EFFECT OF CO_2 SUPPLY STRATEGY ON SPECIFIC ENERGY CONSUMPTION

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Abstract

This paper studies the effect of CO_2-dosing with exhaust gases on the efficiency of glasshouse tomato production. The paper shows that it can be recommended to ensure a continuing CO_2 supply during the warm period. The discussion focuses on exhaust gases as a CO_2 source, but the results also elucidate the effects of pure CO_2
The efficiency is rated with respect to the ratio between primary energy consumption and biomass production. The computations are made with a greenhouse climate simulation model that includes the description of the heating system performance. The results hold for Dutch circumstances with respect to building characteristics, outside weather conditions and horticultural practice.

1. Introduction

Fuel and combustion devices in the Netherlands are of such a quality that the exhaust gases of horticultural boilers can be readily applied for CO_2 dosing. During the cold period of the year when the greenhouse is heavily heated and the windows are mainly closed, the amount of CO_2 in boiler exhaust gases is by far enough to increase the inside concentration up to high levels (some 1000 vpm). In the warm period of the year the heat demand is low, especially during the day. In this paper it will be shown that it can be recommended to ensure a continuing CO_2 supply during the warm period. The discussion will focus on exhaust gases as a CO_2 source, but the results may also apply to the effects of pure CO_2. All results are generated by the IMAG-DLO greenhouse climate simulation model KASPRO and hold for a typical tomato culture in a modern greenhouse under typical Dutch weather conditions. The options under consideration are rated according to their effect on the specific energy consumption, which means the amount of primary energy combusted per unit of photosynthesis. The increment of yearly photosynthesis is considered to be a suitable quantity to express the increment of production because, for tomato, the dry matter distribution to the fruits is not affected by the CO_2 level (Nederhoff,1994).

2. Materials and methods

2.1. Model computations

To be able to study the behavior of a greenhouse-canopy system in relation to the greenhouse climate controller characteristics, the outside weather conditions and the horticultural requests of the grower, a dynamic simulation model was built. The basis of the model are the energy and mass (water vapour and CO_2) balances over the considered lumped parts of the system, resulting in a set of coupled, non-linear, first order differential equations that are solved numerically. The model describes the air temperature, humidity and CO_2 concentration, the canopy and greenhouse cover temperature, the temperature profile in the soil and the dynamic behavior of the heating system. It also computes photosynthesis as a function of temperature, radiation level and CO_2 concentration (Gijzen, 1992).

The resolution in time of the model goes up to one minute. This means that the simulated greenhouse climate can be controlled by (the essentials) of a customary greenhouse climate controller. A thorough and complete description of the model can be found in the work of de Zwart (1996).

The combination of information on photosynthesis end energy consumption and the possibility to determine the greenhouse controller behavior enables to study the effect of different CO_2 supply strategies on the specific energy consumption[1]. The discussion concentrates on the application of boiler exhaust gases as CO_2 source. During cold periods of the year the production of CO_2 is abundant and, together with the low demand of the greenhouse, with windows closed, the inside CO_2 concentration can easily be kept at a high level. In a warm period it is very difficult to realize an substantial increase of the CO_2 concentration, partly because of the low production rate, but more because of the huge losses due to high ventilation rates.

Four CO_2 supply strategies are compared with respect to their effect on specific energy consumption. In the first strategy the CO_2 supply is completely coupled to the actual heat demand of the greenhouse. This means that during warm periods hardly any CO_2 is supplied. The second, third and fourth strategies concern CO_2 production irrespective of the heat demand. In the second strategy, heat excesses are carried off by artificial increment of the heat demand of the greenhouse by means of an increased pipe-temperature. However, this practice forces an increment of the ventilation rate and, and thus an increased CO_2 loss. To overcome this extra ventilation, the third strategy assumes the availability of an external cooling device to carry off heat excesses. In the fourth CO_2 supply strategy the simulation model includes a short term (24 hour) heat storage facility to carry off temporary heat excesses. The storage tank avoids extra ventilation and, at the same time, saves energy for later use.

All four cases are compared with a reference situation without CO_2 supply. The results with respect to CO_2 concentration, energy consumption and daily production of assimilates are shown graphically. The yearly totals are used to calculate the specific energy consumption figures.

2.2. Horticultural context

The results of the CO_2 supply strategies depend to a large extent on the horticultural context. In this paper, this context is a customary way of growing tomatoes in a modern Dutch greenhouse (details below). The weather data are obtained from the SEL-year, which is a set with hourly data for typical Dutch weather (Breuer and Van de Braak, 1989). The daily mean temperature and solar radiation sums of the SEL-year data are shown in Fig. 1. The growing season starts in December when the young tomato plants are planted. During the first three weeks the daytime and nighttime temperature setpoints are 18 °C. In case the solar radiation exceeds 100 Wm^{-2} the air temperature setpoint is increased with 0.02 °C per Wm^{-2} excess until a maximum increment of 2 °C is reached (at an outside global radiation level of 300 Wm^{-2}).

From sunrise to one hour before sunset the greenhouse air CO_2-concentration is increased, only if CO_2 is available, by adding exhaust gases from the boiler, to a maximal concentration of 800 vpm. The maximal capacity of the CO_2 distribution system in the greenhouse is 142 kg CO_2 per hectare per hour, which amount of CO_2 corresponds with combusting 80 m^3 of natural gas per hour. Thus, in case the second, third or fourth supply strategy is applied, the boiler combusts 80 m^3 per hectare per hour (or more if needed for heating) as long as the inside concentration remains below 800 vpm during

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[1] The specific energy consumption is defined as the amount of energy required to produce a unit of biomass.

the supply period. In case of the fourth supply strategy, a 100 m^3 per hectare heat storage tank is available for the temporary storage of heat excesses. In case the storage tank is completely filled the CO_2-supply is stopped.

The humidity setpoint is set to 85% RH. If the actual humidity in the greenhouse exceeds the setpoint the windows are opened proportional to the excess with 1° window opening per percent excess of the RH. The windows are also opened when the air temperature exceeds the setpoint by 1 °C (the dead zone). The opening angle is proportional to the excess, with 3° per °C excess above the temperature setpoint plus the dead zone. Windward side ventilators are opened only if the leeside ones have exceeded an aperture of 20 °.

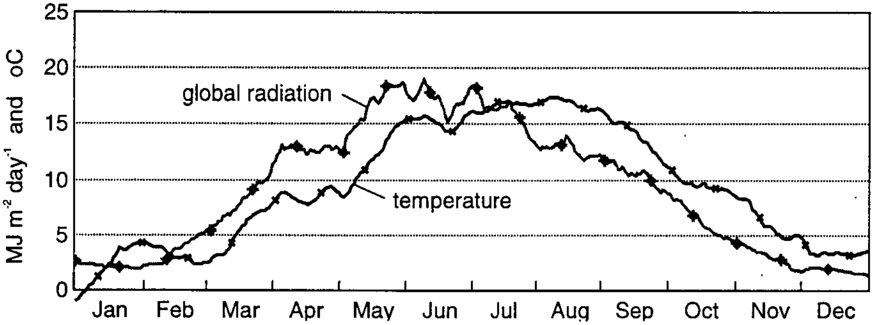

Figure 1: Typical daily mean temperature and solar radiation sum in the Netherlands. (the data are smoothed with a moving average filter)

After the first period of three weeks the daytime temperature setpoint is increased to 19 °C and the nighttime temperature setpoint is lowered to 17 °C. All other settings are left unaltered.

On the first of April the daytime and nighttime minimum pipe temperature2 are set at 45 °C and 40 °C respectively. During daytime, the minimum pipe temperature is lowered linearly towards the air temperature setpoint for outside global radiation in the range between 100 and 300 Wm^{-2}.

The growth season ends on 11 November. On that day the air temperature and minimum pipe temperature setpoints are lowered to 5 °C. Humidity control and carbon dioxide supply are abandoned.

The Venlo-type greenhouse is built from a repeated sequence of 3.20 m wide roof segments. The building is composed of 30 of these roof segments. The gutter length of the greenhouse is 104 meter, resulting in 1 ha greenhouse area. The floor to gutter height is assumed to be 3.5 meter. The roof slope is 25°. One ventilation window per eight glass panels is mounted in each side of the greenhouse cover. The windows are 2 m wide and half the ridge-gutter distance long. When the windows are closed, the leakage of the greenhouse is assumed to be 1.25 10^{-4} m^3 per m^2 greenhouse per unit wind speed (ms^{-1}). This figure is a mean of the leakages determined by De Jong (1990) in four commercial greenhouses.

The heating system consists of primary heating pipes of 51 mm located near the floor and an overhead secondary heating system of 28 mm pipes. With four pipes per roof segment near the floor and half as many overhead pipes, the maximum heating power of

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2 The minimum pipe temperature prevents the temperature of a heating pipe to be lowered beneath this temperature, irrespective of the temperature excess of the greenhouse air.

the heating system, if fed with 90 °C, is about 240 Wm^{-2}. The secondary heating pipes accompany the primary heating pipes in case the temperature of the latter exceeds 60 °C.

3. Results and discussion

Since the resolution in time of the simulation model is one minute the data need to be averaged and smoothed to yield interpretable results. Therefore the model output was condensed to daily data that are displayed graphically. The overall results are presented as yearly totals in Table 1.

Figure 2, presenting the mean CO_2 concentration during 6 hours around noon (from 10: 00 till 16: 00 hour, the period with the highest light intensity), directly shows the large difference between a greenhouse with CO_2 dosing and a greenhouse without. In the latter the concentration hardly exceeds 300 vpm, which is already substantial lower than the outside concentration. The first supply strategy, which supplies CO_2 only during periods with a heat demand, resulting in a yearly supply of 14 kg CO_2 per m^2, shows an important increase of concentration. However, in summer, with hardly any heat demand during the daytime period the increment of concentration is only little compared to the situation without CO_2 dosing. The results of the other three strategies are very much comparable with respect to the resulting CO_2 concentration. The second strategy, where heat excesses are carried off by raising the pipe temperature, induces an increased ventilation, resulting in a somewhat decreased concentration.

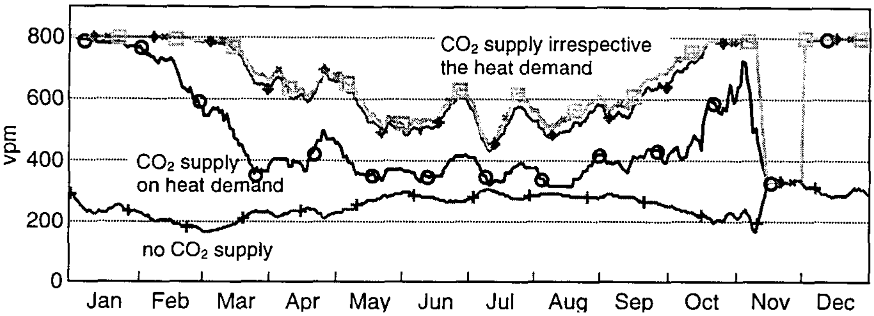

Figure 2: Mean CO_2 concentration (vpm) at daytime between 10: 00 and 16: 00 throughout the year. The curves for the second, third and fourth supply strategy almost coincide. (the data are smoothed by a moving average filter)

Figure 3 shows the mean daily heat demand. As can be expected, in this figure the curve for the greenhouse without CO_2 dosing coincides with the curve for the greenhouse with the first supply strategy. Consequently, the yearly totals are equal as well, (see Table 1.)

The fourth CO_2 dosing strategy, where temporary heat surpluses are stored in a 100 m^3 (per hectare) storage tank shows a somewhat increased primary energy consumption in summer. Part of this increase is caused by losses from the storage tank, but most of the extra energy consumption is caused by structural heat surpluses. This is the amount of heat which is produced at the end of the day during warm periods that cannot be stored, either because the tank is too small or because the heat demand of the preceding night is not sufficient to cool the tank. The structural heat surplus is carried off by an increased pipe temperature.

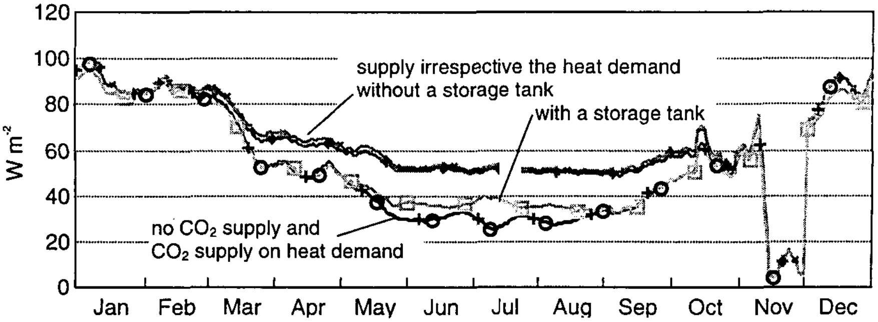

Figure 3: Daily primary energy consumption. The curves for the second and third supply strategy practically coincide. (The data are smoothed by a moving average filter)

The second and third supply strategy result in an almost equal energy consumption (1.97 and 2.00 GJ m^{-2} yr^{-1} respectively, see Table 1). The minor difference is caused by the fact that in case the heat surpluses are carried off by an increased pipe temperature the heating system and greenhouse derives some heat storage characteristics.

Of course the goal of horticulture is to produce products. CO_2 addition is only one of the measures to enhance this production. A suitable entity to study the effect of CO_2 on production is the carbohydrate fixation (Nederhoff, 1994). The daily carbohydrate fixation for the distinguished CO_2 supply strategies and for the greenhouse without CO_2 supply is shown in Figure 4. The figure shows that CO_2 supply on heat demand mainly increases the production levels in spring. The other three strategies show a similar effect in spring but show another increment of production in summer and autumn.

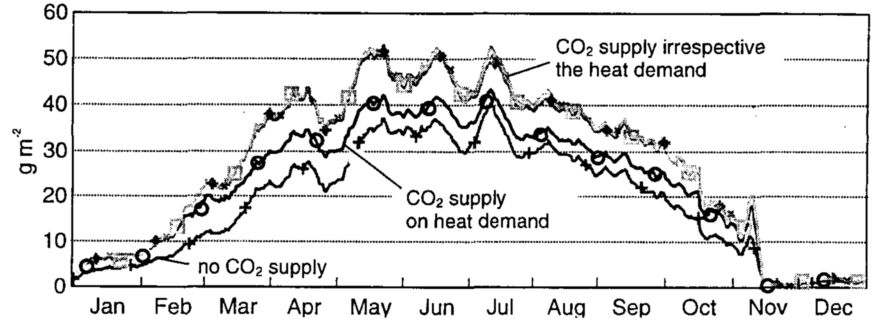

Figure 4: Daily carbohydrate fixation The curves for the second and third and fourth supply strategy practically coincide. (The data are smoothed by a moving average filter)

In order to compare the CO_2 supply strategies, we calculate the specific energy consumption based on annual figures. Specific energy data are interesting because an increased energy consumption per unit greenhouse area is acceptable when it is compensated by an extra production.

Looking at the figures in Table 1 it appears that an efficient tomato production should apply CO_2 supply. Surprising enough the first three strategies result in about equal specific energy consumption figures. However, the application of a storage tank appears to be the best option

In Table 1, besides the specific energy consumption, another column is added, showing the specific CO_2 release. The higher the figure in this column, the more CO_2 per unit of produce is released from the greenhouse site. This last column leads to the conclusion that, in case a greenhouse lacks a heat storage tank, the first supply strategy (CO_2 supply during heat demand only) should be promoted to contribute to the governmental policy of primary energy saving and the decrement of CO_2 release. However, since a unit of extra production increases (about) the full income side and a unit of decreased energy demand affects for only 10 to 20% at the cost side of the enterprise, from business economical point of view it is better to supply CO_2 irrespective the heat demand and carry off the heat excesses (strategy 2 or 3) . The question whether the heat excesses should be carried off by an external cooler or by means of the existing heating system depends on the investments related to the external cooler. An external cooler might also be good in case the fruit quality improves when the greenhouse air temperature is lowered somewhat.

Table 1: Yearly totals

Strategy			Energy cons. GJ $m^{-2} yr^{-1}$	CO_2 gift kg $m^{-2} yr^{-1}$	CH_2O fixation kg $m^{-2} yr^{-1}$	Spec. en. cons. MJ kg^{-1}	Spec. CO_2 release kg kg^{-1}
0	no CO_2 supply		1.65	0	6.7	246	12.7
1	supply during heat demand		1.65	14	8.2	201	10.3
2	supply irrespective the heat demand	excesses carried of by the heating system	1.97	36	9.8	200	10.3
3		excesses carried of by an external cooler	2.00	35	10.0	200	10.3
4		temporary excesses to storage tank	1.68	35	10.0	168	8.6

In case the grower applies pure CO_2 with a rate and amount comparable to the last supply strategies (those irrespective the heat demand), the high carbohydrate fixation levels are combined with the 1.65 GJ m^{-2} yr^{-1} energy consumption level. Thus, pure CO_2 supply results in a specific energy consumption that is even less that 168. From business economical point of view the costs of pure CO_2 supply must be compared to the costs of a heat storage tank.

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