 K compared to the cool season that ranged from 0.2 to 2.5 K even less than 1 K when the plants were fully grown (LAI > 2.00). The reason for the low temperature rise during the matured stage of the crops might be caused by the cooling effect from the evapotranspiration processes of tomato plants in the daytime. Meanwhile the humidity differences, expressed by the daily absolute humidity differences measured during daytime from 8:00 to 17:00 h, had a similar trend and values among the others. Commonly, the humidity difference along the cultivation period of time was ranging from 0.5 g $m^{-3}$ at the vegetative stage up to the 3 - 4 g $m^{-3}$ at the maturity stage even though it was a slightly higher at the hot season, because less humidity and higher solar radiation occurred outside the greenhouse.

Since the air exchange rates were strongly influenced by the microclimate, the measurements of these were carried out at different seasons of the year. Figure 5.5 shows the seasonal air exchange rates measured at the same greenhouse covered by 52-mesh size of net along the experimental period of time (between 2004 and 2005). It is interesting to notice that air exchange rate was differed from the season and crop stage. The trend was quite similar to the microclimate as shown in Fig 5.4 above.

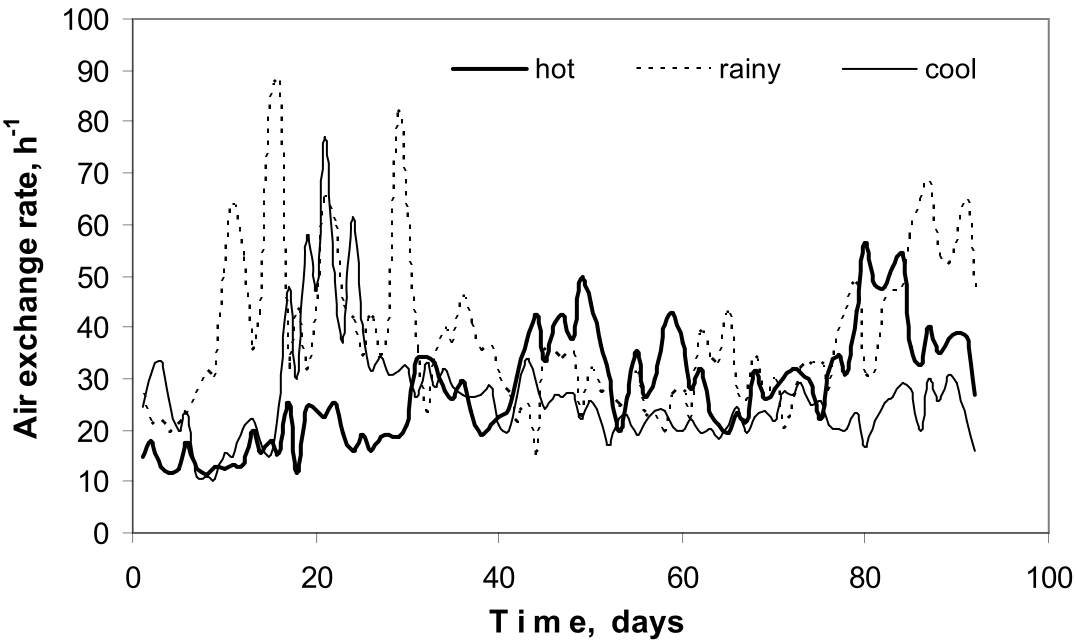



**Figure 5.5: Hourly air exchange rates averaged during daytime (8:00–17:00h) in the 52-mesh greenhouse for different seasons of the year**

The fluctuation of air exchange rates measured during the experiment might be caused by the seasonal effect. Since the air exchange rate is mostly affected by absolute humidity differences which were daily fluctuated, it was interesting to explore the measurement under different seasons of the year i.e. cool or hot season. Figure 5.5 clearly shows that the internal temperature was very close to the ambient temperature but in fact the humidity differences were relatively high especially in the 78-mesh greenhouse. Moreover, the rain water occurred intensively during experimental period could have blocked some of holes of the insect-proof net resulting in reduced vent opening area. In this condition, the water may have acted as a thin film along side wall during some period of time significantly reducing the air flow from outside the greenhouse through the net.

In order to notice the effect of different seasons of the year on microclimate and air exchange rate, a statistical analysis was performed and the result summarized as shown in Table 5.1. It is clear that temperature rise was significantly difference from one season to another. On average, the temperature rise was about 0.5 K from cool to rainy season and from rainy to hot season. This was observed under the greenhouse covered with smaller (52-mesh) mesh-size. For a bigger mesh-size such as 78-mesh, the temperature rise could be up to 5 K even more as shown in Fig. 5.1. Similarly, the trend was followed by the absolute humidity for different seasons of the year. Meanwhile, the air exchange rate has a similar trend for both parameters of microclimate mentioned above. Statistically, there was no significant difference of means between two of hot and rainy seasons, but they were significantly different to the cool season.

**Table 5.1: Mean (± SE) of microclimate and air exchange rate in the 52-mesh greenhouse during daytime at different seasons of the year**

| Season of the year | Temperature difference K | Absolute humidity difference g $m^{-3}$ | Air exchange rate $h^{-1}$ |
|---|---|---|---|
| Hot season | 1.9 $^{a}$ ± 0.1 | 2.17 $^{a}$ ± 0.76 | 28.0 $^{b}$ ± 1.1 |
| Rainy season | 1.5 $^{b}$ ± 0.1 | 1.60 $^{b}$ ± 0.05 | 37.8 $^{a}$ ± 1.6 |
| Cool season | 0.9 $^{c}$ ± 0.1 | 1.94 $^{c}$ ± 0.04 | 26.5 $^{b}$ ± 1.1 |

[a] Whithin column, means followed by the same letters are not significant different at P = 0.05, GLM-LSD Test.

### 5.1.2 Effect of net sizes on air exchange rates and microclimate

Figure 5.6 shows the effect of mesh-size of nets placed on the vent openings on temperature and humidity difference between inside and outside the greenhouse in the rainy season. The temperature and absolute humidity differences were measured by averaging the values from daytime measurement (8:00 to 17:00 h) along the cultivation time. It is clear that the increase of temperature was varied from one day to another. The greenhouse covered by 78-mesh of net generated higher temperature rise and more humidity compared to both greenhouses covered by 52- and 40-mesh size of nets, respectively.

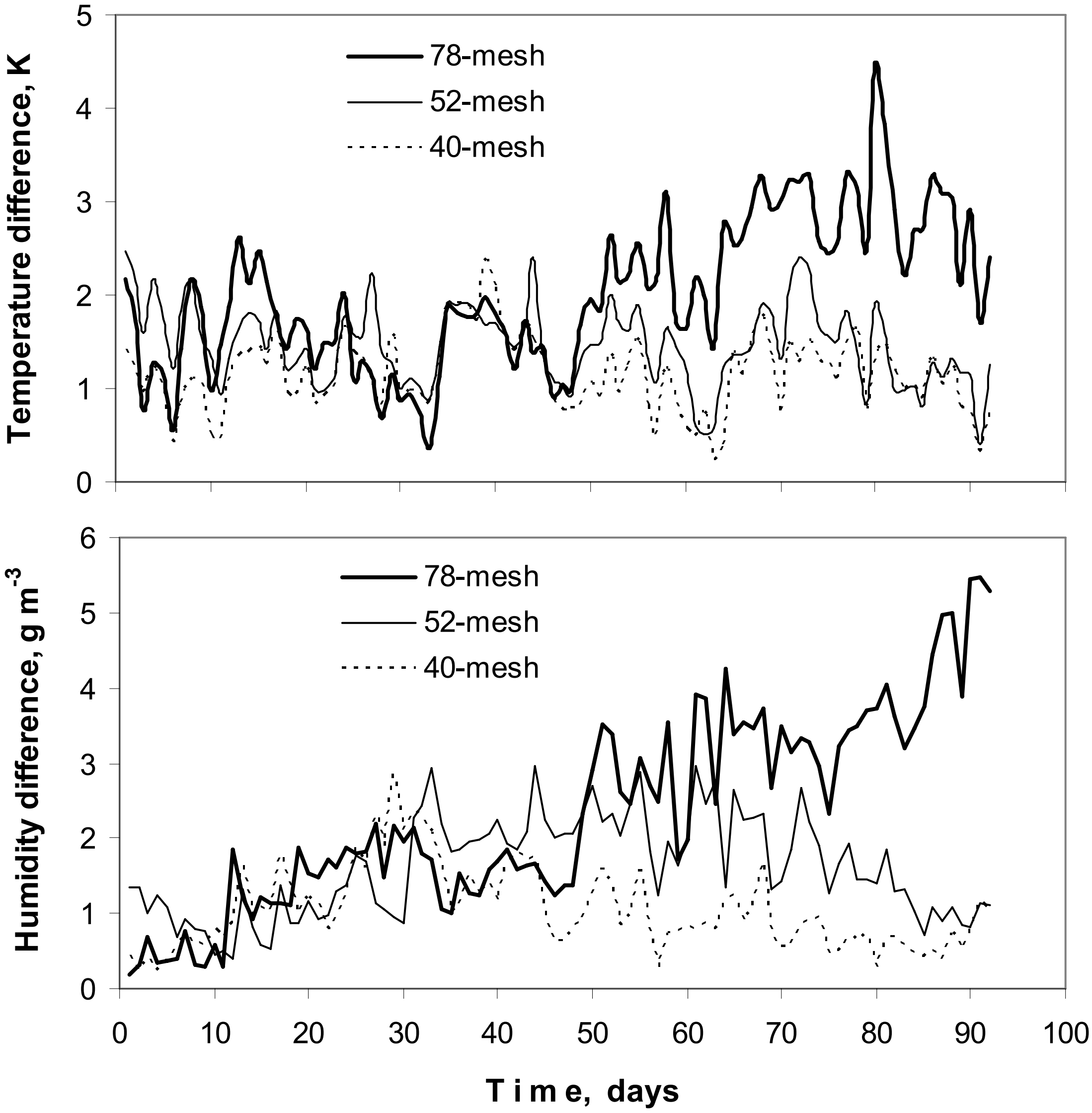



**Figure 5.6: Daily temperature and humidity difference between inside and outside the greenhouse covered by three different net types during daytime (8:00–17:00h)**

The diurnal microclimate (temperature and absolute humidity) in the greenhouse at different mesh-sizes of nets is shown as Fig. 5.7 and 5.8.

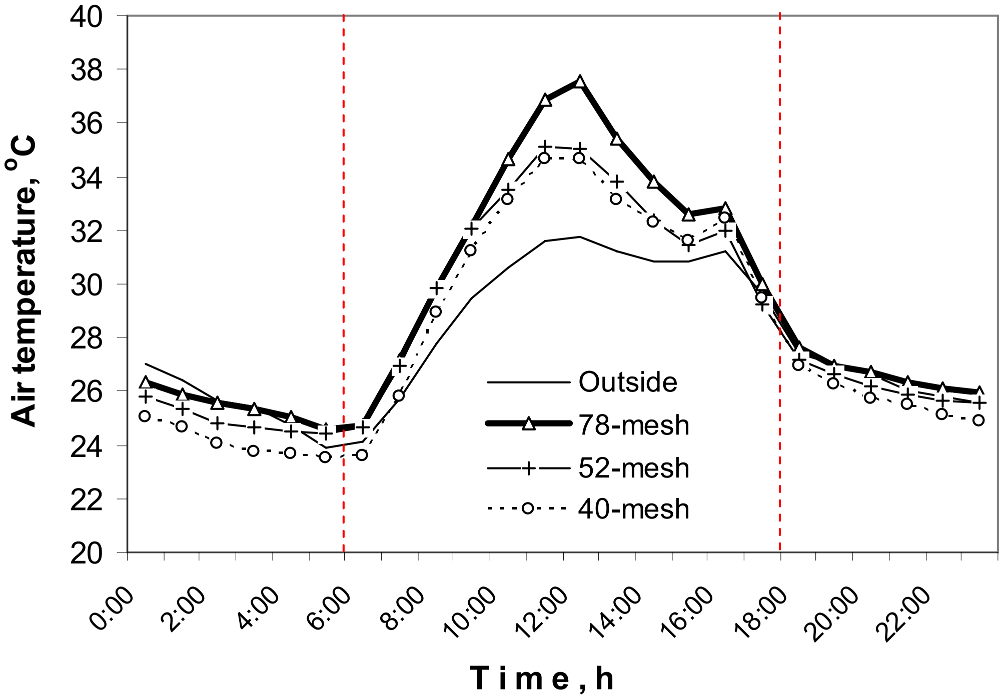



**Figure 5.7: Comparison of air temperature in greenhouses covered by three different net types for typical day recorded on October 8, 2004**

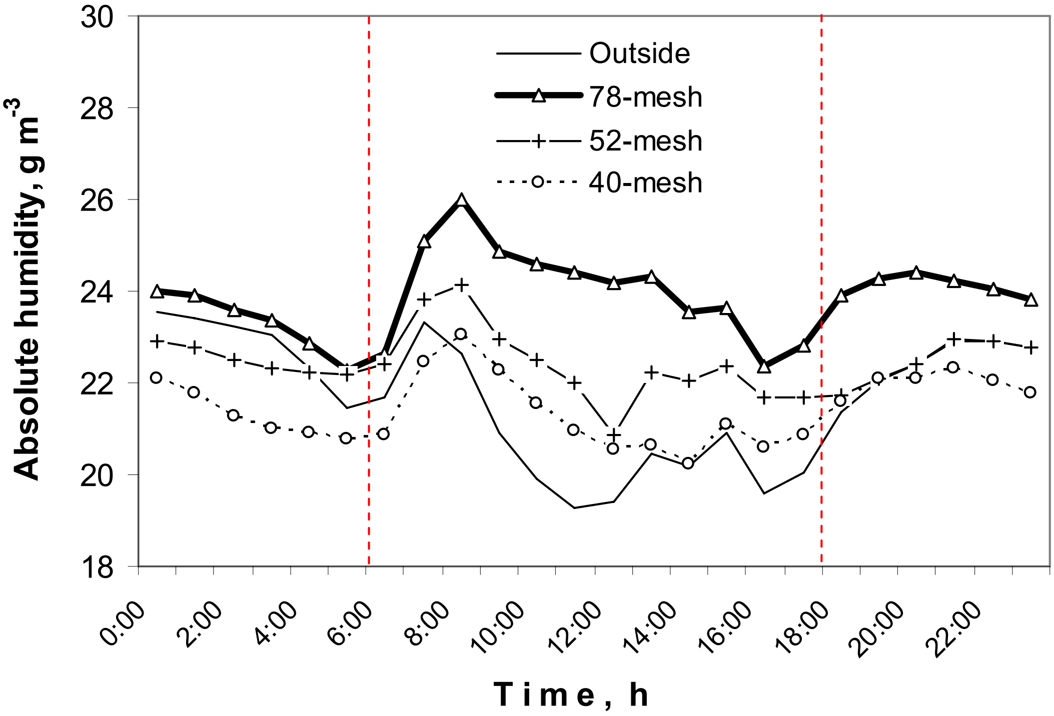



**Figure 5.8: Comparison of absolute humidity in greenhouses covered by three different net-types for typical day recorded on October 8, 2004**

On average, the use of insect-proof net had increased the internal temperature from 0.5 to 4.5 K compared to the ambient temperature during daytime. Meanwhile, the humidity difference was ranging from 0.5 to 5.5 g $m^{-3}$, whereas the higher humidity was found in the 78-mesh greenhouse. It is very interesting to take in to consideration that at the maturity stage (LAI > 2.0) the temperature difference at the 78-mesh greenhouse was much higher than others. The reason was that the humidity inside the greenhouse was also extremely higher (more than 2 g $m^{-3}$) while the air exchange rate was very low (between 10-20 times per hour) as shown in Fig. 5.9. Moreover, the experiment was carried out under rainy season whereas the ambient humidity was already high about 70.3 % (on average).

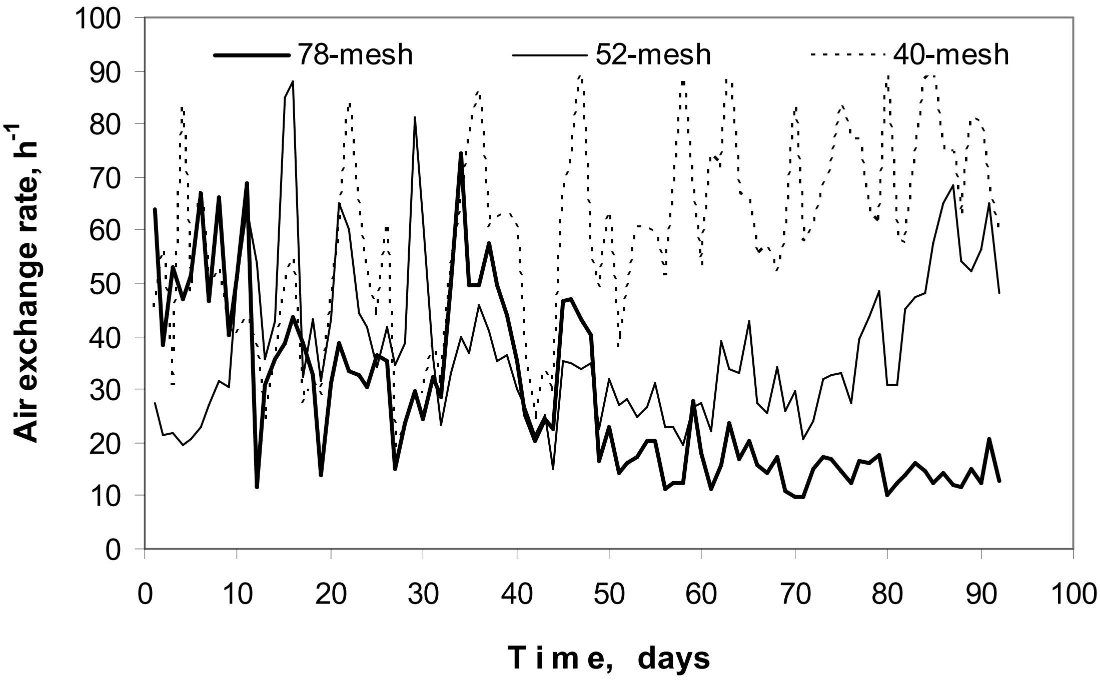



**Figure 5.9: Measured air exchange rates during daytime (8:00–17:00h) in greenhouses covered by three types of nets in rainy season**

The hourly air exchange rate measured using a tracer gas (water vapour) method daily from 8:00 to 17:00 h along the cultivation period is shown in Fig. 5.9. In general, the finer the screen net used on the ventilation openings; the lesser was the air exchange rate obtained in the greenhouse. During the experiment, the 78-mesh greenhouse showed the lowest air exchange rates ranging between 10 to 60 times renewals of air per hour compared to the others. The greenhouse with 52-mesh has from 20 to 60 $h^{-1}$ while at the 40-mesh greenhouse the values were in between 40 to 80 $h^{-1}$. On average, the air exchange rate in the 78-mesh greenhouse was significantly different compared to 52-mesh and 40-mesh greenhouses.

It is noted that the result shown in Fig. 5.9 above was carried out under rainy season. For comparison to the other season of cool, a simultaneous experiment, measuring the air exchange rate along the tomato cultivation period, was done and the results are presented in Fig. 5.10. The air exchange rates measured at the cool season was lower than that in the rainy season. The incident of dust stacked on the net might be the reason why this happened. In addition, the wind speed recorded during the rainy season (on average at 2.7 m $s^{-1}$) was mostly higher than in the cool season (on average at 1.5 m $s^{-1}$) resulted in the higher air exchange rates. However, the effect of the net size on the air exchange rate had a similar trend to the previous one which was conducted under the rainy season.

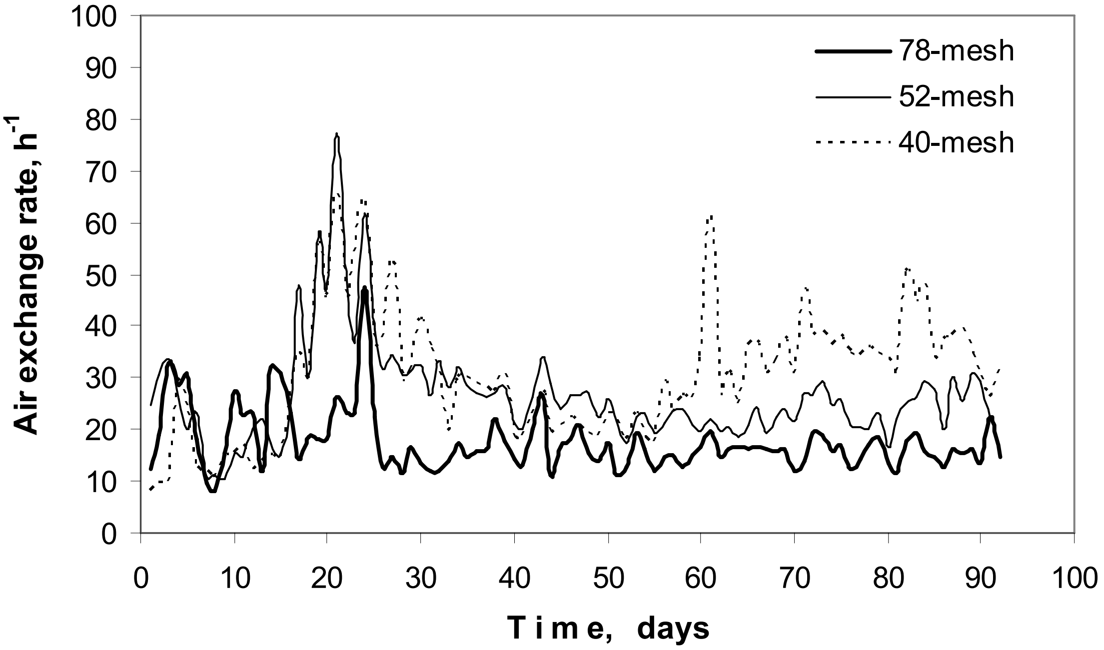



**Figure 5.10: Measured air exchange rates during daytime (8:00–17:00h) in greenhouses with different mesh-sizes of nets in cool season**

To emphasize the effect of net size (mesh) on microclimate and air exchange rate, the means and standard error (SE) of those measurements presented in Fig. 5.6 to 5.10 above were computed and compared using analysis of variance (ANOVA) (GLM procedure; SAS Institute, 2003). The results revealed that there was a significant effect of net-sizes on the air exchange rate even though the very big ventilation opening (ratio of vent opening to the surface floor area is 1.05) was applied. The greenhouse with finest mesh-size (78-mesh, anti-thrips net) showed the lowest mean of air exchange rate compared to the two greenhouses with 40 and 52-mesh, respectively. The reduction was measured up to 50% when it was compared to the 40-mesh greenhouse. Similarly, there is also reduction of air exchange rate for the 52-mesh greenhouse by about 35% compared to the 40-mesh greenhouse. Therefore, the use of insect-proof net with finer hole-size would significantly reduce the air exchange rate (Table 5. 2).

**Table 5.2: Mean (± SE) of air exchange rate, air temperature, relative humidity and absolute humidity difference during daytime (8:00–17:00h) in the 78-mesh, 52-mesh and 40-mesh greenhouses**

| Net size<br>mesh | Air exchange rate,<br>$h^{-1}$ | Air temperature,<br>°C | Relative humidity,<br>% | Absolute humidity difference,<br>$g\ m^{-3}$ |
|---|---|---|---|---|
| 40 mesh | 57.9 [a] ± 1.9 | 30.8 [b] ± 0.1 | 69.3 [b] ± 0.7 | 1.04 [c] ± 0.05 |
| 52 mesh | 37.8 [b] ± 1.5 | 31.1 [b] ± 0.1 | 69.9 [b] ± 0.7 | 1.60 [b] ± 0.07 |
| 78 mesh | 28.2 [c] ± 1.7 | 31.9 [a] ± 0.1 | 74.1 [a] ± 0.7 | 2.33 [a] ± 0.14 |

[a] Within column, means followed by the same letters are not significantly different ($P$ = 0.05, least significant difference, LSD Test [SAS Institute, 2003])

When the season of the year was also taken into account in the analysis as a second factor, and two-way ANOVA used for analysis, the results obtained were as presented in Table 5.3. The means and standard error (SE) of four important parameters were statistically compared using general linear model (GLM – LSD) at the significant level of 5%. The means of both air exchange rate and absolute humidity difference between inside and outside the greenhouse showed a significant difference for both mesh-sizes of net and at different season's treatments. The F-values of air exchange rate for the treatments of mesh-size and season were 112.58 (N=184; P<0.0001) and 204.43 (N=276; P<0.0001), respectively while the F-values of absolute humidity difference were 73.65 (N=184; P<0.0001) and 12.57 (N=276; P<0.0004), respectively. In addition, the only average of internal air temperature in the 78-mesh greenhouse was significantly different compared to the 52-mesh and 40-mesh greenhouses, but the means of air temperature during rainy season were not significantly different at 5% of confident level. A similar pattern was found at the means of relative humidity whereas the use of higher mesh-size such as 78-mesh for covering the greenhouse significantly increased the humidity as compared to both the 52-mesh and 40-mesh greenhouses. Moreover, the relative humidity occurring in all of the greenhouses running under the rainy season was much higher compared to that under the cool season at significant level of 5%.

**Table 5.3: Mean (± SE) of air exchange rate, air temperature and absolute humidity difference during daytime (8:00–17:00h) in the 52-mesh greenhouse at three different seasons of the year**

| Season of the year | Air exchange rate, $h^{-1}$ | Air temperature, °C | Relative humidity, % | Absolute humidity difference, $g\ m^{-3}$ |
|---|---|---|---|---|
| Hot | $28.0^{b}$ ± 1.1 | $32.5^{b}$ ± 0.1 | $60.9^{b}$ ± 0.7 | $2.16^{a}$ ± 0.09 |
| Rainy | $37.8^{a}$ ± 1.6 | $31.1^{b}$ ± 0.1 | $69.9^{a}$ ± 0.7 | $1.60^{c}$ ± 0.07 |
| Cool | $26.5^{b}$ ± 1.1 | $30.7^{c}$ ± 0.1 | $58.6^{b}$ ± 0.7 | $1.94^{b}$ ± 0.09 |

[a] Within column, means followed by the same letters are not significantly different (*P* = 0.05, least significant difference, LSD Test [SAS Institute, 2003])

### 5.1.3 Effect of mesh-sizes of nets on plant growth and yield

During the experiment, the agronomical aspect of tomato cultivation, such as: plant height development, leaf area index (LAI) and tomato yield was also recorded. The result of these measurements is presented in Figs. 5.11 to 5.14. The development of tomato's plant height at the three greenhouses as presented in Fig. 5.11 was simultaneously measured every week. The rate of growth due to the use of nets different mesh-sizes was very close at the beginning stage then they were gradually differed since the fruit setting (after 60 DAT). It is clearly shown that the plant growth in the 52-mesh greenhouse was quite better than those in the 40 and 78-mesh greenhouses. This is because the plants in the 52-mesh greenhouse was relatively healthier (less insect disease attacked the tomato plant) than that in the other greenhouses in the cool season. It was in the last of experiment stage that the population of insect disease (thrips *sp.*) was dramatically increased in the 52-mesh greenhouse then it has a potential to attack the crop plants. This was caused by two reasons. Firstly, the heavily infected plants in some greenhouses around the experiment were removed hence there was a possibility of migration of disease to the experimental greenhouse. Secondly, when the plants were high enough (> 2.5 m height) the climate (season) changed from cool to hot resulting in this condition giving the opportunity of multiplying the number of insect disease which might have been already trapped in the greenhouse. Meanwhile, in the rainy season the plant growth in each greenhouse showed a similar trend and very close to each other. On average, the rate of tomato growth in each greenhouse was about 25 to 30 cm a week and the plant height reached up to 3.5 m.

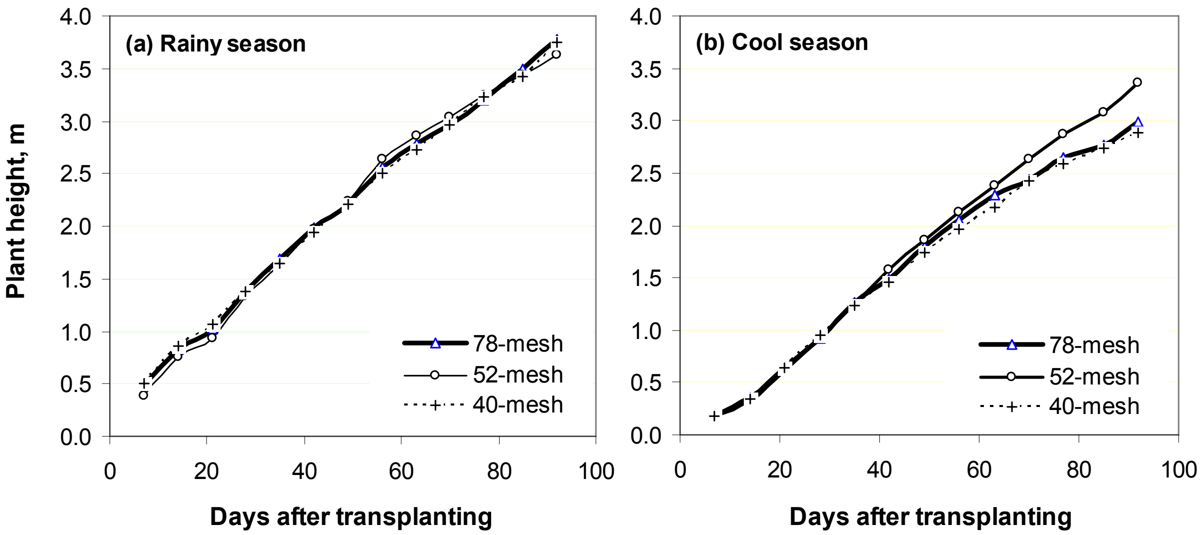



**Figure 5.11: Effects of mesh-sizes of nets on plant height in greenhouse**

Since the measured leaf area index (LAI) had a similar trend with the growth of tomato plants against the cultivation period of time (see Fig. 5.12) and the measurement of weekly LAI needed a lot of destructive sample in each tested greenhouse, a comparison of the means of LAI increment as plant growth indicator was not performed at both treatments of different net-sizes and seasons of the year. Besides, the pruning activity conducted in a particular cultivating time is another reason that has to be put into consideration during the comparison and it caused the breaking line of LAI curve against the observation time as shown in Fig. 5.12. This activity was needed to maintain the plant well grown, to encourage the development of fruit setting and to remove the lower leaf which was the most infected by insects and disease. This sometimes also helps in improving ventilation by enhancing airflow movement inside the greenhouse. In general, the LAI for tomato plants was measured from 0.1 to 3 for FMTT260 cultivar and 0.1 to 4 (with pruning) or 0.1 to 6 (without pruning, single stem) for King Kong II cultivar, respectively (Kleinhenz, 2003).

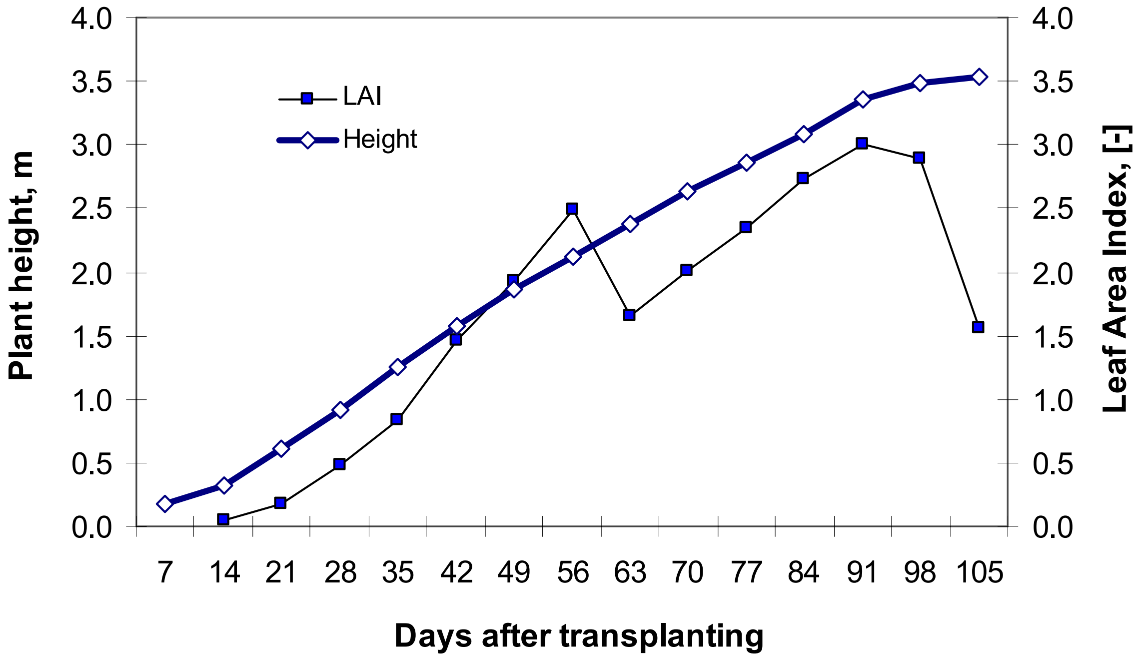



**Figure 5.12: Weekly measurements of Leaf Are Index (LAI) and plant height in the 52-mesh greenhouse**

Statistically, no significant difference of tomato growth rate measured every week in each greenhouse was found at confident level of 5% for both different mesh-size and seasons treatments (Table 5.4). The use of different mesh-size of net installed at the greenhouse's cover did not affect on plant growth rate except on the cool season at the rate of 0.6 to 0.27 m per week. However, the plant growth had a different rate when the cultivation practice was conducted under different seasons of the year. The best time to cultivate the tomato plant was actually in the cool season starting from the month of November until February because it gave the best result of tomato yield in terms of production. In fact, in terms of plant growth Table 5.4 shows that the average plant growth rate in the cool season just lower than the other seasons. This is caused by the different tomato varieties used for each season. Due to the various problem of malfunctioning fruits of King Kong

II variety (mostly cracking and blossom end rot disorders), another type of tomato cultivar namely FMTT260 was cultivated during cool season. According to the physical properties of both varieties released by the company as well as Aung (1999), both tomato cultivars have a similar fruit size and shape at the range of 100 – 150 g per fruit.

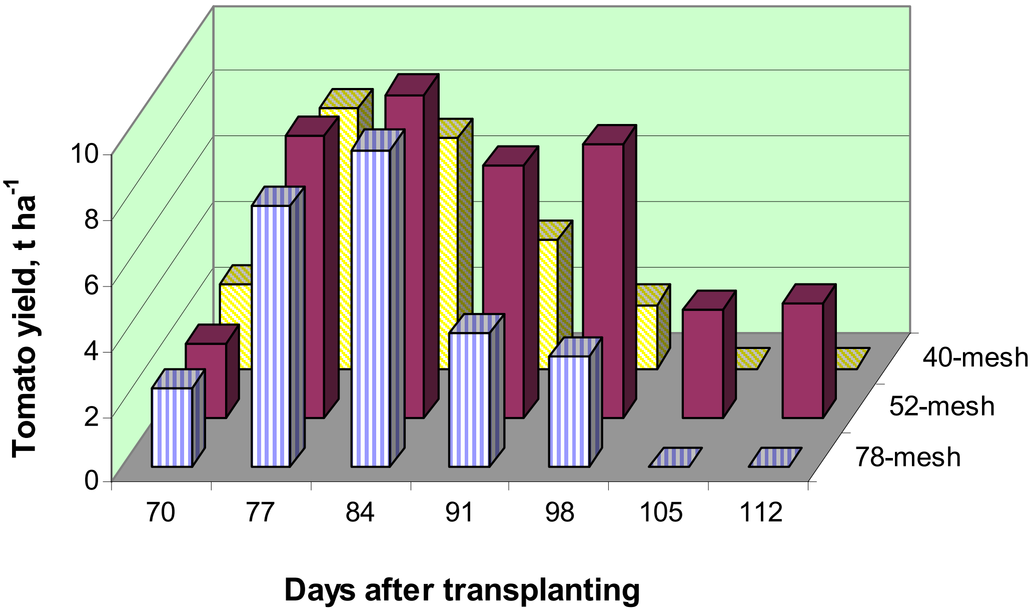



**Figure 5.13: Weekly measurements of tomato yield from greenhouses covered by three different mesh-sizes of nets**

Meanwhile, the tomato yield was collected and recorded every week in each greenhouse covered with different net-sizes starting 70 days after transplanting. A comparison of total tomato fruit yields from the experimental greenhouses is presented in Fig. 5.13. This was carried out under the cool season. It is shown that each greenhouse had a similar trend of yield started at about 2 t ha$^{-1}$ then gradually increased up to 8 – 10 t ha$^{-1}$ for a couple of 2 weeks then it started to decrease to 4 t ha$^{-1}$ every week. So, during the cultivation period of time, the total yield obtained for each greenhouse was about 27, 40 and 23 t ha$^{-1}$ for the 78-mesh, 52-mesh and 40-mesh greenhouses, respectively. It is clear that the higher mesh-size used, the higher the level of protection from disease was obtained resulting in the higher yield of tomato achieved.

Fig. 5.14 supports this and shows that the percentage of good quality, as marketable tomato, was more (> 85%) from the 78-mesh greenhouse than that at the 40-mesh greenhouse. About the medium quality of tomato was obtained from the 52-mesh greenhouse whereas the average of defected fruit was about 20%. The number of defected tomato fruit (unmarketable tomato) commonly increased from the beginning of harvest up to 25% of total yield in greenhouse covered with 40-mesh.

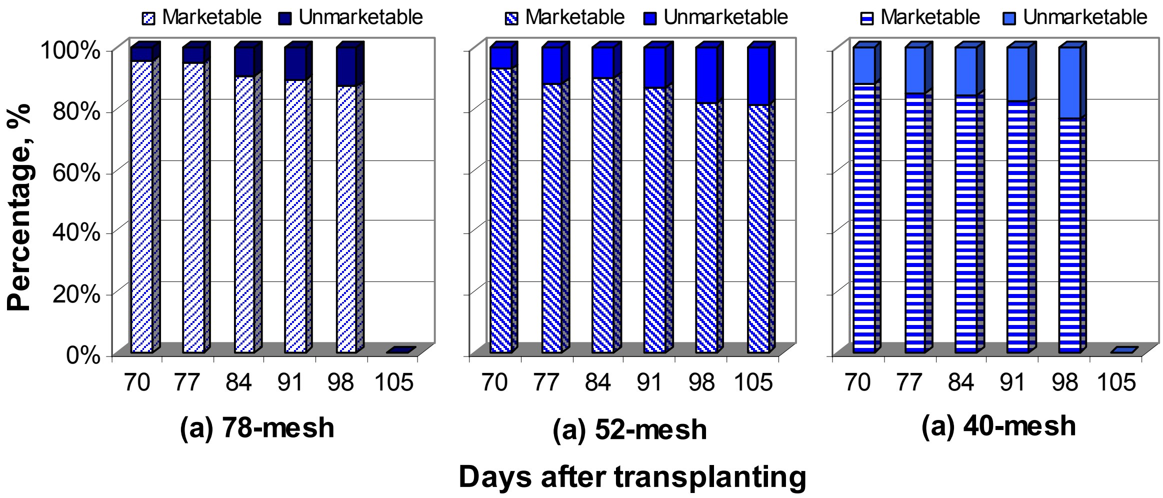



**Figure 5.14: Weekly measurements of tomato quality from greenhouses covered by three different mesh-sizes of nets**

The effect of both treatments (net-size and season) on the crop performance (growth rate and yield) was statistically analysed using analysis of variance (ANOVA) factorial 2-way (SAS, 2003) and the result is summarized in Table 5.4. As it has been already explained before, there was no significant difference in the growth rate of tomato among the greenhouses covered with different net-size at the rate of 0.25 – 0.27 m per week (F=0.38; N=36; P = 0.6832) except during the cool season whereas most of the plants in both 78-mesh and 40-mesh greenhouses were infected by insect disease. In this case, the insect might not have entered the greenhouse through the net-hole but from the door or with people entering the house during cultivation period. Similarly, the tomato yield obtained every week from each greenhouse was not significantly different at confident level of 5% using ANOVA (F-test) (F = 1.46; N = 7; P = 0.2594). No significant effect of using different net-size on the weekly tomato yield was found and the average yield was ranging from 4.66 to 7.33 t $ha^{-1}$ per week.

Nevertheless, the total yield produced from the 52-greenhouse at 0.87 t gave a better result compared to the other greenhouses of 0.55 t and 0.47 t for the 78-mesh and 40-mesh treatments, respectively (Fig. 5.13). In terms of season (Table 5.5), cultivating tomato under cool season had produced better the total yield than running in other two seasons (F = 13.54; N = 5; P = 0.0008).

**Table 5.4: Mean (± SE) of weekly plant growth rate, total yield and tomato quality in the greenhouses covered by three different mesh-sizes of nets and in the 52-mesh greenhouse at different seasons of the year**

| Season | Parameters | Net size | | |
|---|---|---|---|---|
| | | 40-mesh | 52-mesh | 78-mesh |
| **Rainy** | Plant growth rate ( *m week$^{-1}$* ) | 0.27 $^{aA}$ ± 0.06 | 0.27 $^{aA}$ ± 0.08 | 0.27 $^{aA}$ ± 0.07 |
| | Total tomato yield ( *t ha$^{-1}$ week$^{-1}$* ) | NA | 1.46 $^{B}$ ± 0.28 | NA |
| **Cool** | Plant growth rate ( *m week$^{-1}$* ) | 0.23 $^{bB}$ ± 0.07 | 0.26 $^{aA}$ ± 0.07 | 0.23 $^{bB}$ ± 0.07 |
| | Total tomato yield ( *t ha$^{-1}$ week$^{-1}$* ) | 4.66 $^{b}$ ± 0.73 | 7.33 $^{aA}$ ± 0.77 | 5.50 $^{b}$ ± 0.79 |
| | Unmarketable fruit ( *%* ) | 16.96 $^{a}$ ± 0.93 | 12.12 $^{ab}$ ± 0.91 | 8.26 $^{b}$ ± 0.85 |
| **Hot** | Plant growth rate ( *m week$^{-1}$* ) | 0.26 $^{aAB}$ ± 0.07 | 0.26 $^{aAB}$ ± 0.07 | 0.27 $^{aAB}$ ± 0.08 |
| | Total tomato yield ( *t ha$^{-1}$ week$^{-1}$* ) | NA | 3.29 $^{B}$ ± 0.46 | NA |

Means followed by the same lower letters within rows and upper case letters within the columns are not significantly different (P = 0.05, LSD multiple range test [SAS, 2003]).
NA = data not available

The number of defected fruit from the total fruit was also analyzed using ANOVA one-way test and the result showed there is a significant effect of applied different mesh-size of net on percentage of unmarketable fruit (F = 3.81, N = 7; P = 0.0171) (Table 5.4). Based on the weekly measurement, the percentage of unmarketable tomato in the finer mesh-size (like at the 78-mesh greenhouse) assured a better fruit quality at about 95% (on average) compared to the 52-mesh and 40-mesh greenhouses at about 80%. However, growing tomato in the greenhouse covered by 52-mesh of net gave a little bit good results in terms of growth rate, total yield and longer period of cultivation.

In terms of fruit quality, Table 5.5 shows the average tomato yield from the 52-mesh greenhouse for different seasons of the year. At the beginning harvest, the average size of tomato was quite ideal for both hot and cool season at about 120 g per fruit then gradually decreased after a month due to the infection of more insect disease (thrips) till at the end of harvest the size of fruits was just a half of the ideal size at 50 to 85 g per fruit. The exception was occurred in the rainy season where the average of good fruits was ranging from 32 to 79 g per fruit. So, cultivation period of time, in this case, affected the fruit quality of tomato where both cool and hot seasons gave batter result of marketable tomato ($F = 9.25$; $N = 7$; $P = 0.0017$).

Likewise, cultivating crops under rainy season had a big challenge and potential risk in producing the marketable tomato fruit, where at average of 59% was defected fruit ($F = 50.69$; $N = 7$; $P = 0.0001$)

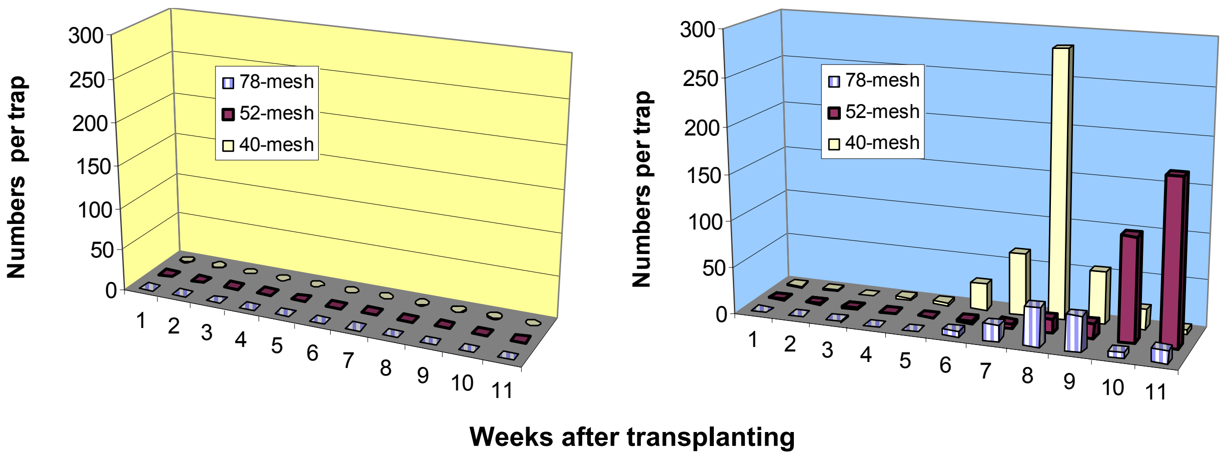
**Table 5.5: Effect of seasons of the year on tomato yield and fruit quality in 52-mesh greenhouse**

| Week | Hot season | | | Rainy season | | | Cool season | | |
|---|---|---|---|---|---|---|---|---|---|
| | Yield | Size | Defect | Yield | Size | Defect | Yield | Size | Defect |
| | *kg week$^{-1}$* | *g fruit$^{-1}$* | *%* | *kg week$^{-1}$* | *g fruit$^{-1}$* | *%* | *kg week$^{-1}$* | *g fruit$^{-1}$* | *%* |
| 9 | 40.1 | 124 | 16 | 23.6 | 79 | 71 | 44.8 | 121 | 7 |
| 10 | 57.1 | 124 | 22 | 40.1 | 77 | 54 | 171.6 | 115 | 12 |
| 11 | 72.7 | 111 | 40 | 29.2 | 60 | 53 | 196.9 | 98 | 10 |
| 12 | 97.4 | 118 | 15 | 32.9 | 48 | 63 | 153.6 | 85 | 13 |
| 13 | 62.0 | 89 | 32 | 19.8 | 37 | 53 | 166.4 | 86 | 18 |
| 14 | 57.3 | 68 | 25 | 14.2 | 36 | 59 | 65.6 | 88 | 19 |
| 15 | 67.6 | 51 | 33 | 10.1 | 32 | 61 | 69.7 | 85 | 34 |
| **Total** | **454** | | | **170** | | | **868** | | |
| **Means** | **65 $^{b}$** | **98 $^{a}$** | **26 $^{b}$** | **24 $^{b}$** | **53 $^{b}$** | **59 $^{a}$** | **124 $^{a}$** | **97 $^{a}$** | **16 $^{c}$** |

[a] Means followed by the same letter within a row at the same parameter are not significantly difference (P=0.05 , GLM-LSD Multiple Range Test)

### 5.1.4 Effect of mesh-sizes of nets on biological plant protection

Fig 5.15 shows the weekly measurements on the average number of the important insect pests namely whiteflies and thrips might attack to the tomato plants along the experimental period. The measurement was done by capturing the flying both whiteflies and thrips which may enter from outside the greenhouse through the net using the yellow and blue sticky traps. It is proven that both 52-mesh and 78-mesh nets installed at the greenhouses were almost insect-proof net and excluded whiteflies while 40-mesh net was not (Fig 5.15 (a)). In addition, all of nets even with the 78-mesh failed to exclude 100% of the thrips entering the greenhouse (Fig. 5.15 (b)). Because based on the recommendation from Bethke (1990), the ultimate size of insect-proof nets against the thrips is 132-mesh, and the use of 78-mesh, in this study, is a compromised size of nets with some assumptions. Firstly, the use 132-mesh insect-proof screen to cover ventilation openings could extremely increase the internal air temperature above 40 °C (in tropical condition). Second, the use of 78-mesh for covering the ventilation opening may protect the adult thrips entering the greenhouse through the net-hole.




(a) Whiteflies (b) Thrips

**Figure 5.15: Weekly variations of insect pest abundances in the greenhouses covered by three different mesh-sizes of nets**

Since thrips is the most important pest attacking tomato plants cultivated in humid tropics because it can also bring along the virus, the use of 40-mesh net seems very difficult to prevent thrips from entering the greenhouse. The use of higher mesh-size such as: 52 or 78-mesh of nets may help to reduce the thrips population. It is proven from Fig 5.15 (b) as well as from Table 5.6 that the number of thrips was reduced from in range of 25 – 270 per trap into the range of 10 – 150 per trap or about 50 - 75% reduction. Fig 5.15 also shows very interesting results that thrips disease started to attack the mature plant when the fruit setting had started to develop (flowering stage). So, it can be inferred that two months after transplanting (flowering stage) was the most crucial time to keep plant away from the insect disease.

Table 5.6 shows that a significant difference of thrips population among the treatment of different mesh-size was found (F = 5.77; N = 11; P = 0.0047). The number of thrips per trap (at the area of 120 $cm^2$) in the 78-mesh greenhouse was relatively less than both 40- and 52-mesh greenhouses. It means that the use of finer mesh would be more secure to exclude the disease than others. However, all greenhouses covered by any mesh-sizes of insect proof nets had possibilities of thrips entering to the greenhouse. The 78-mesh net was not ultimately proofed against thrips. Meanwhile, for whiteflies, it is clear from Table 5.6 that there was a possibility of more whiteflies entering to the greenhouse covered by 40-mesh nets than greenhouses covered by other sizes of either 52- or 78-mesh nets.

**Table 5.6: Mean (± SE) of weekly insect pest population flying in greenhouses covered by three different net-types in the cool season**

| Parameters | Mesh size of net | | |
|---|---|---|---|
| | **40-mesh** | **52-mesh** | **78-mesh** |
| Whiteflies population *( no. per trap)* | 0.34 $^{a}$ ± 0.18 | 0.05 $^{b}$ ± 0.10 | 0.02 $^{b}$ ± 0.08 |
| Thrips population *( no. per trap)* | 42.88 $^{a}$ ± 2.75 | 29.80 $^{b}$ ± 2.30 | 11.57 $^{c}$ ± 1.18 |

[a] Within rows, means followed by the same letter are not significantly different at P=0.05, GLM-LSD Test

In terms of season of the year, Table 5.7 presents the number of population of pests (thrips or whiteflies) per trap (120 $cm^2$ area) that the potential number of thrips in the greenhouse covered with 52-mesh was significantly different from one season to another (F = 6.29; N = 9; P = 0.0064). The tomato plants cultivated during the rainy season had been highly infected by insect pest (thrips) compared to the plants cultivated either under the hot season or cool season of the year. A similar trend was found for the population of whiteflies that there was a significant effect of different seasons on the number of whiteflies (F = 10.30, N = 9, P = 0.0006) flying in the greenhouse covered by 52-mesh nets at the ventilation openings.

**Table 5.7: Mean (± SE) of weekly insect disease population flying in the 52-mesh greenhouse at different seasons of the year**

| Parameters | Season of the year Rainy | Cool | Hot |
|---|---|---|---|
| Whiteflies population *( no. per trap)* | 0.25 [b] ± 0.22 | 0.03 [b] ± 0.09 | 1.41 [a] ± 0.31 |
| Thrips population *( no. per trap)* | 604.53 [a] ± 8.07 | 29.80 [b] ± 2.30 | 36.84 [b] ± 3.62 |

[a] Within rows, means followed by the same letter are not significantly different at P=0.05, GLM-LSD Test

### 5.1.5 Water requirement (evapotranspiration) in greenhouse

Figure 5.16 illustrates the daily crop evapotranspiration or crop water requirement measured in the greenhouse along the cultivation period either for different mesh-size of net (Fig. 5.16 (a)) or different seasons of the year (Fig. 5.16 (b)). The daily evapotranspiration fluctuated according to the plant stages and microclimate (mostly by daily sum of light integral of solar radiation) in a particular time of observation; whereas it was relatively low in the beginning stage at about 0.5 – 1.0 ℓ plant$^{-1}$ day$^{-1}$, and then it gradually increased up to 3 ℓ plant$^{-1}$ day$^{-1}$ in the vegetative stage. The water requirement was then almost constant at 1.5 – 2.0 ℓ plant$^{-1}$ day$^{-1}$ during generative stage although it started to decrease afterward. This pattern was similar for all greenhouses with different mesh size.

Likewise, the daily water requirement occurring at different seasons had also similar trend whereas it started very low (about 0.5 ℓ plant$^{-1}$ day$^{-1}$) then gradually increased up to 4 ℓ plant$^{-1}$ day$^{-1}$ in hot season. This was caused by the higher evaporation due to higher internal air temperature and low humidity around the greenhouse. Cultivating tomato plant in the cool season, however required less irrigation water compared to that in rainy and hot season, but it was not a case, because different variety of tomato (FMTT260) was used in the cool season while during the other seasons, King Kong II was cultivated.

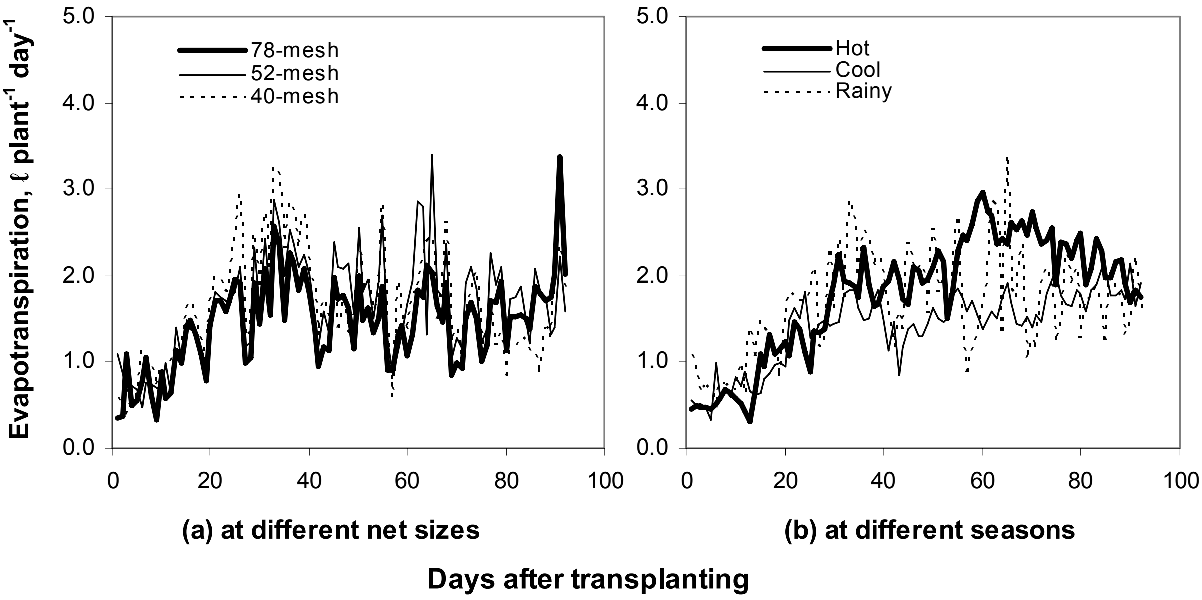



**Figure 5.16: Effect of mesh-sizes of nets and seasons of the year on daily variations of evapotranspiration in greenhouse**

Statistically, there was a significant effect of different net-size put on the vent opening on evapotranspiration at confidence level of 5% ($F = 6.25$; $N = 92$; $P = 0.0022$). The averages of daily evapotranspiration occurring inside the greenhouses with smaller mesh-size (40 and 52-mesh) were higher than the 78-mesh greenhouse for both rainy and cool seasons (Table 5.8). The lower air exchange rate in the 78-mesh greenhouse might cause the accumulation of water vapour inside the greenhouse resulting in lower evaporation process.

From the 52-mesh greenhouse, daily evapotranspiration at three different seasons was also measured along the cultivation period of time and the means were statistically analyzed using ANOVA one-way. The daily evapotranspiration was significantly affected by the season at 5% of confident level ($F = 8.77$; $N = 92$; $P < 0.0002$) whereas the average evapotranspiration in the hot season was recorded to be the highest at 1.77 ℓ plant$^{-1}$ day$^{-1}$ followed by the rainy season and cool season at 1.65 and 1.41 ℓ plant$^{-1}$ day$^{-1}$, respectively.

**Table 5.8: Effect of mesh size and seasons of the year on mean (± SE) of evapotranspiration in greenhouse**

| Season | Parameters | Mesh size of net | | |
|---|---|---|---|---|
| | | 40-mesh | 52-mesh | 78-mesh |
| **Rainy** | Evapotranspiration (ℓ $plant^{-1}$ $day^{-1}$) | 1.618 $^{abA}$ ± 0.084 | 1.649 $^{aB}$ ± 0.081 | 1.457 $^{bA}$ ± 0.076 |
| **Cool** | Evapotranspiration (ℓ $plant^{-1}$ $day^{-1}$) | 1.359 $^{aB}$ ± 0.067 | 1.415 $^{aC}$ ± 0.069 | 1.206 $^{bB}$ ± 0.066 |
| **Hot** | Evapotranspiration (ℓ $plant^{-1}$ $day^{-1}$) | NA | 1.773 $^{A}$ ± 0.045 | NA |

Means followed by the same lower letters within rows and upper case letters within the columns are not significantly different (P = 0.05, LSD multiple range test [SAS, 2003]).
NA = data not available

## 5.2 Simulation and modelling to predict air exchange rate and internal microclimate

### 5.2.1 Air exchange rates along the experimental period of time

In order to evaluate the performance of the greenhouse ventilation system, the rate of air exchange in the greenhouse is the most important parameter. This describes the ability of greenhouse to renew hot air in the greenhouse with cooler air and relatively low humidity from outside the greenhouse so that internal microclimate remains favourable for plant growth. This value can be different according to design of the greenhouse, type of cladding material, ventilation system and altitude where the greenhouse is located. The measurement of air exchange rates was conducted under greenhouses covered with insect-net at different mesh-sizes. Figure 5.17 shows average hourly rates of air exchange on daily basis from the initial stage (young tomato plants) up to harvesting. These values were averaged over 9 hours during day time (starting from 8.00 to 17.00 h) from two different methods i.e.: water vapour balance (a) and energy balance methods (b) in the greenhouse covered by three different mesh-sizes of nets.

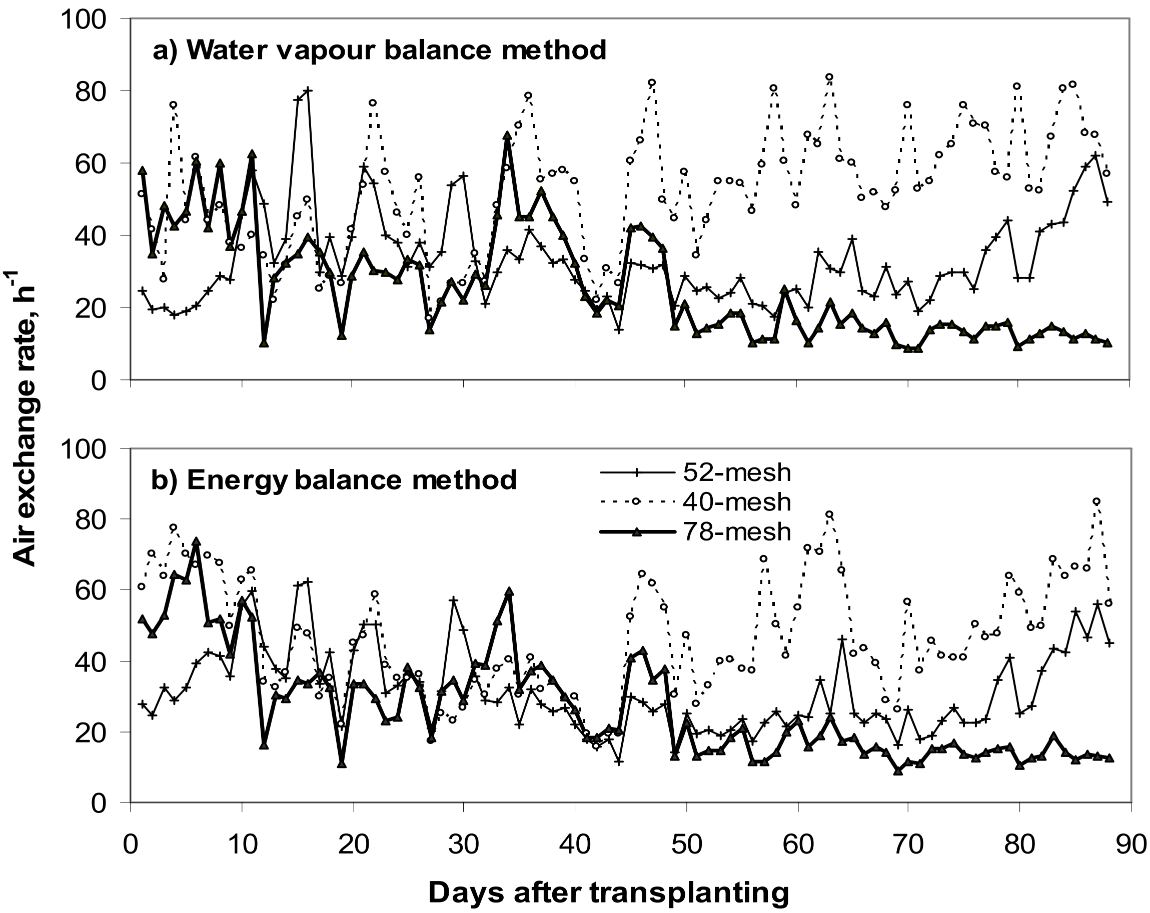



**Figure 5.17: Daily variations of air exchange rate measured using two methods in greenhouses covered by three different net mesh-sizes**

From Fig. 5.17, it can be seen that air exchange rates estimated from two different methods had a similar trend during the experimental period and their values were close. The air exchange rates for each greenhouse were ranging from 10 to 80 times per h. Generally, both values were in close agreement for different mesh-size, hence the energy balance method could be accepted as an appropriate method to estimate the air exchange rate. Air exchange rates also differed for different plant-growth stages and fluctuated day by day according to the microclimatic conditions during the respective day. When the plants were young, the air exchange rates fluctuated more. At maturity, the different values of air exchange rates were clear among the treatments. The fluctuation of weather condition during experiment conducted in the rainy season was believed to be the reason for the daily air exchange rate fluctuations. However, it was not the case that the hourly air exchange rate predicted on daily basis was strongly influenced by the season because a relatively small fluctuation occurred in the cool season as shown in Fig. 5.10.

Figure 5.18 shows the relationship between two methods that predicted air exchange rates calculated from energy balance method was in good agreement with the measured ones calculated from water balance method. For greenhouse covered with net of 78-mesh, the relationships was better ($R^2$ = 0.85, P < 0.0001) than that at 52-mesh and 40-mesh greenhouses which gave the coefficient of correlation of 0.71 and 0.33 (P < 0.0001), respectively. This means that the energy balance method could well predict the air exchange 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 net over its openings.

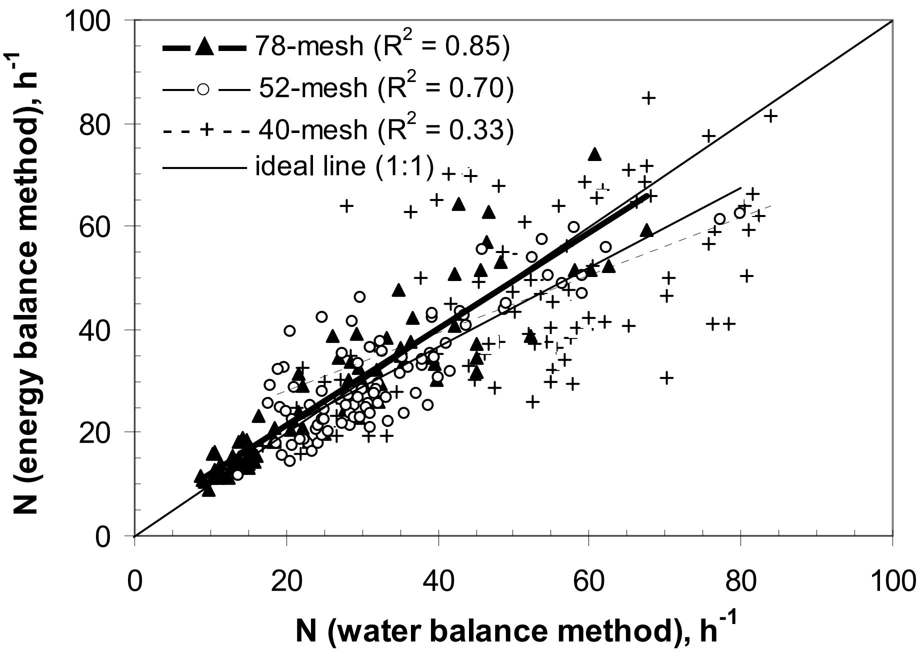



**Figure 5.18: Correlation between two methods in estimating air exchange rate (N) in greenhouses covered by different net-sizes of nets in rainy season ($R^2$ = coefficient of determination)**

### 5.2.2 Development of a model for predicting air exchange rate

A model modified from the combination of chimney effect and wind speed and geometric greenhouse properties from Kittas et al. (1997) was used to predict air exchange rate in the adapted greenhouse covered by different mesh-sizes of insect-proof net. To validate the results obtained from the model, comparisons between predicted and measured air exchange rates for different net-sizes of greenhouses are plotted in Fig 5.19. The results show that the relationship between measured and predicted values occurring in cool season was in fair agreement especially in the 40-mesh greenhouse, while the other greenhouses poor correlations were obtained from the experiment. The relatively poor correlation between measured and predicted values above was mainly caused by the dominant effect of external wind speed parameter involved to the model. Meanwhile the air temperature difference was expected to be a significant contribution to the model when wind speed was quite low at below 1.5 m $s^{-1}$.

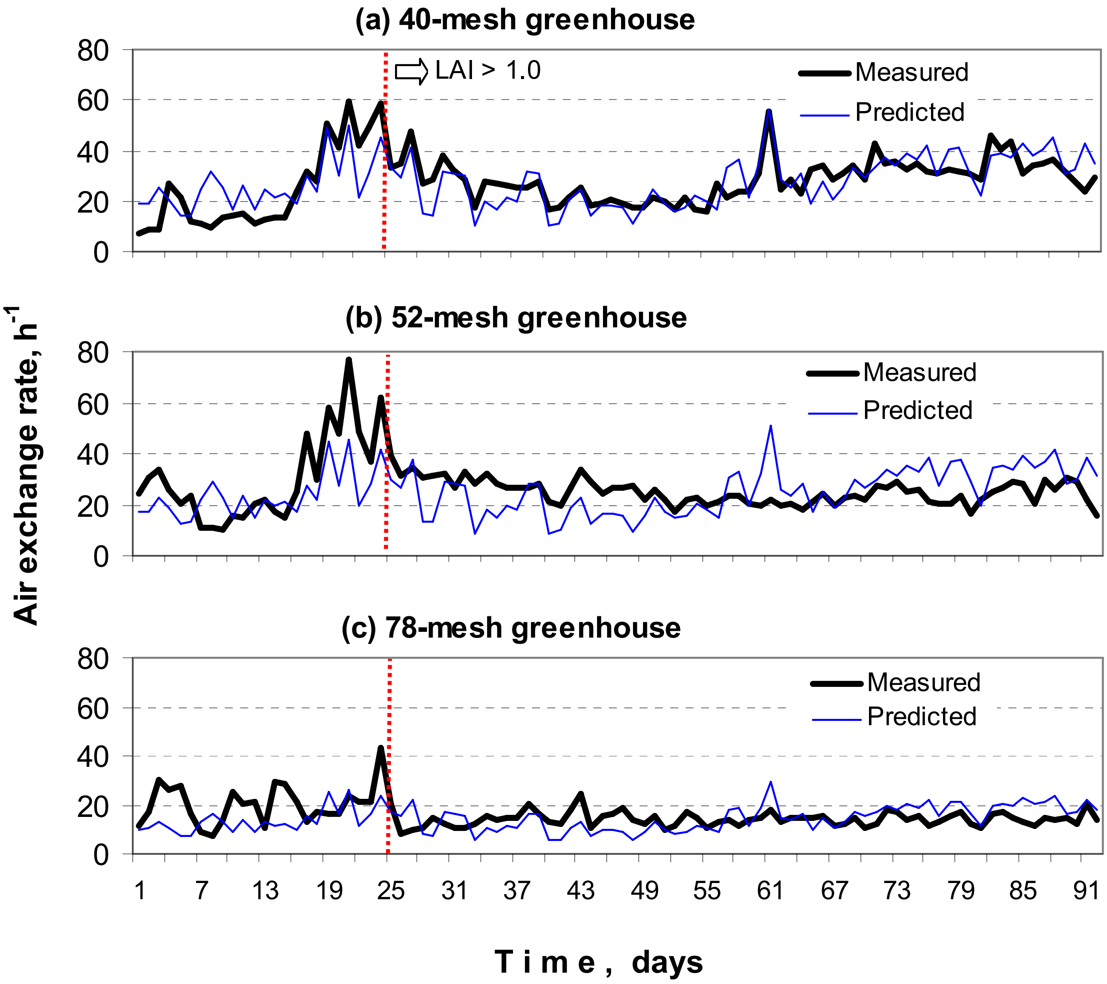



**Figure 5.19: Comparisons between measured and predicted air exchange rates in the 78-mesh, 52-mesh and 40-mesh greenhouses (cool season)**

In addition, the model would give less accurate result when the measurements were conducted under conditions at which no mature plants were existed. When the crops were small or young (at LAI less than 1.0), the water vapour in the greenhouse was also very less. This might affect to the measurement of air exchange rate as the result a comparison between two was relatively poor. In contrast, the model gave a better correlation to the measured air exchange rates when the measurements were done under greenhouse with full of mature plants (LAI more than 1.0) whereas the crops transpiration processes were very high. Since the predicted air exchange rates were very sensitive to the change of climatic parameters, it is suggested that the estimation of air exchange rate should be predicted based on microclimatic data taken from a stable weather condition in order to avoid the measurement errors. In this regard, the estimation of predicted air exchange rate conducted under different seasons i.e. rainy, cool and hot season of the year was performed whereas the best results to predict air exchange rate in the greenhouse were obtained under either in cool or rainy season due to relatively stable condition of microclimate.

In order to further evaluate the model, comparisons between predicted and measured air exchange rate in 40-mesh, 52-mesh and 78-mesh greenhouses were simultaneously carried out and it is presented in Fig. 5.20. For greenhouse covered with net of 40-mesh, the relationships was better ($R^2$ = 0.55, N = 67, P < 0.0001) than that at 52-mesh and 78-mesh greenhouses which gave the coefficient of correlation of 0.39 and 0.26 (N = 67, P < 0.0001), respectively. Predicted air exchange rate occurring in the bigger-hole greenhouse (40-mesh net) gave a better correlation to the measured value than that in greenhouses covered by finer-hole net (52- and 78-mesh). With a relatively constant value of wind speed along the experimental period at 0.8 to 3 m $s^{-1}$, the predicted air exchange rate was just varied according to wind speed. This means that wind speed much more influenced to the air exchange rate rather than temperature difference (buoyancy) effect. This is in line with the study conducted by Kittas et al. (1997) that temperature difference was significant if [$v_w/\Delta T^{0.5}$] <1. For calculation, supposing wind speed averaged at 2.0 m $s^{-1}$ and temperature difference at 1.5 °C, then the value was about 1.63. It can be inferred that the influence of wind speed to the model for predicting air exchange rate was much more dominant than air temperature difference. Fig. 5.21(a) is another evidence that wind speed played an important role in predicting air exchange rate as coefficient of determination was almost 1 ($R^2$ = 0.99). Meanwhile temperature difference was minor to the model. Since the correlation between wind speed and measured air exchange rate was less ($R^2$ = 0.55) during experiment, it was assumed that there were other parameters involved in estimating air exchange rate in adapted greenhouse such as: wind direction and temperature difference.

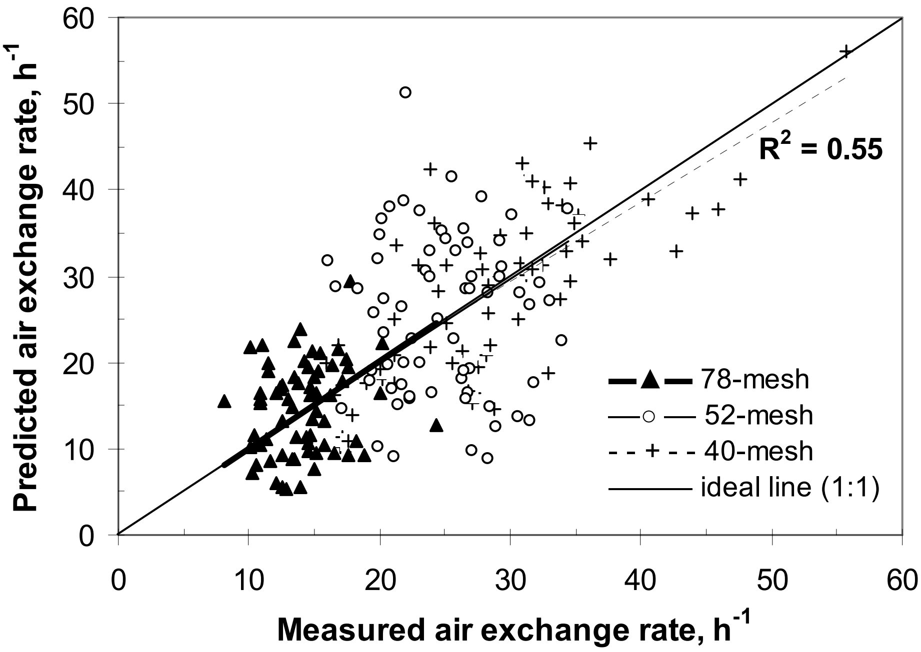



**Figure 5.20: Correlations between predicted and measured air exchange rates in 78-mesh, 52-mesh and 40-mesh greenhouses (cool season); $R^2$ is coefficient of determination**

On the contrary, during the rainy season the prediction of air exchange rate using the model was quite poor compared to that in cool season except in 40-mesh greenhouse as it is shown in Fig 5.21(b). The reason was that the wind speed occurring along the experiment was relatively high at 2 to 7 m $s^{-1}$ (see section **5.2.4**) as main contribution to model in predicting air exchange rate rather than temperature difference in which this parameter was one of important parameters very much influenced to measure air exchange rate using water vapour tracer gas. Moreover, the structure of adapted greenhouse which has ventilation openings at all side walls as entry point for air exchange caused another parameter such as wind direction becoming a key factor influencing to the model to predict air exchange rate. Therefore predicting air exchange rate using the model in both rainy and hot seasons was quite far from the expectation.

A better correlation between wind speed and measured air exchange rate was obtained from the 40-mesh greenhouse conducted in rainy season as presented in Fig. 5.21(b). From the experiment, the coefficient determination ($R^2$) was achieved at 0.45 (N = 67, P < 0.0001) where the measurement was taken from mature plant condition (LAI > 1). This indicates that the correlation between two can be categorized as a fair agreement. As wind speed was measured almost double compared to that in cool season, their correlation from the model was pretty closed to the ideal of $R^2$ = 0.99. It is indicated that wind speed was strongly influenced to the air exchange rate while other parameters were minor. In this respect, the accuracy of wind speed measurement was become very important.

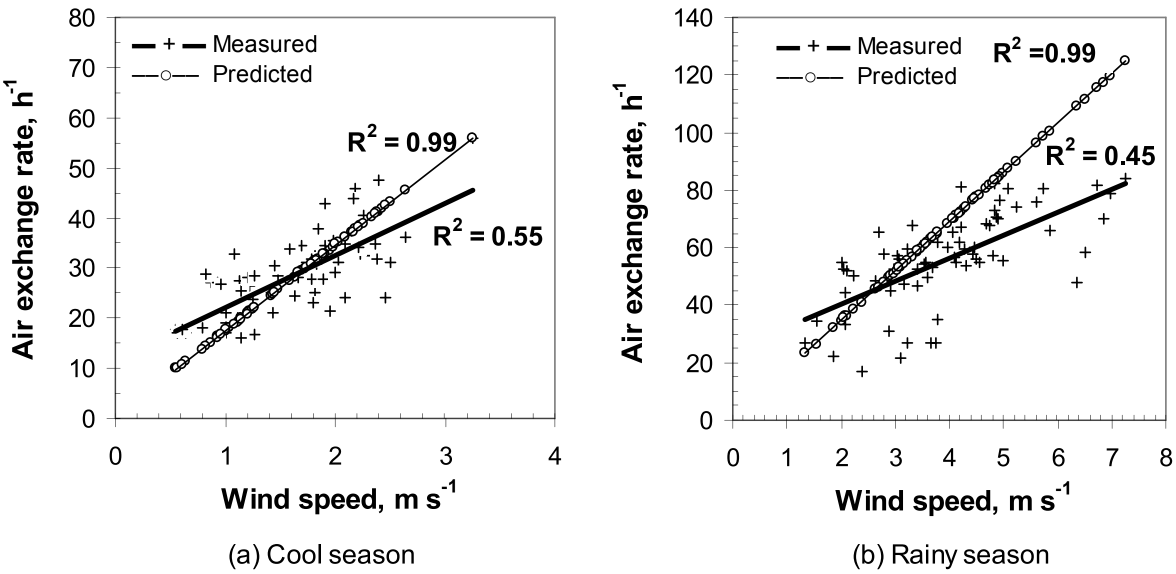



**Figure 5.21: Correlations between wind speed and air exchange rates in the 40-mesh greenhouse in both cool and rainy seasons; $R^2$ is coefficient of determination**

### 5.2.3 Development of greenhouse models to predict internal microclimate

A simplified greenhouse model based on an energy balance method was used to predict internal air temperature, while a water vapour balance model was used to predict humidity inside the greenhouse. The values of microclimate predicted from these models are compared to the values (internal temperature and humidity) measured from the experiment. Fig. 5.22 shows a comparison between predicted and measured internal air temperature conducted under rainy season.

In general, the correlation between predicted and measured air temperature inside the greenhouse was well fitted with a good agreement at $R^2$ =0.88, $R^2$ = 84 and $R^2$ = 87 (N = 92, P < 0.0001, SAS, 2003) for 40-mesh, 52-mesh and 78-mesh greenhouses, respectively. This indicates that the model derived from the sensible energy balance greenhouse is able to predict internal air temperature quite accurately. With a limited parameter available such as ambient temperature, air exchange rate and inside solar radiation, the prediction of internal temperature using the model is very useful as a rapid method for assessing the internal microclimate.

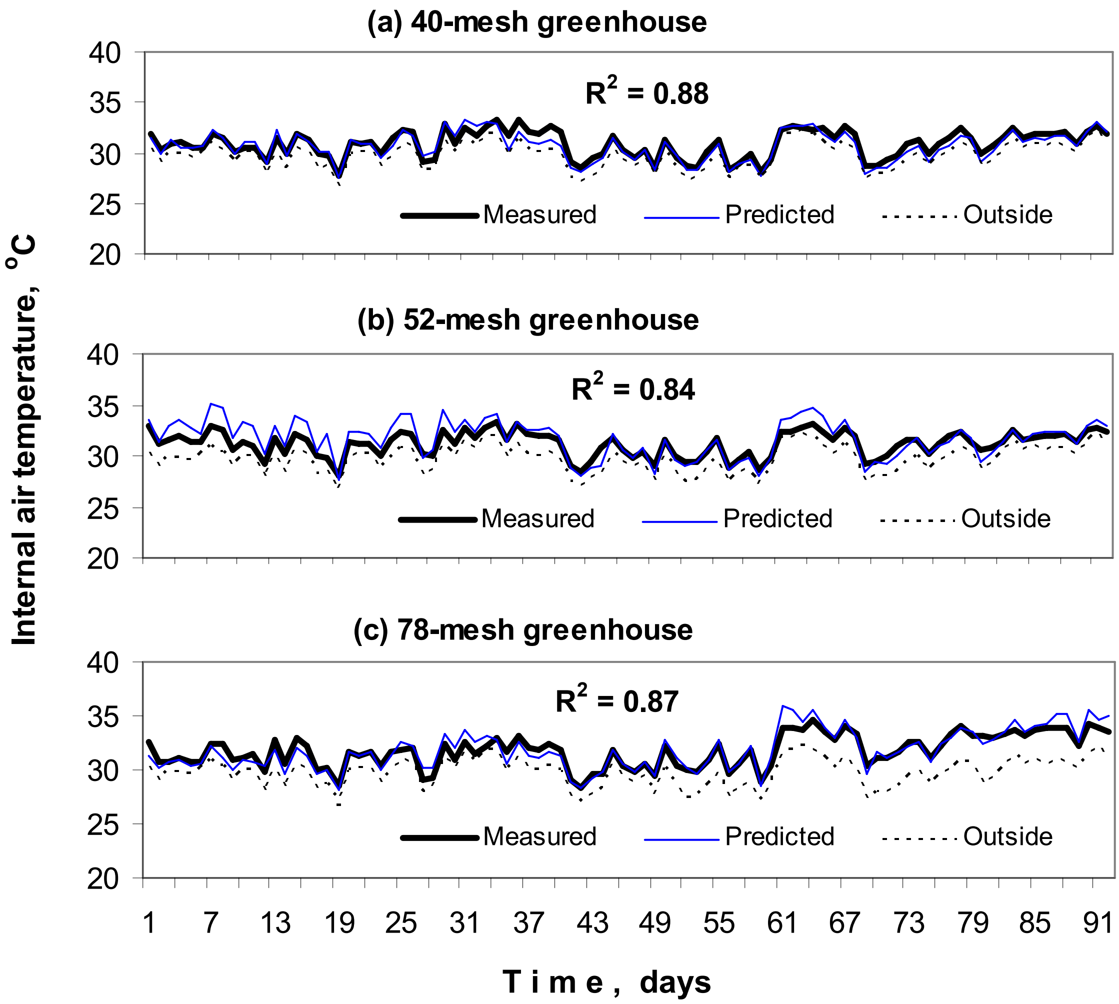



**Figure 5.22: Comparisons between predicted and measured internal air temperature in the 78-mesh, 52-mesh and 40-mesh greenhouses (rainy season); $R^2$ is coefficient of determination**

In terms of season of the year, a similar trend to the greenhouse at different mesh-sizes of nets was obtained that a good correlation was commonly achieved between predicted and measured internal temperature at any seasons of the year as shown in Fig. 5.23. Moreover, a very good correlation ($R^2$ = 0.93, N = 92, P < 0.0001) between two was achieved when the experiment was conducted along the hot season where high temperature played an important role in contributing to the model as sensible heat. In contrast, the correlation between two in the rainy season ($R^2$ = 0.84, N = 92, P < 0.0001) was the lowest among the seasons due to the presence of rain in which the rain water might affect to the humidity in the greenhouse as well as water vapour content around the greenhouse, as the result the ratio of sensible heat to latent heat (Bowen ratio) could not be maintained to be 0.7 as it was assumed in the model.

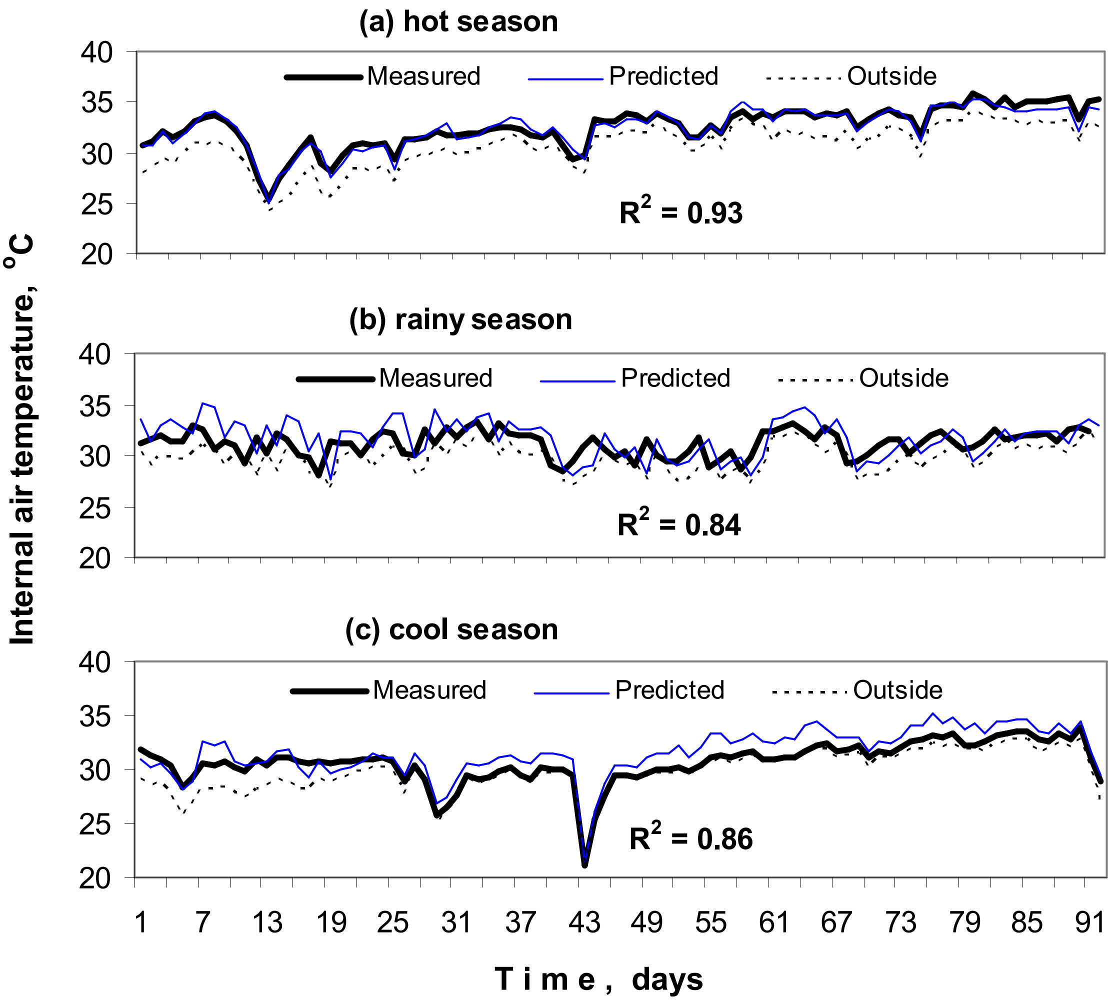



**Figure 5.23: Comparisons between predicted and measured internal air temperature in the 52-mesh greenhouse at three different seasons of the year; $R^2$ is coefficient of determination**

In cool season, overestimation of predicted internal temperature was found as depicted from Fig. 5.23(c), however their relationships was still very good at $R^2$ = 0.87 (N = 92, P < 0.0001). The possible reason was a small of temperature difference as it was seen at the day of 50 (when the crops were mature). If the temperature difference was large enough, the correlation between two was well fitted such as at the beginning of the experiment. Another reason was miss-assumption of Bowen ratio for the model when the crops highly produced water vapour in the greenhouse through the evapotranspiration processes.

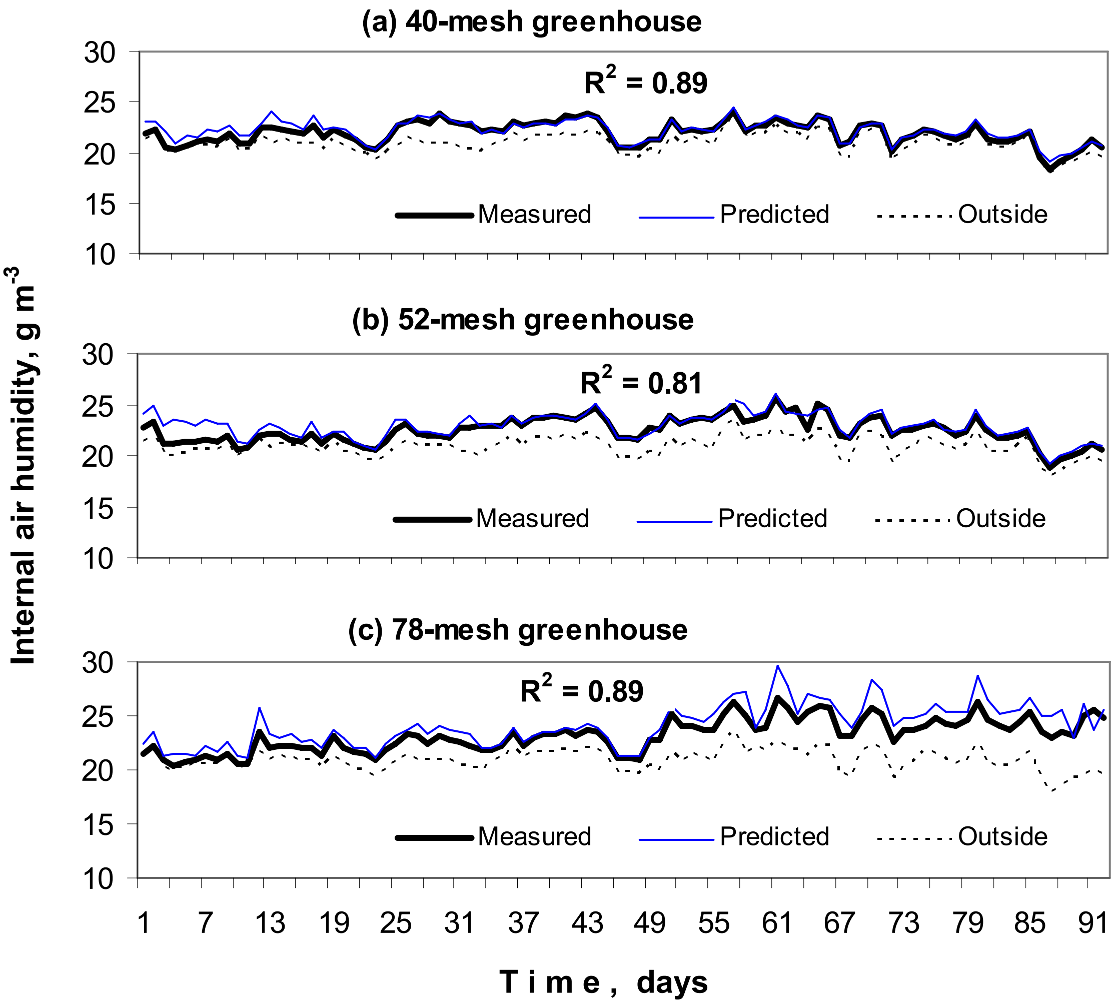



**Figure 5.24: Comparisons between predicted and measured internal air humidity in the 78-mesh, 52-mesh and 40-mesh greenhouses (rainy season); $R^2$ is coefficient of determination**

From greenhouse water vapour balance model, the prediction of air humidity calculated from a very few climatic parameters such outside humidity, air exchange rate and net solar radiation required, was well fitted to the measured ones. Fig 5.24 presents a comparison between predicted and measured internal air humidity conducted under rainy season that a good correlation was obtained at $R^2$ between 0.8 to 0.9 (N = 92, P < 0.0001, SAS, 2003) for any greenhouses covered by different mesh-size of nets. The predicted values of internal humidity at 40-mesh greenhouse compared to measured ones seems to be the best fitted especially when the validation was conducted after 25 days after transplanting or at LAI > 1.0. At the LAI < 1, their relationships were poor. When their relationships were poor, the values from the model were mostly overestimated.

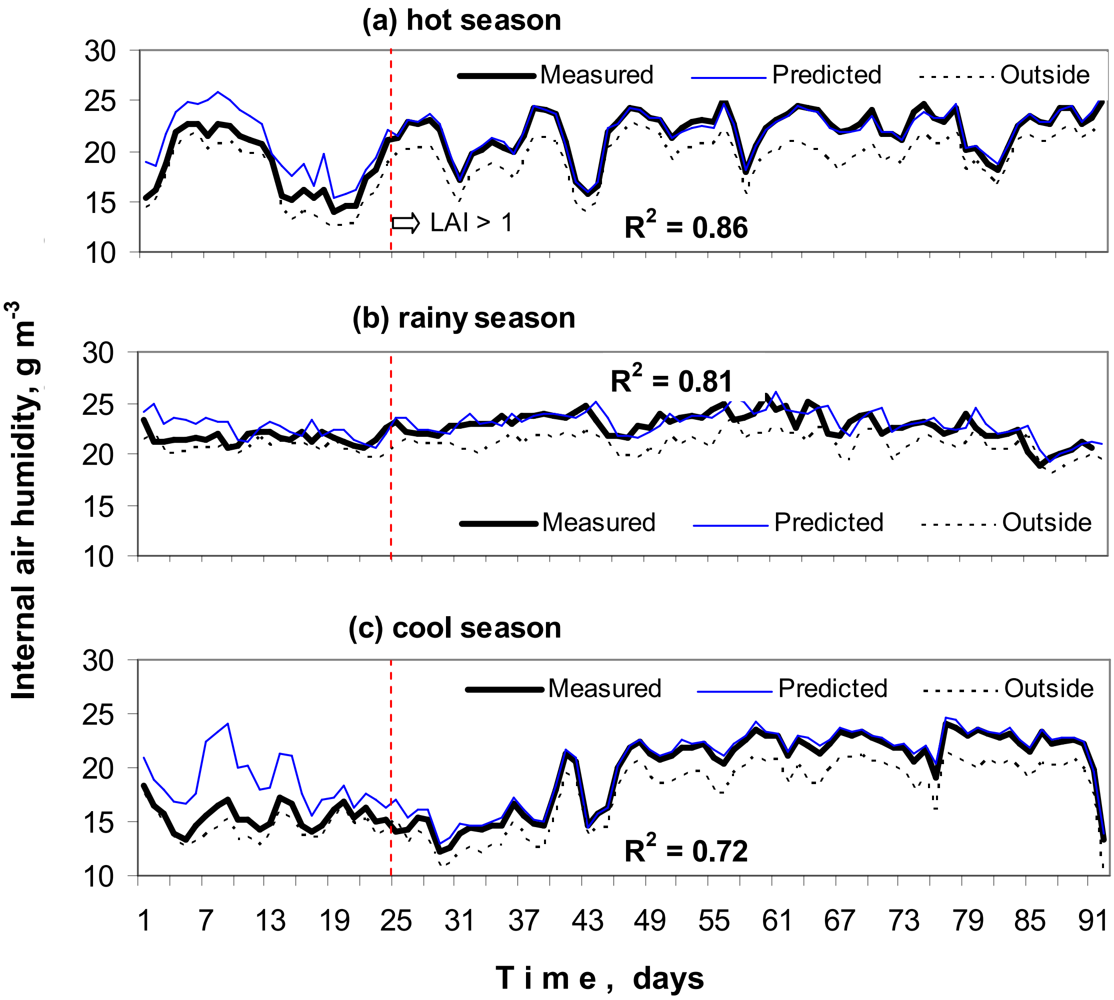



**Figure 5.25: Comparisons between predicted and measured internal air humidity in the 52-mesh greenhouse at three different seasons of the year; $R^2$ is coefficient of determination**

In terms of seasons of the year, Fig. 5.25 presents a comparison between predicted and measured internal humidity that a good agreement was obtained at any seasons at $R^2$ = 0.86, $R^2$ = 0.81 and $R^2$ = 0.72 (N=92, P<0.0001) conducted under hot, rainy, and cool seasons, respectively. Generally, the trend of correlation between two for predicting humidity was just opposite to the air temperature whereas the best correlation was achieved at the greenhouse with full-matured crops but for predicting air temperature the best correlation was achieved at the greenhouse with no crops inside or very young plants. In other word, the best condition for predicting humidity is when the latent heat was dominant while for temperature, the involved latent heat to the model should be less dominant than the sensible heat.

In order to clarify the assumption of the Bowen ratio and to verify some minor parameters involved to the models, the calculation of heat losses for each component along the experiment was analyzed and it is presented in Fig. 5.26. This is also expected that the possible reason of either over estimation or under estimation from measured values presented from Fig 5.22 to 5.25 can be explained through this figure. From heat loss and gain balance, the percentage of heat fluxes component contributed to the total heat losses were mainly caused by ventilation processes of both sensible and latent heat losses (contributed more than 80%), compared to the total heat gain from solar radiation. Heat losses due to soil substrate was varied from 2 – 12 % of total solar gain depending upon plant stage (or LAI) whereas the maximum losses to the substrate was occurred at the beginning stage (crops were small) and harvesting time (layering plant was done). Similarly, the heat loss due to photosynthesis processes was also varied from 0.5 to 4.3% of total solar gain. The measurement of heat loss due to photosynthesis was estimated using dry matter measurement with destructive (sample) methods.

It is clear from Fig 5.26 that the Bowen ratio ($\alpha$), as the ratio of sensible to latent heat losses, used in the model was not fix along the season, but weekly fluctuated according to the plant stages and weather condition. At the beginning week, the $\alpha$ was 1.83 (> 1.0) then it was gradually reduced as the increase of plant growth till the value was settled down at about 0.30 in the end. For simplicity, the value of 0.7 was taken into account as the average of those values during the experiment. This might cause either overestimation or underestimation from the model if the results were compared to the measured ones from the experiment. In this regards, the use of Bowen ratio strictly according to the value shown in Fig 5.26 to the model can enhance the accuracy of the model.

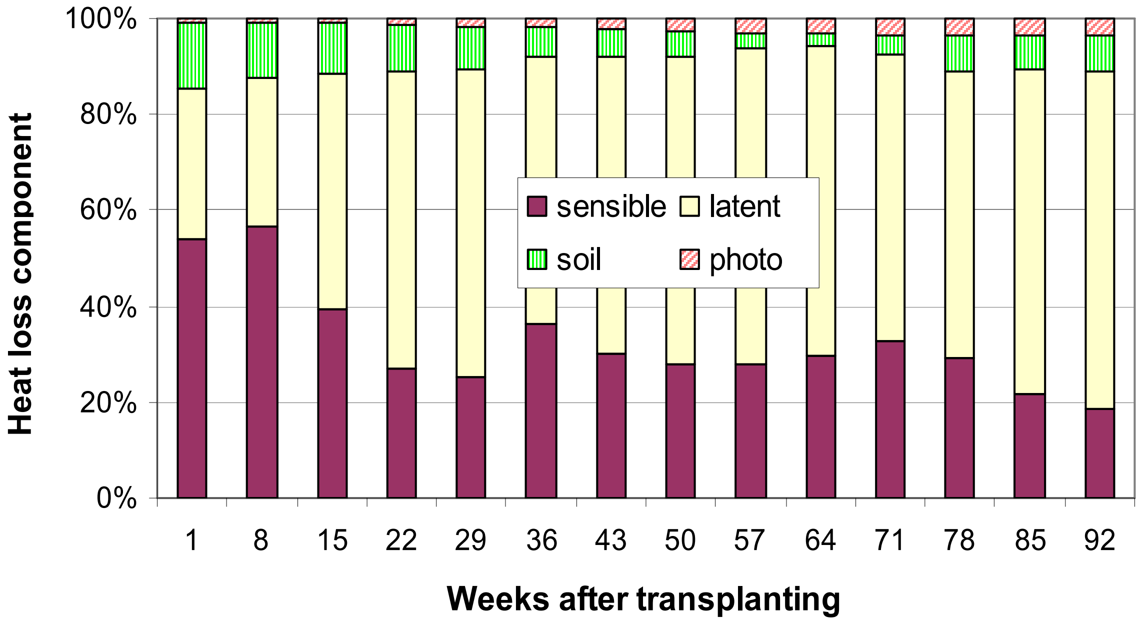



**Figure 5.26: Weekly variations of the Bowen ratio (sensible to latent heat) during experiment and heat-loss components contributed to total heat loss in the 78-mesh greenhouse in rainy season**

### 5.2.4 Influence of external wind speed and buoyancy effect on air exchange rate

In a naturally ventilated greenhouse, especially for the multi-span greenhouse where ventilation opening is mostly located at the roof or side wall, either wind speed or air temperature difference become the main parameter affecting to the ventilation rate. Baptista et al. (1999) found that ventilation rates are a function of the wind speed. Other studies conducted by Shilo et al. (2004) and Muňoz et al. (1999) showed that the ventilation rate significantly depends upon ambient wind speed. It should be noted that all studies mentioned above were conducted under ventilation opening covered with insect-proof net of 40- or 50-mesh and vent ratio less than 0.4. Effects of external wind speed and air temperature difference on air exchange rates in rainy season is shown in Fig 5.27. Correlations between wind speed and air exchange rate in greenhouses covered by three different mesh-sizes of nets is presented in Fig. 5.27(a). Since the adapted greenhouse was designed to maintain internal microclimate to be very close to ambient environment, ventilation area (mostly at the sidewalls) was opened as large as possible or at vent ratio of 1.05. In this case the structure was extremely different to the ones mentioned above. Generally, their relationship ($R^2$) was less than 0.5. The fair relationship was only obtained in 40-mesh greenhouse compared to that in both 52-mesh and 78-mesh greenhouses. However, in cool season their correlation was better at $R^2$ = 0.55 (Fig. 5.21(a)) since the wind speed was about a half lower than that in rainy season. The reason why the external wind speed showed less effect on air exchange rate in recent study is that the greenhouses have large opening along side wall, so that not only the roof vents alternatively act as air entrances but the side wall opening can also act as both air entrances and exits. Therefore, the movement of the air surrounding the greenhouse was difficult to explain. The roof opening, which was assumed to be an entry point of ambient air flowing in to the greenhouse, did not play a vital role as it should be. In fact, the measurement of external wind speed was located at the same height as the position of roof opening thus a possible error may occur. Another possible reason was the accuracy of wind speed sensor being used along the experiment as it did not sometimes obtain the proper reading due to the error occasionally occurred in the logger card of data logging system caused by the extreme heat at the noon time.

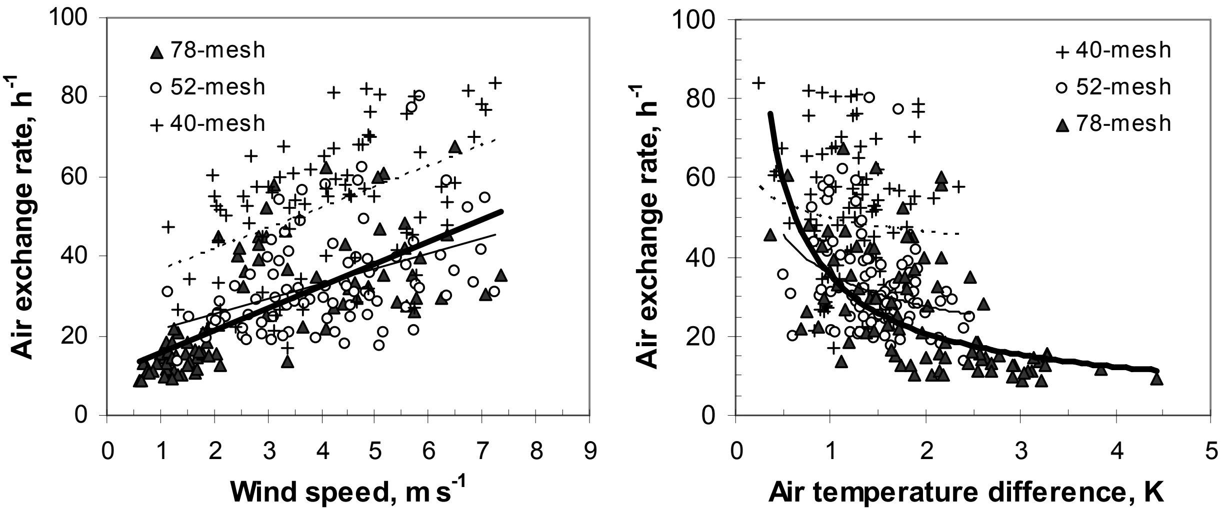



**Figure 5.27: Effect of external wind speed and temperature difference on air exchange rate in greenhouses covered by three different net-sizes of nets in rainy season**

The temperature difference also showed less effect on air exchange rates (Fig. 5.27(b)). The correlation between temperature difference and air exchange rate was very low for all greenhouses except for the 78-mesh ($R^2$ = 0.48, N = 92, P<0.0001). This exception is obtained because the most wind velocity was recorded at the range of 0.5 to 2 m $s^{-1}$ resulted in achieving a better correlation between temperature difference and an air exchange rate. In general, since the daily average external wind speed was more than 2 m $s^{-1}$ or at range between 2 to 7 m $s^{-1}$ (as shown in Fig 5.27(a)), it is clear that buoyancy effect due to temperature difference was not working. Referring to Kittas et al. (1997), temperature-driven ventilation is only significant if [$v_w/\Delta T^{0.5}$] < 1. Assuming that the average wind speed and temperature difference were 4.5 m $s^{-1}$ and 2 K, respectively, the fraction of [$v_w/\Delta T^{0.5}$] would be about 3.2 (> 1). Therefore, the temperature difference between in and outside the greenhouse was less effective to the air exchange rate.

## 5.3 Study on ventilation configuration of adapted greenhouse

This chapter describes some results of the experiment on closing a particular ventilation opening of the adapted greenhouse with UV-absorbing plastic film at five (5) different levels i.e. 100, 80, 60, 40 and 20% of the original total vent area. The evaluation of the treatments was only focused on microclimate, air exchange rate and crops evapotranspiration. The experiment was carried out in two conditions i.e. fully grown tomato and empty greenhouse (with three different elevations vertically). The experiment had also been limited to carry out in the greenhouse covered by insect-proof net of 52-mesh.

### 5.3.1 Effect of vent opening arrangements on greenhouse microclimate

The application of insect-proof net with an appropriate mesh-size on the ventilation opening in tropical greenhouse is very important mainly to control insect pests. Ideally, ventilation opening should be kept as large as possible even all sidewalls would be covered by the net except on the roof (to protect the rain) in order to provide a better microclimate and air exchange rate in naturally ventilated greenhouse. However, keeping ventilation opening with very large area on the vent opening has some limitations. From economical point of view, the cost of insect-proof screen is relatively higher than the normal plastic film which is widely used in the greenhouse. The net is not easily available on the market as cladding material for greenhouses, especially in the country where humid tropic greenhouse is commonly located. In terms of maintenance, a regular cleaning to remove dust that might block the net-hole is needed but for plastic-film, almost no maintenance activity is required. The most important factor in applying the net on the very large vent opening is that the possible intrusion of smaller insect (unexpected insect size compared to the net-opening size) may enter through the selected net, thus in this case, the use of UV-stabilized plastic film is much safer to protect plants from insect disease.

Based on the reason mentioned above, an experiment on the arrangement of ventilation openings (by closing some portion of the net with UV-stabilized plastic film) and their effects on the microclimate, air exchange rate and evapo-transpiration was carried out. The following figures presented below are some results of the experiment which was conducted during two extreme conditions representing the crop stage along cultivation period of time i.e.: during fully-grown tomato (maturity stage) and empty greenhouse (beginning or vegetative stage).

It is clearly shown from Fig 5.28 that the arrangement of ventilation opening by closing the opening from 20% to 100% of the total ventilation opening area in the fully grown tomato greenhouse caused a significant effect on increasing air temperature difference between inside and outside the greenhouse (temperature rise). From Fig. 5.28(a), it shows that at the ratio of vent opening to floor surface area ($V_r$) of 1.05 the temperature rise was 0.5 K (on average), then it was gradually increased up to 1.5 K when the ventilation ratio was arranged at 0.2. In this level ($V_r$ = 0.2), the temperature rise was the highest among other treatments.

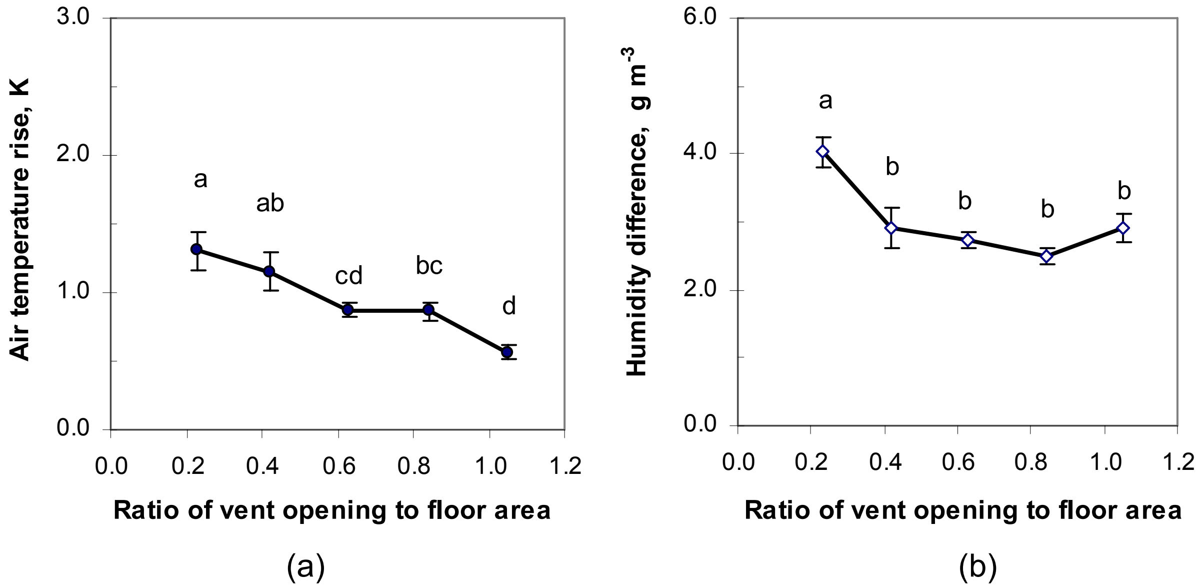



**Figure 5.28: Effect of vent ratio on means ± SE of air temperature rise and humidity difference between inside and outside cropped greenhouse. Means followed by the same letter are not significantly different at P = 0.05, GLM-LSD Test**

The absolute humidity difference measured (means ± SE) between inside and outside the greenhouse had a similar trend whereby the vent ratio of 0.2 had also the highest absolute humidity difference at 4 g $m^{-3}$ (Fig. 5.28 (b)). It means that the lesser ventilation opening area of a greenhouse was arranged, the higher humidity (more humid condition) was obtained. Statistically, there was a significant effect of vent opening arrangement on increasing relative humidity inside the greenhouse at 5% of confident level.

Based on Fig. 5.28, it is obvious that the arrangement of ventilation system which has ratio of ventilation opening to floor surface area of 0.6 was to be a critical point at which internal air temperature rise and at 0.4, the absolute humidity difference had started to increase significantly compared to the other arrangement of ventilation opening at the greenhouse. Similarly, clear evidence was found when the measurement was done in the empty greenhouse as shown in Fig. 5.29. The arrangement to have a ventilation ratio of 0.6 seems critical point as internal air temperature rise was increased remarkably. The temperature was increased by about 2.5 K to 4.5 K (on average) while absolute humidity difference was just increased by 1.0 to 1.2 g m$^{-3}$ due to the absence of crops.

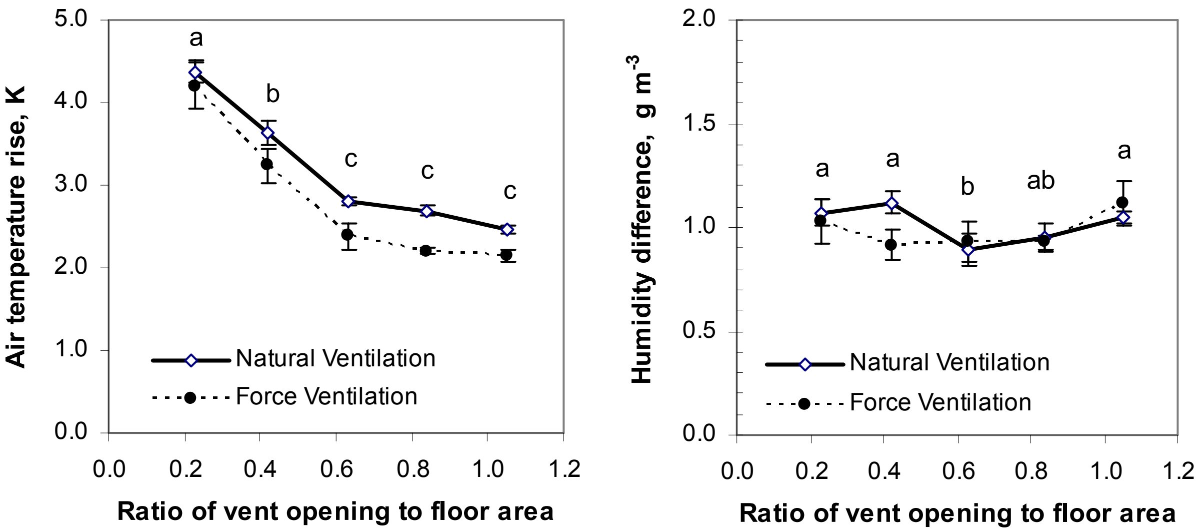



**Figure 5.29: Effect of vent ratio on means ± SE of air temperature rise and humidity differences between inside and outside empty greenhouse. Means followed by the same letter are not significantly different at P = 0.05, GLM-LSD Test**

During the measurement in the naturally ventilated greenhouse under empty condition, switching on the exhaust fan during daytime (treated as force ventilation) was also conducted along the following three days in each treatment. This was to explore the effect of fans at different ventilation ratios on microclimate. With the assumption that the climatic condition during experiment was uniform, the comparison between the two is presented in Fig. 5.29. It is clear that the operation of exhaust fans during daytime at different vent opening arrangement significantly reduced the temperature rise and absolute humidity difference between in and outside the greenhouse even though the reductions were quite small (0.4 K and 1 g $m^{-3}$, respectively). On average, the reduction of 2% was obtained if both exhaust fans were operated during daytime in the naturally ventilated greenhouse.

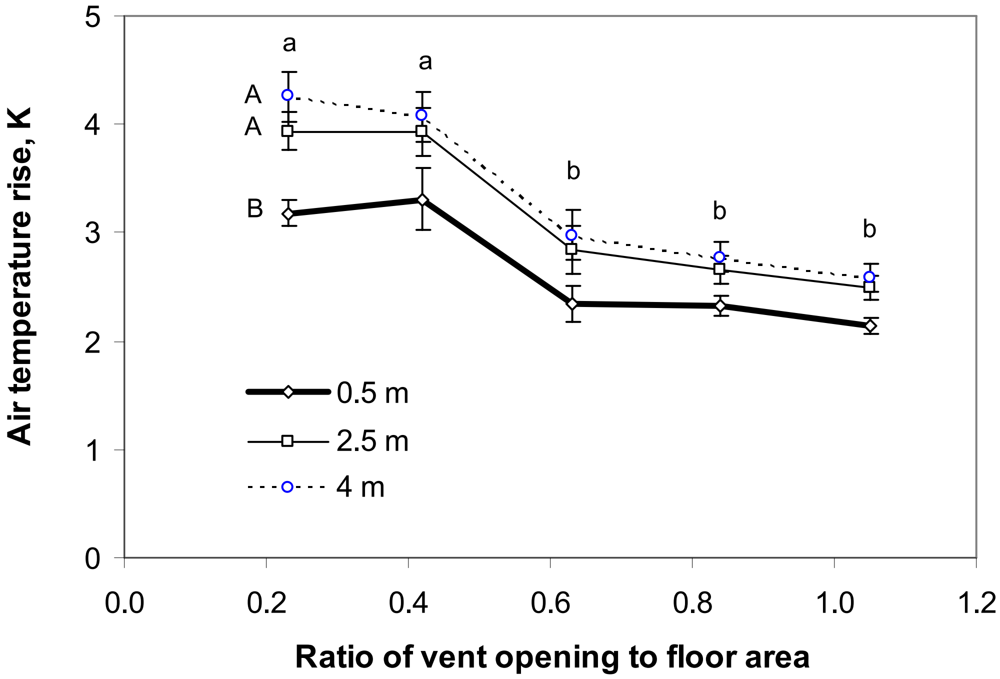



**Figure 5.30: Effect of vent ratio on means ± SE of air temperature rise at three different elevations in empty greenhouse. Means followed by the same lower case letter within a curve and upper case letter between curves are not significantly different at P = 0.05, GLM-LSD Test**

In line with the configuration how to arrange the ventilation opening in each treatment (Fig. 4.6) and their effect on internal temperature distribution, measuring air temperature at different elevation vertically was done at 0.5 m, 2.5 m and 4 m above floor surface. The measurement was conducted together with the measurement of microclimate at different ventilation ratio in the 52-mesh greenhouse under empty condition. Fig. 5.30 shows the vertical distribution of temperature rise occurring in the empty greenhouse at different ventilation ratio (the arrangement of vent opening). It is clear that internal air temperature was vertically different from upper zone to the lower zone in the greenhouse. The upper zone was warmer than the area just 0.5 m above ground level.

Moreover, from ANOVA two-way t-Test (SAS, 2003), there was a significant difference in the distribution of air temperature vertically in the greenhouse (F-value = 14.21, $P < 0.0001$) and the arrangement of vent opening (F-value = 46.62, $P < 0.0001$) but the interaction between two did not have any effect on the temperature rise in the greenhouse (F-value = 0.99, $P = 0.4528$). This evidence is very important in designing the greenhouse ventilation system as the vertical gradient of air temperature and the vent opening area significantly affected the expected temperature rise in the naturally ventilated greenhouse.

In the empty greenhouse, the distribution of internal temperature was not vertically uniform where the air temperature at the lower elevation (0.5 m above ground level) was lower than both at 2.5 or 4m above ground level. This result was in line with the finding reported by Bartzanas et. al. (2002), Albright (2002) and Nielsen (2002). Air at the lower part of greenhouse zone was always replaced by the fresh air from the ambient through the sidewall openings while the upper side was the zone of accumulated heat, so that the temperature was higher than at 0.5 m above ground level. The important point from this result that the effective way to assign ventilation opening as air intake to the greenhouse is at the lower side of the greenhouse (such as sidewall opening), on the contrary the position of ventilation opening for removing hot air in the greenhouse should be at the highest part of greenhouse (at the roof for natural ventilated type or at the position 2.5 m above ground level for force ventilated greenhouse).

It is also interesting to discuss that at ventilation ratio of 0.6, 0.8 and 1.05 at which the sidewall vent openings were opened, the temperature rise was similar and no significant difference was statistically found. If both sidewall vent openings were closed (as treatment $V_r = 0.6$) the temperature rise was drastically increased. This indicated that the sidewall vent opening had played an important role in exchanging air between inside and ambient the greenhouse. Even though a small temperature rise was found in the greenhouse under full-grown tomato condition, the closing of the sidewall vent opening indeed caused the temperature to rise remarkably (Fig. 5.28 (a)). Due to “cooling effect” caused by crops transpiration processes during daytime in the case of fully grown tomato condition, the effect of ventilation ratio on relative humidity difference was not clearly stated like it was in the empty condition, thus the comparison between treatments on absolute humidity difference should be taken into account. The closing of the vent opening to 20% indeed increased absolute humidity difference from 2.5 to 4.0 g $cm^{-3}$.

### 5.3.2 Effect of vent opening arrangements on crop transpiration rate

The arrangement of ventilation opening area also affected the crops transpiration rate during daytime because the microclimate was changed. Statistically, there was no significant effect of changing ventilation ratio ($V_r$) from 1.05 to 0.2 on crop transpiration rate using ANOVA GLM-LSD t-Test at 5% of confident level (F-value = 2.49, P = 0.0562); however the difference between treatments was quite small even their values were very closed each other. A small difference was found between the treatment $V_r$ = 0.2 to $V_r$ = 0.6 (smaller vent opening area) and the treatment $V_r$ = 0.8 to $V_r$ = 1.05 (bigger vent opening area) where the smaller vent opening area seems to be a little bit higher effect in crops transpiration rate than the bigger vent opening area of the greenhouse (Fig. 5.31). When the vent opening was further closed, the water vapour inside the greenhouse was trapped so that this reduced the crop transpiration rate. In fact, a lower vent opening area had a higher rate of crops transpiration than the bigger opening area. The reason was that the internal temperature was higher at this condition and encouraged to increase the transpiration rate, but in the same time the air exchange rate was quite low as the result crops transpiration rate in the treatments of $V_r$ = 0.2 and 0.4 was just slightly higher than that in the treatment of both $V_r$ = 0.8 and 1.05.

The explanation at what it is illustrated in Fig. 5.31 above is supported by the Fig. 5.32 that due to lower air exchange rate and the higher air temperature at $V_r$ = 0.2 treatment, the crop transpiration rate was relatively low. Nevertheless, at $V_r$ = 0.6 arrangement at which the air exchange rate was still as high as at $V_r$ = 1.05 treatment, the crops transpiration rate was the highest. This indicates that the air exchange rate plays a very important role in enhancing crop transpiration rate in the greenhouse at different level of ventilation opening area. The higher the air exchange rate in a greenhouse was, the higher was the crops evapotranspiration.

When the transpiration rate was higher in such greenhouse, the crops should be well maintained and as this may eventually increase the crop yield.

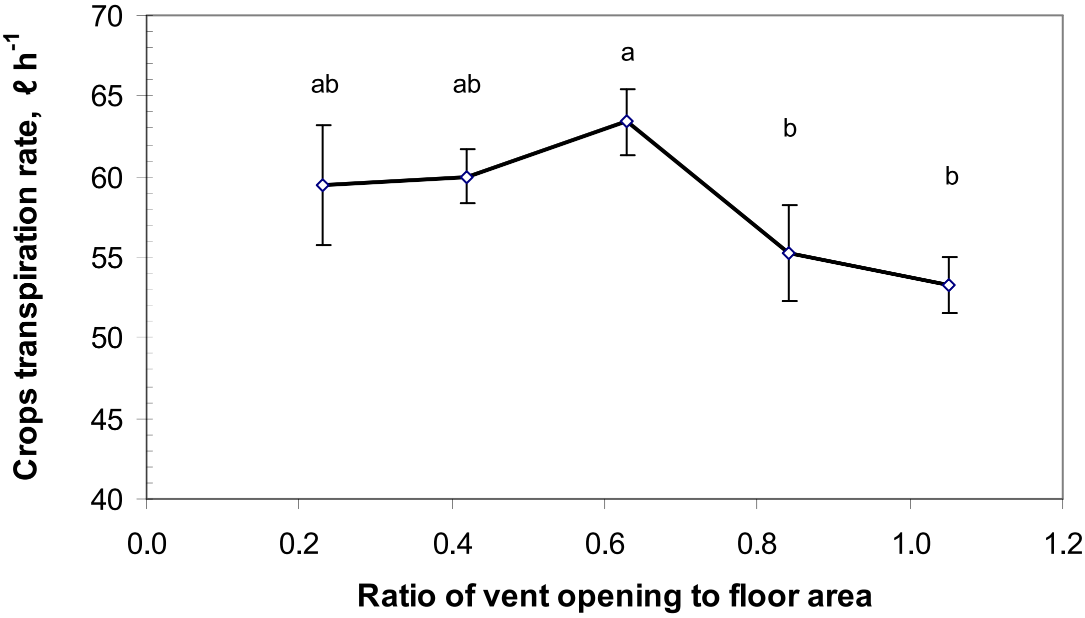



**Figure 5.31: Effect of vent ratio on means ± SE of crop transpiration rate in greenhouse. Means followed by the same letter are not significantly different at P = 0.05, GLM-LSD Test**

### 5.3.3 Effect of vent opening arrangements on air exchange rates

Figure 5.32 shows the effect of ventilation opening arrangement on air exchange rate in the greenhouse. The air exchange rates were calculated based on two methods as described in earlier section i.e. (1) using water vapour balance method and (2) using an energy balance method. Both measured and predicted air exchange rates had a similar trend even though the ratio of vent opening to floor surface area had been originally changed from 1.05 to nearly 0.2. The predicted air exchange rates were always an over estimation than the measured ones at the ventilation ratio from 0.6 to 1.05 where the sidewall opening was still opened. Then, their values were very close when both sidewall openings were totally covered by UV-stabilized plastic film or at the condition at which the $V_r$ was 0.4 or 0.2. In this condition, the greenhouse was most likely a tunnel greenhouse type with the ventilation opening at the back and front side. The heat fluxes occurring in a tunnel greenhouse can be easily predicted through the small vent opening, so that the predicted air exchange rate using the heat fluxes balance model was quite closed to the measured air exchange rate.

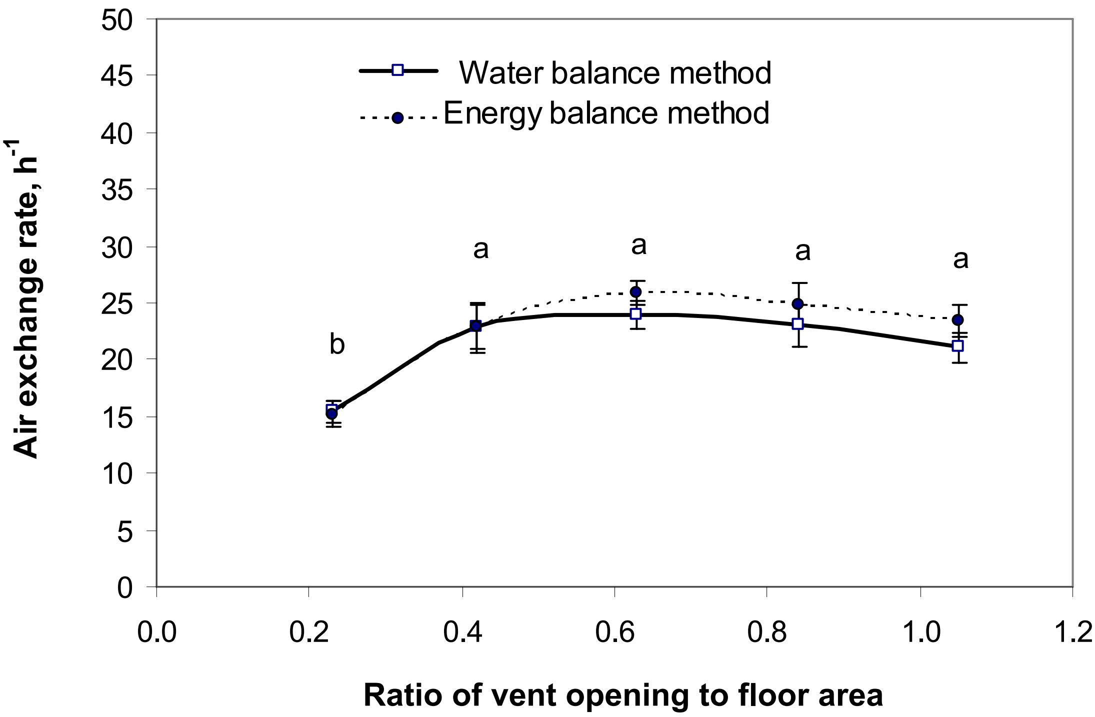



**Figure 5.32: Effect of vent ratio on means ± SE of air exchange rate in fully-tomato grown greenhouse. Means followed by the same letter are not significantly different at P = 0.05, GLM-LSD Test**

Therefore, from Fig. 5.32 it can be inferred that the design of ventilation opening affected to the air exchange rate even though a small difference was found. At the large ventilation (all sidewall + roof openings), the prediction of air exchange rate using a model based on an energy balance method was mostly over estimated compared to the measured one. On the contrary, with a smaller ventilation openings (only back and front side + roof openings), the prediction was much more accurate and very close to the measured air exchange rate. This may the reason why the prediction of air exchange rate using an energy balance model in the smaller opening size even in the most of tunnel greenhouse had a good agreement to the measured ones as similar findings had been already investigated by several authors (Bartzanas et al., 2004; Boulard and Draoui, 1995; Kittas et al., 1996; Muñoz et al., 1999).

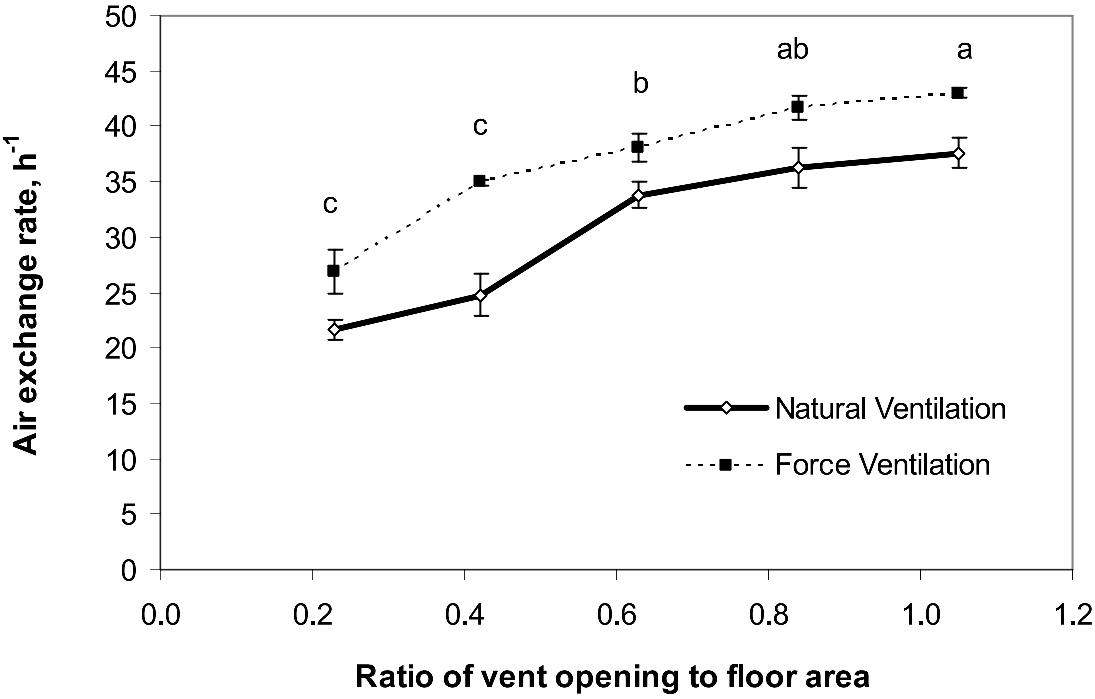



**Figure 5.33: Effect of vent ratio on means ± SE of air exchange rate at two conditions (natural vs. force ventilation) in empty greenhouse. Means followed by the same letter are not significantly different at P = 0.05, GLM-LSD Test**

The reduction of air exchange rate under the fully-grown tomato condition (Fig. 5.32) was found at about 23 air exchanges per h for the ventilation ratio of 1.05 to 15 air exchanges per h for the ventilation ratio of 0.2. Statistically, there is a significant effect of closing the ventilation opening area on air exchange rate in the greenhouse ($F = 5.23$, $P = 0.0015$) but the effect on air exchange rate against the ventilation ratio was not linear. The smaller ratio ventilation opening to floor surface area had been arranged at 0.2, the lower air exchange rate was obtained. On the other hand, the reduction of ventilation ratio (closing the net) up to 0.4 (40% of total vent opening area) did not reduce the air exchange rate at the range of between 22 to 24 air renews per hour, but the rate of air exchange in the greenhouse was drastically reduced at the rate 15 air renews per hour (or decreased by 35%) when further closing the net was done at $V_r = 0.2$.

A similar result on measuring air exchange rate predicted from an energy balance model which had been carried out in the empty greenhouse, is presented in Fig. 5.33. The trend of the predicted air exchange rate against the ventilation ratio was slightly similar to the greenhouse under full tomato condition. The decreasing air exchange rate slowly started from the ventilation rate ($V_r$) of 1.05 to 0.6 at about 37 – 33 $h^{-1}$, then from that point the air exchange rate was also dramatically decreased at 22 $h^{-1}$. Based on this (Fig. 5.33), it can be said that 0.6 was a minimum arrangement of ventilation ratio because of its large decrement of the air exchange rate thereafter. Since the arrangement of ventilation ratio between 0.2 and 0.4 gave a similar air exchange rate and their values were significantly different for the treatments of $V_r$ = 0.6 and 0.8 at 5% of confident level using ANOVA t-Test (GLM-LSD), it is clear that the arrangement of ventilation ratio opening to the floor surface area of 0.6 (minimum) should be taken into consideration.

Another point of exploring the effect of ventilation ratio arrangement on the air exchange rate conducted under two conditions of fully tomato and empty greenhouses was to accommodate the behaviour of air exchange rates along the cultivation period of plants. Two extreme conditions were taken to represent the stage of plant growth i.e. initial stage as the empty condition and maturity stage as fully grown tomato condition. The comparison between the two was slightly similar though more reduction of air exchange rate was significantly achieved if further reduction of ventilation opening area was arranged. One good finding from Fig. 5.32 and 5.33 was that the arrangement of ventilation ratio at 0.4 was the minimum requirement to keep air exchange rate constant when the greenhouse was full with plants while a ventilation ratio of 0.6 was necessary in the initial stage of plant stage of growth to maintain a sufficient air exchange rate.

In connection with the experiment on the use of exhaust fans to increase air exchange rate in the empty greenhouse, Fig 5.33 shows that effect of operating exhaust fans and arrangement of ventilation opening on predicted air exchange rate. The use of exhaust fans in the beginning stage of crops cultivation significantly helped in increasing air exchange rate and reducing the temperature rise which may impact on the plant stress soon after transplanting. Even though the increase of air exchange rate was not as high as 60 air exchanges per h as it was recommended by Albright (2002), operating exhaust fans in case of extremely hot condition inside the greenhouse seems necessarily to do.

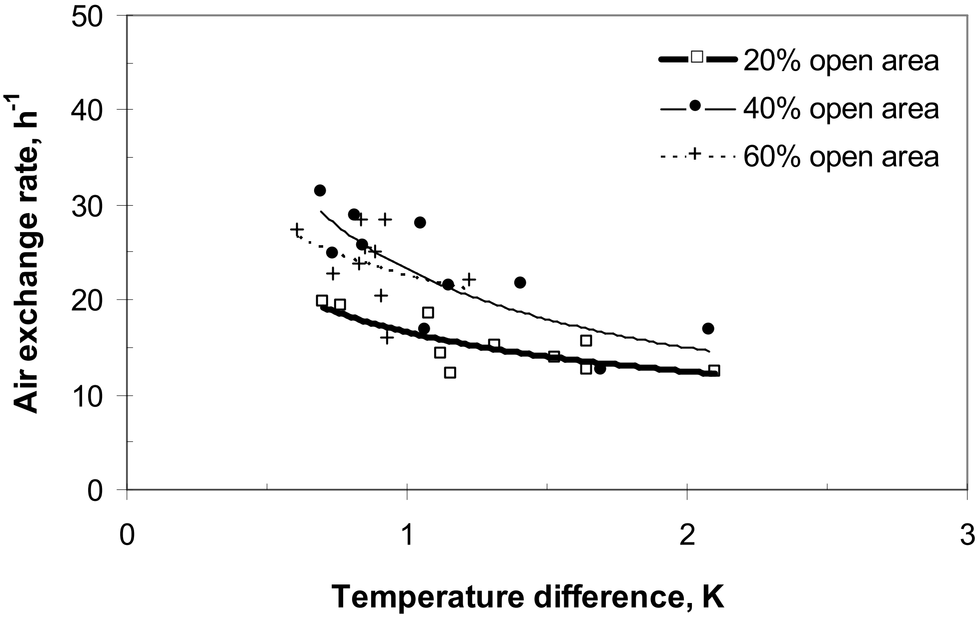



**Figure 5.34: Relationships between temperature rise and air exchange rate in fully-crop greenhouse at different ventilation arrangements**

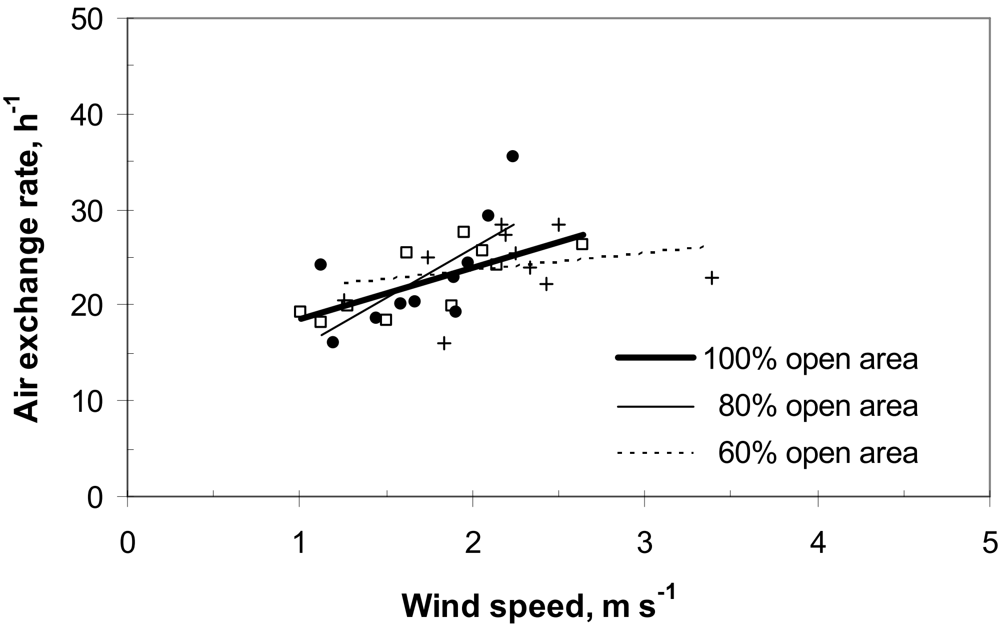



**Figure 5.35: Relationships between wind speed and air exchange rate in fully-crop greenhouse at different ventilation arrangements**

A further analysis on the relationships between temperature rise vs. air exchange rate and between wind speeds vs. air exchange rate at different ventilation ratio

($V_r$) in the greenhouse had been performed and the result is presented in Fig 5.34 and 5.35. Only the arrangement of ventilation ratio that gave a fairly good coefficient of correlation between two is displayed in the curve.

It is clearly shown from Fig. 5.34 that the relationship between temperature difference and air exchange rate was better in the lowest ventilation ratio. Due to non-linear relationships between the two, an appropriate statistical analysis of the Spearman Rank-Order Correlation Coefficient-Test (PROC CORR SPEARMAN in SAS, 2003) was used. This method can be applied to compute the coefficient correlation for the case that one variable is assessed on an ordinal scale and the other variable is assessed on an interval or ratio scale. As, it is shown in Fig 5.34 that only at $V_r$ equal to 0.2 and 0.4 the relationship between temperature rise and air exchange rate had a fairly good agreement ($R^2$ = 0.47, P = 0.03 and $R^2$ = 0.63, P = 0.006, respectively). Meanwhile at $V_r$ was more than 0.4, their relationships was not significant at 5% of confident level, because at bigger vent opening the wind speed surrounding the sidewall may have an effect on the air exchange rate.

The relationship between temperature differences against air exchange rate was not linear, but it seems to be exponential function. In this case, the greater temperature difference did not proportionally reduce the air exchange rate while reducing only a small temperature difference can cause dramatically the increase of air exchange rate or vice versa.

In terms of wind speed, the relationships between wind speed and air exchange rate was just opposite to what it was happening in the temperature difference. When more vent opening area was opened, closer relationships between two was obtained (Table 5.9 and Fig. 5.35). Table 5.11 shows the relationships between air exchange rate and wind speed as well as temperature difference that a good correlation between air exchange rate and temperature difference was obtained when the ventilation openings was small ($V_r$ = 0.2). Conversely, a better correlation between air exchange rate and wind speed was achieved when the ventilation opening was arranged at 100% of opening area ($V_r$ = 1.05).

**Table 5.9: Statistical analysis to correlate between air exchange rate vs. temperature rise and wind speed using the Spearman rank-test at different arrangements of ventilation ratio ($V_r$)**

| Parameters | Data, N | Spearman CC, \| r \| | $R^2$ | Probability, P | Significant |
|---|---|---|---|---|---|
| - Air exchange rate vs. Temperature rise | | | | | |
| At $V_r$ = 0.2 | 10 | **-0.6869** | **0.47** | **0.0282** | * |
| At $V_r$ = 0.4 | 10 | **-0.7951** | **0.63** | **0.0060** | * |
| At $V_r$ = 0.6 | 10 | -0.3309 | 0.11 | 0.3504 | |
| At $V_r$ = 0.8 | 10 | -0.1945 | 0.04 | 0.5903 | |
| At $V_r$ = 1.05 | 10 | 0.1129 | 0.01 | 0.7561 | |
| - Air exchange rate vs. Wind speed | | | | | |
| At $V_r$ = 0.2 | 10 | 0.2000 | 0.04 | 0.5796 | |
| At $V_r$ = 0.4 | 10 | 0.2857 | 0.08 | 0.4236 | |
| At $V_r$ = 0.6 | 10 | 0.2256 | 0.05 | 0.5308 | |
| At $V_r$ = 0.8 | 10 | **0.8754** | **0.77** | **0.0009** | * |
| At $V_r$ = 1.05 | 10 | **0.7903** | **0.62** | **0.0065** | * |

The mark (*) indicated a significant difference at 5% of confident level with Sprearman Coeficient Correlation (CC) - Test ( SAS, 2003)
$R^2$ = coeficient of determination (the absolute magnitude of coeficient correlation, r)

In order to further understand the relationships between air exchange rate and wind speed, the data from the empty greenhouse was plotted and good correlation was achieved as shown in Fig. 5.36 at Spearman coefficient correlation of $R^2$ = 0.63, P = 0.026 and $R^2$ = 0.57, P = 0.043 for the vent ratio of 0.6 and 0.4, respectively. The bigger ventilation opening at 60% had the higher air exchange rate than at 40 and 20% open area. It is clear from the figure that the relationships between wind speed and air exchange rates was linear even though it was tested with the non-linear statistical tool like Spearman correlation test. So that the increasing wind speed would increase air exchange rates in the greenhouse and its effect was more when bigger vent opening of greenhouse was applied. This finding was in line with the result from experiment conducted by several authors (Kittas et al., 1997, Boulard and Baille, 1995, and Roy et al., 2002) where the ventilation rate is a function of wind speed.

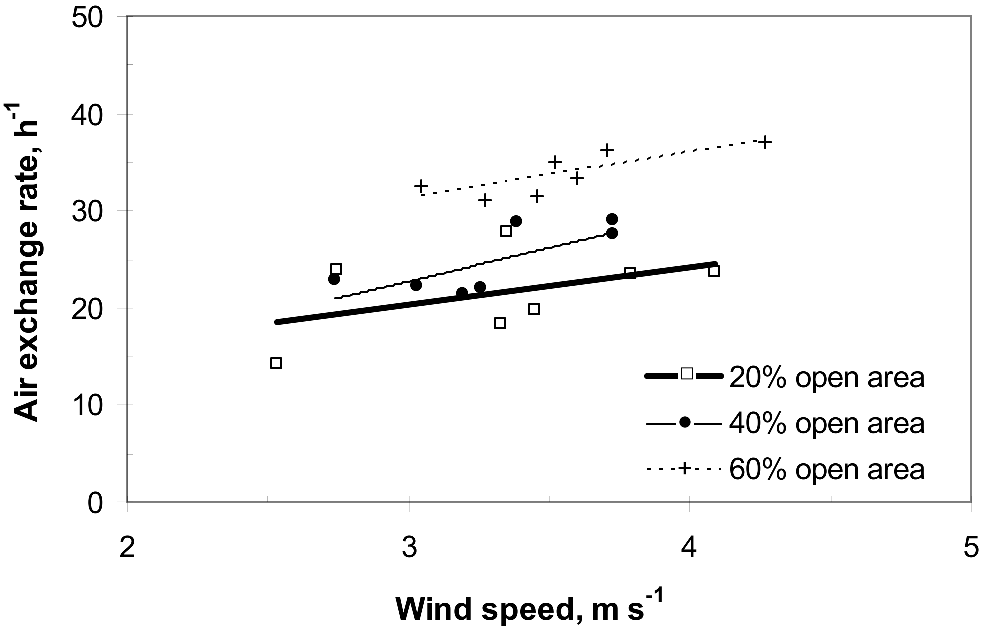



**Figure 5.36: Relationships between wind speed and air exchange rate in empty greenhouse at different ventilation arrangements**

However, this result was a little bit contradicted with the result from the experiment conducted under different net-size over the vent opening (Section **5.2.3**) whereas at 78-mesh greenhouse (smaller vent opening area) gave a better relationship even though correlation was very low (at $R^2$ equal to 0.5). The reason for this was clearly shown in comparison between Fig. 5.27(a) and Fig. 5.35 that at higher range of external wind speeds induced in the greenhouse, the lower the relationship achieved. The experiment on comparing wind speed and air exchange rate at different net-size was conducted under higher external wind speed from 2 – 7 m $s^{-1}$, while the other experiment on comparing wind speed and air exchange rate at different vent ratio arrangement was done under the measurement of wind speed at 2 – 4.5 m $s^{-1}$. In addition, when ventilation opening was too large along all sidewalls of the greenhouse, it was difficult to explain the air movement from the surrounding into the greenhouse through the insect-proof net.

Besides, wind direction during the experiment may have been involved in determining the relationship between wind effect and air exchange rate whereas from observation the wind was most likely directed just from the opposite (backward) of roof opening. Therefore, if external wind had relatively high speed, it may not directly affect directly the air exchange rate due to the direction of wind impacted to the backward of roof vent openings. In this case, sidewall openings had taken into account in renewing air inside the greenhouse, but it was not directly affected by prevailing wind speed at that time.

### 5.3.4 Optimum configuration of vent opening for adapted greenhouse

Since air exchange rate plays an important role in microclimate management in the greenhouse, it is quite interesting from about the results of the effect of vent ratio arrangement on temperature rise in the fully grown tomato greenhouse Fig. 5.28 (a) and air exchange rates (Fig. 5.32 and 5.33) that at a certain point of vent ratio arrangement both air exchange rate and temperature rise in the greenhouse was significantly changed. For this arrangement, the average of air exchange rate started to decrease, when the temperature rise increased significantly. Therefore, it can be concluded from this phenomena that, the point of vent ratio arrangement which caused significant of the change of the microclimate and air exchange rate was assumed as to be the optimum configuration of vent opening for adapted greenhouse.

The arrangement of vent ratio (ratio between vent opening to floor surface area) for adapted greenhouse to be 0.4 to 0.6 along the cultivation period of time was the minimum arrangement in order to maintain microclimate and air exchange rate as favourable as the original design (at $V_r$ equal to 1.05) for growing tomato in the adapted greenhouse. The vent ratio of 0.6 was needed when the crop condition was very young (almost the empty greenhouse) so that by opening the ventilation as big as 60% of total ventilation opening, the microclimate (temperature rise) and air exchange rate in the greenhouse was not significantly changed. On the contrary, the minimum arrangement of vent ratio of 0.4 was necessary for fully grown tomato greenhouse to maintain the air exchange rate (Fig. 5.32) and the water vapour content (Fig. 5.37) at the favourable level for tomato growth. But in terms of temperature rise (Fig. 5.28(a)), the minimum adjustment of 0.6 seems a reasonable effort to maintain the temperature difference does not exceeded 1 K.

It is noted that the wind condition during two different experiments (full tomato vs. empty conditions) was recorded at different ranges. During the empty condition the daytime wind speed was ranging from 2.0 – 5.3 m $s^{-1}$ (on average of 3.7 m $s^{-1}$) while along the full crops condition, the wind speed was ranging from 0.5 – 4.7 m $s^{-1}$ (on average of 2.1 m $s^{-1}$). As a result the air exchange rate at the empty greenhouse was higher than that in the full crops condition. Nevertheless, at that condition the adjustment of vent ratio to be 0.6 was still not adequate to maintain the air exchange rate and temperature rise as high as the original arrangement of $V_r$ equal to 1.05. In this case, it can be said that the arrangement of vent ratio of 0.6 was the minimum requirement. At this condition ($V_r$ = 0.6) the sidewall opening located at the lower part (between 0.8 – 1.8 m above ground level) seems to be an important vent opening and was still needed as a part of microclimate management in the adapted greenhouse.

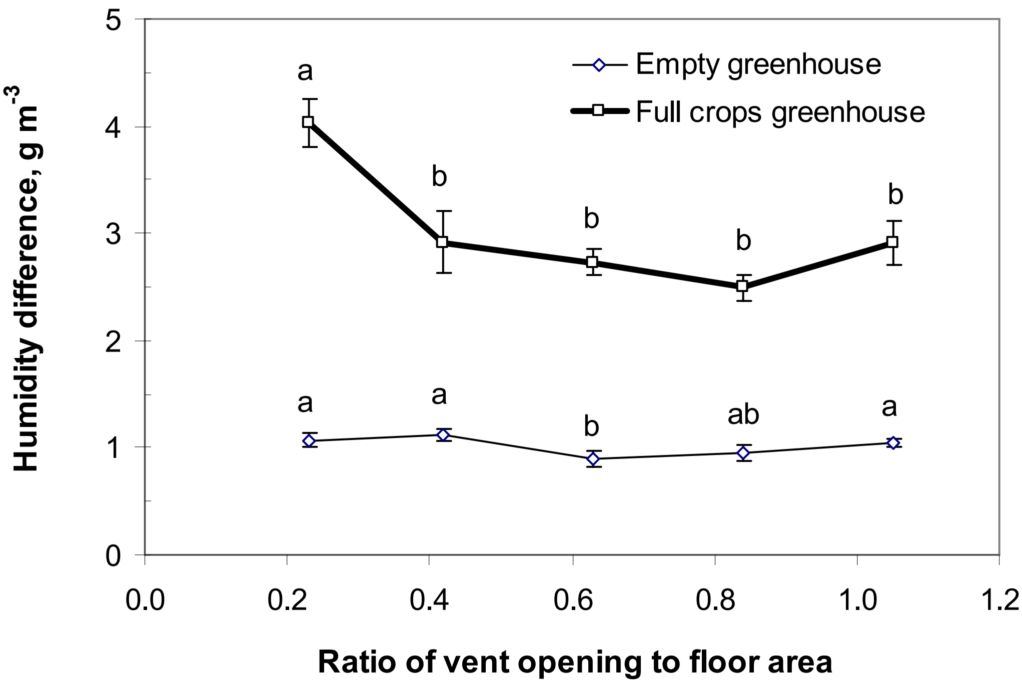



**Figure 5.37: Effect of vent ratio on means (± SE) of absolute humidity difference in greenhouse under two conditions. Means followed by the same letter are not significantly different at P = 0.05, GLM-LSD Test**

In addition, the arrangement of vent ratio to be 0.6 did not significantly increase the humidity difference between in and outside the greenhouse (Fig. 5.37). The absolute humidity difference represents the water vapour content which affects the crops transpiration processes and the incidence of potential fungi disease in the greenhouse. The lower the humidity difference in such a greenhouse was; the better microclimate condition for plant growth was obtained, because it would be encourage the plant growth and avoid the potential disease caused by fungi as also one of the most problems in humid tropic greenhouse.

## 5.4 Effectiveness of exhaust fans used on adapted greenhouse

This section describes the result of some experiments dealing with the comparison between two types of greenhouses i.e. force ventilated (FV) by operating the exhaust fans during daytime and natural ventilated (NV) greenhouse by keeping fans switched off during observation in order to evaluate the effectiveness of exhaust fans installed on the adapted greenhouse. Some important parameters used to evaluate the use of exhaust fans were only specified in to the microclimate condition, air exchange rate, and crops water requirement.

### 5.4.1 Performance of adapted greenhouse with exhaust fans operating under empty condition

It was assumed that the lower internal air temperature and increasing air exchange rate would be expected when exhaust fans were installed and operated in such a natural ventilated greenhouse. In Fig 5.38 illustrates the comparison between two greenhouses, presented as the daily average air temperature rise between two types of greenhouses (78-mesh and 40-mesh) that occurred during experiment at the day time from April 1, 2004 to May 13, 2004.

It is shown that temperature rise in the 78-mesh house ranging from 3.5 to 6.5 K was originally higher than that after operating exhaust fans which was ranging from 3 to 5 K. On average, the use of fans reduced internal temperature by 0.6 K or about 2%. Similarly in the 40-mesh greenhouse, the use of exhaust fans reduced temperature rise in the greenhouse about 0.4 K or 1.2 % only, even though their ranges were very close at 2.5 to 5 K. This experiment was carried out simultaneously in some greenhouses during hot season. With the average of internal temperature for the 78-mesh and 40-mesh greenhouses were 35.3 and 34.7 °C, respectively, the reduction of 0.4 – 0.6 °C due to the use of additional fans might not help to provide better environment for plant growth at the beginning stage.

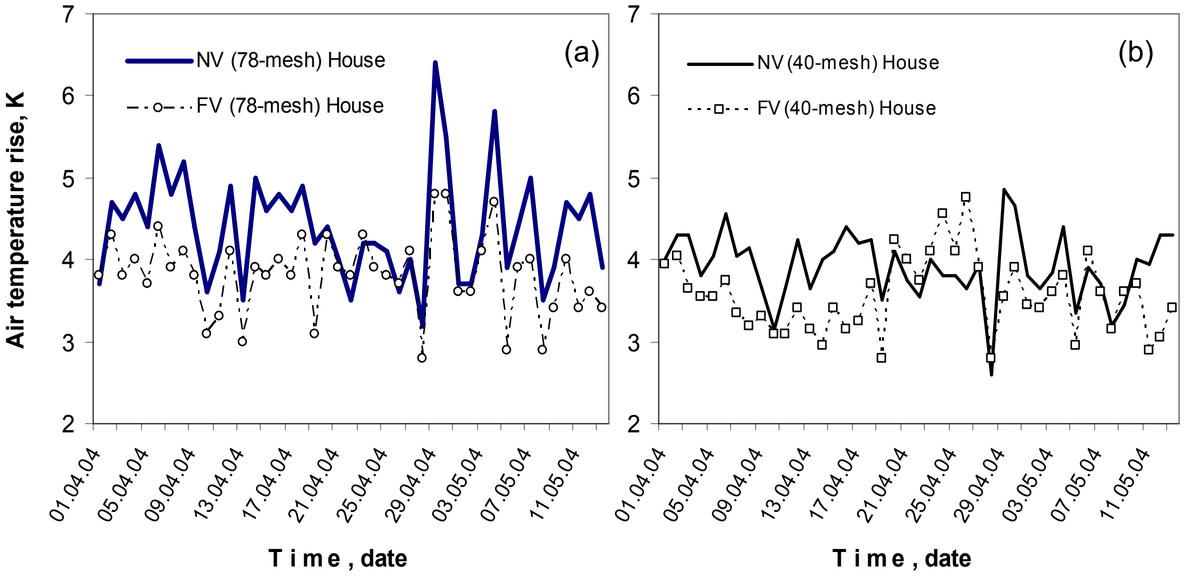



**Figure 5.38: Daily variations of air temperature rise due to exhaust fans operation in the 78- and 40-mesh greenhouses in empty condition**

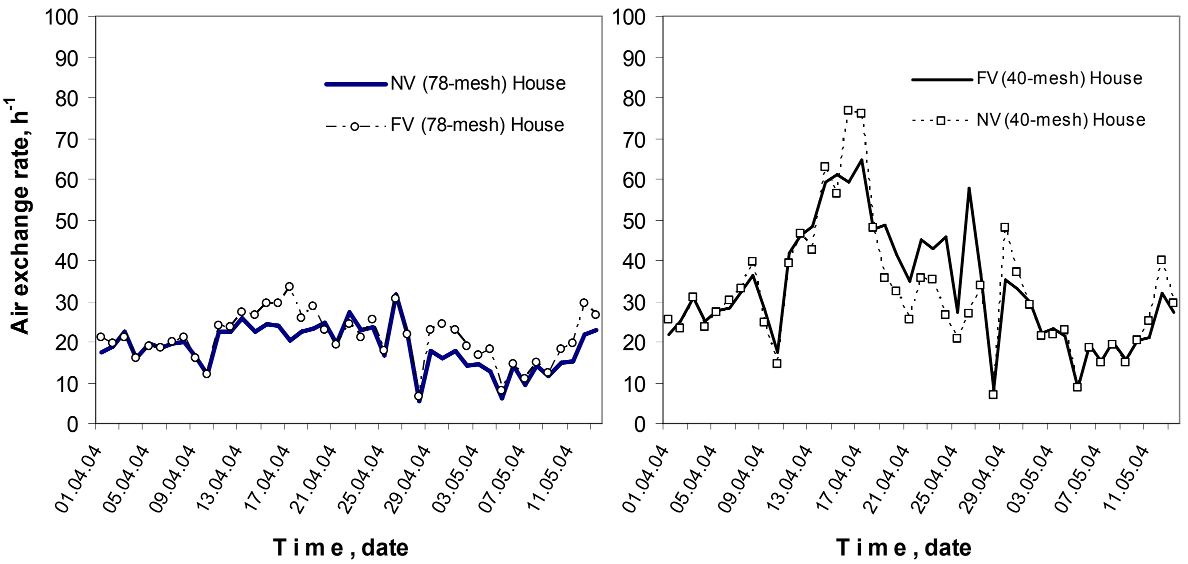



**Figure 5.39: Daily variations of air exchange rate due to exhaust fans operation in the 78- and 40-mesh greenhouses in empty condition**

Estimated air exchange rate calculated based on an energy balance method (Eq. 4.9) was also used to evaluate the effect of additional fan on the adapted greenhouse. Hourly air exchange rates during daytime were averaged and presented in Fig. 5.39. Operating the fans slightly increased the air exchange in the 78-mesh greenhouse, but it was not always in the 40-mesh greenhouse because the predicted air exchange rate in force ventilated (FV) greenhouse was sometimes lower than the natural ventilated (NV) greenhouse.

From the T-test, Table 5.10 summarizes some results of statistical analysis data obtained from the experiment running under some empty greenhouses. There was a significant difference between two treatments on the air temperature rise and predicted air exchange rate in the 78-mesh greenhouse. In addition, applying exhaust fans in the smaller size of 40-mesh greenhouse reduced temperature rise by 0.4 K, but it did not increase the air exchange rate. It is clear that the use of additional fans for the smaller size of net-size (bigger ventilation opening) may not help to increase the ventilation system. The horizontal axial fans (HAF) to be installed in the greenhouse might be a good solution to enhance the air exchange rate. This fan would help to force the hot air inside the greenhouse either by circulating or getting out through the sidewall as vent opening rather than sucking the internal hot air through the existing fans at the front side of greenhouse.

**Table 5.10: Statistical analysis to evaluate operated exhaust fans on air exchange rate and temperature rise using t-test**

| Parameters | Treatment | DF | T-value | Pr > \|t\| | Significant |
|---|---|---|---|---|---|
| Air exchange rate ($h^{-1}$) | 78-mesh | 42 | -4.56 | <.0001 | * |
| | 40-mesh | 42 | 1.22 | 0.2283 | |
| Temperature rise (K) | 78-mesh | 42 | 9.05 | <.0001 | * |
| | 40-mesh | 42 | 4.50 | <.0001 | * |

The mark (*) indicated a significant difference at 5% confident level with T-test
DF = degree of freedom

Figure 5.40 clearly shows that all types of greenhouses there was a significant effect in reducing the temperature difference due to the use of exhaust fans during the daytime. The small reduction of temperature rise from 4 K to 3 K was obtained.

This reduction was actually needed when small crops were transplanted from the nursery in order to avoid stress and wilting due to a very high temperature during daytime. It is also interesting that the reduction of temperature rise was not similar from one type of greenhouse to another whereas in the 78-mesh greenhouse, the reduction was more than in both 52-mesh and 40-mesh greenhouse. So it can be inferred that operating exhaust fans in the bigger vent opening greenhouse like in the 52-mesh or 40-mesh greenhouse was less effective than that in the smaller vent opening even in the tunnel greenhouse.

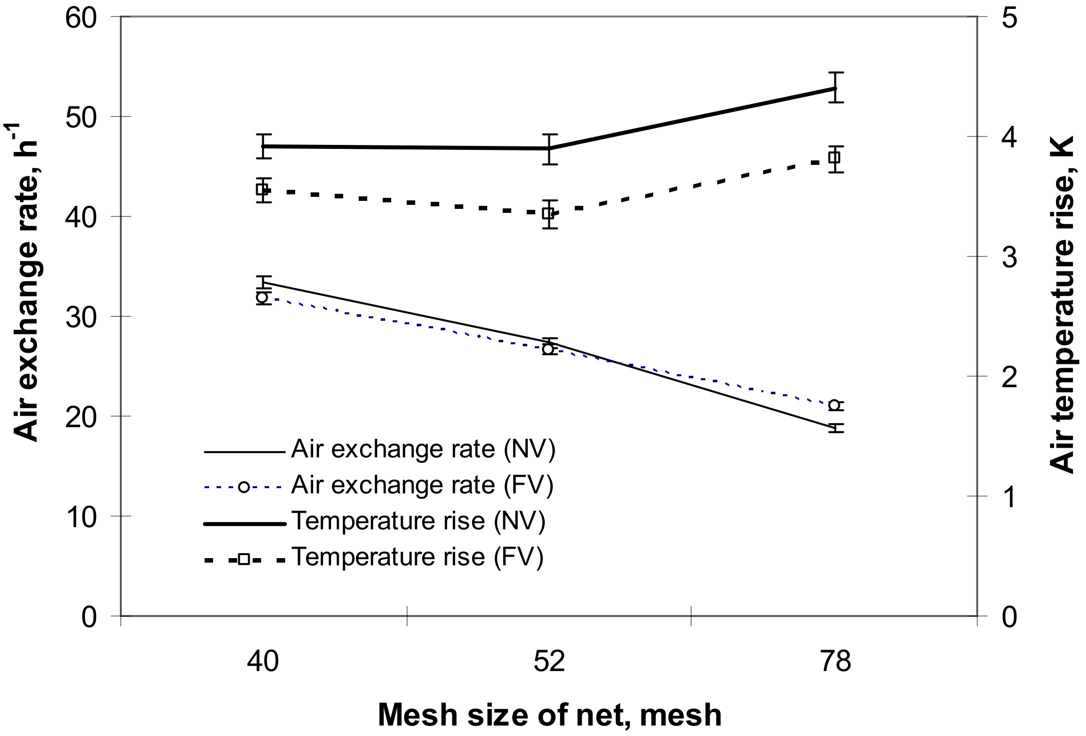



**Figure 5.40: Effect of exhaust fans operations on air exchange rate and temperature rise in the 78-mesh, 52-mesh and 40-mesh greenhouses in empty condition**

In terms of predicted air exchange rate, the force ventilated greenhouse had increased the air exchange rate only at the 78-mesh greenhouse but the others were not (Fig. 5.40) even their means were less than the naturally ventilated greenhouses. This indicated that operating exhaust fans to help to remove hot air in the smaller mesh-size was less effective due to very big ventilation that it had. Because the use of exhaust fan operated in such a greenhouse would be effective if both sidewall were totally closed with UV-plastic film and a small vent opening just in the opposite direction of fans was necessary. On the other word, the exhaust fans would not be effective to operate in the empty greenhouse especially when a very large ventilation opening is applied. As the adapted greenhouse was constructed with very large vent opening in both sidewall and in the roof, so the function of fans was not optimal.

### 5.4.2 Effect of operated exhaust fans on microclimate and air exchange rate in fully tomato-grown greenhouse

Again, the effect of exhaust fans operated in the adapted greenhouse on microclimate, air exchange rate and crops evapotranspiration was tested in the fully tomato-grown condition instead of the empty greenhouse. The experiment was simultaneously conducted in some greenhouses from January 7, 2005 to April 5, 2005. Fig 5.41 shows the comparison of daily average internal air temperature (daytime) between two greenhouses (NV vs. FV) from two types of greenhouse (covered by 40-mesh and 78-mesh nets). It is revealed that operating exhaust fans during daytime reduced a little bit internal air temperature in the 78-mesh and 40-mesh greenhouses averaged by 0.8 °C and 0.6 °C, respectively. On the other hand, the reduction of 2 – 2.5% was obtained when exhaust fans were operated during daytime in the fully grown tomato condition.

Statistically, there is a significant effect of operating exhaust fans during daytime on internal temperature using T-test at 5% of confident level as shown in Table 5.11 even though the reductions were quite small compared to the original ones (Fig. 5.41). The use of exhaust fans in fully grown-crop condition seems more effective than in the empty greenhouse (beginning of plant stage), because air temperature in FV-greenhouse was always lower than that in NV-greenhouse (Fig. 5.41). This could be due to the arrangement of the plants (rows) perpendicular to the fans hence helping to increase the airflow inside the greenhouse through the fans.

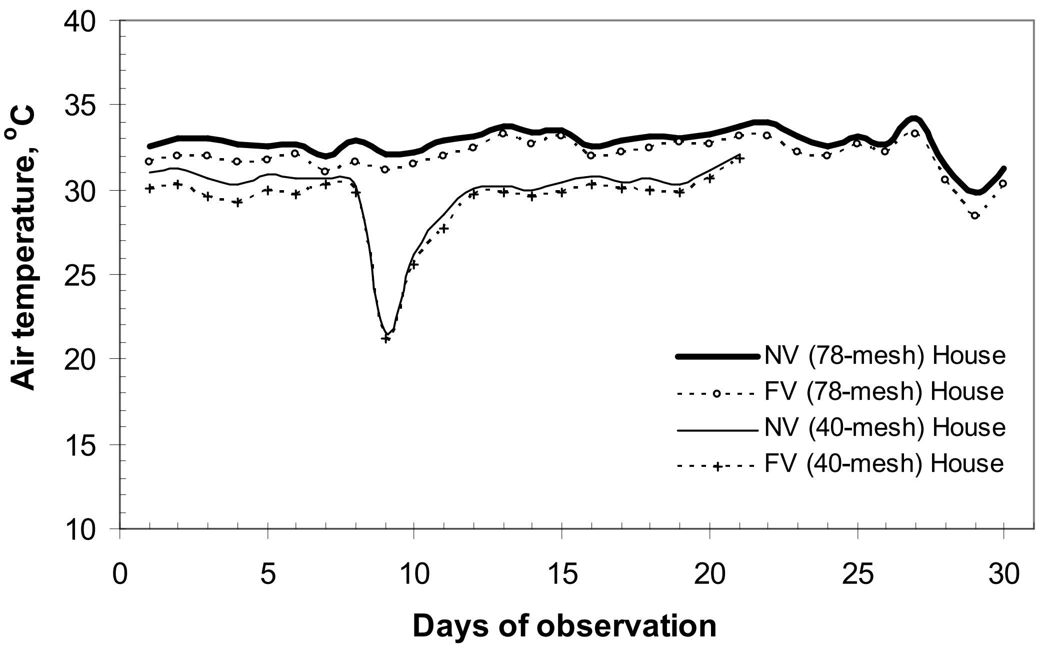



**Figure 5.41: Effects of exhaust-fans operation on internal air temperature in cropped greenhouses (NV = natural ventilated, FV = force ventilated greenhouse)**

In line with the findings above, it is clear from Fig. 5.42 that there was a significant effect of the operating exhaust fans on average absolute humidity in both treatments of NV- and FV-greenhouses even though the reduction of humidity was quite less. This trend was occurred in both 78-mesh and 40-mesh greenhouses. Statistically, there was a significant difference between two greenhouses (NV vs. FV) on internal absolute humidity using T-test at 5% of confident level (Table 5.11). Therefore, the use of exhaust fans in the fully grown-tomato greenhouse helped to reduce internal absolute humidity (water vapour inside the greenhouse) although the reduction was averagely quite small at less than 1 g $m^{-3}$.

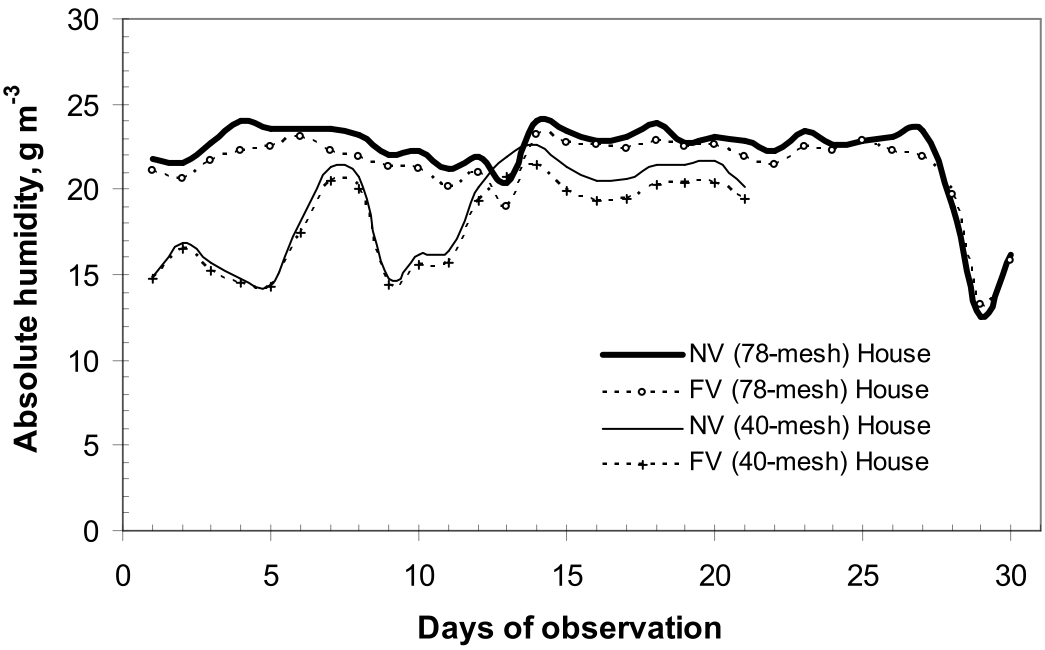



**Figure 5.42: Effects of exhaust-fans operation on absolute humidity in cropped greenhouses (NV = natural ventilated, FV = force ventilated greenhouse)**

In terms of air exchange rate measured using a tracer gas (water vapour) method, the use of exhaust fans during daytime helped to increase air exchange rate in both types of greenhouse (78- and 40-mesh) as presented in Fig. 5.43. The increments of air exchange rate obtained from the 78-mesh and 40-mesh force ventilated greenhouses were about 70% and 30%, respectively.

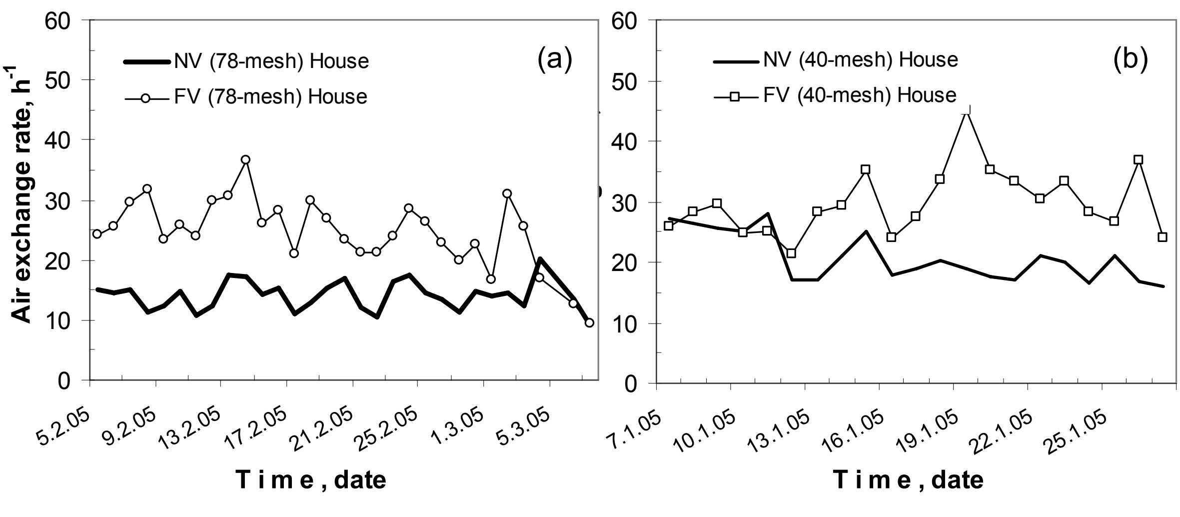



**Figure 5.43: Effects of exhaust-fans operation on air exchange rate in the 78-mesh and 40-mesh cropped greenhouses**

From T-test, statistically the air exchange rate in the FV-greenhouse was higher than that in the NV-greenhouse (Table 5.11) showing that there was a significant effect of exhaust fans operated during daytime on increasing air exchange rate especially in the 78-mesh greenhouse. Consequently, the concentration of water vapour inside the greenhouse was also decreased due to the increase in the number of air renews against of time. Reducing water vapour in the greenhouse might also help to reduce the incident of fungi disease.

In line with the result of air exchange rate mentioned above, crops evapotranspiration in the FV-greenhouse was also higher than that in the NV-greenhouse (Fig. 5.44). This actually occurred due to the increase of air exchange rate forced by exhaust fans. In the 78-mesh greenhouse, increasing air exchange rate by 70% caused the increase of crops evapotranspiration ($ET_C$) by 25%, while in the 40-mesh greenhouse increasing air exchange rate by 30% caused the increase of $ET_C$ by 15%.

**Table 5.11: Statistical analysis to evaluate operated exhaust fans on some selected parameters using t-test**

| Parameters | Net house covered by | DF | T-value | Pr > \|t\| | Significant |
|---|---|---|---|---|---|
| Air exchange rate ($h^{-1}$) | 78-mesh | 29 | -10.52 | <.0001 | * |
| | 40-mesh | 20 | -5.78 | <.0001 | * |
| Air temperature ($^oC$) | 78-mesh | 29 | 16.00 | <.0001 | * |
| | 40-mesh | 20 | 9.97 | <.0001 | * |
| Absolute humidity (g $m^{-3}$) | 78-mesh | 29 | 7.27 | <.0001 | * |
| | 40-mesh | 20 | 8.75 | <.0001 | * |
| Crops evapotranspiration | 78-mesh | 29 | -13.98 | <.0001 | * |
| ( ℓ $day^{-1}$ $plant^{-1}$) | 40-mesh | 20 | -5.94 | <.0001 | * |

The mark (*) indicated a significant difference at 5% confident level with T-test
DF = degree of freedom

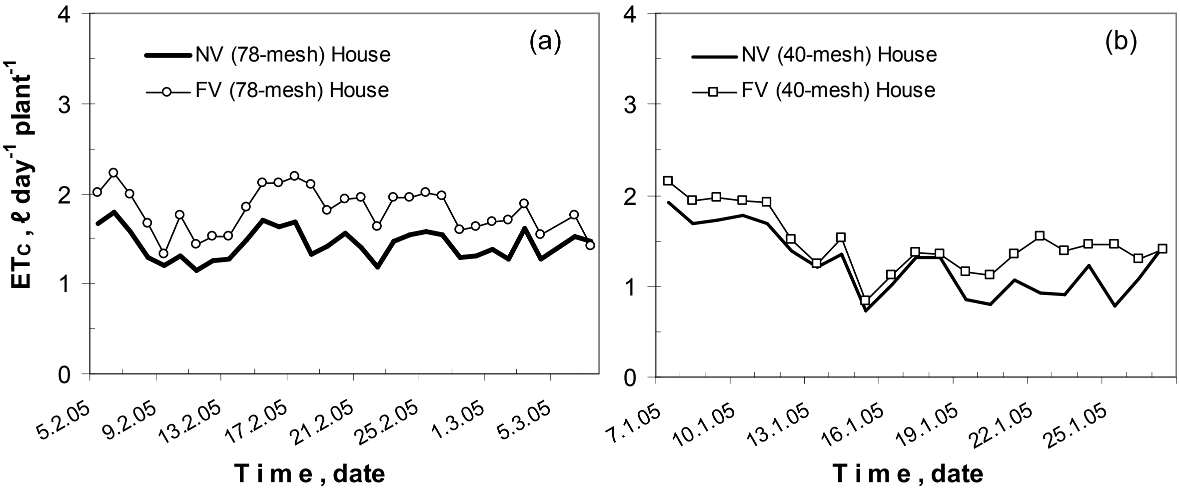



**Figure 5.44: Effects of exhaust-fans operation on crop evapotranspiration ($ET_C$) in the 78-mesh and 40-mesh cropped greenhouses**

The result is also statistically supported by T-test from Table 5.11 that the use of exhaust fans during daytime can increase crop evapotranspiration significantly in the adapted greenhouse. The increase of this evapotranspiration would encourage photosynthesis processes thus lead to an increase in crop yield. However, this may increase the cost of irrigation water, fertilizer and additional electricity in tomato production under protected cultivation. Please note that all means comparison performed using T-test above (Table 5.11) was carried out under similar condition of incoming solar radiation (on average) in each tested greenhouse where the uniformity of incoming solar radiation had been checked using ANOVA LSD – test at 5% of significant level. No significant different was found between tested greenhouses (F = 0.02, P = 0.997).

# 6. Discussions

## 6.1 General

The main findings of this study was the evaluation of some critical points on how to appropriately manage microclimate and air exchange rate (ventilation system) in greenhouses located in the humid tropics so that it will be favourable for growing crops against several major constraints such as: extremely high air temperature and humidity, rainfall and insect pest diseases. Some efforts on how to provide a relatively simple structure greenhouse, which is cheap in capital and low-cost in maintenance, had been made. In addition, the greenhouse has to be able to maintain internal microclimate close to the environment surrounding it in order to overcome these problems. Naturally ventilated greenhouse system is required to meet the above requirements. This approach of design is called adapted greenhouse in this study. In addition, the application of insect-proof net put on the greenhouse ventilation opening as cladding material to exclude some selected insect pests is another effort to band against the invasion of serious insect pests. The use of insect-proof net for covering ventilation opening now is becoming popular and widely used in modern greenhouse due to its advantage in excluding insect disease which is mostly a major problem for vegetable crops (tomato) in humid tropical region such as Thailand (Murai et al., 2000).

The selection of proper mesh-size of insect-proof net to be installed on the vent opening of tropical greenhouse is very crucial because this is not only for excluding the insect pests and the disease pathogens they vector, but also it affects to microclimate, air exchange rate, irrigation system and the response of crops (tomato) cultivated in the greenhouse. Three different mesh-sizes of insect-proof nets were selected and tested in adapted greenhouse in order to evaluate integrally from technical, agronomical and entomological point of view. The integral evaluation from many aspects is necessary to achieve a compromise choice of proper mesh-size of net according to the best composition of result from each different aspect; even an optimization on selecting mesh-sizes of insect-proof nets is possible (section **5.1**).

Since the microclimate management plays an important role in the key success of crops cultivation in humid tropics greenhouse, a further evaluation of the adapted greenhouse was continuously carried out by comparing the microclimate and air exchange rate as main parameters within two conditions i.e. natural ventilation (NV) and forced ventilation (FV) system (by switching “on” the exhaust fans during daytime) as mentioned in section **5.4**. Even though exhaust fans significantly affected (increased) the air exchange rate, but the rate was still inadequate at 30 $h^{-1}$ and 35 $h^{-1}$ in the 78-mesh and 40-mesh greenhouse, respectively (Fig. 5.40). It is recommended from previous study (Albright, 2002; Kozai et al., 1980; and ASAE, 1989) that about 60 times of air renew per hour (or one air exchange per minute) is needed to achieve better ventilation system in warmer greenhouse. Moreover, the exhaust fans operated during daytime in the empty greenhouse were also inadequate to increase the air exchange rate, so that the effort should be made either by installing additional horizontal axial fans (HAF) in the greenhouse or adding with the positive pressure fans located just the opposite of existing the exhaust fans as it was done by Mears and Both (2002).

Due to its great importance of air exchange rate mostly influencing on microclimate, a modified model adopted from the equation developed by Kittas et al. (1997) was developed and used in the recent study. The model is mainly calculated based on geometric properties of greenhouse (porosity, $\varepsilon$ and ventilation openings, $A_f$ and $A_s$) and the microclimate (temperature difference and wind speed). The modified model was validated with the experimental data and fair agreement was obtained. The other models were also developed based on energy balance and water vapour balance methods occurring in greenhouse and used to predict internal microclimate (air temperature and humidity). A good correlation ($R^2$ was between 0.8 and 0.9) was obtained from comparisons between predicted and measured microclimate. These models would be very helpful as a quick tool to predict air exchange rate and microclimate and only simple and a few climatic parameters set was required. Those are also very useful in designing and evaluating such a greenhouse in humid tropical condition (section **5.2**)

The optimization of insect-proof net then was continued by carrying out the determination of a minimum size of ventilation opening in order to maintain the microclimate and air exchange rate insignificantly changed inside greenhouse (section **5.3**). Since some reasons, such as: possible penetration of unexpected pests (thrips) migrate to the greenhouse through the net, availability of selected insect-proof net at local market and material cost, were taken into considerations, it is possible to determine the optimum ratio of ventilation opening to the floor surface area adequate for tropical greenhouse. The result from the experiment on varying vent ratio from 0.23 to 1.05 seems very interesting that closing vent opening area up to 40 – 60% of total vent opening area did not significantly affect in changing microclimate and air exchange rate in greenhouse.

## 6.2 Performance of adapted greenhouse in tropics

The introduction of adapted greenhouse concept was quite reasonable for the humid tropics. This is mainly addressed to maintain microclimate condition especially the temperature rise inside greenhouse as small as possible even equal to the ambient, thus the application of naturally ventilated system for greenhouse is possible due to the reason of low in capital investment and operational cost. If the ambient temperature reaches the extreme condition such as 35 to 42 °C in hot season (as shown in Fig. 5.1), hot air inside greenhouse should be taken away by an additional means to reduce internal air temperature during that season. Therefore, an adequate size and type of fans is needed to reduce the temperature rise as well as to increase air exchange rate in the greenhouse. Moreover microclimate and air exchange rate in the greenhouse was significantly influenced by the changing of different seasons along the year.

Results from this study (section **5.4**) show that the operation of exhaust fans with the measured capacity of 1,100 $m^3$ $min^{-1}$ (equal to 66,000 $m^3$ $h^{-1}$) during daytime was insufficient to bring the air exchange rate to 60 $h^{-1}$ as recommended by some authors (Albright, 2002, Kamaruddin, 2002). It was measured that the greenhouse volume was nearly 1000 $m^3$, and surface floor area was 200 $m^2$. In order to achieve an ideal air exchange rate at 60 $h^{-1}$, then fans with a capacity of 60,000 $m^3$ $h^{-1}$ would be required. This means that the specification of exhaust fans capacity was technically fitted with the ideally required ventilation rate. In fact, the increase of the air exchange rates (in both empty and full crops conditions) due to the operation of the fans failed to bring up the ideal level of 60 air exchange per hour. The possible reason was that very large opening area on all sidewalls was not effective in sucking the hot air inside the greenhouse (even just around the fans) out through both exhaust fans. On average, the air exchange rate just reached up to 30 and 35 air exchanges per hour in the 78-mesh and 40-mesh greenhouses, respectively. In addition, the reduction of temperature rise at 2 to 2.5% or about 1 K (Fig. 5.38 and 5.41) was obtained as the result of operating exhaust fans during daytime (8:00-17:00h) in the adapted greenhouse ($t = 16.55$, $DF = 29$; $P < 0.0001$). Likewise, a small difference of absolute humidity tested either in 78-mesh or 40-mesh greenhouse was obtained due to the operation of two exhaust fans ($t = 7.27$; $DF = 29$; $P < 0.0001$).

Even though there was a significant effect of operated exhaust fans on microclimate (temperature and humidity), the reduction was quite less compared to that microclimate from natural ventilation. The main reason of this was that the fans were not working to suck hot air inside the greenhouse properly due to the structure having very large opening at both sidewalls. From the observation, the suction of operated fans could be physically detected just 2 – 3 m around the fans and it failed to cover all spaces in the greenhouse. Moreover, the exhaust fans seem effective to work if fans were applied to the greenhouse in which structure of sidewalls were totally closed or having small opening area located just the opposite to the fans (tunnel structure). It can be concluded that the use of exhaust fans operated during daytime had less influence to the microclimate.

However, there was a significant effect caused by the operation exhaust fans during daytime on average air exchange rate if matured tomato crops were grown at LAI of 3.0 ($t = -10.52$; $DF = 29$; $P < 0.0001$). The increment of air exchange rate up to 70% was achieved (Fig 5.40) resulted in the increase of crop evapo-transpiration about 25% ($t = -13.98$; $DF = 29$; $P < 0.0001$). It can be said from the evidence that increasing air exchange rate in greenhouse led to boost crop transpiration rate during the photosynthesis processes. This helps the plants to perform more active in producing more fruits and to maintain their growths. The use of exhaust fans in the full crops greenhouse was more efficient and effective than that in the empty greenhouse because rows formed by the crops (>3.5 m height) might help to direct air moving inside greenhouse to the exhaust fans. Meanwhile, in empty greenhouse air movement just occurred at around two exhaust fans where they were located. As the result no significant difference of increasing air exchange rate was obtained when the exhaust fans were operated during daytime (t = 1.22; DF = 42; P = 0.2283). The reason for this was clear that air movement inside the greenhouse was necessary in case of the temperature difference between inside and outside greenhouse was very low. In a naturally ventilated greenhouse, such temperature difference was required as "buoyancy effect" to generate heat transfer (later to increase the rate of air exchange) and air movement from inside to the outside greenhouse if wind velocity around the greenhouse was quite low (Roy et al., 2002; Kittas et al., 1997). It was measured that wind speed in the greenhouse was quite low at the range between 0.1 and 0.3 m $s^{-1}$.

In this regards, installing additional means either horizontal axial fan (HAF) or positive blower in the greenhouse may be an alternative to improve ventilation system in case extreme temperature was occurred. The main purpose of this effort is to generate air movement inside the greenhouse so that hot air would be easily circulated and then sucked by existing exhaust fans. As it is mentioned before that Mears and Both (2002) used a positive pressure (blowing fans) to enhance the ventilation system in tropical greenhouse with insect-proof net, the HAF can be operated when the crops are still young (small). They further stated that a positive pressure ventilation system with screening can offer several advantages over standard exhaust systems. Maintaining internal greenhouse pressure at high enough pressure that air velocities out through small open doors, or other openings in the structure, exceed the flying speed of the insects of concern should be more effective in excluding insects than an exhaust system which tends to draw insects in through openings. With proper design, insect exclusion can be achieved with only one application of screening at the air inlet and small openings in the greenhouse glazing should not provide easy entry for insect. This concept will be later examined in a particular greenhouse (covered by 52-mesh net) by closing some ventilation opening area with plastic film in order to determine a minimum size of ventilation opening for humid tropics greenhouse (section **5.3**).

In the normal condition, as naturally ventilated greenhouse system, evaluation on the adapted greenhouse had been integrally attempted. With three types of insect-proof nets i.e. 78-mesh, 52-mesh and 40-mesh and three different seasons of the year i.e. hot, rainy and cool season as the main treatment, the evaluation of adapted greenhouse performance can be comprehensively conducted and it would be very helpful for crops cultivation along the year. As the effect of mesh-sizes of nets on exclusion of insect type had been already studied by Bethke (1994), Bell and Baker (1995) and Sase and Christianson (1990), however the knowledge of their effects on microclimate, air exchange rate, plant growth and irrigation system for tropical greenhouse was still not understood very well. In general, it is very interesting result from this study that the use of different mesh-sizes of nets, placed on the ventilation opening, had significantly affected to microclimate and air exchange rate inside greenhouse. Likewise, crop production (total yield, and fruit quality), insect abundances and crop water requirement were also significantly influenced by the use of different insect-proof nets.

It is very clear that the effect of different mesh-sizes of nets have significantly changed internal microclimate and air exchange rate inside greenhouse. Based on the 40-mesh greenhouse, the use of finer insect-proof net (78-mesh) indeed reduced the air exchange rate by 50%, while with 52-mesh has significantly reduced it up to 35%. The reduction might be due to the porosity 78-mesh net was less and the resistance of the finer net was higher compared to 40-mesh so that the accumulation water vapour due to crop evapotranspiration processes can not be easily removed out. In addition, more humidity in the 78-mesh greenhouse was found as the absolute humidity difference in 78-mesh house was highest among other greenhouses (52- and 40-mesh greenhouse (Table 5.2)).

Since absolute humidity difference between in and outside greenhouse in 78-mesh greenhouse was significantly higher (2.3 g $m^{-3}$) than that in the 52- and 40-mesh greenhouse at 1.6 and 1.0 g $cm^{-3}$, respectively, it is obvious that the accumulation of more water vapour in the finer greenhouse had a contribution in reducing air exchange rate. A smaller opening of net would become a resistance for airflow processes from inside the greenhouse or vice versa. If the air temperature in the finer greenhouse was also accumulated, then the potential of incidence of fungal disease should be taken into consideration, especially when crops are cultivated in rainy season.

This result is in line with the findings of Fatnassi et al. (2003); Bailey et al. (2003) and Kamaruddin et al. (2002) 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 net. 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 use of finer meshes of nets for ventilation openings become an obstacle to air flow or air exchange to renew interior microclimate resulting the increase of air temperature and humidity.

The use of insect-proof net, however, might be able to increase the ventilation rate when the ventilation opening is kept to open as large as possible. Therefore, the ratio of ventilation opening area to the floor area is important. For instance, in Hannover, Germany, this value should be more than 0.15 (von Zabeltitz, 1999). In this study, the ratio was 1.05 in order to achieve high air flow rate and improved ventilation system. This is also supported by the result of Muňoz et al. (1999) who remarked 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 (at 40-mesh). Tanny et al. (2003) also emphasized that the ventilation rates at the screen house (no plastic film on the roof) with Bio-Net 50-mesh were higher than the normal greenhouses with the same size.

Concerning to microclimatic condition during rainy season, the average air temperature in the greenhouse covered with 78-mesh during experiment was increased by 1 °C (or 3% increment) compared to the 40-mesh greenhouse, while about 0.5 °C higher was found in the 52-mesh greenhouse (Table 5.2). The internal temperatures among the treatments were mainly different during the daytime, especially at noon time, but their values were very close in the night. This pattern can be seen from the diurnal air temperature in the greenhouses covered by three different mesh-sizes of nets (Fig. 5.7). Similarly, the trend of diurnal absolute humidity was closely related to the trend of air temperature, but it was different during night time. Entirely during the experiment, the means of absolute humidity among mesh-size treatments showed a significant difference ($F=14.87$; $N=92$; $P<0.0001$) whereas the highest absolute humidity was obtained in 78-mesh greenhouse followed by 52-mesh and 40-mesh greenhouse, respectively.

Even though there was less significant difference of air temperature between the greenhouses covered by 40- and 52-mesh, the temperature inside the greenhouse was persistently higher than outside (Fig 5.7). This is true since the long wave radiation reflected inside the greenhouse was unable to get out due to the boundary of cladding material resulting in the increase of accumulated heat which caused the temperature rise inside the greenhouse. 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. Since the number of air renewals per hour was lower in the 78-mesh greenhouse, the increase of air temperature in the greenhouse was also higher compared to the ambient temperature. In this regards, the temperature rise may affect the growth of tomato crops cultivated under the greenhouse for longer period of time, especially in the 78-mesh greenhouse.

In terms of seasons of the year, the study shows that microclimate (internal temperature and humidity) was significantly different from one season to another. During hot season the internal temperature was quite high ranging from 27 to 43 °C with very large variation of relative humidity at 40 – 95%, while in rainy season the high relative humidity (RH) inside was observed ranging from 70 to 96% at temperature in the range of 25 to 33 °C. These two extreme conditions of high temperature and relative humidity are crucial and ought to be taken into consideration in microclimate management, because of their effect on plant stresses (leaf burn problem), potential loss of total yield and fruit quality (section **5.1.3**). In contrast, cultivation along the cool season seems to be the best time for plant growth with favourable climate ranging from 15 to 30 °C (RH between 40 to 95%). As the result the total yield as well as fruit quality can be maximized.

However, outdoor cultivation of tomato production during cool season may encounter several risks. From the experience, the fruit set and the incidents of insect pest (mostly thrips) are two major problems in tomatoes production in humid tropic environment. Microclimate in the cool season might be favourable for fruit set due to lower in temperature, but if the incident of insect pest could not be avoided (the population of thrips was still appeared from experiment) then it will affect to crop growth, yield (production) and fruit quality.

As previous studies were just concerned with the use of different mesh-sizes and their effect on microclimate, airflow resistance and discharge coefficient, the recent study was dealt with their effect on plant growth, crop yield and crops evapotranspiration. Interestingly, a small increase of temperature rise due to the use of finer nets of 78-mesh as cladding material did not significantly affect the rate of plant height at about 0.26 m per week and weekly tomato yield. However, total yield from the 52-mesh greenhouse gave a better fruit production at 4.35 kg $m^{-2}$ compared to the 78- and 40-mesh greenhouses at 2.75 and 2.35 kg $m^{-2}$, respectively. This was because the harvesting time at 52-mesh greenhouse was 2 weeks longer than that in both 78- and 40-mesh greenhouses. Moreover, Dayan et al. (1985) measured cumulative dry matter tomato production in relation with the air exchange rate and reported that these values were well correlated to the photosynthesis rates which are strongly influenced by air exchange rate in the greenhouse. In line with this finding, it is clear that a better total yield of tomato from the 52-mesh greenhouse was greatly also contributed by better air exchange compared to the 78-mesh greenhouse. At the 40-mesh greenhouse actually had a potential for higher total yield but the incidence of insect pests (mostly attacked by thrips *sp.*) was a serious problem (section **5.1.4**).

In addition, the percentage of unmarketable (or defected) fruits was significantly influenced by the use of different mesh-size nets whereas the quality of fruits from the 78-mesh greenhouse was better than that from other greenhouses. Since the incidence of thrips *sp.* pest which was strongly believed as the barrier of virus disease was recorded in all of tested greenhouses, the worst tomato fruits were obtained from the later harvesting time. When the insect pest was trapped in the greenhouse during harvesting time, it was very hard for the plants to recover resulting in a shorter harvesting period because virus disease (brought by thrips) was attacked and easily spread out to entirely plants in the greenhouse. This was mostly common in the trial done during rainy season. From the experiment, the 78- and 40-mesh greenhouses produced very less yield due to unhealthy plants (mostly fungi and black leafmold) and heavy thrips infection, while from the 52-mesh greenhouse a higher tomato yield was obtained.

Therefore, the effort on exclusion from the invasion of some insect pest diseases as well as to minimize their development in the greenhouse is very important in order to achieve the maximum yield. The monitoring on insect population using blue and yellow sticky traps showed that the major problem of thrips *sp*. can not be ultimately blocked using the 78-mesh net (section **5.1.4**). Even though the number of thrips *sp*. trapped in the 78-mesh greenhouse was relatively lower at 11 per 120 $cm^{-2}$ compared to the 52- and 40-mesh greenhouses at 30 and 43 per 120 $cm^{-2}$, respectively, it is evident that its potential hazard after attacking on tomato plant was a serious problem. The shorter harvesting period of time due to heavy plant infection was mainly caused by the incidence of insect pest (thrips *sp*.) which carried the virus disease to the tomato plants in all the greenhouses. This is another fact how the problem should be answered with an appropriate solution. Either crops rotation along the year or adjusting the harvesting time of tomato cultivation to be laid on relatively cooler condition as well as reducing vent opening covered by nets may be an example of some efforts to solve the problem.

In the meantime, whiteflies *sp.* population which was monitored using yellow sticky traps had very low number for all tested greenhouses ($F=0.77$; $N=11$; $P=0.4703$) and the number was averaged at less than 1 per 120 $cm^{-2}$. This indicated that the mesh-sizes of all tested nets were effective to exclude the whiteflies *sp*. invasion. Another possibility is that the population of whiteflies *sp.* outside the greenhouse was quite low compared to other insect's pest such as thrips *sp*. However, the number of this insect population in the greenhouse seems apparent only at the 40-mesh greenhouse even though their numbers were quite less at < 1 per trap (on average). Generally, the number of insect pest population was more in the rainy season when the both temperature and humidity were quite high.

In terms of water requirement, both insect-proof net types and seasons of the year had significantly influenced on water requirement of tomato plants. The crops cultivated inside the greenhouse with a higher air exchange rate will have more transpiration rate hence demanding higher amount of irrigation. This finding was in line with the result from Dayan et al. (1985) that the better air exchange rate encouraged the increasing transpiration rate and photosynthesis processes, thus a higher water requirement of the crops was required. The proper management of irrigation system should be re-evaluated that for a greenhouse with a finer net, less irrigation water should be given rather that in greenhouse with bigger opening net. This is also in order to avoid very humid conditions in the finest net greenhouse when over irrigated was occurred.

Microclimate had much more influence on the water requirement of tomato crops as it was shown from the study that during hot period the average water requirement was 1.77 $\ell$ plant$^{-1}$ day$^{-1}$. This was extremely different from the other condition of rainy and cool seasons averaging at 1.65 and 1.41 $\ell$ plant$^{-1}$ day$^{-1}$, respectively ($F = 8.77$; $N = 92$; $P = 0.0002$). As it can be predicted from the famous model developed by Penman-Monteith (Allen et al., 1998) that water requirement is mainly influenced by microclimate (temperature, relative humidity and solar radiation), the result was also in line with the model. Therefore, decision on applying irrigation water to achieve proper irrigation system in an effective and efficient way based on microclimate (even only relied on the solar radiation) is still acceptable, and the changing of the season along the year should be taken into consideration.

## 6.3 Simulation and modelling in a naturally ventilated greenhouse in the humid tropics

It has been already mentioned that air exchange rate and microclimate are mainly some important parameters influencing to the crops production in the greenhouse. The knowledge about these parameters is become very important in order to manage somehow that the environment inside greenhouse can be maintained to be favourable for crops growth. A better air exchange rate and microclimate inside such greenhouse leads to enhance the $CO_2$ exchange for improving the ventilation efficiency (von Zabeltitiz, 1999) as well as to improve the transpiration rate and photosynthesis processes (Dayan et al., 1985). Therefore, it is very useful if the value of air exchange rate in such greenhouse can be easily determined in just very short period of time. In this case, the development of a model to instantly predict the air exchange rate based on the availability of limited microclimate data and geometric parameter of greenhouse (porosity and vent opening area) will be urgently needed.

Since the greenhouse structure used at present study was totally different to the greenhouses which already have the mathematical models used by several authors (Bailey et al., 2003; Kittas et al., 1997; Roy et al., 2002; Vassiliou et al., 2000; Baptista et al., 1999 and Bartzanas et al., 2004) to predict air exchange rate, a modified model suitable to the adapted greenhouse for humid tropics condition was established. The model was developed from the adoption of the equation proposed by Kittas et al. (1997) in which the model was mainly a function of the combination of chimney effect (temperature difference) and wind speed. The model was also developed in considering to several greenhouse‘s geometric parameters such as screen porosity and the presence of ventilation opening area of roof and side walls where the structure was similar to the greenhouse used for the study. A constant was also introduced to the modified model in order to meet the values of air exchange rate measured from the experiment.

Air exchange rates predicted from the model was then validated using the values measured from the experiment in cool season. A fair agreement was obtained between two. Among the greenhouses covered by three different net-sizes, a better correlation was achieved at the 40-mesh greenhouse whereas total vent opening was larger due to having bigger hole-size of the net. Statistically, in the 40-mesh greenhouse the comparison between predicted and measured air exchange rate was relatively better ($R^2$ = 0.55, N = 67, P < 0.0001) than the other greenhouses (52- and 78-mesh). Both houses showed that correlation between two values was poor. A similar trend of those was also found when the validation was conducted in rainy season.

It is indicated from above evidence that the model was relied very much on wind speed since the correlation between wind speed and air exchange rate in 40-mesh greenhouse was better than other houses. However, a better correlation between two was obtained when sidewalls were particularly closed or vent opening ratio was reduced to 0.2 (Fig. 5.36). This is due to the model was originally applied for the greenhouse with vent ratio less than 0.4 even for tunnel greenhouse. Moreover, the lack of relationship between wind speed and measured air exchange rate (in section **5.2.4)** was mainly the reason why the correlation between predicted air exchange rate from the model and measured ones from the experiment was relatively poor Furthermore, the lack of correlation was due to the large ventilation opening (mostly on sidewalls) of the adapted greenhouse and ignoring wind direction which may affect to the model. Although high wind speeds were recorded, their effect on air exchange rate would be less if the wind direction was not perpendicular to the vent opening of greenhouse or vice versa.

In line with the notice from Kittas et al. (1997) and poor correlation between wind speed and air exchange rate, the prediction conducted under both rainy and hot seasons having wind speed in between 2 to 7 m $s^{-1}$ and the temperature difference at 1 to 3 °C was quite far from the expectation. Their correlation was also poor. This means that wind speed was more dominantly affected to the model than the temperature difference since their relationships between wind speed and predicted air exchange rate was pretty high ($R^2$ = 0.99). In other hand, it was observed that air exchange rate measured from water vapour balance method was considerably influenced by temperature difference.

The portion of main parameters influencing to the predicted air exchange rate from the model whether from chimney effect or wind speed can be clearly explained through Fig. 5.27. From the experiment, a better correlation between air exchange rate and temperature difference was obtained rather than that between air exchange rate and wind speed. In contrast, it is clearly shown from the model that the value of wind speed at more than 1.5 m $s^{-1}$ (for rainy and hot season) obviously gave more contribution to the model than the chimney effect. In cool season, although lower wind speed was recorded (on average 1.5 m $s^{-1}$), it was still dominant influencing air exchange rate than temperature difference.

The influence of temperature difference on air exchange rate was significant when the experiment was conducted in the 78-mesh greenhouse in rainy season. A fair agreement was obtained from the experiment at $R^2$ = 0.5 and 0.63 (Spearman rank test – SAS, 2003). It is important point that air exchange rates were not a linear function but it's an exponential function of against temperature difference. Hence, reducing air temperature difference was not proportional to the increasing air exchange rates. This is might be a main reason why the correlation between predicted values from model was less fitted to the measured air exchange rate from the experiment.

Regarding to the constant, *a*, introduced to the modified model (Equation 4.10), it is interesting to discuss that the constant have been determined from the experiment by comparing the values from the original model to the air exchange measured from the experiment. From validation, it was found to be in between 0.3 and 0.4. This seems the reflection of some values derived from the sensible heat constant of $(1 - \alpha)$ in which $\alpha$ is the Bowen ratio, defined as the ratio of sensible to latent heat occurring in the greenhouse. For humid tropic condition, the presence of latent heat involved in the model can not be ignored, so that the constant of $(1 - \alpha)$ might be very useful included to the model in order to achieve the proper value of predicted air exchange rate. In addition, there are two other possible reasons for the overestimated values from the model. Firstly, the structure of greenhouse might be not identical to the one used by Kittas et al. (1997). Another is that wind speed was actually a minor parameter influencing to air movement inside greenhouse because very low wind speed in the greenhouse ($< 0.1$ m $s^{-1}$) was consistently recorded for all seasons during experiment.

Furthermore, two models which are able to predict microclimate (temperature and humidity) accurately and suitable for tropical condition was developed. It is expected that those are very useful as a rapid tool for assessing the internal microclimate in such greenhouse if a different type (size) of insect-proof net, for instance, would be applied to the adapted greenhouse.

The thermodynamic approach derived from an energy balance and water vapour balance methods which involve all major heat fluxes taking place in a greenhouse was used to develop these models. To simplify the complex processes of both heat and water vapour fluxes occurred in the greenhouse, some assumptions and ignoring less important factor involved to the model had been made. As the result, these models were mainly a function of air exchange rate and net solar radiation.

A good correlation between predicted and measured microclimate was achieved as the value of coefficient of determination ($R^2$) was between 0.8 and 0.9 (N = 92; P < 0.0001; SAS Institute, 2003).

Internal air temperature, for example, can be easily determined using a simplified model at any greenhouses covered by different insect-proof net sizes. In terms of seasons of the year, generally their relationships between two was also quite good for any seasons. The best relationships between two was achieved in the hot season when the sensible heat (temperature difference) was more dominant than latent heat. Meanwhile, predicting air temperature along the cool season was a little bit overestimation along the experimental period of time. The reason for this may be due to the estimation of the Bowen ratio ($\alpha$) was too low.

In detail, the assumption of overall heat loss coefficient used in this model was also quite excellent to predict air temperature for both treatments of net-sizes and seasons of the year. The constant was taken from the formula of [$2.97\Delta T^{0.33}$] for screened greenhouse (Miquel et al., 1998) or at averaged value of 4.27 W $m^{-2}$ $K^{-1}$. So, it can be inferred that the prediction of internal air temperature using the model was generally to be accepted method to predict air temperature accurately.

Another simple equation derived from water vapour balance in greenhouse model to predict internal humidity was validated with the measured ones. A good correlation ($R^2$ between 0.72 and 0.89) was obtained at any greenhouses covered by different net-sizes. During the experiment, a better correlation between two was performed when the validation was conducted in the greenhouse with fully-mature plants (LAI > 1.0) as shown in Fig. 5.25, but poor at the beginning of experiment (LAI < 1.0). This indicated that the ratio of sensible and latent heat involved in the greenhouse model was very significant. Therefore, for better result, the prediction of internal humidity in such greenhouse would be more accurate when the latent heat was more dominant than sensible heat. Conversely, the prediction of internal air temperature using the model would be very accurate if condition in greenhouse was represented the domination of sensible heat over latent heat.

To examine the value of the Bowen ratio ($\alpha$), a further analysis from the energy balance greenhouse model was performed (Fig. 5.26). The figure clearly shows that the major component contributing to the total heat losses was caused by ventilation processes via both sensible and latent heat fluxes at 80 to 95%. The rest will be the component of heat loss due to soil substrate and photosynthesis from the leaf ranging from 2 to 12% and 0.5 to 4.3%, respectively. In terms of percentage, the average component of total heat fluxes (losses) was 35% for sensible heat, 55% for latent heat, 7% for soil substrate heat and 3% for photosynthesis processes, respectively. So, if both minor components of heat losses from energy balance approach will be taken into account, the maximum error was about 10% (on average). During the experiment, a large error occurred in the beginning of plant stage when the plants were very young with very less crop evapotranspiration processes; therefore the sensible heat fluxes were more dominant than the latent heat fluxes. In this case, the prediction of air temperature was better than humidity because their values of humidity from the model were overestimated. On the other hand, the latent heat fluxes were more dominant than sensible heat fluxes when the plants were bigger with actively higher transpiration processes (LAI > 1). In this respect, the prediction of internal humidity was quite well to the values measured from the experiment.

In addition, neglecting the heat losses due to photosynthesis from energy balance greenhouse model is quite reasonable because its contribution is only about 4.3% of the net radiant energy ($R_n$). This estimation was obtained through the measurement of dry matter from harvested sample plants each week. According to Montheith (1972), an estimate of the magnitude of this energy rate can be made through the energy content of dry matter (about $17.5 \times 10^6$ J kg$^{-1}$) and the photosynthetic efficiency, i.e. the energy stored in dry matter expressed as a fraction of incoming radiant energy. If the typical efficiency of leaf absorption in the PAR (photosynthetically active radiation: $400 < \lambda < 700$ nm) of ($\approx 0.85$) and the ratio of PAR to total solar radiation of ($\approx 0.5$) are taken in to account, a typical photosynthetic efficiency in terms of incident solar radiation is, therefore, between 4 and 7% (Stanghellini, 1987). It can be said that the estimation of heat loss due to photosynthesis at 4.3% above, in this study, is within the range proposed by Stanghellini (1987). With the combination of error estimated from heat fluxes to soil substrate at maximum 10% of the net radiant energy, then the main portion of heat loss from total gain from net solar radiation will be the composition of both sensible heat and latent heat. The use of a constant value of $\alpha$ = 0.7 to these models seems to be acceptable to predict internal microclimate as their relationships between predicted and measured values remains good at $R^2$ between 0.8 and 0.9.

For the model applicability, these models presented in this work employ four external climatic variables (wind speed, solar radiation, outside air temperature and outside relative humidity) as the main inputs. These variables can be easily measured in most agricultural weather stations. To determine net radiation inside the greenhouse, the multiplication of solar radiation by the plastic film's transmissivity from the roof can be considered. Thus, in principal, the model can be used to predict the internal climatic conditions for a greenhouse with similar configurations to the adapted greenhouse in virtually all regions in the humid tropics. Some input parameters for these models should be strictly followed in order to achieve the proper and accurate results. The changing of some constants to be used to these models can reduce the accuracy of predicted values.

## 6.4 Optimum arrangement of vent opening ratio

An experiment on varying the ventilation opening was conducted to evaluate the performance of ventilation system of the adapted greenhouse designed for tropical condition. It is not the case that the arrangement of ventilation opening to be as large as possible even the application of totally opened vent area (screen house) will assure the best performance. If some constraints would be considered, an optimization of ventilation opening area should be carried out. The following concerns were taken into account why the experiment had been done:

- the material cost of insect proof net; because the most expensive part of greenhouse components is at the ventilation system,
- the potential of smaller insect pest infestation; with larger vent opening there is a possibility of smaller insect may attack through the net hole,
- the performance of exhaust fans is necessary to improve in order to meet ideal air changes per minute at 0.75 – 1.0 (ASAE, 1989) and only a smaller vent opening is more effective to enhance the suction of exhaust fans.

Based on those reasons, the determination of minimum ventilation opening area for the adapted greenhouse in tropical condition will be very useful, because there is no single recommendation of ventilation ratio so far to be applied to adapted greenhouses which are mostly located in lowland and humid tropical region. 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% (White, 1975; Hanan, 1998), in USA at 15 – 25% (ASAE, 1989) and other place at 30 – 33% (Montero et al., 2001).

The minimum vent ratio was determined by closing some particular vent opening areas covered by insect proof-net with PE-plastic film. The ventilation ratio was varied from originally 1.05 to 0.2. A good result had been achieved from the experiment that closing the ventilation opening by 60% (ventilation ratio of 0.6) did not have a significantly effect on air temperature ($F = 8.22$, $N = 10$, $P < 0.0001$) and changing the relative humidity for both fully tomato plant condition (Fig. 5.32) and empty condition greenhouses (Fig. 5.33). Similarly, air exchange rates were not also significantly reduced in both fully crop greenhouse ($F = 5.23$, $N = 10$, $P = 0.0015$) and empty greenhouse ($F = 29.90$, $N = 10$, $P < 0.0001$) when the ventilation ratio was reduced to the 0.6 level. Please note that these findings was carried out in the greenhouse covered by 52-mesh (with the porosity of 0.38). For different net-sizes, 78-mesh net for instance, the minimum vent opening area requires bigger than 60%. The parameter of porosity may be helpful to predict the minimum vent openings for greenhouse covered by 78-mesh net. If the correlation were linear, for 78-mesh having the porosity of 0.30, the minimum vent opening ratio would be about 0.76. The similar method can be applied if lower net-size of 40-mesh for example would be used for covering ventilation opening.

According to the valuable findings achieved from the recent study, it is very clear that the arrangement of ventilation ratio at minimally 60% gave unchanging microclimate and air exchange rates in the humid tropic greenhouse. This means that about 40% of material cost contributed from the use of insect proof net would be saved as the capital cost from this effort. It is noticed that the price of insect-proof net is extremely higher than the UV-stabilized plastic film as cladding material. The Bio-net (52-mesh net), for instance, has the material price of 2.5 times higher than the price of UV-absorbing plastic film; even the Econet-T (78-mesh net) is 4.5 times more expensive than the cost of the same plastic film. Moreover, more saving can be achieved if the normal PE-plastic film, which is commonly used and relatively cheaper than the UV-absorbing plastic film, is used.

The explanation on the effect of vent ratio on crop transpiration rate seems to be difficult to figure out. This is because all treatments of vent ratio were not carried out at a similar condition in the greenhouse. The adjustment of vent ratio from 1.05 to 0.2 was done when plants were still growing. This may affect to transpiration rate even though the increment of plant height was recorded very small (< 0.1 m weekly). In general, it can be said that almost no significant effect of vent ratio on crops transpiration rate ($F = 2.49$, $N = 10$, $P = 0.0562$). This parameter was then minor in determining a minimum size of vent opening area. Therefore, based on microclimate and air exchange rates, the arrangement of vent opening area to be minimally 60% of surface floor area is acceptable for humid tropical greenhouse.

From the configuration, the arrangement of vent ratio of 0.6 was that the lower pat of sidewall was opened. Vent ratio at below 0.6, the sidewalls were totally closed. It can be inferred that sidewall openings played an important role for improving ventilation system. The sidewall opening was assumed to be the entry point of ambient air flowing to the greenhouse, while roof opening was supposed as discharging hot air from the greenhouse. Hence, the combination of both sidewall and roof openings at the minimum vent ratio of 0.6 was believed to be the best combination of ventilation opening for naturally ventilated greenhouse in humid tropical region.

It is noticed that the experiment was conducted in 52-mesh greenhouse having the porosity of 0.38. The adjustment or even a similar experiment is necessary if the other net size will be applied to the greenhouse as cladding material. For the 40-mesh greenhouse (screen porosity of 0.41), for example, the minimum ventilation ratio would be lower than 60% as the results revealed from the study. Conversely, for finer net (78-mesh), the minimum ventilation opening area should be arranged even more than 60% of surface floor area in order to compensate the changing of microclimate and air exchange rate due to the use of the net.

# 7. Conclusions

In general, the use of different mesh-size of insect-proof net as cladding material over ventilation opening has a significant effect on microclimate, air exchange rate, crops performance (total production and fruit quality), insect disease infestation, and crop water requirement. The reduction of air exchange rate 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 also increased by 1 to 3 °C. Even though, a small temperature rise was observed, the absolute humidity among treatments was significantly different. The use of a higher mesh-size resulted in more humidity. The use of finest hole-size of insect-proof net significantly increased internal air temperature and absolute humidity during day time which might promote the incident of fungal diseases.

In terms of total production and fruit quality as well as the ability to exclude smaller insect disease, the 52-mesh greenhouse performed better results than both the 78-mesh and 40-mesh greenhouses. Thus, the 52-mesh has been chosen as a compromise size appropriate for the adapted greenhouse in humid tropical region. Compared to the 40-mesh, the use of 52-mesh of nets did not largely change microclimate and air exchange rate inside the greenhouse, but it was better in protecting against insect pests (thrips and whiteflies). In comparison to the 78-mesh greenhouse, the 52-mesh greenhouse performed a better crop yield and similar fruit quality although 78-mesh house was better in protecting thrips.

The season of the year has also a significant effect on the internal microclimate, air exchange rate, crop production, insect-pest abundance and irrigation water requirement in the greenhouse. For the scheduling of the cropping period, the fact that maximum yields and highest fruit quality only could be achieved when fruit set is planned to be in cooler periods. Furthermore, cultivating under the rainy season encountered some potential hazards on booming population of serious insect pest of thrips *sp.* which was believed carrying the virus diseases to the crop. The other diseases such as: fungi and black-mould leaf was also observed during the season.

The operating of exhaust fans during daytime to reduce internal temperature as well as to increase air changes rates has been tested. The small reduction of air temperature at 1 – 2 °C as well as the increase of air exchange rates at 25 – 75% was obtained due to the use of exhaust fans during daytime. However, the significant increase still can not bring air exchange rates to the ideal value of about 45 – 60 air changes per hour (ASAE, 1989). Moreover, the operation of exhaust fans conducted in the greenhouse with small crops had less effect on the reduction of internal air temperature even though its effect was significant.

Since the very large ventilation opening (mostly on sidewalls) was applied to adapted greenhouse in order to maintain air temperature close to the ambient temperature, the external wind speed showed less effect to the air exchange rates. However, a fair correlation was found between air exchange rates and wind speed whereas the air exchange rates were a linear function of wind speed. Similarly, the relationship between air temperature difference between inside and outside the greenhouse and measured air exchange rates was also less, although a fair correlation was found at the finer net greenhouse. The effect of temperature difference on air exchange rate was better correlated if the daily average wind speed was less than 2 m $s^{-1}$. In this regards, a model developed from a combination of both temperature difference and wind speed was used to predict air exchange rate. A fair agreement ($R^2$ = 0.55) was obtained when the model was validated using air exchange rate data from the measurement. The model was unable to predict air exchange rate accurately in such greenhouse when averaged wind speed was recorded at more than 2 m $s^{-1}$.

Two simple models developed using energy balance and water vapour balance methods based on the weather station data such as temperature, relative humidity and solar radiation, were used to predict internal microclimate (temperature and humidity) in humid tropical greenhouse. The simulation using these models showed a good agreement ($R^2$ was about 0.8 to 0.9) with the microclimate directly measured from the experiment. More accurate prediction of internal temperature and humidity was achieved when these models were validated using the proper value of air exchange rate in respective period of time and the Bowen ratio ($\alpha$) whereas the matured crops were planted in the greenhouse (LAI > 1).

Finally, in order to further reduce the material cost and to inhibit the potential attack of smaller insect disease to the greenhouse, the determination of minimum ventilation opening was performed. The results revealed that the minimum ventilation opening area at 60% of total surface floor area is necessary to maintain microclimate and air exchange rate favourable for plant growth in the adapted greenhouse. The combination of sidewalls and roof opening played a significant role in enhancing ventilation system for naturally ventilated greenhouse under humid tropical condition.

# 8. Recommendations

The following attempts may be very helpful to improve the existing ventilation system and to further reduce the internal temperature in tropical greenhouse based on the present studies:

– The installation the proper size of horizontal axial fans in the adapted greenhouse would be very useful to maintain pressure difference and airflow inside the greenhouse. The improvement of air exchange rate then will be expected from this effort.

– Since all types of tested nets were not ultimately proof-nets against smaller insect pest *(*thrips*)*, the use of the insect-proof net at size of 52-mesh seems a compromised choice. Moreover, 52-mesh greenhouse showed a better performance in terms of tomato production, air exchange rate and microclimate.

– It is very important that the determination of a good opening efficiency is essential because the large part of the greenhouse construction cost is due to the cost of the vent openings (insect-proof net). The configuration of sidewall and roof openings with minimum ratio of ventilation opening to floor surface area of 0.6 was to be the best arrangement in order to maintain microclimate and air exchange rate favourable for plant growth.

– The effort on reducing internal air temperature greenhouse such as: applied near infrared (NIR) absorbing plastic and floor coloured mulch could be attempted.

– Since a number of mesh sizes of nets used for present study was limited, it is suggested that a further research on the optimization of insect-proof net seems to be promising and optimistic when more net-types were involved towards the study.

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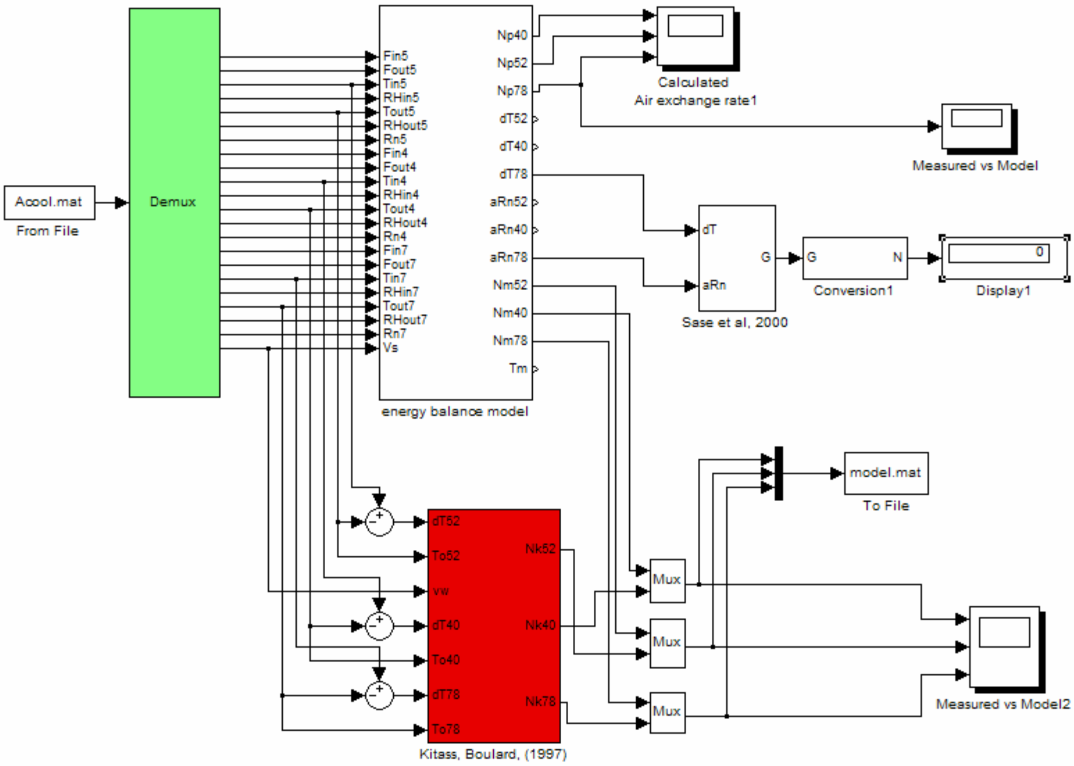
# Appendixes

### Table A-1: Technical specification of the tested insect-proof screen nets used for study

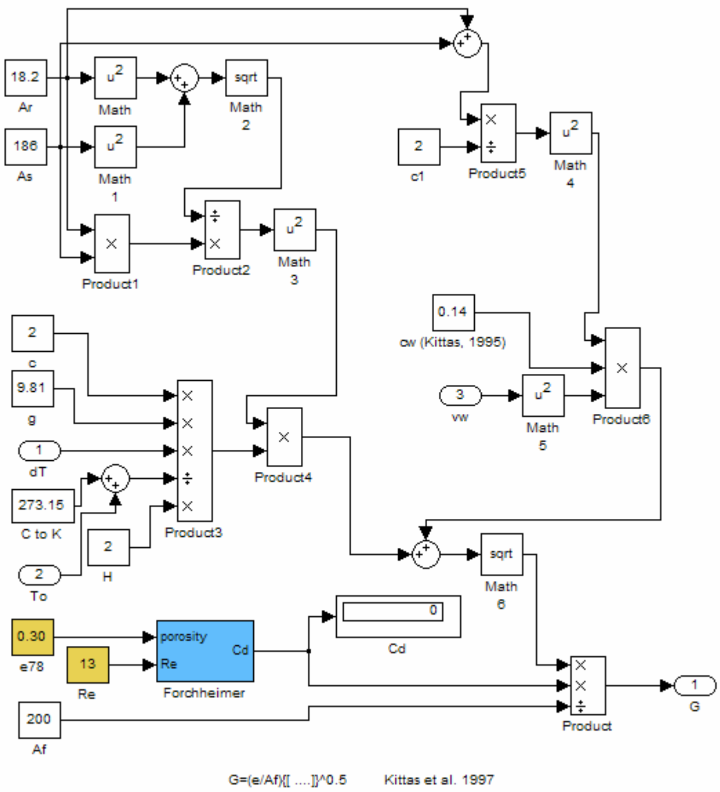
| Parameter | 40x38 – mesh | 52x22 – mesh | 78x52 – mesh |
|---|---|---|---|
| - Trade name | LS Econet M | LS Econet | LS Econet T |
| - Company | Ludvig Swensson | Ludvig Swensson | Ludvig Swensson |
| - Longevity (years) | 5 to 8 | 5 to 8 | 5 to 8 |
| - Price ( € $m^{-2}$) *) | 1.50 | 1.70 | 2.99 |
| - Airflow reduction (%) | 35 | NA | 47 |
| - Measured airflow reduction (%) | 38 **) | 44 **) | 56 **) |
| - Light transmission (%) | 90 | 85 | 85 |
| - Measured light transmission (%) | 87 ***) | 70 ***) | 86 ***) |
| - Hole size (in mm) | 0.40 × 0.45 | 0.35 × 0.6 | 0.15 × 0.35 |
| - Measured hole size (in mm) | 0.39 × 0.44 | 0.25 × 0.8 | 0.17 × 0.29 |
| - Hole size (in $mm^2$) | 0.18 | 0.22 | 0.05 |
| - Measured hole size (in $mm^2$) | 0.17 | 0.20 | 0.05 |
| - Measured thread diameter (mm) | 0.25 | 0.31 | 0.19 |
| - Measured net thickness (mm) | 0. 38 | 0. 39 | 0. 28 |
| - Discharge coefficient, Cd (-) | 0.31 | 0.28 | 0.22 |
| - Calculated Cd (-) | 0.31 ****) | 0.28 ****) | 0.21 ****) |
| - Calculated screen porosity ($\varepsilon$) | 0.41 | 0.38 | 0.30 |

Note: *) the price of an UV-stabilized plastic film is 0.68 € $m^{-2}$.
**) measured by Ajwang (2005).
***) measured by Klose and Tantau (2004).
****) calculated based on the Forchheimer equation (Bailey et al., 2003) with Re≈13 Klose and Tantau (2004) or Re<40 (Teitel and Shklyar, 1998).

## Figure A: Simulation model for predicting air exchange rate

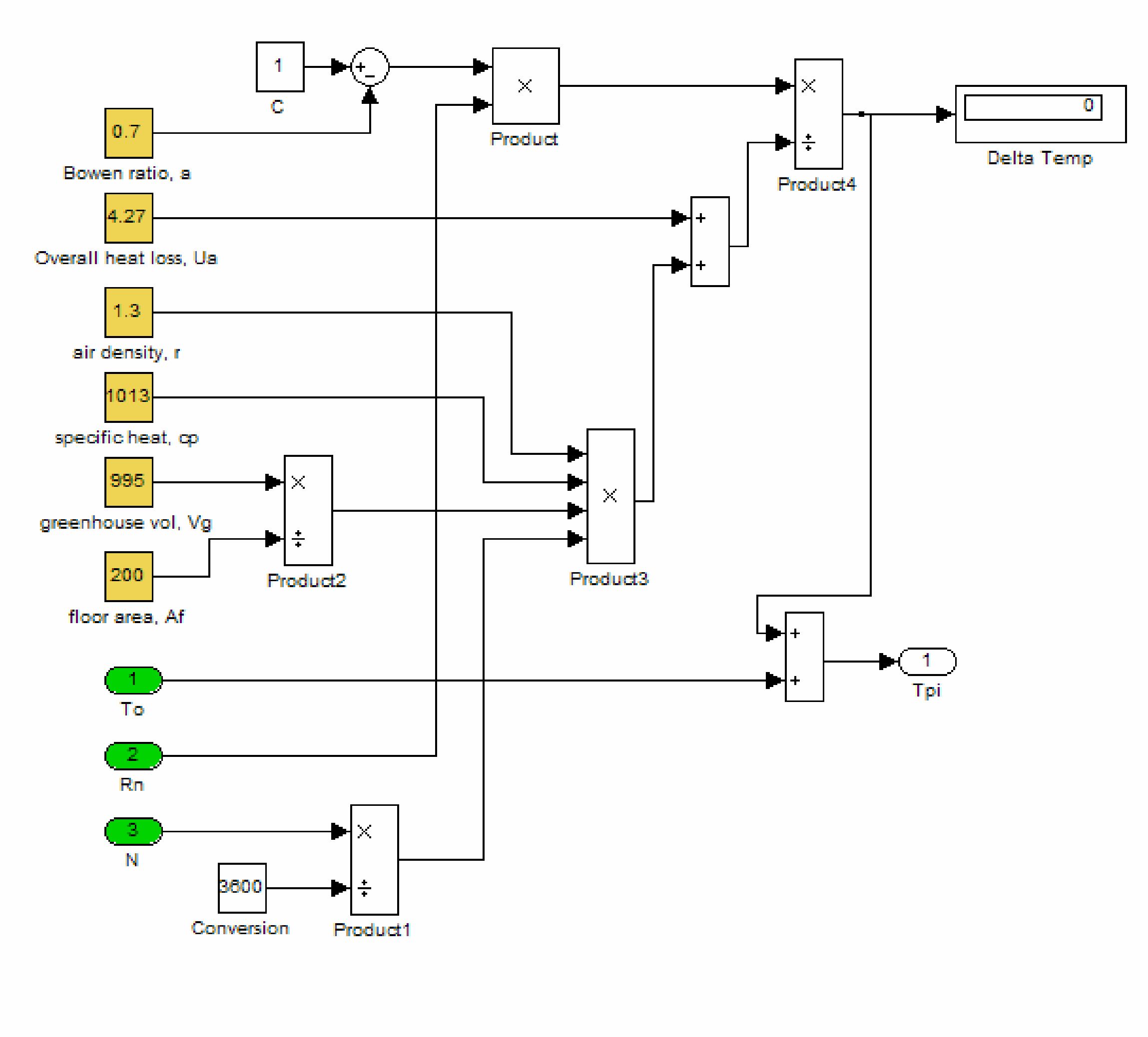



### A-1: The model for predicting air exchange rates of three selected greenhouses covered with different nets sizes.

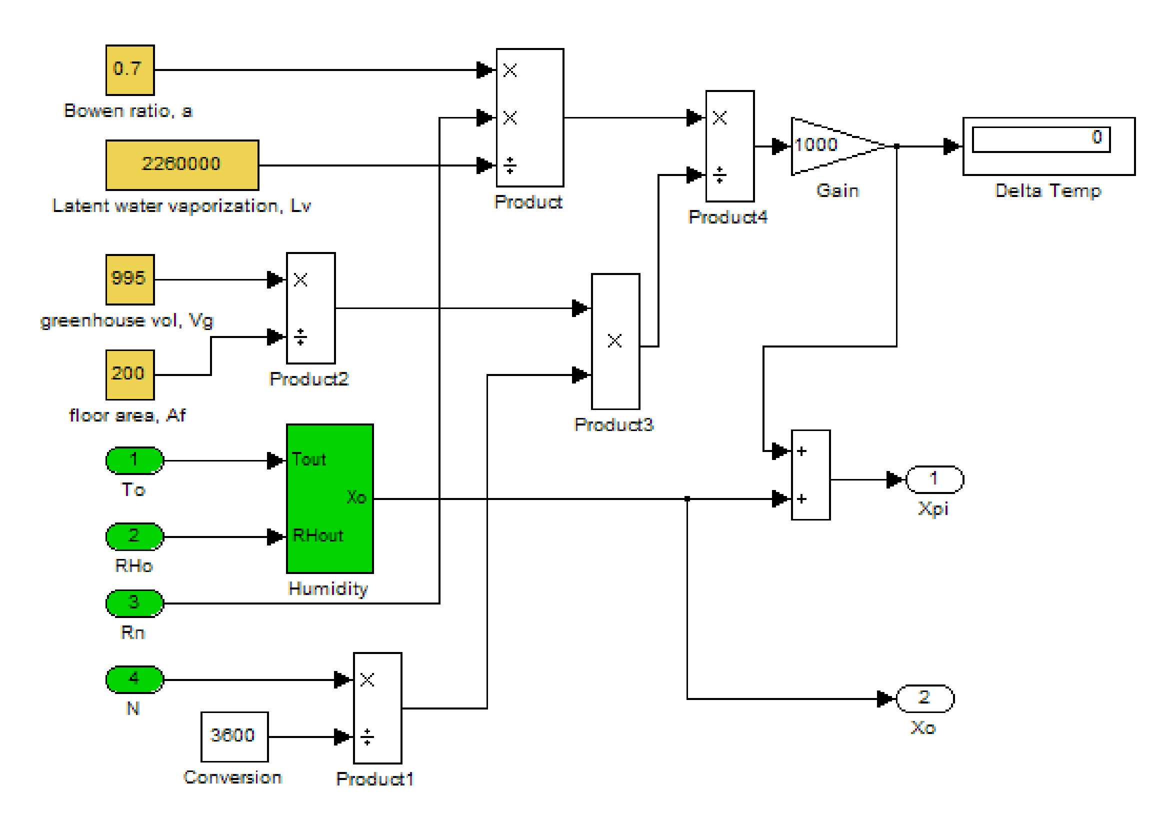



### A-2: A sub-system model to predict air exchange rates in the particular greenhouse covered by 78-mesh net.

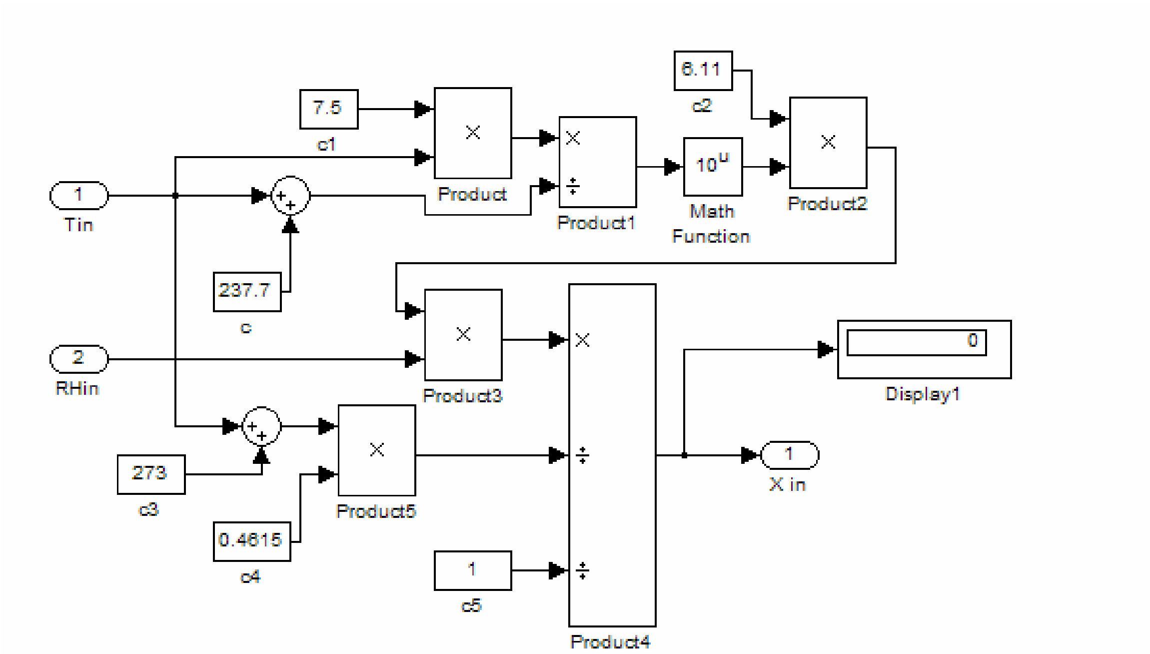
## Figure B: Simulation model for predicting internal air temperature



## Figure C: Simulation model for predicting internal humidity




### C-1: A water vapour balance model to calculate internal humidity




### C-2: A sub-system model to calculate absolute humidity based on air temperature and relative humidity measurements.

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# Curriculum vitae

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- Harmanto, H. J. Tantau, and V.M. Salokhe, 2006. Influence of Insect Screens with Different Mesh Sizes on Ventilation Rate and Microclimate of Greenhouses in the Humid Tropics. Agricultural Engineering International: the CIGR Ejournal. Manuscript BC 05 017. Vol. VIII. January, 2006.
- Harmanto, Salokhe, V.M., and M.S. Babel, 2003. Estimating Crop Water Requirement in Tropical Greenhouse: Evapotranspiration and Micro Climate Approaches. Agricultural Engineering Journal, Vol. 1 No. 1, April 2003.
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