Heating system position and vertical microclimate distribution in chrysanthemum greenhouse

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Abstract

In the cultivation of greenhouse chrysanthemums, the main heating system is often positioned overhead. Under unfavourable conditions, this can lead to unacceptable vertical temperature differences or high relative humidity (RH) in the crop and ultimately to increased risk of diseases. Moreover, the overhead heating pipes will result in higher energy loss compared to a heating system at a lower position. Heating circuits at different heights, controlled independently of each other, can help to prevent these problems. To see the effects of the vertical position of independent heating circuits in chrysanthemums, the distribution of air humidity and that of air and leaf temperatures have been measured under a range of ambient conditions, using three combinations of two heating circuits at varying heights. All three configurations provide higher air temperatures above the crop than within, but the air temperature above the crop is decreased under cold outside conditions by about 1.5°C when the primary heating system is mounted low in the crop. The large vertical temperature differences in the crop when using the traditional heating system with overhead pipes can be avoided by applying a crop heating system instead. Using the lower circuit as a primary heating system increases, on cold nights, the air temperature in the lower layers of the crop by about 3°C, reduces the RH there by about 7% and decreases more quickly the dew point below the crop temperature after irrigation. The low positioned heating system had 7–9% lower heating requirement than the traditional system with heating pipes overhead. Between the three compartments, no significant differences occurred in leaf area index (LAI), and length and weight of stems. Nor was any difference found in flower quality. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Temperature distribution; Relative humidity; Heating system; Heating requirement; Chrysanthemum

1. Introduction

The final target of environmental control in greenhouses is the optimisation of crop production. The greenhouse cover and heating system cause a change in the climatic conditions compared to those outside, such as increased temperature and water vapour pressure of the air, reduction of radiation and air velocity, and larger fluctuations of the carbon dioxide concentration. These changes have an impact on growth, production and quality of the greenhouse crop (Bakker, 1995). Generally, the control actions in greenhouses are based on temperature and humidity measurements made at a representative location in the greenhouse, either at a fixed height or near the growing point of the crop (Gieling and Schurer, 1995).

In greenhouse cultivation of chrysanthemums, the main heating system is often positioned overhead to facilitate labour. Consequently, the greenhouse climate will not be homogeneous, which under unfavourable conditions can lead to unacceptable high relative
humidity (RH) and/or vertical temperature differences in the crop. The combination of these two can cause condensation on the crop, and consequently, increase the risk of diseases. Moreover, compared to pipes at a lower position, the overhead heating pipes will result in an increase in energy loss from the greenhouse due to increased thermal radiation exchange between the heating system and the roof (Bot and Van de Braak, 1995).

Independently controlled heating circuits at different heights can help to prevent these problems and enable local crop heating to influence crop development in greenhouses, as the temperature has a direct effect on the sink strength with respect to assimilates of the individual parts of the plant (De Koning, 1994; Marcelis and De Koning, 1995). Furthermore, the rate of development (leaf unfolding and flowering) in many crops responds, over a wide range of temperatures, linearly to temperature (e.g. Karlsson et al., 1991; De Koning, 1994). Consequently, local crop heating can be used to control the partitioning of assimilates or to enhance crop development (Verkleij, 1985).

Several authors have reported on vertical temperature distribution in greenhouses. Winspear (1978) concluded that, when the heating pipes in a tomato crop were mounted below the top of the crop, the air temperature above the crop became lower than that in the crop. Yang (1995) found the same for potted chrysanthemums on air permeable benches. Both Winspear and Yang found that leaf temperatures were, in general, below the air temperature in the canopy. Aubinet and Deltour (1993) developed a model to predict the vertical air temperature profile in the plume above a heating pipe. None of these authors considered local leaf temperature effects of the heating pipes. Kempkes et al. (2000) developed a model to predict vertical leaf temperature distribution in a greenhouse tomato crop as a function of the prevailing air temperature. However, no detailed information is available on the temperature distribution in a chrysanthemum crop cultivated in beds. Therefore, to meet the objectives of this study, an experimental approach was chosen in order to determine the effects of the position and use of independently controllable heating circuits on the microclimate and energy efficiency of greenhouse chrysanthemum cultivation. Temperature and humidity distribution were measured under various night time conditions, using three combinations of two heating circuits at varying heights.

2. Experimental setup

In three compartments (numbered 1–3) at the experiment station ‘Zuid Nederland’ in Horst NL: latitude, 51°27′44″N; longitude, 6°01′31″E; altitude, +20 m, two cultivars of chrysanthemums, Sunny Reagen and Red Reagen, were grown during the winter period 1997–1998 with differing configurations of heating pipes. As is common in practice, assimilation lighting was applied. The power of the lamps installed was 4000 W m⁻², which equals 9.2 W m⁻². The artificial light was generally switched on from 6:45 a.m. until the light level outside increased above 200 W m⁻², but the lights were always switched off at sunset. So, on dull days (global radiation < 200 W m⁻²), the lamps were switched on until sunset. The compartments have a black out screen, which was kept closed daily from sunset until sunrise. The compartments have an area of about 300 m² each. There were two crop beds of 1.2 m width per bay of 3.2 m (one with each cultivar) with a plant density of 35 m⁻². Each bed had two heating circuits (upper and lower) with two pipes (27 mm diameter) each. The height of the heating circuits varied between the compartments. In Compartments 2 and 3, the upper circuit, and in Compartments 1 and 3, the lower circuit, were raised gradually from 0.05 to 0.5 m, depending on the stage of the crop. In Fig. 1a–c, the heating system configurations are shown schematically. The cultivation period was divided into two phases, the starting phase, just after planting (16 December 1997–26 January 1998) to create an equal crop of sufficient size to apply different treatments, and the test phase until harvest (26 January 1997–10 March 1998) in which the effects of different treatments are investigated. During the starting phase, the heating was controlled in such a way that differences in greenhouse climate (temperature and humidity in the climate control measuring box) between the compartments were minimised, despite the differing pipe configurations. As the plants are small, especially in the beginning of the starting phase, the maximum temperature of the lower circuit was 38°C during this period in all compartments in order to prevent burning of the leaves.
The treatment and climate control during the test phase are shown in Table 1 and can be characterised as 'traditional' in Compartment 1, 'lower circuit fixed low and upper circuit raised with crop' in Compartment 2 and 'upper and lower circuits raised with crop' in Compartment 3. Apart from the aspirated sensors for climate control, located near the top of the crop, in all three compartments, two additional aspirated dry

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**Table 1**

Overview of the experimental treatments during the test phase

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Compartment 1</th>
<th>Compartment 2</th>
<th>Compartment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of the upper heating circuit</td>
<td>Fixed at 2.65 m</td>
<td>0.5–0.75 m above the crop</td>
<td>0.5–0.75 m above the crop</td>
</tr>
<tr>
<td>Height of the lower heating circuit</td>
<td>Up with grid(^a)</td>
<td>Fixed at 0.1 m</td>
<td>Up with grid(^a)</td>
</tr>
<tr>
<td>Maximum temperature of the upper heating circuit</td>
<td>95°C</td>
<td>95°C</td>
<td>95°C</td>
</tr>
<tr>
<td>Maximum temperature of the lower heating circuit</td>
<td>38°C</td>
<td>60°C</td>
<td>38°C</td>
</tr>
<tr>
<td>Temperature control in the heating pipes</td>
<td>Lower and upper circuit equal until maximum pipe temperature of the lower circuit is reached, then upper circuit</td>
<td>Lower circuit first until the maximum pipe temperature is reached, then upper circuit</td>
<td>Lower and upper circuit equal until the maximum pipe temperature of the lower circuit is reached, then upper circuit</td>
</tr>
</tbody>
</table>

\(^a\) A steel grid (0.1 m x 0.1 m) is used to keep the stems upright as they grow. This grid is resting on the lower heating circuit, which is raised every 2 weeks.
and wet bulb temperature sensor sets were installed at heights of 0.15 and 2.2 m for temperature and humidity measurements (Fig. 1). In Compartment 2, leaf temperatures were measured by 56 thermocouples, distributed over 3 m of bed length and width, and crop height. Another five thermocouples in Compartment 2 measured soil temperatures at a depth of 0.1 m over half a span width (1.6 m). As a limited amount of equipment was available, only one compartment could be considered for the detailed measurements. Compartment 2 was chosen because the high maximum temperature of the lower heating circuit in the crop would show the largest influence on the crop temperature distribution. An automatic datalogging system and computer network collected all temperatures. During the experiment, several times leaf area index (LAI) and the length and weight of stems were determined.

3. Results

3.1. Microclimate and crop temperatures

The air temperature and humidity measured in the aspirated boxes showed, averaged over the test phase period, large differences between the compartments (Table 2). In the lower layers of the crop, the air temperature of Compartment 2 is almost 3°C higher than in the other two compartments and the RH in the lower part of the greenhouse is about 7% lower in Compartment 2 than in the other two compartments. The sensors used for climate control in the three compartments (0.75–1.2 m height) with equal temperature set-points show almost equal temperatures (maximum difference 0.5°C).

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Compartment 1</th>
<th>Compartment 2</th>
<th>Compartment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_a$ (°C)</td>
<td>RH</td>
<td>$T_a$</td>
</tr>
<tr>
<td>0.15</td>
<td>17.2</td>
<td>91.6</td>
<td>19.9</td>
</tr>
<tr>
<td>0.75–1.2</td>
<td>19.4</td>
<td>77.0</td>
<td>19.9</td>
</tr>
<tr>
<td>2.25</td>
<td>20.3</td>
<td>72.8</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Fig. 2a shows the outside air temperature and the global radiation versus time during 2 days with low temperatures. The first day is sunny, so the artificial lighting in the compartments was switched off between 10:00 a.m. and 4:00 p.m. On the second day, the global radiation was low and the lights were switched on until sunset. Fig. 2b–d show air temperatures (in the aspirated boxes) for these two days at a height of 2.2, 0.9 and 0.15 m, respectively. At a height of 2.2 m (Fig. 2b), Compartment 3 had systematically the highest temperature during the night, caused by the heating system that was located below the measuring box. In Compartment 2, more heat was supplied in the lower part of the crop just above the ground, while in Compartment 1, the upper heating system was located at 2.65 m, above the temperature sensors that were at a height of 2.2 m. As a consequence, the vertical temperature gradient of about 3.5°C in the crop of Compartment 1 reduces to about 0.5°C in Compartment 2.

As during the daytime, air mixing above the crop level was good, air temperatures at equal heights differed less between the compartments than at night when less air mixing occurred. On the first day, the daytime air temperature became high due to the sunny weather. Cloudiness on the second day resulted in a daytime greenhouse air temperature around the set-point of 18.5°C. At a height of 0.9 m (Fig. 2c), the temperature difference between compartments was small because the climate control was based on the temperature at this height (0.4°C of the difference was caused by an off set of the control sensor of Compartment 1).

At a height of 0.15 m (Fig. 2d), the differences between the Compartments 1 and 3 were small, but in Compartment 2, where the lower circuit at a height of 0.10 m was the primary heating system, the average air temperature at 0.15 m was about 2.5°C higher. This also has consequences for the RH at this height, which was 7% lower in Compartment 2 than in Compartments 1 and 3. The absolute humidity at this height is higher in Compartment 2 (average 11 g kg$^{-1}$), compared to Compartments 1 and 3 (average 10 g kg$^{-1}$).

The low position of the heating pipes in Compartment 2 and its use as the primary heating system increased the soil temperature (about 1.3°C higher) and the evaporation of water from the soil.

For a period with higher outdoor temperatures (Fig. 3a), when less heating is required, the trends are
similar to those at low outdoor temperatures (compare Fig. 3c and d with Fig. 2c and d). Due to the lower heating requirement, at a height of 2.2 m, the effect of the upper circuit in Compartment 3 disappeared (Fig. 3b) and the difference between the compartments was small (0.1°C), while at 0.15 m (Fig. 3d), the large differences in temperature between compartments were similar to those at lower outdoor temperatures. The latter are therefore apparently less dependent on the outside conditions. On the warmer days, Compartment 2 was on an average almost 3°C warmer than Compartments 1 and 3 at a height of 0.15 m. Due to the higher temperature in the lower crop layers, the RH in Compartment 2 was the lowest — on an average, 83% over the period from 1 March 17:00 hours until irrigation. In both of the other compartments, the average RH over this period was 91%. The absolute humidity in Compartment 2
was, however, higher — on an average, 12 g kg\(^{-1}\), against 11 g kg\(^{-1}\) in Compartments 1 and 3. During the second night at 4.00 a.m., an overhead sprinkler irrigation system was switched on (marked point in Fig. 3b). This decreased the air temperature in all compartments by about 1°C at 2.2 m (Fig. 3b; an effect of evaporative cooling) and by about 0.5°C in the climate control measuring box (Fig. 3c). In the vertical direction, the temperature differences in Compartment 2 were about 2°C and smaller than in Compartments 1 and 3, where these differences reach up to 4°C. In all compartments, the vertical temperature differences above the crop were small.

The leaf temperatures that were measured in Compartment 2 have been grouped in five horizontal layers with centres at 0.06, 0.24, 0.36, 0.55 and 0.64 m...
Fig. 4. Dew point, air and crop temperatures at two levels in Compartment 2 on 26 January at 17:00 hours to 28 January at 17:00 hours: (a) lower half — dew point at 0.15 m (---), dry bulb temperature at 0.15 m (--), plant temperature at 0.06 m (----), plant temperature at 0.24 m (--), plant temperature at 0.36 m (--); (b) upper half — dew point at 0.9 m (---), dry bulb temperature at 0.9 m (--), plant temperature at 0.55 m (----), plant temperature at 0.64 m (--).

and averaged to obtain vertical temperature profiles for the flower-bed at the end of January. Fig. 4a and b show the dew point, the air and the crop temperature that are, respectively, low and high, in the crop of Compartment 2 for the same cold period as that shown in Fig. 2. In Fig. 4a, the leaf temperatures at heights of 0.06, 0.24 and 0.36 m are presented together with the air temperature and dew point temperature at a height of 0.15 m. The leaf temperatures at 0.24 and 0.36 m were almost equal and above the air temperature, while the crop temperature of the lowest layer of leaves (centre at a height of about 0.06 m) was always below the air temperature. During the night, the temperature differences between the leaves and the air were relatively large (up to 2°C), but during the daytime, these differences were very small.

In Fig. 4b, the leaf temperatures at heights of 0.55 and 0.64 m are presented together with the air temperature and dew point temperature at a height of 0.90 m. Fig. 5a and b are similar to Fig. 4 but for the warmer period of 1–3 March. As the crop was higher here, the leaf temperatures are grouped in six layers with centres at 0.06, 0.24, 0.36, 0.54, 0.67 and 0.79 m. The temperature profiles in this period are almost similar to that during the colder days, but as less heating was required, the temperature differences in the crop were consequently smaller. The crop temperature never dropped below the dew point temperature, so no condensation occurred. When irrigation was switched on (second night, about 4.00 a.m.), only a small decrease was observed in the air and plant temperatures, but a significant increase (4°C) was observed in the dew point temperature. Thereafter, it took many hours before the dew point temperature became lower than the leaf temperature again. Consequently it took a long time before the crop got the opportunity to dry. In Compartments 1 and 3, this unfavourable situation lasted even longer because the maximum temperature of the lower circuit was limited to 38°C instead of 60°C. Table 3 shows the averages of leaf, dew point and air temperature for both periods.

3.2. Heating requirement

To compare the heating requirements of the three compartments, the energy input during the test phase is determined by cumulating the calculated heat transfer from the heating system to the greenhouse air:

\[ Q = \sum \left( (\alpha_l A_l (T_l - T_a) + \alpha_u A_u (T_u - T_a)) t \right) \]
where $Q$ is the energy supplied per m$^2$ greenhouse area in J m$^{-2}$, $\alpha$ the heat transfer coefficient of the heating pipe in W m$^{-2}$ K$^{-1}$, $A$ the surface area of the heating pipe per m$^2$ greenhouse area in m$^2$ m$^{-2}$, $T$ the temperature in K and where $t$ is the time period in s in which the temperatures occur. Subscript $l$ indicates the lower and $u$ the upper heating system and $a$ the air near the heating pipe. The heating requirement during the test phase (26 January 1997–10 March 1998) for Compartments 2 and 3 was 89% compared to Compartment 1, where the traditional overhead heating system was mounted. As expected, the configurations with the heating systems at a lower position used less energy.

### 3.3. Crop response

Between the three compartments, no significant differences occurred in leaf area index, and length

**Table 3**

Average temperatures (in °C) of leaves, dew point and air and the absolute humidity (in g kg$^{-1}$) in the crop at various heights during a cold period (26 January at 17:00 hours to 28 January at 17:00 hours) and a warm period (1 March at 17:00 hours to 3 March at 03:00 hours) in Compartment 2

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Cold period</th>
<th>Warm period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leaves</td>
<td>Dew point</td>
</tr>
<tr>
<td>0.0–0.15</td>
<td>15.8</td>
<td>19.3</td>
</tr>
<tr>
<td>0.15</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>0.15–0.30</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>0.30–0.45</td>
<td>19.4</td>
<td></td>
</tr>
<tr>
<td>0.45–0.60</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td>0.60–0.75</td>
<td></td>
<td>13.8</td>
</tr>
<tr>
<td>&gt;0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
and weight of stems. Nor was any difference found in flower quality. In Compartment 2 with the high maximum temperature (60°C) of the lower heating circuit, leaf burning occurred to a small extent where the leaves touched the heating pipes. As these were the lowest leaves, they could be removed without loss of quality.

4. Discussion

The results show that, in general, the air temperatures above the crop were higher than within the crop, especially in Compartment 1 with the heating system mounted overhead. When the primary heating system is mounted low in the crop, the greenhouse air temperature above the crop can be decreased by about 1.5°C. This is in agreement with the temperature profiles Winspear (1978) reported for overhead and ground level heating pipes. Yang (1995) found that air temperatures above a crop of potted chrysanthemums on permeable benches were lower than within the crop in experiments where all of the heating power was supplied below the benches. This agrees with our observation in Compartment 2 and the general expectation that the more the heat supplied in the lower part of the crop or below the crop, the greater is increase in the air temperature within the crop with respect to the temperature above the crop.

The leaf temperatures were very close to the air temperatures within the crop. When the heating requirement is high (low outside temperatures), the leaves have slightly higher temperatures than the air, and during warmer periods, the leaves are slightly colder than the air. Yang (1995), who used a heating system under benches with potted chrysanthemums, found that leaf temperatures were generally below the air temperature within the crop, and Zhao et al. (1985) measured leaf temperatures that were higher than air temperatures when using infrared heaters and vice versa when using air heaters. This shows that, if sufficient heat is supplied to the crop, either by heating pipes or by infrared radiation, the crop temperature will be at least locally above the air temperature. This provides, on the one hand, a means of control to prevent condensation on the crop, and thus, reduce the risk of diseases, and on the other hand, a tool to influence the growth and development of the crop. In our experiments, however, the latter was not noticeable as no significant difference was found between the crops in the three compartments.

The heat transfer coefficients we used in our calculation of the heat consumption are, in general, dependent on the direct environment of the heating pipes. As this environment is similar for the three compartments and the outcome is applied in a comparative way, this method can be used without introducing larger errors than when using standard flow meters combined with the measured temperature difference over the heating system (Knies et al., 1999). As a result of reducing the air temperature above the crop, the heating requirement during our test phase decreased by about 11%. Accounting for the distribution of the energy demand over a year, the energy conservation will be about 7–9% for a whole year. Nijeboer and Van Holsteijn (1981) reported a much larger reduction of 20%; but they examined one cold day only, which is not representative for a longer cultivation period with varying conditions.

5. Conclusions

The following conclusions can be drawn:

- The three configurations of heating systems for chrysanthemums that were investigated provide higher air temperatures above the crop than within, but the air temperature above the crop can be decreased by a few degrees when the primary heating system is mounted low in the crop.
- With crop heating as the main heating system, the heating requirement will decrease by 7–9% on a yearly basis as a result of the reduced air temperature above the crop.
- The combination of an upper heating circuit at 0.50–0.75 m above the top of the crop, and a lower circuit as the primary heat source will reduce vertical temperature difference in the air and in the crop. When the upper circuit is used as a primary heater, the temperature profile is the same as with the traditional system.
- Using the lower circuit as a primary heating system reduces the RH in the lower layers of the crop. It reduces the risk of condensation on the crop and enables the crop and air to dry quicker after irrigation.
Acknowledgements

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