A Simulation Model for Functional Design of Insect-Proof Greenhouses for the Humid Tropics

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Abstract - A simulation model based on energy and mass balance method was developed in MATLAB\SIMULINK in order to predict the effect of insect-proof screen properties on climate in naturally ventilated greenhouses in the humid tropics. The model uses the four commonly measured weather parameters (wind speed, global solar radiation, air temperature and relative humidity) as input variables. The model was used to evaluate the effects of discharge coefficients (Cd) and area of insect-proof screen materials on greenhouse climate**.** The discharge coefficients of the insect-proof screening materials were determined by relating static pressure drop and airflow rates using the Bernoulli and continuity equations. External and greenhouse climate measurements were made at the Asian Institute of Technology (AIT) campus in Bangkok, Thailand. The internal climate measurements were made concurrently in two similar, naturally ventilated greenhouses covered with different insect-proof screens on ventilation openings. Tomato (*Lycopersiconesculentum* 'KingKongII') plants were grown in the greenhouse during the experimental period. Model predictions of greenhouse air temperature were then compared to the measurements from the two greenhouses and good agreement was achieved. The results show that insect-proof screens with discharge coefficients between 0.2 - 0.3 would provide adequate ventilation for the screened greenhouse prototype investigated in this study.

Keywords: Energy and Mass Balance Model, Insect-proof Screens, Greenhouses, Humid Tropics

I. INTRODUCTION

Protected cultivation offers a promising approach to sustainable vegetable cultivation in the humid tropics. Some studies have shown that with well managed protected cultivation systems tomato yields can be more than double compared to the yield of open field (Anais et al. 1997). Therefore, greenhouse systems which can provide the optimal plant growth environment while offering maximum protection against pests need to be developed. The use of insect-proof screens on greenhouse vent openings as a physical protection against pests is an increasingly popular approach to achieve this objective. However, the insect-proof screens affect the ventilation efficiency hence climate of the greenhouse. Several important questions therefore arise from a horticultural engineering perspective: Which pests can be excluded by a particular insect-proof screen?

What is the optimal ratio of insect-proof screen area to greenhouse floor area? What reduction in airflow would occur due to the use of a particular insect-proof screen? What is the effect of the reduction in airflow on greenhouse climate (air temperature and humidity)? Lastly, how do these changes in climate affect the crops in the greenhouse e.g. with regards to leaf temperature, evapotranspiration and growth?

Considerable research efforts have been devoted to finding answers to the questions posed above. For example, the pest exclusion efficiency of various insect-proof screens has been investigated (Bethke 1994, Bell and Baker 1997). These studies established the dimensions of screen holes that would be effective in preventing infestation of greenhouses by insects of various sizes. Antignus et al. (1998) investigated the efficacy of plastic screens with ultra-violet spectral absorbency in the UV-A and UV-B range (bionets) in comparison to conventional nets of the same mesh size for protection against vegetable insect pests and spread of virus. Research on coefficients of discharge (which characterizes the ventilation efficiency of openings) has been conducted by several authors (Sase and Christianson 1990, Montero et al. 1997, Munoz et al. 1999, Mears and Both 2001, Teitel 2001, Fatnassi et al. 2001 and Demrati 2001). Several simulation studies have

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shown that greenhouses with insect-proof screens placed on side and roof ventilation attain higher air temperatures compared to greenhouses with no screens on the openings (Teitel, 2001 and Fatnassi et al. 2003).

Most of the above studies have been done using insect-proof screened greenhouses in the temperate regions. There has been a gap in the literature with regard to insect-proof screened greenhouses for the humid tropics. Further, although the use energy and mass balance models provides an integrated approach to predicting greenhouse climate hence form a good basis for functional design of greenhouses, it has not been applied to the case of insect-proof greenhouses in the humid tropics. The present study was therefore geared towards developing and validating an energy and mass balance model that can be used for design of insect-proof screened greenhouses in the humid tropics, with a special emphasis on the effect of discharge coefficient of different screens on the greenhouse systems (Ajwang, 2005).

The energy and mass balance approach for predicting internal greenhouse climate is based on the first law of thermodynamics. For a system that does not involve mechanical work, such as an unheated greenhouse, the law states that any increase in the intrinsic energy of a system is equal to the algebraic sum of the energy flows to and from it. The term energy balance is used to refer to the mathematical analysis of the gains, losses and storage of energy by an object. With the exception of solar radiation, the energy fluxes created by the individual heat transfer processes can be formulated in terms of differences in temperature (DAY and BAILEY, 1999). Thus, in principle, if the temperatures of all the objects which interact with an object are known, it is possible to determine the temperature of that object by solving its energy and mass balance equations.

II. MATERIALS AND METHODS

Field experiments were carried out at a purposely-built greenhouse complex at the Asian Institute of Technology (AIT) which is located approximately 42 km to the north of Bangkok in Thailand. The 200 m2 greenhouse (see fig. 1) had surface area to floor area ratio of 2.25. It was fitted with ant-insect screen on the ventilation openings, i.e. on both the wall and roof openings. It had optional ventilation fans which were not used during the experiments. The total area of the screened ventilation openings was 228 m^2. The rest of the surface area of the greenhouse was covered with polyethylene film.

Tomato plants were grown in pots placed at 1.60 m spacing (between rows). A drip fertigation system was installed to supply water to the plants. Automatic control of the drip fertigation system was achieved through the use of solenoid valves. Irrigation control was based on radiation sum.

III. Experimental Measurements

Light transmission of the nets and plastic films was determined using a photometer. The dimensions of the screen holes were adopted from measurements by KLOSE (2002). In order to calculate the discharge coefficients of different screen materials, airflow and pressure drop measurements were carried out using a wind tunnel set-up. Discharge coefficients were determined by relating the pressure drop to airflow using the Bernoulli and continuity equations as outlined by Ajwang et al. (2002).

Greenhouse air temperature and relative humidity measurements were achieved using aspirated psychrometers. Two psychrometers were installed in each greenhouse at a height of 1.5 m above ground level. Leaf temperature was estimated using the regression model by Wang and Deltour (1999). Global radiation was measured using solarimeters from Kipp and Zonen Ltd, Delft, Netherlands. For outside global radiation measurement, the solarimeter was positioned at 1 m height. In the greenhouse, the solarimeters were positioned above the plant canopy on the rails. Wind speed measurements were made using a cup anemometer with a measuring range of 0.5-50 m/s from Thies Klima GmbH, Germany. The instrument was mounted on 8 m high mast next to the greenhouse complex in an area free of obstructions. All the instruments were connected to MCU-ITG 1996 data logger developed by the Biosystems and Horticultural Engineering Section of the Liebniz University Hannover. The data loggers in the greenhouses were connected to one central computer via a RS-485 bus cable. All the data from the sensors were sampled at 15 second intervals and mean values computed at 30- minute intervals were recorded on the computer.

Data Analysis A coupled energy and mass balance model of the greenhouse air was built using the MATLAB\SIMULINK toolbox (Mathworks, 1991). Greenhouse ventilation rate calculation was based on wind and buoyancy model according to Kittas et al. (1997).The wind effect coefficient was assumed to be 0.09 based on literature (Boulard and Baille 1995, Baptista at al. 1999). Greenhouse evapo-transpiration was estimated using the Penman-Monteith equation for greenhouse tomatoes presented by Boulard and Wand (2000). Other equations for the model were obtained from standard greenhouse engineering literature (Ajwang, 2005). The model uses four weather parameters as input variables namely; wind speed, global solar radiation, outside relative humidity and outside air temperature. The effect of the changes in several parameters including the discharge coefficient of screens, leaf area index (LAI), and ratio of vents to screen area could be examined using the model. The model outputs include predicted greenhouse air temperature, relative humidity, evapo-transpiration rate, vapour pressure deficit and ventilation rate.

Using weather data obtained from the AIT campus in Bangkok between 10th -14th August, 2003, scenario simulations were carried out to examine the effect of discharge coefficient on ventilation rate, temperature and vapour pressure deficit (VPD). It was assumed that the greenhouse had a tomato crop of leaf area index 4. The total opening of the screened area was taken to be 228 m2 (same as the actual total screened area on the experimental greenhouse).

Data for validation of the energy and mass balance model was obtained from the experimental site during the period between 15th and 29th August, 2003. Measurements were made concurrently in two greenhouses covered with screens of different mesh - 78x52 and 40x38 (abbreviated as 78- and 40-mesh respectively in the following paragraphs). Tomato plants were planted in both greenhouses on 10th August 2003 such that leaf area index (LAI) of plants in the two greenhouses were the same during the experimental period. The values of LAI for different growth stages were adopted from the work of KLEINHENZ (2003).

IV. RESULTS

Properties of insect-proof screens Figure 2 shows the relationship between approach velocity and static pressure drop for an opening fitted with different insect-proof screens. For the same approach velocity values, the static pressure drop is higher in screens with small hole sizes such as Econet S. This implies that screens with small hole sizes offer higher resistance to airflow than those with large hole sizes. The static pressure drop across screens is important in the design of forced and natural ventilation systems apart from being used in the determination of discharge coefficients.

Table 1 shows a summary of the air permeability, hole size and percentage ventilation reduction of the insect-proof screens that were tested in the laboratory at the Liebniz University Hannover. Screens with small hole sizes had the smallest discharge coefficients. The lowest discharge coefficient was that of Econet S which is an anti-thrips screen while Econet B which has the largest hole size has the largest discharge coefficient also. For the 78- mesh and 40-mesh screens used in the experiment, the discharge coefficients were determined to be 0.22 and 0.32 respectively. The discharge coefficient of the opening without insect-proof screen was 0.5 and formed the basis of calculation of reduction of ventilation. A logarithmic relationship was established between the discharge coefficients of the screens and their hole size in mm2. Fig. 3 illustrates the relationship. Using the relationship, the discharge coefficient of very small hole sizes (less the 0.05 mm2) tend to be close to zero. For hole sizes greater than 4 mm2 the discharge coefficient approaches 0.5 asymptotically.

Model validation In fig. 4 it can be observed that the air temperature in the two greenhouses was generally higher than the outside air temperature. Larger differences between the greenhouse air temperature and the outside air temperature is evident during the day. During some periods the difference between inside and outside air temperatures was as high as 5 ^{o}C. In the evenings and at night, the recorded inside and outside air temperatures were comparable. The temperatures recorded in 78-mesh greenhouse were generally higher than in the 40-mesh greenhouse during periods of high irradiance. During night time, the differences in temperature between the two greenhouses were minor. Larger differences in temperature were registered during the day time, with the highest difference of about 3 ^{o}C between the two greenhouses.

Model predictions of the air temperature in the two greenhouses were in good agreement with the measured values (see fig. 5). Differences between the predicted and measured values were more pronounced during the day-time. Over-predictions and under-prediction of temperatures are evident from the figure suggesting the randomness of distribution of the simulation errors. Both the measured and predicted temperatures in the 78-mesh greenhouse were marginally higher than those in the 40-mesh greenhouse. The result suggests that the discharge coefficients of 0.22 for 78-mesh greenhouse and 0.32 for the 40-mesh greenhouse satisfactorily describe the restriction of air flow in the two greenhouses. The correlation coefficient for measured and predicted temperature in the 40-mesh greenhouse was 0.89 (fig 6).

In the 78-mesh greenhouse the vapour pressure profiles predicted were higher than in the 40- mesh greenhouse (fig.7). The higher vapour pressure deficit in 78-mesh greenhouse is attributable to higher temperature in the greenhouse. Higher values of vapour pressure deficit are predicted when plants have small LAI than when the LAI is large. In the day time, the vapour pressure deficit was generally above 2 kPa in both greenhouses.

Simulation of effects of discharge coefficients

Figure 8 illustrates the effect of discharge coefficient on greenhouse ventilation rate. Discharge coefficients above 0.2 generally provide ventilation rates above 0.75 volume changes per minute which can be considered adequate. However, the ventilation rate is strongly dependent on wind speed as is implicit from the fluctuations on the graph.

Discharge coefficients of 0.3 and above resulted in ventilation rates of about 1 volume change per minute and above. But given that the nets with discharge coefficients of 0.3 and above are likely to be penetrated by smaller insects like thrips it would not be safe to use them under field conditions. Therefore, to provide adequate ventilation for cooling while preventing the entry of harmful insects into the greenhouse, the discharge coefficients of the openings should be between 0.2 to 0.3.

The effects of discharge coefficient on greenhouse air temperature are illustrated in figure 9. The lowest temperatures are predicted for the highest discharge coefficient i.e. 0.5. On the other hand, when the discharge coefficient is 0.01, the predicted temperature rises significantly depending on the external weather conditions, principally solar radiation and wind speed. A difference in temperature of about 10 ^{o}C can be realized between a greenhouse covered with a net of 0.5 discharge coefficient as opposed to a closed greenhouse (discharge coefficient 0.01). Larger discharge coefficients in the range of 0.2-0.5 results in small temperature increases i.e. below 1 ^{o}C.

The predicted vapour pressure deficit in the greenhouse increased with increasing temperature (see fig 10). The simulation results suggest that closed greenhouses will have higher vapour pressure deficit than open greenhouses during periods of high solar radiation.

The changes in discharge coefficient affect on the evapo-transpiration rate in the greenhouse. This is illustrated in figure 11. The evapo-transpiration rate for a discharge of 0.5 is consistently higher than those for lower discharge coefficients. This difference in evapo- transpiration varies from day to day and is influenced by the external climatic conditions, notably solar radiation.

V. DSCUSSIONS

Results from the model validation exercise show that the simulation model developed in this study gives a good correlation between measured and predicted values of air temperature and relative humidity. Thus, the model can be applied to predict the climatic conditions and evapo-transpiration in similar screened greenhouses for different regions in the humid tropics. The model requires only standard weather station data as input variables. This makes it attractive for use in different regions in the humid tropics. It would reduce the need for costly experimentation and can be used when only historical weather data is available.

Discharge coefficient is the most important characteristic of insect-proof screens in so far as ventilation efficiency is concerned. The discharge coefficient values used in this work were determined under laboratory conditions. They are likely to be different from the discharge coefficients of the screens when placed on greenhouse openings due to differences in geometry, dimensions and aspect ratio. The performance of the model could therefore have been affected by the values of the discharge coefficients. Different authors have reported different values of discharge coefficients of greenhouse openings in the literature, perhaps indicating the differences in greenhouse configurations that have been studied. Sase and Christianson (1990) reported discharge coefficient values ranging from 0.05 to 0.5 for greenhouse ventilation openings covered with different insect-proof screens. Munoz et al. (1999) reported global (whole greenhouse) discharge coefficients ranging from 0.182 to 0.426 for roll-up roof vents with insect-proof screens located on central and lateral spans. Mears and Both (2001) reported discharge coefficients of 0.28 for screens used to exclude whiteflies and 0.09 for a screen effective against thrips. Montero et al. (1997) reported discharge coefficients of 0.32 – 0.35 for anti-thrips nets on a continuous roof vent located in a lateral span.

There have been some suggestions in the literature that the discharge coefficients based on the Bernoulli and continuity equations do not provide a reliable approach to estimating the ventilation rate of insect–proof greenhouses because they do not take account of the viscous effects of fluid flow at low velocities. Miguel et al. (1997) argued that when the Reynolds number (based on pore size) was less than 100-150, then the inertial forces do not dominate and so the viscous forces cannot be neglected. They proposed the use of the Forchheimer equation for determination of pressure drop across insect-proof screens. However, it has been shown that for practical purposes, the choice of either the Forchheimer or Bernoulli equations makes little difference in the estimation of pressure drop coefficients and air flow rates across insect-proof screens (Bailey et al. 2003).

The prediction of higher temperatures for lower values of discharge coefficients of screened greenhouse ventilation openings is generally the case in the literature available. However, the extent of increase in temperature for decreasing values of discharge coefficients varies from author to author. It is also important to note that the temperature increase due to decrease of discharge coefficient will also depend on the greenhouse configuration, notably the ratio of the floor area to the greenhouse surface area. Using simulation results from a 27 m by 7.2 m greenhouse with 0.9 m opening side vent and 0.8 m opening roof vents, Sase and Christianson (1990) showed that with a discharge coefficient of less 0.05, a 10 ^{o}C increase in greenhouse air temperature could be realized in a screened greenhouse as compared to an open one, when net radiation is 500 W/m^2 and wind velocity is zero. This result was, however, not verified by field experiments and there were no plants in the simulation study. In this study, the increase in air temperature attributable to a discharge coefficient of 0.05 is generally about 5^{o}C (depending on the climatic conditions). The differences in predictions of increase in air temperature can be attributed to the differences in greenhouse configurations and the fact that the present study uses a holistic energy and mass balance of the greenhouse. For a discharge coefficient of 0.22, the increase in temperature attributable to effect of screens for a greenhouse with full crop canopy is generally between 0.5 and 3^{o}C depending on the external weather conditions. Thus for design purposes, it would be appropriate to consider a 3^{o}C increase in temperature attributable to the use of an anti- thrips net.

The difference in greenhouse air temperature between the two materials used in the validation is not quite pronounced i.e there was a minor differences in air temperatures in greenhouses with discharge coefficients of 0.22 and 0.32. Larger differences were predicted for smaller discharge coefficients (below 0.1). This implies that for the greenhouse configuration that was used in the experiment, significant differences in climate will only occur if reduction in ventilation efficiency is about 80 % and above.

The predicted vapour pressure deficit values were generally in the range of 0 to 4 kPa which is similar to values commonly found in the greenhouse literature. Higher values of vapour pressure deficit were predicted for a greenhouse with young crops (lower LAI) than in that with full plants. Higher vapour pressure deficit was predicted in the 78-mesh greenhouse than in the 40-mesh greenhouses. This implies that higher vapour pressure deficit is experienced in the greenhouse at low ventilation rates. This result agrees with the observation of Critten and Bailey (2002) in which they showed a similar trend by simulation.

VI. CONCLUSSION

The most notable effect of the anti-insect screens was on greenhouse air temperature. The study has established that the ambient temperature in the Bangkok region was generally above 24 ^{o}C during day-time and occasionally fell below this external climatic conditions. Theoretical simulations using different areas of leaf area index (LAI) showed that a 2 ^{o}C reduction in greenhouse air temperature can be attributed to a value during the night. Ambient temperatures often exceed 30 ^{o}C during the day for most periods of the year. With the greenhouse design used in the study and assuming a young tomato crop, the results showed that the use of an anti-thrips net with a discharge coefficient 0.22 can cause a temperature increase of up to 5 ^{o}C relative to the ambient, depending on the full tomato canopy. Thus the increase in temperature in an anti-thrips greenhouse could be as high as only 3 ^{o}C after considering the evapotranspirational cooling effect of a full tomato crop. Generally, tomatoes grow best in temperatures ranging from 20 to 27 ^{o}C (Hanson et.al., 2000). Fruit setting is poor when average temperatures exceed 30 ^{o}C or fall below 10 ^{o}C. It can thus be concluded that the adapted greenhouse used in this study would require cooling in order to make tomato production efficient.

The present results show a good agreement between the predicted and measured values of climatic parameters. However, it would still be necessary to test the model using data from other regions before it can be adopted for use.

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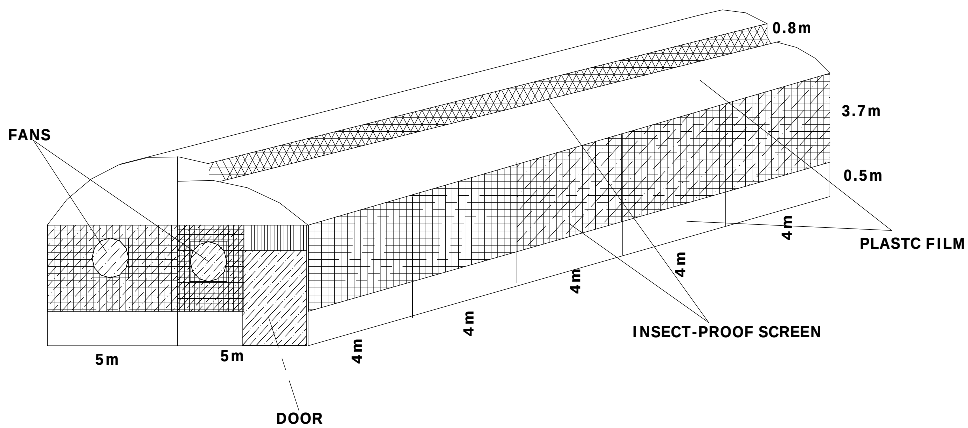

Fig. 1: Sketch of the experimental greenhouse

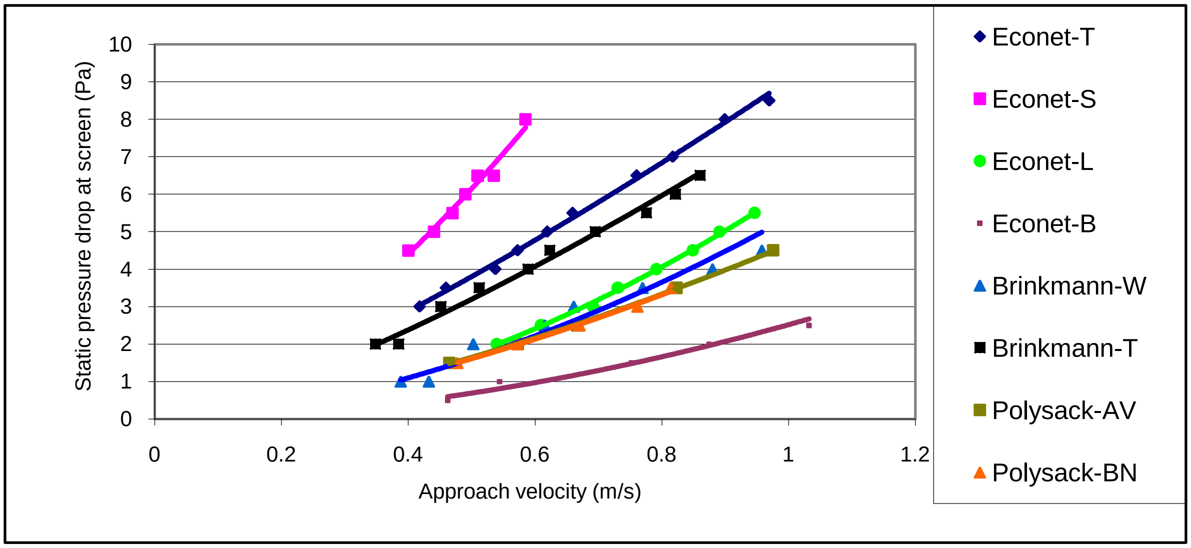

Fig. 2. Static pressure drop versus approach velocity for different insect-proof screens

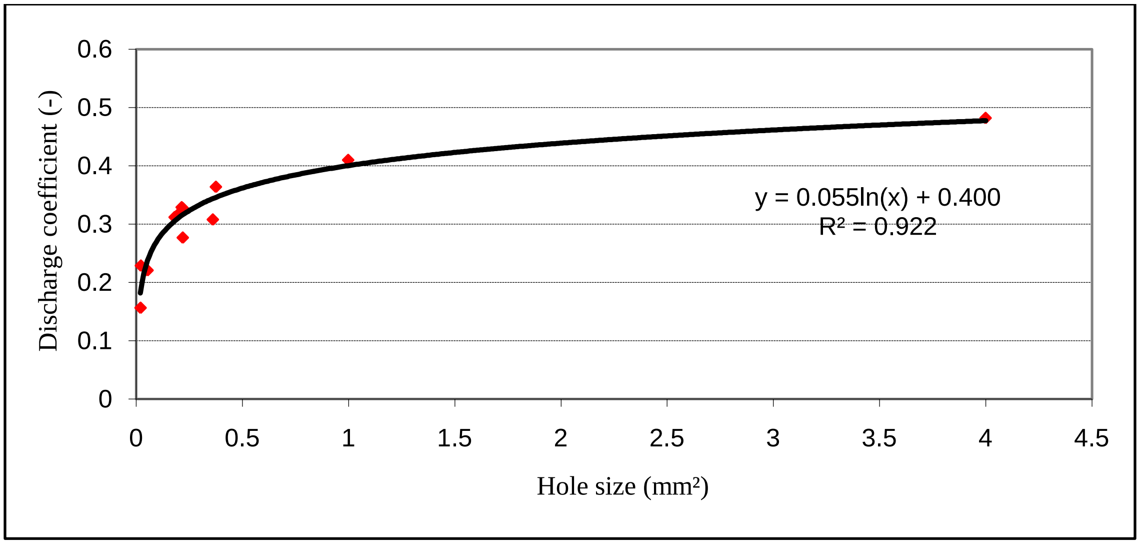

Fig. 3: Logarithmic relationship between discharge coefficient and hole size of screens

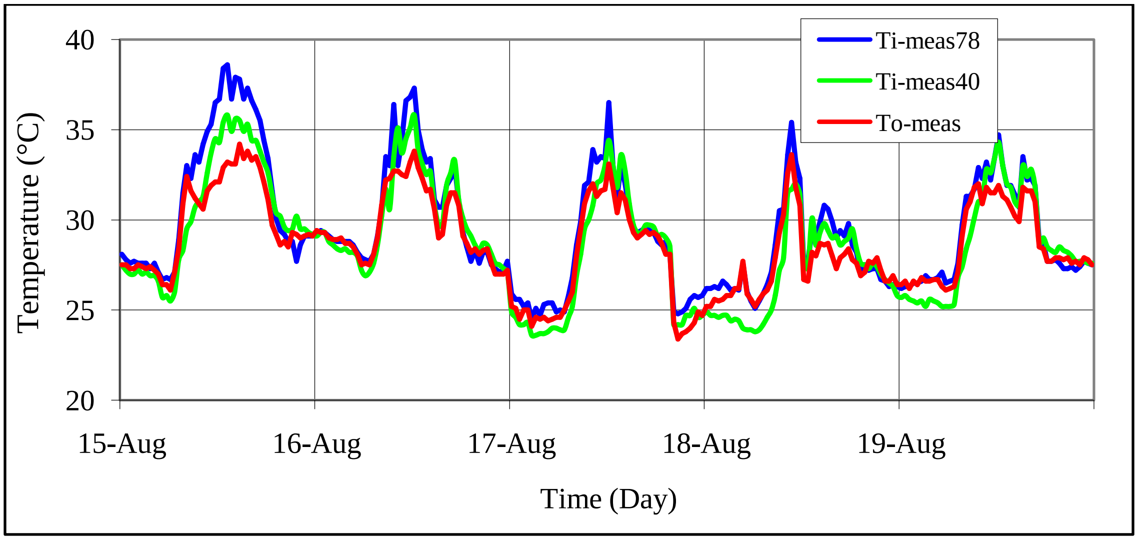

Fig. 4: Comparison of measured outside and greenhouse air temperatures. Ti-meas78 = measured temperature inside 78-mesh greenhouse. Ti-meas40 = measured temperature inside 40-mesh greenhouse. To-meas = measured outside air temperature.

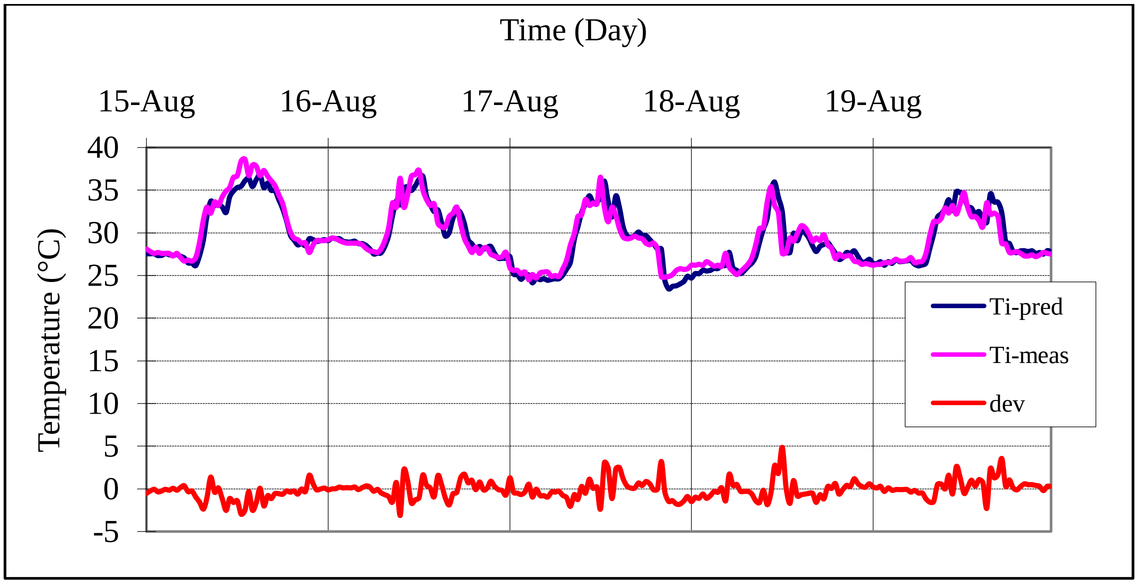

Fig. 5: Predicted (Ti-pred) vs. measured (Ti-meas) air temperature for 78-mesh greenhouse. dev= difference between predicted and measured temperature

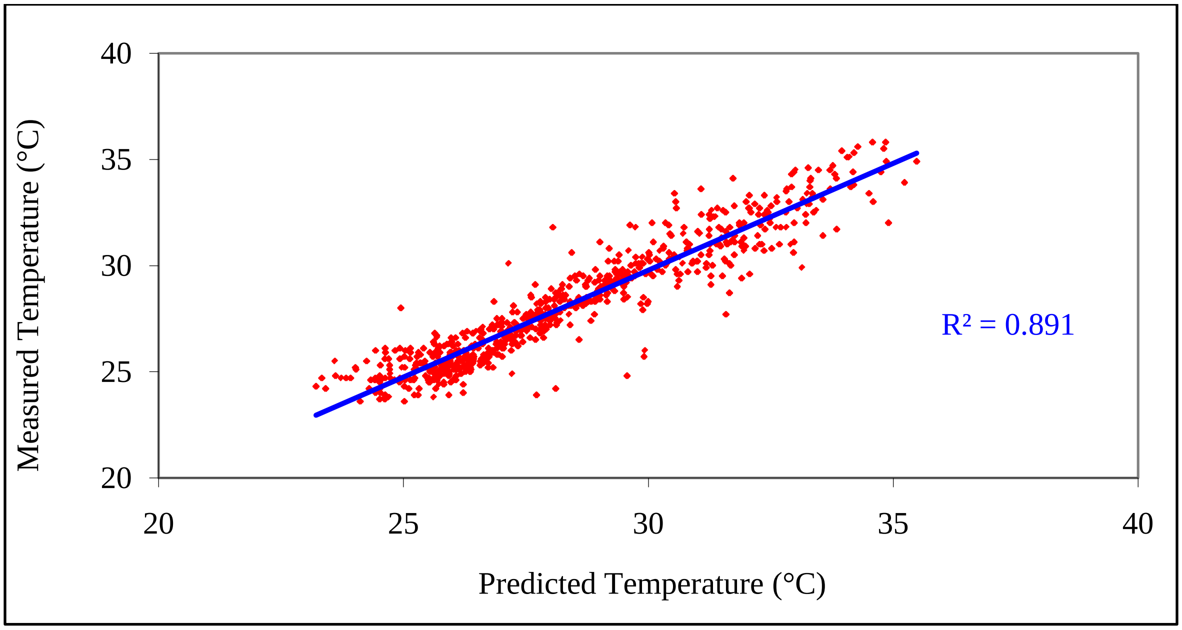

Fig. 6: Correlation between measured and predicted temperature in 40-mesh greenhouse

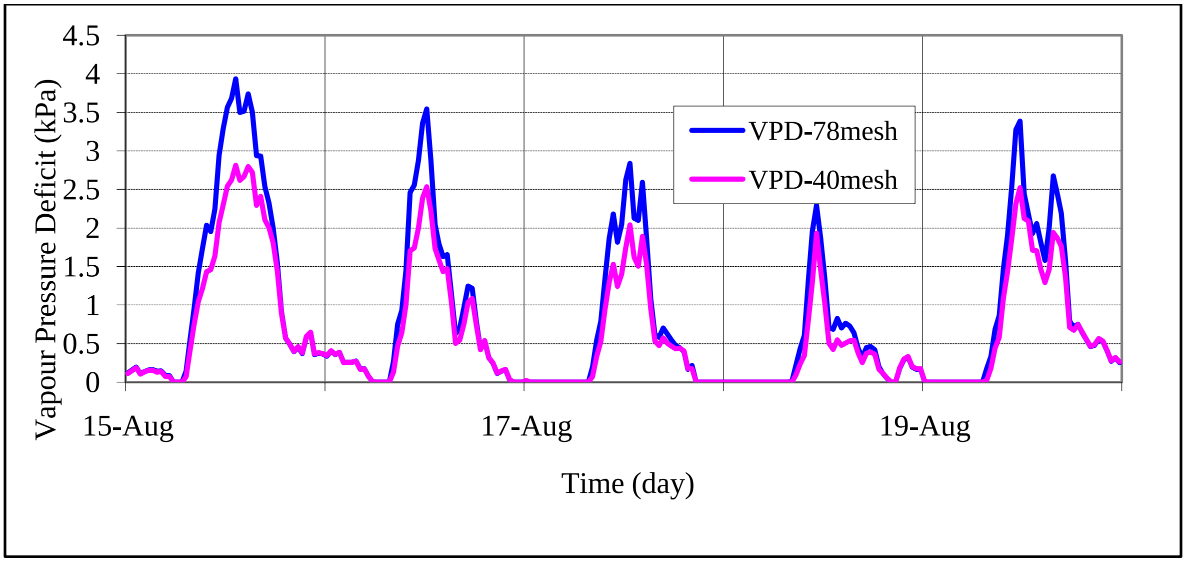

Fig. 7:Comparison of vapour pressure deficit in two greenhouses

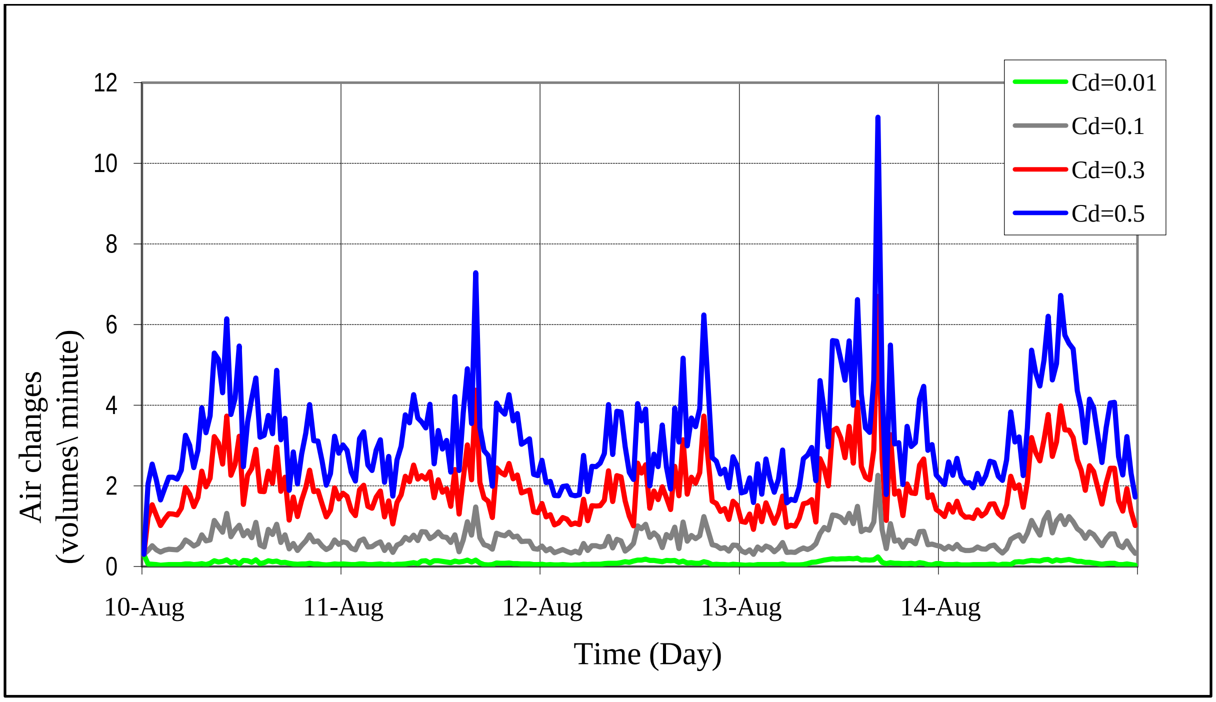

Fig. 8: Effect of discharge coefficient on predicted greenhouse ventilation rate