Evaluation of Combined Application of Fog System and CO_2 Enrichment in Greenhouses by Using Phytomonitoring Data

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Abstract

A two-stage experiment was performed to determine the influence of a high-pressure fog system on the CO_2 concentration and gas exchange efficiency (GEE) in greenhouses with CO_2 enrichment. The experiments were carried out with tomatoes (*Lycopersicon esculentum*). Photosynthetic GEE was introduced as a new evaluative quantity to represent the short-term CO_2 uptake capacity of the plant canopy. The physiological data for the plants were measured with a phytomonitoring system. The ratio between the measured and the calculated CO_2 uptake GEE was calculated and coded on a color scale. With the Mollier plot method, ranges with a maximum GEE can be located for several temperatures and relative humidities. Plant yields and quality were also recorded. A preliminary test identified an increase in GEE with higher relative humidity, with a dependence on leaf transpiration ($r^2 = 0.56$). In the main experiment, the effects of the combined application of fog and CO_2 enrichment were estimated. A higher diurnal average CO_2 content was observed in the fog cabin. This was induced by the cooling effect of the fog and the associated smaller ventilation openings.

INTRODUCTION

With global warming, higher external temperatures can be expected, which will demand greater attention to climate control in greenhouses, especially in summer. Air exchange by forced or free ventilation is mainly used for greenhouse cooling. However, many side effects are incurred with air exchange via open ventilation. With open ventilation, water vapor and CO_2 escape from the greenhouse. Both gas components are significant in the optimization of microclimatic conditions.

Alternative control processes are necessary to solve this problem. First, it is essential to concentrate on the microclimate of the crop. Second, a change is necessary from the control of single variables (temperature, humidity, CO_2) to a gas-component management system.

Evaporative cooling methods are predominantly used in areas with low external relative humidity. This is an essential prerequisite to enhancing the cooling effect. Another relevant factor is the equability of the climatic conditions inside the greenhouse. With fan and pad cooling, horizontal inclines in temperature and humidity may occur. In exceptional cases, these horizontal inclines in temperature and humidity can lead to significant differences in growth conditions. The advantages and drawbacks of the two systems have been discussed intensively by many authors (Giacomelli et al., 1985; Kittas et al., 2003).

Using fog systems with high-pressure nozzles, evenly distributed conditions can be achieved if the deviations and the positions of the nozzles are optimized. Fogging systems are less expensive to install and operate. The cooling efficiency of fogging systems has been described well by many authors (Abdel-Ghany and Kozai, 2006). The cooling efficiency of wet pad and fan systems has been calculated based on the differences between the wet bulb temperatures inside and outside the greenhouse. Using this method to calculate the cooling efficiency of fog systems results in unrealistic assessments (Öztürk, 2003; Handarto et al., 2005), because of the uncertain estimation of the air exchange between inside and outside the greenhouse. This air exchange rate plays an important role in the cooling efficiency (Boulard and Baille, 1993).

Changing the conditions of water-vapor transport by using fog systems has been well described. Under mist conditions, the air temperature and the vapor pressure deficit (VPD) decrease significantly. The low VPD level allows the plants to maintain higher stomatal conductance during times of higher global radiation. The physiological status of the crop improves, as indicated by higher stomatal conductance (Katsoulas et al., 2001).

An adverse effect of using fog occurs when the relative humidity inside the greenhouse is too high and the plant tissue temperature is below the dew point. This leads to wet leaves and fruits, which are thus susceptible to fungal diseases. This can only be prevented by more precisely controlling the microclimate and by changes in the control strategy.

An essential prerequisite is knowledge of the plants' responses to the higher humidity. For this, a Mollier diagram or a psychrometric chart provides an adequate and complex description of the changes in temperature and relative humidity that result from technical systems such as the heating, ventilation, and fog systems (Abdel-Ghany et al., 2006). The Mollier diagram of water vapor and enthalpy is a useful tool with which to design a combined model for temperature and humidity control (Schmidt, 2005a). Using the evaluation quantity called 'gas exchange efficiency' (GEE), it is possible to appraise the efficiency of light use (Schmidt, 2005b).

MATERIALS AND METHODS

A two-step program was used to determine the influence of higher concentrations of water vapor on GEE. First, in preliminary experiments, the influence of higher vapor content on GEE was investigated; second, the combined use of fog and CO_2 enrichment was evaluated.

The experiments were conducted with tomatoes (*Lycopersicon esculentum*) in two 75 m^3 single-span greenhouse cabins situated in a north–south direction on the Dahlem campus, Humboldt University, Berlin. The height of the Venlo-type greenhouse was 4.5 m, and the ventilation opening ratio was 50% (roof ventilation only). The fog system included a reverse osmosis system for producing pure water, a storage tank, a high-pressure pump with an adjustable valve, high-pressure tubes, and electrically operated solenoid valves to switch the fog system on and off. The water pressure inside the system was 120 bars, which produced very small drips (< 20 µm). Fog nozzles (0.05 nozzles/m²) were first installed at a height of 2.5 m.

The microclimatic conditions and outside meteorological data were measured with the Plantputer control system, which was integrated into the greenhouse. To measure the plant responses, a PTM 48 Phytomonitor was used. The EPM 2006 Phytomonitor (Schmidt, 1998), (both Steinbeis GmbH & Co., Germany) was used for process control.

Net photosynthesis, transpiration, and microclimate were measured at 5 min intervals. GEE was calculated from the measured CO_2 uptake (CO_{2Um}) and the calculated CO_2 uptake (CO_{2Uc}), estimated from the correlation between net photosynthesis and photosynthetically active radiation (Eq. 1.).

$$GEE = \frac{CO_{2Um}}{CO_{2Uc}} \qquad \text{Equation 1}$$

The GEE values were organized into different classes and arranged on a color scale.

The GEE values were plotted on a digitized Mollier h-x diagram to determine the quality of the climate control (circumference of the scatter plot) and to estimate the range of the highest GEE. A counting algorithm in the software estimated the hold of the condition point at different levels of GEE.

In the first trial, we only examined GEE at different vapor concentrations. The fog system was switched on when the relative humidity dropped below 60%. The fog system was interlocked against ventilation.

In the second trial, GEE was compared between one cabin with fog and CO_2 enrichment and another cabin with CO_2 enrichment without fog. Both cabins were controlled in a conventional way (heating < 18°C, ventilation > 25°C, fog system < 60%, CO_2 900 ppm). Fog and CO_2 were locked against ventilation opening. The fruits were classified in A-Quality (>70 g/fruit), B-Quality (50-70 g/fruit) and C-Quality (<50 g/fruit). Furthermore the fruits with blossom-end-rot, fruit cracking and other diseases were throw out.

RESULTS AND DISCUSSION

In the first trial, high GEE measurements were observed between 24°C and 26°C and at a relative humidity of 70%–90% (Fig. 5). There was a positive correlation between GEE and relative humidity and a negative correlation between GEE and leaf transpiration (Fig. 1). It is reasonably expect an influence of transpiration mass flow to gas exchange at the boundary layer. However, lower stomatal conductivity was observed in similar experiments. Low VPD levels allow plants to maintain higher stomatal conductance (Katsoulas et al., 2001). A 17.8% higher yield (Table 1), an increase in fruit quality, and a lower tendency for fruit to crack were also observed (21% to 14% in this trial).

In the experiment that compared the effects of CO_2 enrichment with and without fog, significant increases in the diurnal mean absolute humidity and CO_2 content were observed between the plants under the two sets of conditions. As expected, there was a higher mean absolute humidity and also a higher mean diurnal CO_2 concentration (Fig. 3). This can be attributed to shorter periods of ventilation opening and less frequent vent opening, induced by the cooling effect of the fog system. As a result, a shift of the scatter plot to the right was observed in the Mollier chart (Fig. 6). Thus, many dry and hot climatic conditions were avoided. The highest GEE was found between 80% and 90% relative humidity (Fig. 7). This was also the Zone with the highest leaf transpiration mass flow witch indicates a high stomatal conductivity (Fig. 6). Compared with CO_2 enrichment without fog, a 22% higher hold with GEE > 100% was measured with fog (Fig. 2). With higher cumulative CO_2 uptake, there was an 8% increase in yield (Table 1). This was also documented with a higher cumulative CO_2 uptake in the fog cabin measured by the PTM-48 phytomonitor (Fig. 4).

From these data, the following points should be emphasized: (1) the application of fog in greenhouses with CO_2 enrichment leads to higher CO_2 concentrations, especially in times of high global radiation; (2) many critical climatic situations with high vapour concentration deficit (VCD) can be prevented; and (3) higher GEE should produce higher yields.

CONCLUSIONS

These results clearly demonstrate the beneficial contribution of evaporative cooling to the effects of high-pressure fog systems on microclimates. The combined application of vapor and CO_2 may support the fixation of CO_2 by plants, leading to higher vapor content in the greenhouse. Thus the microclimate conditions will improve, causing elevated GEE and greater vegetative and generative growth.

However, these advantages are restricted by conventional control in summer. To protect plants against high tissue temperatures, ventilation acts against the principle of fixing CO_2 and vapor inside the greenhouse. In most commercial greenhouses, fog systems involve spraying with low-pressure systems, which produce large drips. These drips do not evaporate. Furthermore, adverse positioning of the fog nozzles leads to wet leaves and fruit. To avoid this deleterious effect, new control strategies are necessary.

To protect plants against wetness, an interception of the VCD is an essential prerequisite. By removing vapor during short periods of ventilation, and thus controlling the relative humidity in the roof, excess sensible heat can be transformed to latent heat and leave the greenhouse on a short way.

Further investigations are necessary (a) to optimize the system setup and (b) to characterize the air flow in the greenhouse using Computerized Flow Dynamics (CFD) technology.

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Tables

Table 1. Difference in fruit yield and quality (g/plant).

2006	2007					
	without CO_2 enrichment			with CO_2 enrichment (900 ppm)		
	no fog	fog (> 60%)	difference	no fog	fog (> 60%)	difference
yield	3680	4335	17,8%	3265	3525	7,9%
A-Quality	1398	1864	38% / 43%	1175	1445	36% / 41%
C-Quality	662	824	18% / 19%	686	670	21% / 19%
Cracked fruits	773	607	21% / 14%	490	423	15% / 12%

Figures

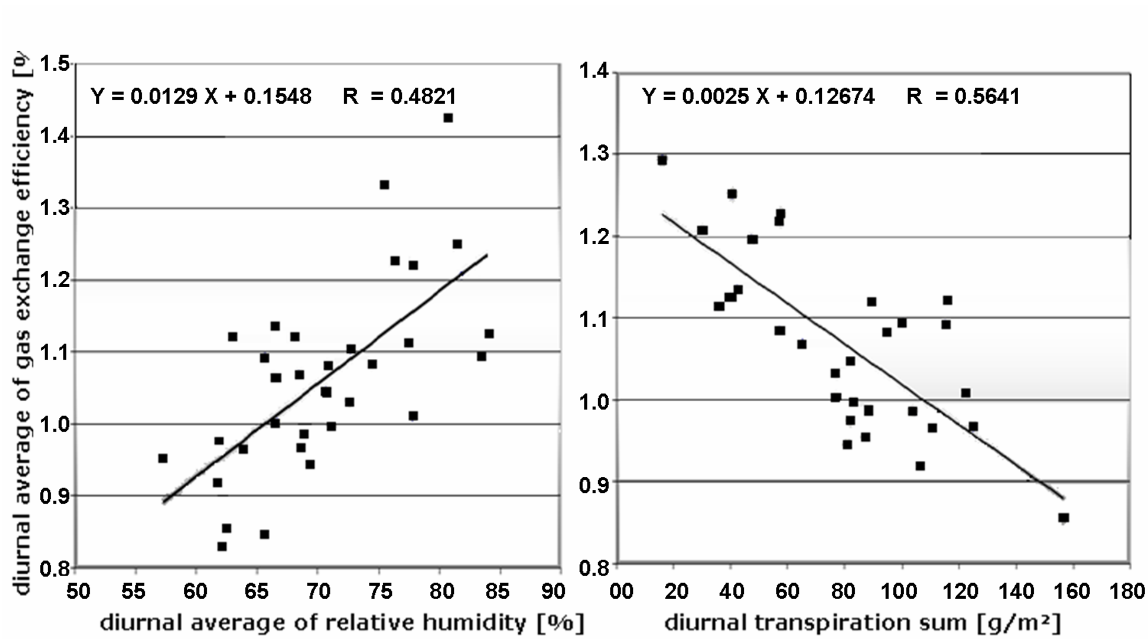

Fig. 1. Dependence of GEE from relative humidity and leaf transpiration without CO_2 enrichment.

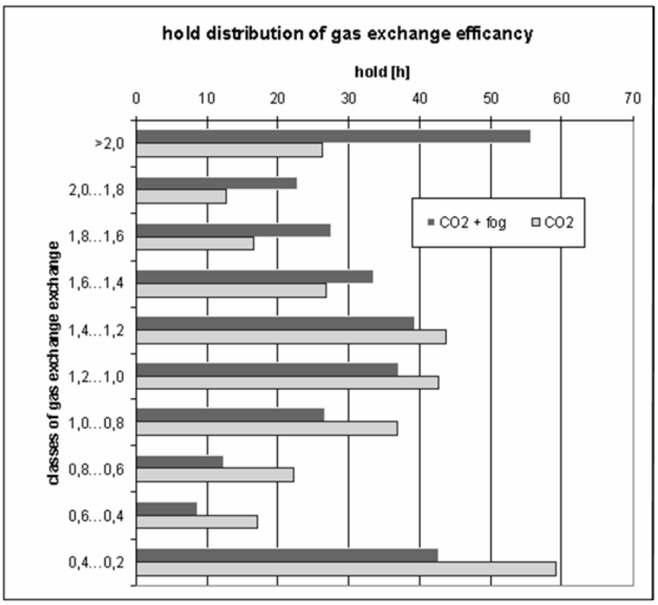

Fig. 2. Hold of gas exchange efficiency at different classes.

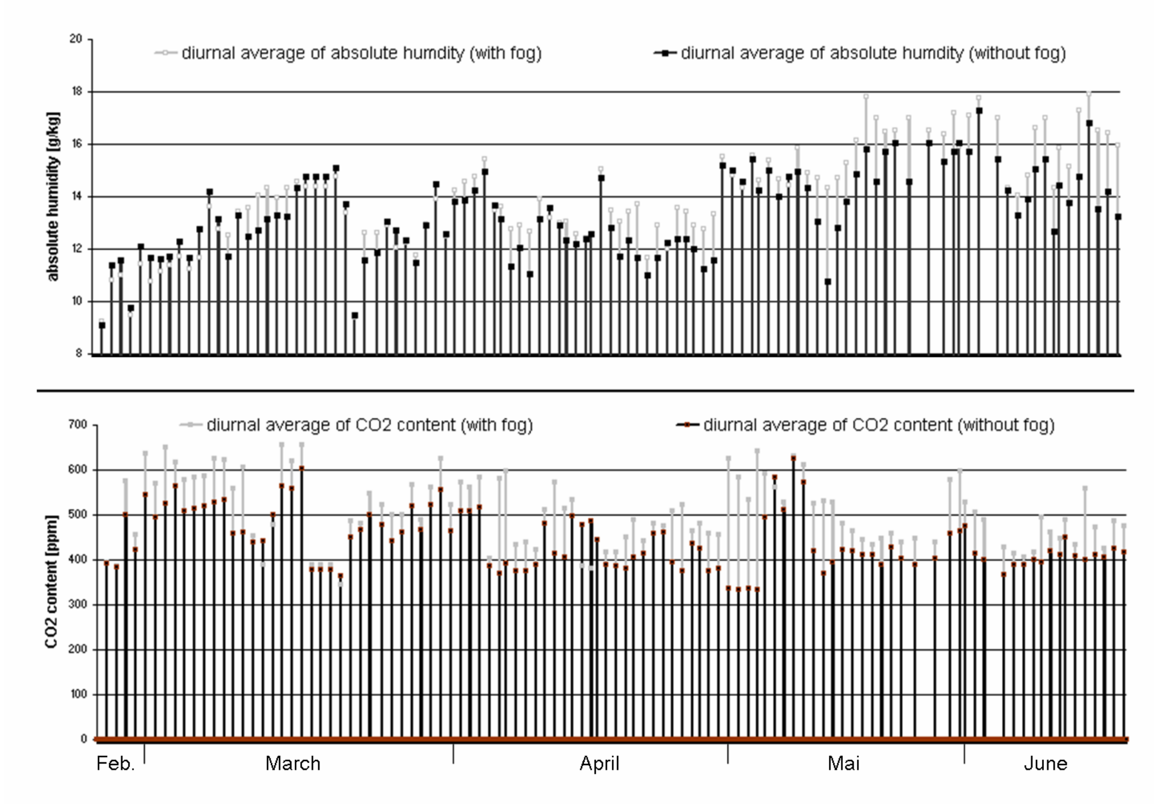

Fig. 3. GEE - Scatter plot of CO_2 + fog greenhouse (left) vs. CO_2 only (right).

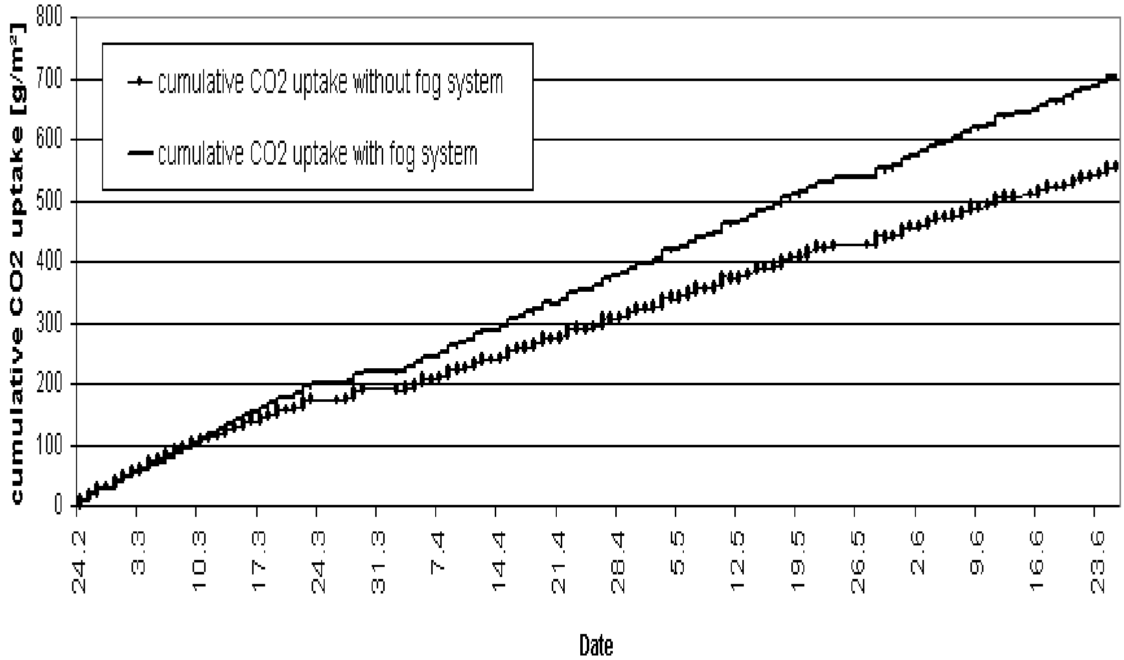

Fig. 4. Comparison of measured cumulative CO_2 uptake between CO_2 enrichment and CO_2 enrichment with fog application.

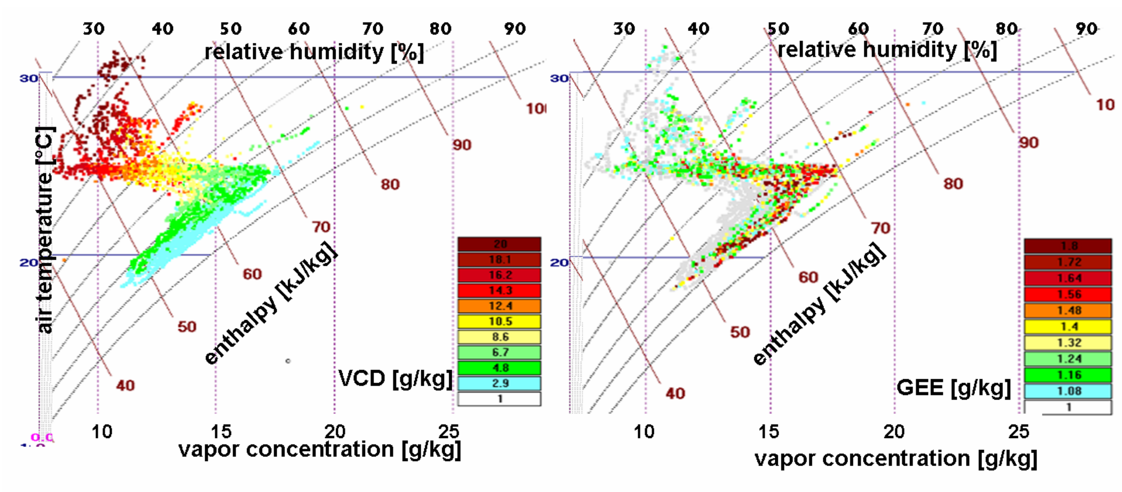

Fig. 5. Scatter plot of VCD (left) and GEE (right) using fog system (n= 15,000).

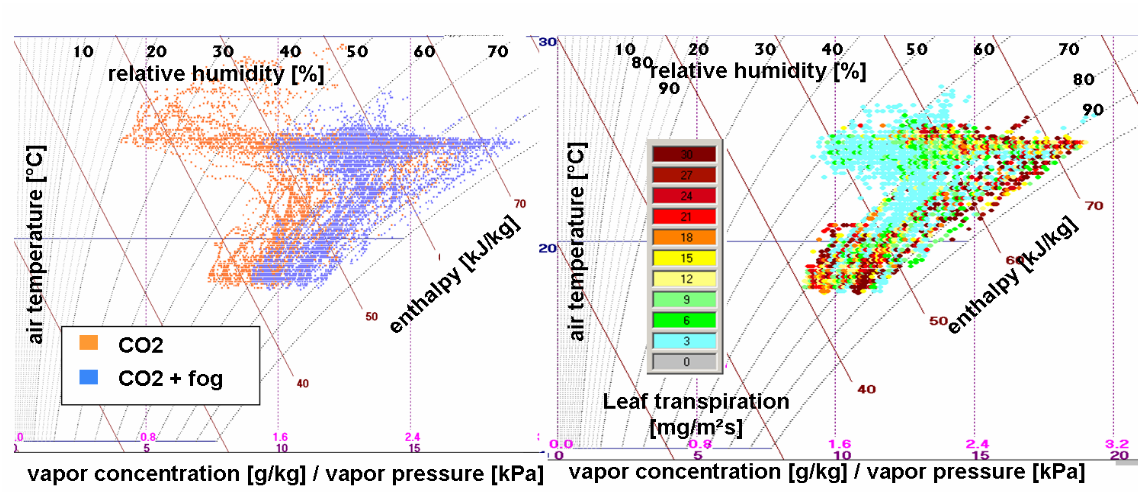

Fig. 6. Scatter plots of CO_2 + fog vs. CO_2 only (left) and leaf transpiration with fog (right).

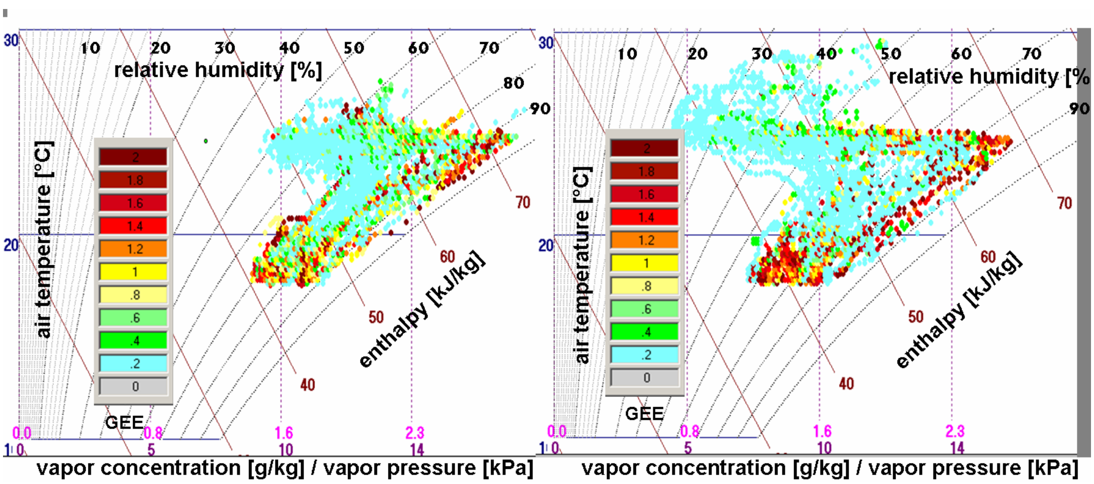

Fig. 7. GEE - Scatter plot of CO_2 + fog greenhouse (left) vs. CO_2 only (right).